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Proceedings from the Seventh International Conference on Fires in Vehicles

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Abstract

This report includes the Proceedings of the 7th International Conference on Fires in Vehicles – FIVE 2023, held in Stavanger, Norway, April 24-25, 2023. The Proceedings includes 21 papers given by speakers in 8 different sessions: Fire development, Bus fires, 3 sessions on Alternative fuels, Car park fires, and 2 keynote sessions. Each day was opened by invited keynote speakers addressing broad topics of interest. In addition, 6 extended abstracts are included in the proceedings presenting posters exhibited at the conference.

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Preface

These proceedings include papers and extended abstracts from the 7th International Conference on Fires in Vehicles – FIVE 2023, held in Stavanger, Norway, April 24-25, 2023. The proceedings include an overview of research and regulatory actions coupled to state-of-the-art knowledge on fire related issues in vehicles, such as passenger cars, buses, trucks and trains, or related infrastructure, such as car parks or vehicle transport at sea.

Fires in transport systems are a challenge for fire experts. New fuels that are efficient and environmentally friendly are rapidly being introduced, with emphasis on high energy density batteries. This rapid development, however, introduces new fire risks not considered previously and we risk getting a situation where we do not have enough knowledge to tackle them. In this context FIVE represents an important forum for discussion of the fire problem and for exchange of ideas.

Fire protection in road, rail, air, and sea transport is based on international regulations since vehicles cross borders and the safety requirements must be the same between countries. Therefore, understanding of safety and regulations must be developed internationally and the FIVE-conference has a significant role to play as a place to exchange knowledge. FIVE attracts researchers, operators, manufacturers, regulators, rescue services and other key stakeholders. Of particular value is the mix of expertise and the international participation in the conference. The conference is unique as it includes fires in different types of vehicles. In recognition of the fact that many of the fire problems faced by these vehicles are the same, the solutions to them can also be similar.

In the proceedings you will find papers on vehicle fire development, bus fires, alternative fuel and electric vehicles, and car park fires. We are grateful to the renowned researchers and engineers presenting their work and to the keynote speakers setting the scene. We sincerely thank the scientific committee for their expert work in selecting papers for the conference.

Petra Andersson
Chair FIVE 2023 Scientific Committee

Ola Willstrand
Chair FIVE 2023 Organizing Committee

Note: the views expressed in the papers are those of the authors and not necessarily those of RISE Research Institutes of Sweden.
Table of contents

Keynote speakers

Car Park Fires: A Review of Fire Incidents, Progress in Research and Future Challenges.  
Dr. Christoph Meraner, RISE Fire Research, Norway

Vehicle fire suppression systems – retrospect, current and future regulation initiatives  
Fredrik Rosén, Dafo Vehicle Fire Protection, Sweden

A guide concerning "Risk assessment and handling of fire in Lithium-ion batteries"  
Kjetil Solberg, The Norwegian Directorate for Civil Protection (DSB), Norway

Fire development

Experimental investigation of the HRR of modern ICE vehicles  
Jean-Baptiste Tramoni1, Christophe Fraud2, Mathieu Suzanne3, Gildas Auguin4, Christophe Thauvoye1 and Bin Zhao1,  
1CTICM  
2GagnePark  
3LCPP  
4Efectis, France

Fire, Due to Improper Maintenance  
Robert Bruce McKay*, McKay Forensic Investigations, Australia

An Analysis of Cabin Exhauster Vents and Body Structure Pass-Throughs in Post-Collision Vehicle Fires  
Christopher Clarke*, Brian Herbst, Lauren Bell, Christopher Newton, Jack Bish, SAFE, USA

Bus fires

Fire safety of Zero Emission Buses depots: fire prevention and incident response  
Nils Rosmuller* and Johan Reinders, NIPV, The Netherlands

Development of toxicity assessment method for bus interior materials  
A. Klippel1*, A. Hofmann2, K. Piechnik1, T. Gnutzmann2,  
1Otto von Guericke University Magdeburg,  
2Bundesanstalt für Materialforschung und -prüfung, Germany

Fire safe bus interior materials – flame retardants and the effect on smoke production and smoke gas toxicity  
Anna Sandinge*, Per Blomqvist, Henrik Fredriksson, RISE Research Institutes of Sweden, Sweden
Alternative fuels 1
(Fire) statistics on incidents with alternative fuel vehicles in The Netherlands
Tom Hessels*, NIPV, The Netherlands

Fire suppression and manual firefighting of battery electric vehicle fires on ro-ro ships
Magnus Arvidson¹, Jonatan Gehandler¹* and Jaime Bleye²
¹RISE Research Institutes of Sweden
²Centro de Seguridad Maritima Integral Jovellanos, Spain

Large-scale tests of firefighting technologies for extinguishing electrical vehicles on board of ro-ro ferries
Thushadh Wijesekere*, Elena Funk, Konrad Wilkens, Bjarne Husted, Danish Institute of Fire and Security Technology, Denmark

Alternative fuels 2
Fire Suppression Studies on Large Lithium-ion Batteries
Judith Jeevarajan, Taina Rauhala, Mohammad Parhizi*, UL Research Institutes, USA

Study on Water Injection Methodology Applied to Lithium-Ion Battery Fires
David Sturk¹,², Per Ola Malmquist¹*, Lena Håkansson³
¹Swedish Civil Contingencies Agency (MSB)
²AB Sturk Consulting
³Cold Cut Systems, Sweden

Li-ion battery full scale thermal runaway test: environmental and personnel exposure influence in case of rescue operations
Marco Aimo-Boot¹*, Marco Pazzi -Valter Maurino², Fabrizio Malaspina³
¹Iveco Group
²University of Turin
³Italian National Fire Corp, Italy

Alternative fuels 3
Analysis of combustion gases and fire water run-offs from passenger vehicle fires
Jonna Hynynen*, Maria Quant, Ola Willstrand, Tove Mallin, RISE Research Institutes of Sweden, Sweden

Fire Performance of a Cryogenic UN-T75 Storage Tank: Phase II – LNG
Jason Huczek¹*, Kyle Fernandez¹, Marc Janssens¹, Bill Bendele¹, Keith Friedman², Garrett Mattos²
¹Southwest Research Institute (SwRI)
²Friedman Research Corporation (FRC), USA

Fire propagation and temperature distribution in the vicinity of CNG fuel tanks during a bus fire
Václav Vystrčil¹,²*, Lucie Hasalová¹, Jan Karl¹, Milan Jahoda²
¹Technical Institute of Fire Protection in Prague
²University of Chemistry and Technology, Prague, Czech Republic
Car park fires

Hazards of EVs in the built environment and firefighting tactics
Victoria Hutchison, FPRF, USA

Fire safety in semi-automatic parking systems
Ellen Synøve Skilbred*, Ole Anders Holmvaag, Vidar Stenstad, Janne Siren Fjærestad, Tian Li, RISE
Fire Research, Norway

Fire safety engineering case study of an electric vehicle car park fire
Bertrand Girardin, Virginie Driane*, Mohamad El Houssami, Efectis, France

Posters

Submerging container and its possible alternatives: a comparative assessment study
Tom Hessels, Netherlands Institute for Public Safety, The Netherlands

Bench-scale fuel fire test for materials of rechargeable energy storage system housings
Carl-Christoph Höhne*, Volker Gettwert, Andreas Menrath, and Sergej Ilinzeer, Fraunhofer
Institute for Chemical Technology ICT, Germany

Firewall Design in Buses to Mitigate the Propagation of Engine Fires
Jason Huczek* and Marc, Southwest Research Institute (SwRI), USA

New Initiation Methods for Thermal Propagation Tests of Traction Li-Storages
Tamas Gyulai1, Sebastian Knapp2, Sebastian Mock3, Daniel Pacner4, Sebastian Scharner5
1 Audi AG, Development Cell / Cell module, Germany
2 Fraunhofer Institute for Chemical Technology, Energetic Systems, Germany
3 Mercedes-Benz AG, System Development HV Batteries, Germany
4 Verband der Automobilindustrie e.V., Germany
5 BMW Group, Battery Cell Competence Centre, Germany

On the effect of ventilation conditions in naturally ventilated car parks on fire safety
Christoph Meraner*, Kemal Sarp Arsva and Tian Li, RISE Fire Research AS, Norway

Battery fires: triggering and stopping of thermal runaway on cylindrical lithium-ion batteries
studied with Accelerating Rate Calorimetry
Sebastian Ohneseit1, Philipp Finster1, Nils Uhlmann1, Ethan Schneider2, Carlos Ziebert1, Hans J.
Seifert1
1 Karlsruhe Institute of Technology (KIT), Institute for Applied Materials - Applied Materials Physics
(IAM-AWP), Germany
2 Department of Physics & Astronomy, The University of Texas at San Antonio (UTSA)
Car Park Fires: A Review of Fire Incidents, Progress in Research and Future Challenges.

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ABSTRACT

Fires in road vehicles are common, but a large part is associated with crashes. Of all vehicle fires registered in the USA between 2013 and 2017, 16% have occurred in a parking area and only a fraction of these involved vehicles parked in car parks. Furthermore, car park fires often involve few cars only and do not lead to fatalities. However, major car park fire incidents in the last years have shown that fires can lead to significant property and environmental damage if the fire can spread to a large enough number of adjacent vehicles. Large-scale experiments conducted in the 2000-10s have shown that it can take between 10 to 20 minutes before a car fire spreads to an adjacent car. Essential factors for the fire development are ventilation conditions within the car park, air supply to the burning car’s interior (i.e., breaking windows), and fuel involvement (i.e., breaking fuel tanks, a thermal runaway in lithium-ion batteries or gas releases from pressure release devices). Recent large-scale experiments involving a battery electric vehicle showed fire spreading 5 minutes after the first car was ignited. Thus, early detection and a quick response to the fire are essential to prevent a fire from spreading to multiple cars. Modern cars have become bigger, are thus parked closer to adjacent cars and contain more combustible material, especially plastics. A larger plastic content can increase the fire size of car fires, while an increased share of combustible material on the exterior and a decreased distance between cars may aid a faster fire spread. The increasing share of alternative fuel cars introduces new fire and explosion hazards and poses challenges for extinguishing efforts. However, early detection and quick response time still play an essential role in mitigating the associated risks.

KEYWORDS: car park fires, parking garage fires, fire incidents, car fire statistics, alternative fuel vehicles.

INTRODUCTION

Historically it was long believed that car park fires are associated with low risk as it was expected that a vehicle fire would not spread to one or two adjacent vehicles before it would die out or be extinguished by the fire service. Unfortunately, fire incidents, such as the car park fire in Liverpool and the car park fire at the Stavanger airport, have shown that major fires involving many cars are possible and can lead to significant property and environmental damage. The present paper provides fire statistics relevant to car park fires and reviews selected multi-storey car park fire incidents. Furthermore, relevant research is discussed, with a focus on large-scale fire experiments involving multiple cars, with and without suppression systems. Finally, an outlook of future challenges related to modern vehicles, alternative fuel vehicles and, to a small extent, car park design is provided.
HISTORICAL FIRE DATA

Vehicle fire statistics
NFPA provides extensive data on fire loss in the United States, which contains fire losses in highway vehicles dating back to the 1980s [1]. Highway vehicles refer in this context to the type of vehicle and not the fire location, i.e., vehicles intended for use on roadways. This data shows that fires in road vehicles are common, although the total number of fires has decreased if we compare the last decade with the decades before (see Figure 1). The most significant reduction is observed in the period from 1995 to 2010. The total number of vehicle crashes also decreased during the same period [2]. The reduction of vehicle fires due to an overall increase in road safety is, of course, not relevant for car park fires. Notably, almost two-thirds of car fires that lead to death are attributed to collisions or related events [3]. However, there seems to be a considerable reduction in fire frequency, which is not linked to a reduced crash frequency, as the number of vehicle fires does not follow the trend of crashes in the last decade. The total number of car fires since 2011 is relatively constant, with annual deviations from the 10-year average of around 5% in the USA. The United Kingdom and Sweden follow a similar trend with a larger annual fluctuation of up to 15% (see Figure 2).

Of all vehicle fires registered in the USA between 2013 and 2017, 16% have occurred in a parking area, 135,440 fires in total. For car fires, large trucks and buses, it was 17%, 11% and 14%, respectively [3]. The term parking area is broad. Therefore, the portion of vehicle fires in car parks is less than the presented numbers. Merci and Shipp [6] provide statistics for car park fires specifically. The statistics comprise 3,096 car park fires that have been registered in the UK during 12 years from 1994 to 2005. Of these fires, 52% (i.e., 1,592) had started in a vehicle. On average, 258 fires occurred per year in car parks within buildings. The number of these fires shows a decreasing trend until 2005.

Figure 1  Fires in cars, trucks, motorcycles, buses, recreational vehicles in transit, and other vehicles intended for roadway use [1] compared to vehicle crashes [2].

Figure 2  Yearly change of the number of fires compared to the 10-year average from 2011 – 2021. The data for the USA includes fires in cars, trucks, motorcycles, buses, recreational vehicles in transit, and other vehicles intended for roadway use [1]. The data for the UK includes cars and vans [4] and the data for Sweden includes only passenger cars [5].
Two fatalities were reported during the period. One of the main conclusions was that car park fires rarely spread to additional cars. However, it is pointed out that significant structural damage is possible where the fire can spread to multiple vehicles. A similar conclusion was drawn by Collier [7] based on the New Zealand Fire Service database. In the period from 1995 to 2003, a total of 101 vehicle fires were registered, of which 93 were single-vehicle fires. These statistics seem to confirm the belief from the 70s and 80s that fires in car parks would be confined to a single car or spread only to one or two adjacent cars before the fire service would put the fire out. However, in recent years multiple fire incidents in car parks, well known to the fire safety community, have shown that this assumption is invalid. In recent years, many fire incidents have occurred in car parks, some are provided as examples. Note that most such fire incidents are not well documented, i.e., only referred to briefly in news reports.

Fire in an eight-storey car park in Liverpool, December 2017
One of these fires is the car park fire in Liverpool, England [8]. The fire broke out on New Year’s Eve 2017 in the Kings Dock car park, an open-sided eight-storey car park constructed with precast reinforced concrete. The construction had the following fire resistance (according to the design specifications):
- 15mins fire resistance – open-sided car park.
- 2hr to stair walls/1hr to compartment floors provided by slabs (additional fire protection may be provided by spray applied system).

The fire is believed to have started in a 2002 model Land Rover and spread to a total of 1 200 cars across seven floors. The firefighters reported that the fire involved additional vehicles “every 30 seconds” [8]. The car park had to be demolished due to the extent of the structural damage. An important factor is that it took 27 minutes from the first signs of fire (i.e., smoke recorded by a CCTV camera) until firefighting began.

Fire in a five-storey car park in Cork, August 2019
Two years after the Liverpool fire, another major fire incident occurred. This time, in August 2019, a fire in the Douglas Village Shopping Centre car park in Cork destroyed 49 cars and caused the buckling of steel girders in the structure. It is estimated that the fire reached temperatures of 1 000°C. Much of the car park had to be demolished and rebuilt due to the extent of structural damage. The damage caused by the fire is around 30 million Euros [9,10]. The fire had started in an Opel Zafira B model. The driver noticed smoke coming from the front when she was about to get out of the car after parking it [11].

Fire in a multi-storey car park at Stavanger airport, January 2020
Five months after the Cork fire, another Opel Zafira started a car park fire. The fire occurred in the five-storey car park at Stavanger airport, Norway. This car park consists of three connected buildings, referred to as building A, B and C in the evaluation report by Storesund et al. [12]. The car that started the fire was parked on the ground floor of building B, which is completed in concrete elements with a steel stabilising framework and R60 fire resistance. The adjacent building in the downwind direction was building C, completed in a steel main structure and deck elements consisting of steel plates and concrete. The fire rating for building C was R15 for Columns and R10 for beams. The fire resistance for beams is a deviation from the applicable building code, which prescribed R15 as a pre-accepted performance level. This deviation was deemed acceptable partially on the basis that the open design, with at least 50% open facades, would ventilate hot flue gases well enough to prevent the steel structure from reaching its critical temperature [12,13]. The car that started the fire ignited shortly after it had been started. However, it took eight minutes before the driver contacted the fire service. The fire service reached the car park twenty minutes after the fire had started. The fire was able to spread to the first floor 35 minutes after it had started. Parts of the car park (building C) collapsed 2 hours after the start of the fire. The fire involved 200 – 300 vehicles and damaged a further 1 300 [12].
Fire in a two-storey car park in Märsta, August 2021

One of the most recent fires occurred in Märsta, close to Stockholm, Sweden. Around 200 cars burned in a two-story car park on August 26th 2021. The fire was so intense that the roof collapsed, and the building could not be saved [14].

Note the fires mentioned above do not represent a complete list of large car park fires (i.e., fires involving more than two or three cars). However, all of these fires reached a size which led to the destruction of the car park, showing the potential consequence of car park fires that spread to multiple cars. Historical data has, fortunately, shown that car park fires seldom involve fatalities [3]. The main concern is, therefore, on mitigation of the consequences for property and the environment. The question is: will modern vehicle and car park design lead to an increased number of major car park fires involving a large number of vehicles?

RESEARCH ON FIRES IN PARKING GARAGES

There is a large number of research on car park fires available. A search in the Scopus database1 with the keywords: TITLE-ABS-KEY ( (“car park” OR “parking garage”) AND “fire”) returns 209 scientific articles (data retrieved on March 30th). However, only a few recent full-scale experiments with multiple vehicles are available. This section focuses, therefore, on notable large-scale experiments.

Joyeux [15] (1997) conducted full-scale experiments under a hood to study the fire spread from a Renault Twingo to a Renault Laguna (experiment 9) and vice versa (experiment 10). The radiative feedback from the ceiling jet in these experiments is lower than in actual car park fires since the experiments were carried out underneath a hood, removing the hot combustion gases. The distance between the two cars was 0.7 m. The fire spread to the adjacent car after 8 minutes in experiment 9 and 14 minutes in experiment 10. The first component to ignite on the second car was the rubber in both experiments.

Steinert [16] (2000) conducted six experiments with two and one with three vehicles. The experiments were conducted in a partially open-sided rig with a ceiling height of 4.5 m and a floor area of 35 m². The results from the experiments are summarised in Table 1.

Table 1  Overview of selected experiments from Steinert [16].

<table>
<thead>
<tr>
<th>Experiment ID</th>
<th>Car model</th>
<th>Distance between cars (m)</th>
<th>Time between the ignition of the first and second car (min)</th>
<th>First component to ignite on the adjoining car.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 4</td>
<td>Volkswagen Golf, Limousine Trabant and Ford Fiesta</td>
<td>0.8</td>
<td>14.5</td>
<td>Window rubber / rubberised trim</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>Peugeot 309 and Limousine Trabant</td>
<td>0.4</td>
<td>20</td>
<td>Window rubber / rubberised trim</td>
</tr>
<tr>
<td>Experiment 6</td>
<td>Limousine Trabant and Volkswagen Polo</td>
<td>0.8</td>
<td>7.5</td>
<td>Window rubber / rubberised trim</td>
</tr>
<tr>
<td>Experiment 7</td>
<td>Limousine Trabant and Citroen BX</td>
<td>0.8</td>
<td>12.0</td>
<td>Window rubber / rubberised trim</td>
</tr>
<tr>
<td>Experiment 8</td>
<td>Fiat Ascona and Volkswagen Jetta</td>
<td>0.8</td>
<td>10</td>
<td>Window rubber / rubberised trim</td>
</tr>
<tr>
<td>Experiment 9b</td>
<td>Limousine Trabant and Citroen BX</td>
<td>0.8</td>
<td>28.6</td>
<td>Window rubber / rubberised trim</td>
</tr>
</tbody>
</table>

1 https://www.scopus.com/
Kitano et al. [17] (2000) conducted a full-scale fire experiment on a four-storey car park with a storey height of 2.9 m. In the experiment, twelve cars were placed on each floor. However, the fire was extinguished after eight cars at the ground level were involved. Figure 3 shows the car location within the car park at ground level and provides ignition times for each car.

![Sketch of the car placement in the car park at ground level. Drawing based on [18]. The grey boxes indicate the car's location and include the time of ignition (mm:ss after the first car was ignited). The colour shade indicates the ignition time (lighter shade means early and darker shade is late ignition). The red line marks the closed sides of the car park.](image)

Figure 4 shows the number of cars involved in the fire over time. It can be seen that the fire spread rate increases exponentially until all cars directly adjacent to the initial car are involved in the fire. At this point, six cars have been involved in the fire. It took longer until cars 7 and 8 were ignited. It is unclear if this is partly caused due to a larger distance between the cars (columns separate the cars) and if a beam reduced the exposure of cars 7 and 8 to the radiation from the hot ceiling jet.

![Number of cars involved in the fire over time.](image)

Figure 4: Number of cars involved in the fire over time.

The test campaign by BRE [19] (2010) investigated 12 different scenarios, of which five involved multiple cars:
- Test 1: Three cars
- Test 2: Three cars with sprinklers
- Test 3: Three large cars
- Test 4: Four cars, one of which converted to LPG
- Test 11: Two cars located on a “stacker” frame.

The test campaign was conducted in a parking garage enclosure. One side was fully open with a 0.5 m down stand. In addition, ventilation openings along one side and the back wall were provided. The ceiling was relatively flat, with a height of 2.5 m.

The tests showed that the ceiling temperatures reached 1100°C, after 10 to 20 minutes when the second vehicle was involved in the fire. Once the windows of the second car broke and the interior was involved, the fire quickly spread to a third car, separated by one parking slot from the other two cars. The tested sprinkler system contained the fire to the first car. The experiment on a stacker frame showed the potential very rapid fire spread from the lower to the upper car. A different test conducted by BRE [20] showed that sprinklers could prevent the upper car in the stacker from being fully involved in the fire.

Santangelo et al. [21] (2016) conducted seven experiments with three cars per experiment placed in a chamber constructed with corrugated steel walls. The chamber size was 6.8 m x 11.6 m and had a height of 3.5 m. The study aimed to evaluate the performance of a water mist and a sprinkler suppression system. Both systems were tested for two different nozzle configurations. The central car in each experiment was ignited by a heptane fire below the car to create a challenging configuration for the suppression systems. Note that all fuel and other liquids had been removed from the cars. The authors claim that fuel would only be relevant later in the fire, while the suppression systems are intended to activate much earlier. Both systems, water mist and sprinkler, were able to control the fire, prohibiting it from spreading to either of the adjoining cars.

Tramoni et al. [22] (2020) conducted five experiments involving two cars in each experiment. The experiments were conducted underground. In addition, a 5 m x 5 m large steel structure was built around the cars, with a ceiling height of 2.55 m. The study’s main objective was to assess the thermal load on the steel structure due to car fires involving different alternative fuel vehicles. The alternative fuel car, designated as car 1, was placed between a wall and a second car, which was, in all experiments, an internal combustion car filled with 20 L diesel. The fire was always started in the passenger compartment of car 1. The windows of car 1 were always kept open.

Experiment 1)
This experiment was intended as a reference case. The fire was started in a BMW 5.24 td filled with 60 L diesel and broken windscreen (car 1). The second car was a Volvo S40 I.

Experiment 2)
The fire was started in a Renault Mégane I. A 74 L hydrogen tank, filled to a pressure of 77 MPa, was installed in the upper local, with a line leading to the trunk of car 1, where the thermally activated pressure relief device (TPRD) was located. The outlet of the TPRD was located underneath the car trunk. The adjacent car was a Renault Laguna.

Experiment 3)
The fire was started in a Volkswagen Passat 5.5, which had a 56 l natural gas tank installed in the trunk. The second car was a Ford Mondeo TDCI.

Experiment 4)
Car 1 was a Bolloré Bluecar, a battery electric vehicle using a lithium metal polymer (LMP) battery. Note that this technology differs from the more commonly used lithium-ion batteries (LiB). During the fire, wood pallets were added, attempting to cause a thermal runaway in the battery. The second car was an Opel Zafira I with a broken rear windscreen.
**Experiment 5**
The fire was started in a Renault Clio IV, with broken windscreens, filled with 20 L diesel and a 36 L liquified petroleum gas (LPG) tank added in the trunk. The LPG tank had a pressure relief valve fitted in addition to the TPRD. A tire and two wooden pallets were added to car 1 to increase the fuel load. The adjacent car was a SAAB 9-3 I.

The experiments confirmed the importance of the ventilation conditions inside the car, controlled by the windows’ breaking. The rear window screen broke between 7 and 11 minutes, leading to a more rapid temperature increase. A second important event is the involvement of the fuel (i.e., fuel tank failure or TPRD release). It took longer for the diesel tank in car 1 to fail (24 minutes) compared to the TPRD activation times (17 – 19 minutes). Note that the LPG tank’s pressure relief valve was activated after 6 minutes the first time. The battery in the electric vehicle did not appear to have undergone a thermal runaway. However, the investigated technology does not represent the most common battery electric vehicles (BEVs) using LiBs. In all experiments, the second car ignited shortly (around 2 minutes) after the fuel of car 1 was ignited. The fuel tank for the second car failed between 11 and 25 minutes after the car ignited. The study showed a rapid temperature increase for all TPRD releases, although the release durations are relatively short. Note that no car was parked adjacent to the trunk of the alternative fuel cars. It can, therefore, not be concluded if the jet fire from the TPRD release would increase the fire spread to other cars. The authors conclude: “These tests suggest that the stability of the structure is not adversely affected by the type of vehicle.”

The **ELBAS project [23] (2022)** conducted nine experiments within a test rig constructed with two 40 ft ISO shipping containers and an additional roof. The rig was 12.2 m x 7.13 m x 2.4 m in dimensions and had two fully open sides. In each experiment, one BEV was surrounded by eight internal combustion engine vehicles (ICEVs) containing no fuel or other liquids. The lateral distance between cars was 0.4 m, and the frontal distance was 0.2 m. In total, seven Renault Fluence ZE (22 kWh), one 2021 Tesla Model 3 (55 kWh) and one 2011 Nissan Leaf (24 kWh) were burned. The experiment’s objective was to evaluate different firefighting techniques for BEV fires on the deck of passenger ferries. All batteries were at 100% state of charge (SoC), except the battery in experiment 4, which was overcharged to 130%. It was attempted to initiate a thermal runaway by short-circuiting the battery. A diesel pool fire beneath the battery was used to aid the initiation of the thermal runaway in some experiments, where short-circuiting did not succeed in starting it. The fire was not in all experiments able to spread to adjacent cars before the start of the firefighting ten minutes + detection time after ignition. The time it took to spread to other cars varied. The fastest flame spread was observed in experiment 4, where the fire spread five minutes after the ignition of the BEV.

The study tested indirect and direct cooling methods, showing that direct cooling of the battery was the most efficient in lowering the battery temperature. However, some tools (e.g., to penetrate the battery) may be challenging to operate in a crowded parking space with tightly parked cars. Cooling with a water mist system showed to be very effective in preventing the fire from spreading to other vehicles but not in fully extinguishing the BEV fire. Early detection is essential for stopping the fire from spreading for all tested methods.

A similar experiment was conducted in another research project, **LASH FIRE [24]**. The main aim of this experiment is to evaluate the effectiveness of manual firefighting in a ro-ro space. During the experiment, a single BEV and two ICEVs were placed inside a simulated ro-ro environment (a building with openings less than 10% of the total area of the space sides). The fire was initiated by a liquefied petroleum gas burner located underneath the BEV. At 10 min, the fire was manually intervened with a 25 mm water hose. However, the fire could not be fully extinguished, and the intervention had to be stopped. At 13 min, the second attempt was made with one 25 mm hose and a fog nail on a 45 mm hose, which successfully extinguished the fire. Note this is still an ongoing study. More details concerning this experiment will be published soon.
THE CHALLENGES AHEAD

NFPA issued a report [25] investigating and evaluating the fire hazards associated with modern vehicle fires in car parks. The main focus was on the following development:

- Vehicles are becoming larger, increasing the amount of combustible material and reducing the distance between adjacent parked vehicles.
- The use of polymers and other combustible materials in vehicle construction and hence the relative energy content in vehicles has increased.
- Alternative fuel vehicles, until now, mainly BEVs and plug-in hybrid electric vehicles (PHEVs), but vehicles using gas (e.g., compressed natural gas (CNG) or hydrogen-electric) are replacing vehicles driven by liquid fossil fuels.

In addition to changing vehicles, one can also expect the development of car park design to affect the fire risk. Important factors are design aspects that change overall ventilation conditions, fire load and local factors such as distance between cars. The following sections discuss these four issues.

Vehicle size

Many markets have seen an increase in larger and heavier personal vehicles, increasing the potential fuel load per vehicle [25,26] and decreasing the distance between cars, a crucial parameter for how fast a fire can spread in a car park [27,28]. One example of increased car size is the global success of sports utility vehicles (SUVs). SUVs became popular in the USA in the 1990s and became the most-sold car class worldwide in the mid-2020s [29]. Figure 5 shows the increasing registration of SUVs in key car markets.

![Figure 5](image-url)

Figure 5  New registrations of SUVs in key car markets, 2010 – 2021. [30]

A typical parking space in the EU is 5 m x 2.5 m, in the UK 2.4 m x 4.8 m and in the USA 5.48 m x 2.44 m) [31]. Larger vehicles for a given parking space size lead to a reduced distance between cars. The reduced distance will, furthermore, affect the fire spreading rate and the working conditions for firefighters. The accessibility to individual cars is essential if larger specialised equipment is used, for example, to extinguish BEVs as tested in the ELBAS project [23].

Plastics and other combustible materials

The content of combustible material in a car increases with increasing car size. In addition, an increase in the relative plastic content was observed until around 2009, reaching an average weight of 173 kg before falling slightly to between 140 kg and 160 kg in the last ten years [25]. Figure 6 shows considerable variation in the reported peak heat release rate (HRR). It is, therefore, difficult to
establish a clear correlation between the model year and HRR, which was also found by Tohir and Spearpoint [26] after collecting a large number of vehicle fire test data.

![](image)

**Figure 6** Average plastic content in light vehicles in the USA (left) based on [25]. Peak heat release rate (HRR) obtained in different fire tests. The year corresponds to the car model. “Light” cars (L3, L4), “compact” cars (C2, C3, C4) and “medium” cars (MED2, MED3) from [26]; ICE-A, ICE-B, PHEV-C, PHEV-D, BEV-A 2013, BEV-A 2014 and BEV-B from [32]; Test 7 from [19]; Nissan Leaf and Honda fit from [33]. For some of the tests, no precise year was given.

It can be assumed that the larger relative plastic content in modern vehicles will lead to a higher relative mass loss during a fire which can be seen in Figure 8 (left). Boehmer et al. [33] proposed the hypothesis that newer vehicles are, therefore, more likely to result in large fires as they contain more material that will be consumed in a fire (see Figure 8 right). However, the authors point out that older and smaller vehicles can potentially lead to high peak HRR.

![](image)

**Figure 7** Peak heat release rate vs mass loss fraction with bubble size indicating the total heat release (left). Peak heat release rate vs total mass loss with bubble size indicating curb weight. Based on data collected by Boehmer et al. [34].

For vehicle fires in a car park, it is essential to distinguish between the location of plastic components. Combustible material in the car’s interior will contribute to the fire size. However, as seen in the literature, fire spreading often involves the exterior trim, window rubber and other combustible material on the car’s exterior. Hence, it can be expected that a larger amount of combustible materials on the exterior of vehicles will aid a more rapid spreading of fires in car parks.

Plastic fuel tanks are an important factor in the vehicle fire hazard due to a breaking fuel tank’s impact on fire growth, as shown by Tramoni et al. [22]. Plastic tanks have been discussed by Boehmer et al. [25] but have become standard in today’s car market. Therefore it is not expected to see a significant change in the future.
The plastic content has been more stable between 2009 and 2018, as seen in Figure 6. However, two factors may drive the amount of plastic and other combustible material further up in the future. One is the increasing demand for fuel-efficient cars as a response to the threat of climate change [35]. More stringent government regulations on fuel efficiency provide the incentive to reduce vehicle weight by supplementing metals with plastics and composite materials. The other driving factor is the increasing popularity of alternative fuel vehicles, specifically PHEVs and BEVs, which will be further discussed in the next section. Electric vehicles (EVs) have a different material composition and use more thermoplastics than ICEV [36], as seen in Figure 8. However, a large part of the different material content is attributed to the battery. Therefore, monitoring the plastic content in vehicles, as Boehmer et al. [25] did up until 2018, may not have the same implications for vehicle fire safety hazards as in previous years.

![Figure 8](image.png)

**Figure 8** Cumulative sales weighted average material composition for ICEVs and BEVs. Figure reprinted from Sun et al. [36].

**Alternative fuel vehicles**

**Battery electric vehicles and plug-in hybrid electric vehicles**

The share of alternative fuel vehicles, specifically PHEVs and BEVs, in the global passenger car fleet has increased considerably within the last few years. Especially Chinas EV market has been booming, with a 162% increase in EV sales in 2021 compared to 2020 (see Figure 9). It can be expected that BEVs will be the dominant technology as it has shown a faster growth rate compared to PHEVs [37].
Norway has the largest share of EVs in its fleet. In 2022, 21% of all registered passenger cars in Norway were EVs [39]. The Norwegian market has seen a decrease in petrol and diesel cars since 2016 and an increase in EVs and “other fuel” cars, representing mostly hybrid cars (see Figure 10 left). Looking at the fire statistics within the same period, we can see a relatively small number of EV fires (see Figure 10 right). When considering the larger number of petrol and diesel cars compared to EVs and hybrid cars, we see that, on average, 20% of the car fires from 2016 to 2022 involved EVs (see Figure 11). Note that this does not consider important factors, such as the car’s age, the reason for the fire (e.g., collision) or the involvement of the battery pack. Nevertheless, it is not to be expected that the number of car park fires will increase due to the increased number of EVs. On the other hand, car park fires involving EVs will increase.
EVs will still affect the car park fire risk, even though a larger share of EVs will likely not increase the fire frequency. This is because of the different fire hazards attributed to a LiB, the dominant technology, compared to a petrol or diesel tank. A LiB fire is generally attributed to a thermal runaway, an uncontrolled exotherm process in the battery that consumes the components in battery cells. Once a LiB reaches a temperature around 70°C, for example, due to an internal failure, a short circuit caused by mechanical abuse or the heat flux from an external fire, an exotherm reaction starts involving the anode and electrolyte. If heat losses to the surroundings do not offset the generated heat, the temperature will increase further. At a temperature between 90°C and 120°C, CO₂ and flammable hydrocarbons are formed. The separator between the anode and cathode melts at 135°C to 166°C, which can lead to an internal short circuit. Some separators may sustain higher temperatures. The cathode starts to decompose at higher temperatures, releasing oxygen. Once the temperature increases by 10°C/min we refer to the event as thermal runaway. [41]

LiBs are constructed based on multiple cylindrical, pouch or prismatic cells combined in battery modules. A battery pack consists of several such modules. Hence, how a LiB fire evolves depends on how the thermal runaway propagates from cell to cell, which differs based on the battery design. Several studies have conducted fire tests with single EVs [32,33,42–44], showing a comparable HRR for EVs and ICEV, which also can be seen in Figure 6. Plastics within the battery and the flammable electrolyte will contribute to the combustion. However, a concern are the gases formed during the thermal runaway, which are vented from the battery, leading to jet flames if ignited. A lithium-ion battery cell typically releases 1-2 litres of gas per Ah [45], containing toxic and flammable (hydrocarbons and hydrogen) components [42]. These gases, if ignited, form a jet flame with relatively high momentum, although the duration is short compared to the duration of a complete vehicle fire. Little research on fire tests involving multiple cars, including EVs such as the ELBAS [23] and LASH FIRE [24] projects, is available. Therefore, it is unclear if such directional fires can increase the fire spread rate in car park fires. The peak HRR (PHRR in MW) form LiB fires can be estimated based on the battery’s energy content ($E_B$ in Wh) $PHRR = 2E_B^{0.6}$ [46]. Therefore, the fire risk is largest for fully charged batteries, i.e., the state of charge (SOC) is 100%. However, the explosion risk associated with releasing flammable gases may be larger for lower SOC. This has, however, not been studied at system level. The explosion hazard of LiB is an important factor as it is not clear how it will affect the statistics for car park fires which historically have involved few casualties. Explosions are a primary concern for firefighters working close to the vehicle on fire. The above-discussed hazards are related to an EV fire involving the LiB. This can be the case if:

A) the fire started within the LiB, or
B) the fire has spread from the car to the LiB.

In scenario A, the LiB burns before any other vehicle is involved in the fire. As discussed in the present paper, detecting and initiating extinguishing or suppression efforts early is essential, as the fire spread rate increases with the number of vehicles involved [23]. Real-world incidents have shown that it is difficult to fight car park fires once a larger number of vehicles are involved. The onset of thermal
runaway is normally not observable from the outside before the LiB starts venting. A LiB fire can therefore develop very rapidly.

In scenario B the EV and potentially other vehicles are already burning when the LiB gets involved in the fire. Therefore, it can be assumed that the explosion risk is lower compared to scenario A. It is important to note that LiBs in EVs are designed to withstand thermal abuse. Different standard tests are employed to ensure fire resistance. For example, the fire resistance test in R100 Anex 8E [45] requires that the LiB pack is exposed to external flames for 2 minutes. The test is passed if there is no evidence of explosion or fire for at least 3 hours or until the surface temperature reaches ambient temperatures after the exposure. The test can also be performed on vehicle level, where it does not pose a major challenge, as shown by Bischop et al. [47]. It typically takes 25 – 40 minutes before the LiB starts burning. The good thermal insulation of LiB packs is, on the flip side, challenging for extinguishing efforts because it makes efficient cooling from outside the battery difficult [23].

Several researchers are also concerned with the toxicity of EV fires. Willstrand et al. [42] compared gases released from EV and ICEV fires, showing that several toxic gases, including hydrogen fluoride (HF), are released independent of the vehicle type. However, the amount of HF released from EVs is larger compared to ICEV.

**Hydrogen**

Biogas and hydrogen vehicles have been considered promising alternatives to liquid fossil fuel due to the generally increasing demand for alternative fuel vehicles combined with the rapidly increasing demand for lithium, cobalt, and nickel used in EVs [48]. However, gaseous fuel vehicles involve different fire and explosion hazards than petrol and diesel vehicles. Hydrogen requires special attention to be safely used in vehicles due to its low minimum ignition energy and vast flammability range and is thus the focus of this section.

There are different ways to store hydrogen; the most common method for vehicles is storing in high-pressure tanks, where hydrogen is typically compressed up to either 35 MPa or 70 MPa at ambient temperature. When a hydrogen tank is exposed to an external heat source, which would be the case in a car park fire, it is important to mitigate pressure build-up, avoiding a tank rupture. This is done by employing a thermally activated pressure relief device (TPRD), allowing the controlled release of hydrogen. The TPRD reduces the chance of a catastrophic tank rupture greatly. However, such a rupture may still happen due to various reasons, e.g., TPRD failure [49]. In the case that the TPRD opens due to the heat exposure of a car park fire, one scenario is that the released hydrogen will immediately ignite and form a jet fire. How such a jet fire affects fire spread between cars has not been tested in full-scale experiments. The TPRD in the experiments performed by Tramoni et al. [22] was not directed towards the adjacent car. Note different release directions are possible, but it is prohibited to have horizontal releases [50].

Another scenario is a delayed ignition, which can lead to an explosion or detonation. Such a delayed ignition is one of the most hazardous situations in a confined space. Thus, it has been studied extensively. Many studies focus on understanding the dispersion of hydrogen in confined spaces, particularly the effects of ventilation and obstacles, using numerical simulations [51–54] and experiments [55,56].

**Car park design**

There is less evidence for a clear direction in the future development of car parks. However, the densification in cities can be a driving force for optimising car park capacity per floor area. One approach to achieve this is employing stacking systems. These can be fully automatic or semi-automatic systems. Both systems have in common that they increase the fire load and complicate working conditions for firefighters.

In order to increase the capacity, it is also desirable to design car parks with long spans, providing column-free parking space. These constructions require large beams that can trap hot combustion
gases and form pockets [57]. How the ceiling construction affects the fire spread rate in modern car parks has so far not been studied in large-scale experiments.

Modern vehicles provide increasing self-driving capabilities. Future cars may provide self-parking, which would allow to reduce the distance between cars significantly [58]. The effect this would have on the fire hazard would, of course, need to be considered.

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REFERENCE LIST


Vehicle fire suppression systems – retrospect, current and future regulation initiatives

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ABSTRACT

Since the mid-1970s, there has been an increased focus on the fire risks related to heavy vehicles. Frequent vehicle fires have driven the development of fire suppression systems and installation in engine compartments from being non-existent to now being commonplace. Developments of standards and legislation have followed, mainly in Europe, North America and Australia, but lately also in the Middle East and India. This development has mainly related to internal combustion engines (ICE). Over the past decade, the technology powering the automotive and transport markets has evolved significantly. The global push for ambitious sustainability agendas has seen a rapid increase in demand for vehicles with alternative energy carriers, such as electric and hybrid electric vehicles, CNG, LNG and hydrogen as environmentally friendly alternatives to traditional, combustion engine vehicles. This shift is mainly supported by the rapidly advancing lithium-ion (li-ion) battery technology, which is now responsible for powering the vast majority of today’s electric transport. However, the fire risks associated with li-ion batteries, principally thermal runaway, have quickly become a growing safety concern for many users, business owners and industry regulators. Evidenced by an array of vehicle battery fires across the globe, occurring as a result of an internal short-circuit inside the li-ion battery, thermal runaway can often lead to toxic gas emissions (often including hydrogen fluoride (HF), carbon monoxide (CO) and carbon dioxide (CO₂) and cyanide), fire and sometimes even large explosions (Christensen, 2023). This paper explores, among others, the findings of pioneering research conducted by Dafo Vehicle Fire Protection (funded under the EU Framework Program for Research and Innovation – H2020 – under the SME Funding Scheme,), which analyses three years of data collection and extensive testing on li-ion batteries and electric vehicles to uncover the optimum criteria for effective electric vehicle fire suppression as current fire suppression systems have failed to effectively deal with li-ion fires.

KEYWORDS: fire, fire suppression, lithium-ion/li-ion batteries, electric vehicles, hybrid electric vehicles, fire protection system, public transport.

INTRODUCTION AND RETROSPECT

Retrospect on bus fire suppression systems

Vehicle fire suppression systems are an effective way to mitigate fire hazards in engine compartments in the case of a thermal event. These systems have evolved from the in the forestry industry in the mid-1970s, where forestry machines caught fires on a fairly frequent basis. In this context, fires mainly originated from the engine compartment due to the challenging environment, which includes flammable liquids, heat and high levels of airflow and in many cases large openings, all of which increase the likelihood and severity of the fire. As a result of this, Swedish insurance companies then made a concerted action requiring that forestry equipment, and any other heavy-duty mobile equipment operating in hazardous environment, would have to be equipped with a fire suppression system in order to receive insurance. The Swedish Fire Protection Association was appointed for
developing the test standard SBF 127 in order to test and evaluate the fire suppression performance of such systems.

A similar scenario also began to emerge for buses and coaches in Sweden. Before 2004, there were approximately six to seven complete burnouts of buses each year in Sweden due to fires that started in the engine compartment. In 2004, Swedish insurance companies made a new concerted action requiring that to receive insurance, all buses had to be equipped with a fire suppression system in the engine compartment. The Swedish Fire Protection Association was appointed for developing the test standard SBF 128 in order to test and evaluate the fire suppression performance of such systems.

In September 2005, a fatal bus fire occurred in Wilmer, Texas, where 23 nursing home passengers were fatally injured. In November 2008 there was a fatal bus fire outside Hanover, Germany, where 20 people were fatally injured. Both these events were a starting point for an increased focus on bus fire safety, both in Europe and in the US. Previously, buses had mostly relied on the efforts of the OEM’s, operators and suppliers of fire systems to ensure safety with few strict regulations, but now fire safety was becoming a more urgent priority.

**Bus fire suppression systems in Europe**

In Europe, the Hanover event led to bus fire safety being introduced on the agenda of the UNECE (United Nations Economic Commission for Europe) Working Group on General Safety Provisions (GRSG). As part of this effort, the Norwegian and the Swedish Road Administrations initiated a bus research project, ‘Bus Fire Safety,’ together with RISE (former SP Technical Research Institute of Sweden) in 2005. In one part, the project explored a test method for fire suppression systems in engine compartments.

During 2010, RISE carried out a pilot study on behalf of the National Road Authority in Sweden, concerning the development of a test method for fire suppression systems in engine compartments in buses and coaches. All results from the study and a first draft of a test protocol were presented in SP Report 2011:22. The project continued, and an engine compartment mock-up was built where the impact of various parameters was being examined. The aim was to design an enclosure with ‘typical’ bus engine compartment characteristics, — enclosure size, hot surfaces, obstructions, ventilation and openings — rather than to create a replica of a specific engine type. In the generic enclosure, different petrol-based fires with various fire sources, airflows, aperture sizes and hot-surface temperatures were initiated that were to test the ability of a fire suppression system. The systems’ nozzles were in a fixed position for all test scenarios.

After a lot of testing with different type of extinguishing agents such as water mist, wet chemical, dry chemical powder etc. the test standard SP method 4912 was published in 2012. The standard contained 11 different test scenarios including a re-ignition test. The standard was presented at one of the GRSG meetings in 2013. Finally, 4 of the 11 tests were adopted by Working Party 29 and published in 2016 in the documents Addendum 106 – UNECE Regulation No. 107 - Revision 6 - Amendment 3 and 5.

As of July 11 2018, it is mandatory to install of fire suppression systems to new vehicle types of single-deck, double-deck, rigid or articulated vehicles of category M2 or M3 and specifically Class III - vehicles having a capacity exceeding 22 passengers in addition to the driver. Class III vehicles are constructed exclusively for the carriage of seated passengers, more commonly referred to as ‘coaches’. The requirement applies in the case of vehicles having an internal combustion engine or a combustion heater located to the rear of the driver's compartment. As of July 11, 2019, this applies to all new Class III vehicles.

As of September 1st, 2020, it is mandatory to install of fire suppression systems to new vehicle types of single-deck, double-deck, rigid or articulated vehicles of category M2 or M3 and specifically vehicles having a capacity exceeding 22 passengers in addition to the driver - Class I and Class II. Class I vehicles are constructed with areas for standing passengers, to allow frequent passenger movement and Class II vehicles are constructed principally for the carriage of seated passengers and
designed to allow the carriage of standing passengers in the gangway and/or in an area which does not exceed the space provided for two double seats, more commonly referred as ‘city buses’ and ‘inter-city buses’. The requirement applies in the case of vehicles having an internal combustion engine or a combustion heater located to the rear of the driver's compartment. As of September 1st, 2021, this applies to all new Class I and Class II vehicles.

The fire suppression system manufacturer’s UNECE approval will be used as a part of the bus manufacturer’s vehicle approval for UNECE Regulation No. 107 concerning fire suppression systems. On a global scale the publishing of UNECE Regulation 107 has led to an increased safety awareness in other countries. Local standards have been published, which, in most cases, have been based on the fire testing procedure part of UNECE Regulation 107. Countries to be mentioned are India (AIS 135), Israel (IS 6278), Saudi Arabia (SASO 2946) and The United Arab Emirates (UAE.S 5041).

Bus fire suppression systems in North America
Following the Wilmer Texas bus fire, the Volpe National Transportation Systems Center carried out a study for the Federal Motor Carrier Safety Administration (FMCSA). The objective was to gather and analyse information regarding the causes, frequency and severity of motorcoach fires that were caused by mechanical or electrical failure. Based on this study, the U.S. Department of Transportation issued a Motorcoach Safety Action plan. In this plan, the National Highway Transportation Safety Administration (NHTSA) identified upgrading motorcoach fire safety requirements as a priority safety area, and as part of this, to evaluate the need for a Federal Motor Vehicle Safety Standard (FMVSS) that would require installation of fire detection and suppression systems on motorcoaches.

Although, currently, there is no national requirement or standard for fire suppression systems on buses, there are some individual requirements at the state level. In addition, some OEMs and operators have chosen to voluntarily install automatic fire suppression systems. The over-the-road coach market began making fire suppression system standard on wheelchair lift-equipped buses and optional on some buses more than ten years ago. Its use has since grown steadily. Several states, including Florida, Georgia, Pennsylvania and New York, have requirements for fire protection systems on wheelchair lift school buses and paratransit buses. This is mostly due to the need for additional evacuation time in these cases.

City transit buses have been using fire suppression systems for more than 20 years. Early adoption was driven by concerns over risks associated with alternate fuels, such as methanol. Today, a vast majority of the transit operators are specifying fire suppression systems on their buses. The American Public Transportation Association (APTA) formed a Bus Safety Working Group in recent years, which consists of operators, OEMs and fire suppression systems manufacturers. The group has developed and published four standards and recommended practices relating to bus fire safety.

U.S. federal regulations only require that a bus carry a small fire extinguisher. There is little possibility that a fire extinguisher will assist in any bus fire. On average, 20 to 25 bus fires are reported each year, according to Lancer Insurance Co. The majority of these fires are electrical, turbo or brake related. They generally engulf the engine compartment, and without a fire suppression system, these fires often result in serious physical damage to the bus. The average cost of these fire claims is $80,000.

New energy carriers - new risks
Vehicle propulsion technology is undergoing its biggest change in automotive history (Ringen, 2020), driven by growing demand for environmentally friendly solutions in line with the global 2030 Agenda for Sustainable Development. As vehicle technology evolves to meet growing consumer demand and ambitious government targets, the nature of fire risks facing the automotive and transport sectors is continually changing.

There are a number of different technologies driving the shift to sustainably sourced vehicle power, most commonly lithium-ion (li-ion) batteries for electric vehicles, but also hydrogen as an energy
carrier and compressed natural gas (CNG) or liquified natural gas (LNG) for natural gas vehicles. Hydrogen, formed from renewable electricity via electrolysis, is seen as a highly competitive energy solution. However, due to the current lack of infrastructure investment, the use of hydrogen as an energy carrier is currently limited, principally to road vehicles, and is unlikely to dominate the vehicle landscape for the next ten years or more. Natural gas vehicles, powered by CNG or LNG are more readily available in today’s marketplace than hydrogen powered vehicles, however, there are a number of factors limiting the market’s growth, including lack of renewable biogas, raw material dependence on politically unstable countries, compulsory annual fuel system inspections, as well as, for CNG, limited refuelling infrastructure, reducing consumer convenience. As a result, li-ion batteries powering electric vehicles is currently the automotive and transport sector’s dominant sustainable fuel solution. However, li-ion batteries do bring about unique fire safety risks, which need to be addressed to ensure electric vehicle safety as the market continues to scale. Importantly, it is not about bigger fire risks, but different fire risks. It is no bigger challenge; it is simply a different challenge.

The primary risk for li-ion batteries, and as a result, electric vehicles, and the electric component of hybrid electric vehicles, is thermal runaway fuelled by the oxygen the cell produces. Thermal runaway is a dangerous process, referring to a chemical reaction within the li-ion battery as it is exposed to increased temperatures. In turn, these temperatures will cause the li-ion battery to release energy, prompting further temperature increases at rapid rates, eventually causing the electrolyte to catch fire, and with all the ingredients – oxygen, fuel and heat – within the battery to sustain that fire, it is very difficult (if not impossible) to extinguish. As both heat and fuel sources are present in the li-ion battery, the fire will typically develop extremely quickly and essentially sustain itself from within, producing its own source of oxygen to propel flames. In thermal runaway, a li-ion battery will also release toxic gas emissions, often including hydrogen fluoride (HF), carbon monoxide (CO) and carbon dioxide (CO₂) and cyanide.

Thermal runaway occurs as the result of a battery malfunction, represented by an internal short-circuit in the battery cells. This can occur for a number of reasons, including overheating, overcharging, overvoltage, physical damage (from impact, for example in an EV’s car collision) or mechanical failure. Both external and internal factors should be taken into account when addressing risk, as although the primary thermal reaction may begin as a result of an outside event, it can be sustained or worsened by secondary damage within the battery cells, caused by the fire from the initial incident. There have been cases of EV batteries catching fire as a result of a collision up to two weeks after the collision due to the time it takes for li-ion batteries to reach a critical point, such is the delayed reactive nature of thermal runaway.

A fire in a li-ion battery is not, as sometimes stated, a class D or a metal fire, as there is no pure lithium present. Instead, it consists of lithium salts, which behave rather differently. The major flammable component in li-ion batteries is the electrolyte, which is typically a hydrocarbon. The electrolyte by itself is highly flammable and should any leakage occur, it can easily catch fire. As a result, the application of class D dry chemical (powder) is not the most effective way to suppress li-ion battery fires.

Current and future regulation initiatives
There are different regulations, both current and emerging, that are starting to govern fire safety for li-ion batteries. However, these vary across different uses and industries and some are more advanced than others. In general, though, while li-ion battery technology is rapidly advancing, regulations are striving to keep pace, but there is a significant lag, where safety is left in the hands of individual electric vehicle owners and operators.
LI-ION BATTERY FIRE RISKS IN CONTEXT

As electric vehicle technology adoption continues to grow around the globe, its presence is evident across a range of contexts and industries. Each different use case carries its own risks, which can amplify the core risks presented by the li-ion batteries, explored above.

Individual consumers

Inevitably, protecting individual consumers, as well as the transport of electric vehicles, as numbers continue to grow worldwide, is a huge part of ensuring electric vehicle safety for the future. Although there has been much debate around the likelihood of electric vehicle fires vs traditional combustion engine vehicle fires (Adam, 2016), it is clear that, when electrical fires do occur, they have the potential to leave far more severe consequences. There are several ways the likelihood of thermal runaway can be reduced for individual electric vehicles, including: raising awareness of critical risks with consumers and emergency service responders, alongside actions that can be taken to minimise these risks effectively, as well as ensuring effective detection at storage facilities and repair workshops, to adequately detect risk at the earliest possible stage.

For individual consumers, the electric risk also extends to new trends – including the rise in popularity of the electric scooter. As these often contain li-ion batteries, they are susceptible to many of the same safety and fire risks as electric vehicles, including thermal runaway. This risk is widely evidenced in many reports of electric scooter fires, which are – more often than not – occurring in homes when the devices are left to charge overnight, without being disconnected from the power supply once the battery reaches full charge. (Blankstein, 2023) (Hocy, 2022) (Vertzoni, 2022) Where these are being charged in bike storage facilities, shared spaces in apartment blocks or inside individual apartments, the risk is even greater, as the potential for damage to surrounding apartments, and the safety risks for those living inside them, is significantly high. In New York City, it is no longer legal to charge a bike in a public building. Buildings are also going to need to be adapted to accommodate this new technology, safely. This risk is starting to be addressed through new regulations and standards, including UL 2849, (the Standard for Electrical Systems for eBikes) and additional safety guidance from the National Fire Protection Association (NFPA) pertaining to electric bike and scooter safety.

Buses and other public transport

When it comes to combustion engine buses, there are clear regulations, stipulating the need for suitable detection and suppression systems. However, for electric buses, there is no mandatory requirement for even a detection system. Over the last five years, the potential fire risks for buses have come to centre stage, as Regulation 107, introduced by the United Nations Economic Commission (UNECE), has made it a legal requirement for every combustion engine vehicle in the sector to be equipped with an automated fire suppression system in its engine compartment. However, this regulation is yet to extend to electric buses, which, powered by li-ion batteries, inevitably carry additional fire risks that are not suitably addressed in existing regulations. Like many sectors capitalising on electric as a sustainable fuel source, ensuring the safe future of the electric bus market requires more stringent, standardised, worldwide regulation, which directly addresses the risks associated with li-ion batteries.

The latest draft of UNECE Regulation 100 (Construction and Safety of Electric Powertrains) outlines a new proposal, which requires an early fire warning system in the event of battery failure and/or rechargeable electrical energy storage systems (REESS). This regulation states that, when there is a risk of thermal runaway, the vehicle system or REESS should offer early warning signals. To enable potential battery failure to be detected at the earliest possible stage, preventing a fire from taking hold, in line with Regulation 100, fire suppression systems could be used as a retrofitted device to release cooling agents to mitigate associated risks. In addition to this, Regulation 100 also includes a requirement for fire testing REESS from an external fire source.
Ground support equipment (aviation)
Over the last fifteen years, the aviation industry has experienced a sustained increase in demand (excluding the impact of the global pandemic), leading to intense service schedules, with significant repercussions for any periods of downtime. Responsible for 12% of the global transport sector’s CO₂ emissions, it is no surprise the industry is seeking sustainable alternative fuel sources, particularly for its ground support equipment, from push back tractors to transfer buses and refuellers. However, this requires careful planning and tailored fire detection and suppression solutions. Due to the context these vehicles and equipment operate in, the standard li-ion battery risks can be amplified quickly, having the potential to spread to surrounding aircrafts, creating a much greater fire risk and increasing safety risks for passengers travelling through the airport apron.

Ports
For the port industry, it’s a similar story; demand is increasing rapidly and pressure to reduce carbon emissions is growing. Again, this is seeing an increase in the adoption of battery as an alternative fuel source for vehicles and machinery powering port operations. However, despite their imminent and growing presence, and obvious evidence of electric vehicle fires at ports across the globe, existing port safety regulations do not explicitly account for electric vehicle risks. There is also an evident risk for car carriers transporting electric vehicles and batteries overseas to consider. (Sams, 2022) Like other sectors, ideally, safety would be driven by standardised regulations, however, in the absence of these, responsibility falls to trade organisations, individual ports, OEMs and, perhaps most significantly, insurance companies, to campaign for change and act to enhance the safety of future, electric-powered ports. This will not only help to encourage greater safety today, but also to influence the development of future standards.

Mining
Much like ports, demand and sustainability pressures, have driven many mine operators to seek electric alternatives to the vehicles and machinery enabling everyday operations. This is also accelerated by the industry’s need to improve the safety of the mining working environment for miners. This shift, again like the port sector, has been accompanied by evidence of a surge in vehicle fires with extensive consequences. However, as the mining industry has developed, it appears to be leading the way in electric vehicle fire safety, with the Global Mining Guidelines Group publishing Recommended Practices for Battery Electric Vehicles in Underground Mining in 2022 (Group, 2022) to guide the industry to safety, helping to protect revenue, capital, operating costs, as well as overall health and safety for workers.

RESEARCH INTO LI-ION BATTERY FIRES
A multitude of test programmes, carried out by different research bodies and organisations, such as the National Fire Protection Association (NFPA) (Thomas Long Jr, 2016) and Research Institutes of Sweden (RISE) (Bischoff, 2019), evidence that the key to effectively controlling a li-ion battery fire in any application, where thermal runaway is active, is through extensive cooling, preferably using large volumes of water, or water-based extinguishers, for prolonged periods of time. The necessary length of time for extinguishing a li-ion battery effectively using water can be incredibly long, with tests (Juarez, 2013) showing that, even if a li-ion battery appears to be fully extinguished, it can spontaneously re-ignite after 20 hours or more. For battery packs, this may be even longer, as each cell can burn on a different timeline, which can elongate the necessary period of suppression application.

Further, Dafo Vehicle Fire Protection conducted extensive research (funded under the EU Framework Program for Research and Innovation – H2020 – under the SME Funding Scheme.), which collected and analysed three years of data from extensive testing on li-ion batteries and electric vehicles to uncover the optimum criteria for effective electric vehicle fire suppression. This study highlighted that a battery on its way to thermal runaway will follow a clear pattern of behaviour, as excessive heat starts to develop within the cells. Due to internal pressure build-up within the li-ion battery, caused by the release of gases as temperatures increase, the battery’s over-pressure safety vents will open, releasing
the toxic gases, ahead of thermal runaway starting. The research also revealed that if the risk is
detected, and the appropriate cooling applied, at this early stage, there is a high probability that the
process can be delayed, enabling safe evacuation for passenger vehicles, for example, or, more likely,
halted entirely, with the battery returning to a dormant state.

RESEARCH INTO LI-ION BATTERY SUPPRESSION

Early detection
To effectively prevent hazardous temperature increases, a system needs to incorporate a detection
method, which is able to accurately identify the emission of toxic gases at this early venting stage of
the battery failure pattern. Tests conducted by Dafo Vehicle Fire Protection at RISE as part of the EU-
funded research showed that the vapour released at this initial stage consists of a combination of
halocarbons, alongside a large portion of carbon monoxide (CO) (Figure 1). This is a suitable indicator
to detect risk at this stage, as CO sensors are often extremely reliable over time, and they can also be
easily packaged in a format that allows for installation into battery packs, either at manufacturing stage
or retrofitted to existing batteries.

Figure 1  CO detected at the beginning of the temperature increase.

Early use of fire suppression system
The tests also highlighted that a specially designed li-ion fire prevention system, as opposed to a
conventional suppression system, is the most effective non-intrusive way to secure the safety of
electric vehicles using li-ion batteries. This is because a properly-designed li-ion fire prevention
system is able to detect risk and activate at the venting stage (Test 7 module – Figure 2), offering the
best solution to stop a thermal runaway event from progressing. However, a more conventional system
will often only be able to detect risk and activate once rapid temperature increases are detected, when
thermal runaway has already commenced (Test 8 module – Figure 2).
ALTERNATIVES TO LI-ION BATTERIES

Over recent years, there has been a large amount of research into the solid-state battery, as an alternative to the li-ion battery, for electric vehicles, due to its higher energy density capacity. However, there are a number of practical challenges hindering the development of solid-state li-ion batteries (Kerman, 2017), including the fact that they are currently unsuitable for rapid charging.

Further on there are other alternatives battery technologies being developed and used such as lithium iron phosphate batteries, aqueous magnesium batteries, sodium-based and graphene aluminum-ion batteries to mention a few.

As a result, it is unlikely these will be adopted for widespread use in both individual and commercial applications any time soon, and with alternatives falling behind on practical use and convenience for users, it is highly likely that li-ion batteries will continue to be the main power source for electric vehicles, long into the future, as risks reduce with technological advancements and new developments.

OTHER FIRE SAFETY REGULATION INITIATIVES

The UNECE Working Party on the Transport of Dangerous Goods (WP.15) has developed and adopted draft amendments to Annexes A and B of ADR for entry, which came into effect on 01 January 2023. The amendments include the mandatory use of fire suppression systems and tyre fire protection systems of vehicles carrying dangerous goods to reduce the likelihood of a boiling liquid expanding vapour explosion (BLEVE) or other catastrophic failure of the cargo due to a fire. These requirements apply to FL vehicles (vehicles intended to carry flammable liquids, flammable gases or a certain type of hydrogen peroxide or electric vehicles) and EX/III vehicles (vehicles intended for the carriage of explosive substances and articles). In terms of technical provisions and timings, the Working Party agreed that work on such provisions should continue at future sessions to better define the technical provisions to be implemented and to consider whether the presentation of the new provisions should be organised differently.
CONCLUSION

Investment in infrastructure, over the last five years, to support the rising trend and resulting electric vehicle market growth will now enable an even bigger ‘boom’ in demand for li-ion battery powered vehicles and machinery over the coming years. As evidenced over the past decade, a lot can change in a short time, and technology is likely to advance significantly over the next ten years, with other sustainable fuel sources, such as hydrogen potentially coming to the fore. However, the foreseeable future is clearly dominated by the li-on battery, which is likely to continue to develop and evolve to increase its density and energy storage capacity to improve convenience for electric vehicle owners and operators.

While li-on batteries remain at the fore, addressing the unique fire risks effectively is key. That has to be enabled by an early fire warning system, which can detect the venting of hazardous gases as a precursor to thermal runaway, applying spot cooling with a suitable suppression agent, to prevent thermal runaway from progressing, returning the battery to a dormant state, while also halting and diverting the spread of toxic gas emissions. This will inevitably alleviate critical concerns around electric vehicle fire risk, improving safety for drivers, those in the vicinity and surrounding valuable assets, as well as minimising operational downtime for commercial operations.

What all the above makes clear, is the need to train every professional in the myriad sectors affected by the use of EVs, whether those vehicles are as small as a scooter or as significant as a ferry. Education needs to extend beyond the first and second responders, manufacturers and maintenance people, to all those who use EVs. Every role and industry will, most likely, be affected by the move to EVs, which calls for a reset of how we assess, judge and mitigate risk based on a thorough understanding of how the technology works. The switch to EV has already happened. As it gathers pace, regulators and best practice across every industry must now catch-up.

BIBLIOGRAPHY


Christensen, P. (2023, March). Detonation of lithium-ion battery vent gas. Retrieved from LinkedIn: https://www.linkedin.com/posts/paul-christensen-a2bb6b82_detonation-of-lithium-ion-battery-vent-gas-activity-7042437748774830080-m0FF


A guide concerning "Risk assessment and handling of fire in Lithium-ion batteries"

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ABSTRACT

In Norway we have many electrical vehicles on the roads and due to tax rules on these vehicles almost all new personal cars sold are EV's. The fire statistics shows that petrol and diesel cars start to burn more often than EV's. Most of the EV's in Norway are new cars and this may change when they start to reach end of life. Not many fires in EV's are battery fires.

Battery fires are challenging and unpredictable. After fires and unforeseen behaviour in vessels with larger battery installations we made a guide to the fire services on how to approach fires in Li-Ion batteries. Four risk levels were identified to clarify the risk.

Used high energy batteries from EV's can have a high value when the car no longer is suitable for use. The car industry including sales of new cars, workshops and disassemble of car after end of life of the vehicles contacted us because many of these batteries were sold between private persons and in private garages this may be of high risk. The industry wanted professionals to handle these batteries to reduce risk of fires and electric shock. We are running a campaign to inform the players about the responsibility they have as sellers and buyers of these batteries.

KEYWORDS: Fire statistics, A guide for the fire services, reuse of high energy batteries.

INTRODUCTION

The Norwegian Directorate for Civil Protection's (DSB) most important task is to prevent accidents and crises in the Norwegian community. Effective prevention and preparedness/handling require that we have a good overview of and understand society's risks and vulnerabilities. Not just individually, but as a whole.

An accident or crisis often affects several sectors and actors. The consequences can be difficult to see if you stand alone. It is therefore important to work holistically with prevention and preparedness.

DSB has a coordinating role in social safety. We will simply contribute to relevant actors sharing information and getting a common picture of the situation - and thus the best possible basis for being prepared for, and dealing with, what may come.

While introducing batteries in vessels we saw an unpredictable behavior in Li-Ion battery fires. On the first accidents we had unexpected explosions without injuries on personnel and knowledge led to the guideline for handling fire in lithium-ion batteries.

Fire statistics on cars

Among the new cars sold in Norway 96.5% is with a Li-Ion battery, 3% gasoline and 3% diesel. The total number of EVs is 600,000 and we have some experience with battery fires in cars and vessels on sea. First, we will look at the numbers from Bris. That is DSBs database on fire service calls. If we ask
the insurance companies, they will have a larger number on fires in cars. These number is the largest fires where fire services are involved.

<table>
<thead>
<tr>
<th>Fuel type for the car/vehicle in which the fire started</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>24.03.2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrol/diesel</td>
<td>862</td>
<td>861</td>
<td>1062</td>
<td>1002</td>
<td>953</td>
<td>968</td>
<td>1005</td>
<td>185</td>
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<tr>
<td>Other</td>
<td>97</td>
<td>114</td>
<td>44</td>
<td>35</td>
<td>46</td>
<td>44</td>
<td>51</td>
<td>4</td>
</tr>
<tr>
<td>EV</td>
<td>33</td>
<td>40</td>
<td>9</td>
<td>19</td>
<td>23</td>
<td>37</td>
<td>36</td>
<td>12</td>
</tr>
<tr>
<td>Hybrid</td>
<td>1</td>
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<td>7</td>
<td>5</td>
<td>15</td>
<td>16</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>Autogass</td>
<td>12</td>
<td>4</td>
<td>12</td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>12</td>
<td>1</td>
</tr>
</tbody>
</table>

This database registrations started in 2016 and in the beginning some electric fires in cars were reported as fire in EVs but from 2018 the quality of the registrations is good.

**Guideline for handling fire in lithium-ion batteries.**

This is a guide for the fire and rescue services on how to handle fires in Li-Ion batteries. It is made by DSB together with fire departments in the largest cities in Norway and the Norwegian Defense Research Establishment. Responses must be based on knowledge, and it operates with 4 risk levels:

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

Topics for this guide I will speak about is hazards, extinguishing methods, Gas detection, how to secure the location and decontamination of personnel and equipment. How to handle high risk objects and in particular all the fires in waste disposal plant are mentioned in this guide.

**Campaign: Safety with used electric car batteries.**

In the spring last year, we were contacted by the organizations for the life cycle of cars in Norway. Importing, sales, repairs, and handling recycling of cars. And the company handling batteries after end of life. We can see an increasing number of high energy batteries sold on marked places like Finn.no between private persons and the industry wanted help to handling of electric vehicle batteries after the end of use in a safe matter. An information campaign was made and are rolled out in December 2022 and an evaluation has been made. The campaign is adjusted and will continue to inform the stakeholders, both sellers and buyers, on their responsibilities. One thing is for sure and that is the demand for reuse of these batteries, and it is important with responsible actors in this business to avoid accidents and fires.
CONCLUSION

Battery fires are unpredictable and the risk in firefighting can only be done in a safe way with knowledge. An overview of the probability of accidents to happen is important and the technology should be handled by professionals to reduce the risk.

REFERENCES

1. BRIS, Brannstatistikk.no is a service from The Norwegian Directorate for Civil Protection that provides an overview of tasks handled by the fire and rescue service.
Experimental investigation of the HRR of modern ICE vehicles

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ABSTRACT

This paper is intended to verify the validity of real fire scenarios currently used in fire safety engineering studies of car parks. The data used were obtained from vehicle fire tests performed in the 90s and have not been updated since. For this purpose, the Heat Release Rate (HRR) of modern Internal Combustion Engine (ICE) vehicles is studied and compared to previous measurements.

Two experiments were carried out: the first one on a vehicle with an empty tank and the second one with the tank filled to its 2/3 with diesel fuel. The HRRs were measured using a Large-Scale Heat Release rate apparatus coupled with load cells to obtain the mass loss. In addition, temperatures and heat fluxes were recorded all around the vehicles. These tests showed a fuel load and HRR in the same order of magnitude as vehicles of the same brand from the 1990ies. This confirms the validity of the data currently used in fire engineering studies. Moreover, HRR peak and combustion dynamics are highly influenced by window breakage times. Early window breakage leads to rapid fire growth and increased the measured HRR during this period.

KEYWORDS: modern vehicle fires, calorimetry by oxygen consumption, Heat Release Rate

INTRODUCTION

In France, from the early 2000s, fire safety engineering studies are applied to verify the fire resistance of car park structures. Currently, two types of vehicles are considered: light commercial vehicles (LCVs) and passenger vehicles. HRR of LCVs was the subject of a previous experimental study [1]. HRR of passenger vehicles are based on measurement from the 1990s [2]. However, the amount of plastic elements used in vehicle design has drastically increased over the last decades [3]. Consequently, this may have an influence on the combustion dynamics and HRR of modern cars. A limited number of articles mention an equivalence in terms of energy released with older vehicles [4]. Nevertheless, no time-dependent HRR data is yet available. Therefore, an experimental campaign was conducted to verify the validity of the input data used in engineering studies and eventually update them.

This test campaign, conducted by the CTICM at the Efectis France facilities, involved two partners, namely GagnePark and the LCPP, with the support of the Renault group for the supply of the vehicles studied.

First, this paper describes the vehicles studied, the protocol and the experimental setup, including the ignition method. In the second part, the results obtained for the two tests are described and compared between them. This part includes the results of HRR, total heat released, mass loss, heat of combustion and incident radiative fluxes measured. Finally, the third part consists of a comparison of the results presented with those available in the literature.
MATERIALS AND METHODS

Vehicles
The two involved vehicles were Internal Combustion Engine (ICE) large family cars “Renault Talisman”. They were supplied by the Renault Group. Although the choice of model was available, their finishing was subject to the availability of the Renault fleet. Thus, the first vehicle tested had a top-of-the-range finishes "Initiale Paris". This finish has the particularity of having a sunroof on the whole central part of the passenger compartment as well as leather coverings. The second vehicle had standard finishes. The vehicles and their respective interior and dimensions are shown in Figure 1 and Figure 2. The pressurized components and batteries, with the exception of the airbags, were removed on both vehicles for safety reasons. In order to better compare the growth phase between the vehicles, two aluminium plates were installed to close the sunroof of the top-of-the-range vehicle. These plates disappeared during the test as the fire increases in intensity but after the initial growing phase.

Figure 1 Exterior and interior photos of first vehicle (left) and second vehicle (right)

Figure 2 Vehicle dimensions
Unladen weights of the vehicles are 1580 kg and 1540 kg for the top-of-the-line Talisman and the classic, respectively. Large family car tested by Joyeux et al in the 1990s weighed 1300 kg [2]. Although the mass of the tested vehicles is 20% higher, they are direct replacements on the market of the Renault Laguna (1993-2015). Therefore, it was chosen to follow the evolution of the vehicle fleet.

The first test was carried out on the top-of-the-range model with its fuel tank empty and the second test on the classic model with its tank filled to 2/3, i.e. 33L of diesel (as during the 90s test). In the following, the tests will be named "Talisman without diesel" and "Talisman with diesel" for the first and second test, respectively.

**Experimental configuration**

The fire tests took place under a 7.7 × 5.3 m² Large Scale Heat Release apparatus (LSHR) (Figure 3). This facility allows the measurement of the Heat Release Rate (HRR) over time up to 15 MW. The measure is based on the oxygen consumption calorimetry principle. Three types of sensors were installed in the duct: five thermocouples associated with five McCaffrey probes and a sample gas probe. These sensors enable the acquisition of the temperature and velocity of the exhaust smoke as well as the molar fractions of oxygen, carbon dioxide and carbon monoxide (O₂, CO₂ and CO). In addition, a ceiling was suspended at a height of 2.6 m to reproduce the experimental configuration of Joyeux et al. tests and get closer to the conditions encountered in car parks. This ceiling also prevents flames from reaching the measuring section in the duct and disturbing the measurement (Figure 3).

![Figure 3 LSHR (left) and suspended ceiling at 2.6 m height (right)](image)

Vehicles were placed on a tray on load cells to measure the mass over time (Figure 4). This data, coupled with the estimation of the effective heat of combustion, allows the verification of the HRR measured by calorimetry. 36 Type K Inconel thermocouples, 1.5 mm in diameter and 0.5 Hz sampling rate, were placed all around and in the vehicle at heights of 1.5 m, 2.0 m and 2.5 m. Finally, 4 radiative heat flux gauges were installed at the front and on the right side to measure the radiative heat flux emitted by the vehicles. Two types of locations were chosen:

- Two radiative flux meters were placed at the front and right side of the vehicles at a distance of 1m and 1m height.
- Two radiative flux meters were positioned at the front and right rear bumpers at a distance of 0.8m and 0.7m height.
The ignition was carried out with a rag soaked with heptane placed in a pan of 12 cm of diameter at the front side passenger. In order to facilitate the ignition the pan was placed under the dashboard and the seats were put forward to obtain flames licking these combustible elements. For the two tests, the left rear window was opened to the 1/3 in order to support the development of the fire in the passenger compartment. Indeed, Boehmer et al [3] pointed out that the method of ignition, ventilation and other environmental factors have an important impact on the development of vehicle fires. Therefore, it was chosen to approach the experimental configuration of the tests carried out in the 1990s by Joyeux et al [5] in order to be able to compare the measured HRR.

RESULTS

In this section, the events observed during the two tests are first presented. Then, the measured HRR, total heat release, mass losses, heat of combustion and incident radiative heat fluxes are then compared between the two tests.

It should be noted that, during the tests, a small amount of smoke leaked from the calorimetric hood (Figure 5). This occurred during the full development of the fire when the smoke ceiling dropped below the level of the cladding surrounding the hood. However, the amount of unmeasured smoke is small in relation to the global smoke flow. This loss should have a limited impact on the measured data.
The two tests are divided into three to four major phases running in parallel:

- Passenger compartment combustion.
- Rupture of the tank and the combustion of its content (Talisman test with Diesel).

The events and the HRR associated with these phases are presented in this part.

Figure 6 shows the major phases of the two tests. The presence of the tarpaulin, intended to channel the fumes, makes it difficult to formally identify the end of these different phases.

During the test without diesel, the fire grows with difficulty in the passenger compartment after the ignition. The front right door is temporarily opened to favour the ignition and is closed permanently after 4 minutes. Shortly before, the windshield partially broke, then almost completely at 7 minutes (Figure 7a). A column of flame licking the ceiling appears. At 8 minutes, the fire spreads to the rear of the passenger compartment with a flame exiting through the left rear window. The right rear window and the rear window break quickly after (Figure 7b), at 9 and 11 minutes, respectively. The breakage of the front windows occurs 12 minutes after the ignition.

At the same time, the fire spreads to the front of the vehicle. Flames appear at the front wheel arch at 10 minutes. Along with the combustion in the engine compartment at 11 minutes, the fire spreads to the tire and the right front fender at 13 minutes (Figure 7c). The fire is fully developed in the car front at 20 minutes (Figure 7e).
The fire takes more time to spread to the rear of the vehicle. First, it spreads to the left rear tire at 15 minutes and then to the bumper at 17 minutes (Figure 7d). The fire spreads mainly through the exterior of the vehicle (plastic body parts) until 20 minutes. At this point, the flames penetrate the trunk compartment from the inside, accelerating the fire spreading. At 22 minutes, the rear bumper is melting and burning at ground level. The full combustion of the rear of the vehicle can be observed around 23 minutes (Figure 7f). Finally, the empty diesel tank melts and is consumed under the car at 20 minutes.

For the test with diesel, the fire also grows with difficulty in the passenger compartment until the total breakage of the windshield at 11 minutes (Figure 8a). At the same time, small flames appear in the right front window seal and the rear windows at 9 and 10 minutes, respectively. The front windows break at 16 minutes. At the rear of the vehicle, the last window pierces at 16 minutes. The piercing of the rear window occurred lately at 31 minutes (Figure 8e).

Following an airbag explosion at 13 minutes, the fire spreads to the side-view mirrors. This causes them to melt and fall to the ground near the front wheels. Propagation to the front bumper occurs through the wheel arch and the melted mirror via the front tire at 17 minutes (Figure 8b). The front bumper finally melts and falls to the ground at 28 minutes. The full development of the fire in the front is observed at this time (Figure 8d).

The propagation to the rear of the vehicle occurs later. It follows the fall of the side seals of the rear windows at 22 minutes. This is followed by a spread to the left rear tires, then to the bumper at 24
minutes (Figure 8c). Finally, the bumper fell to the ground at 31 minutes with full fire development in the rear at 33 minutes (Figure 8f). The diesel tank is pierced at 31 minutes (Figure 8g). The fuel contained in the tank falls to the ground and burns, intensifying the combustion. However, the exact duration of the diesel combustion is difficult to identify because of the large quantity of various fuels present at this level. Intense combustion is observed during the 10 minutes following the rupture of the tank.

Figure 8 Progress of combustion: a) windshield breakage, b) spread to front bumper, c) spread to rear bumper, d) full development of fire in front, e) rear window breakage, f) full development of fire in rear, g) diesel combustion

Figure 9 shows the different events identified and associated with the HRR. During the first test, the window breaks all happen during the first phase of the fire. This increases the amount of air available in the passenger compartment and the HRR, which reaches a plateau of 4 MW. Then, the fire spreads to the front and rear bumpers of the vehicle. The HRR reaches 6.1 MW: the major part of the fuel elements of the vehicle are burning together.
Another combustion dynamics is observed for the second test. The side window breakage occurs in parallel with the spread to the bumpers. The breakage of the windows is spread out over time. Some occur after the propagation to the bumpers. As a result, there is no sudden increase in HRR. The spread to the front bumper occurs at the same time as in the first test. However, the propagation to the rear is slightly delayed by the late breakage of the rear window, which limits the temperature rise at the rear of the vehicle. The rupture of the diesel fuel tank is late and occurs during the reaching of a plateau of 4.6 MW.

For the two tests, the burning of the bumper elements is progressive. It is difficult to identify their effect on the HRR. Finally, a rather brutal phase of decrease follows the HRR peak when the majority of the combustible elements have burned.

The fires are extinguished by firefighters at 79 and 85 minutes for the Talisman tests without and with diesel fuel, respectively. At these times, only small flames are observable (Figure 10). Therefore, some of the vehicle’s fuel elements have not been fully consumed yet. An estimation of the amount of this energy not released is made. This is based on a linear extrapolation of the HRR considering a total extinction at 100 minutes for the test without diesel and at 105 minutes for the test with diesel.

A quantity of heat of 6 640 MJ is released during the first test and 6 207 MJ during the second. Including the still burning elements, the overall energy released is estimated at 6 894 MJ and 6 291 MJ for the test without diesel and with diesel, respectively. It should be noted that, for the Talisman test without diesel, if the tank had been filled to 2/3, i.e. 33L, the total energy released would have been 8,016 MJ.
considering the hypothesis that the total combustion of the diesel was obtained with an efficiency of 100% and a combustion heat of 34 MJ/L.

A total of 310 kg of fuel is consumed during the Talisman without diesel and 296 kg for the Talisman with diesel test, or 19.6% and 19.8% of the total vehicle mass, respectively. Based on the mass loss and energy released (without unburnt elements), an average effective heat of combustion of 21.7 MJ is estimated for the first test. Despite the presence of highly combustible diesel fuel in the second test, a lower average heat of combustion of 21.0 MJ is obtained. These values suggest that the combustible elements present in the conventional vehicle produce less heat than those of the top-of-the-line vehicle. The reduced opening area and the late breakage of some windows could also cause a lower combustion efficiency for the second test.

HRRs can also be reconstructed from the heats of combustion and MLR. These are presented in Figure 11 with the HRR measured by calorimetry. The two curves from the talisman test without diesel are close in terms of trend and order of magnitude. More important differences can be observed on the test with diesel. However, the trends and order of magnitude are also identifiable. The main differences observed are due to the computation process based on the derivation of a physical measure (the mass) which is noisy. Nevertheless, the good coherence of the measurements can be observed.

The measured radiative heat fluxes are shown in Figure 12 and Figure 13 for the test without diesel (left) and the test with gasoil (left). During both tests, close maximum incident radiative heat flux values are measured at the front bumper and right side of the vehicles. These are 39 kW/m² (without diesel) and 38 kW/m² (with diesel) at 0.8 m from the front bumper and 35 kW/m² (without diesel) and 36 kW/m² (with diesel) for the right side. The most important differences are observed at the front of the vehicle with 38 kW/m² measured for the test without diesel and 33 kW/m² for the test with diesel. The presence of a sunroof on the first test may be the reason for this difference. This allows the flames to emerge vertically in the center of the vehicle and less through the various windows all around the vehicles. Finally, at the rear of the vehicle, the presence of diesel in the tank leads to a peak of incident radiative flux of 47 kW/m², against 29 kW/m² for the test without diesel. However, following the rupture of the diesel tank, the heat deteriorates the sensor, which stops working. It is not possible to know if this value continues to increase. Although this value is important and is sufficient to cause a propagation to nearby elements, the rupture is late (31 minutes) and occurs after the propagation time considered in the studies of 12 minutes.
DISCUSSIONS

The HRR measured during the two tests as well as those obtained in the 90s by Joyeux et al. are presented in Figure 14. Overall, the combustion durations are close for the three tests. A HRR plateau, of variable duration, is observed following the ignition with a value of approximately 1.5 MW (i.e. approximately 1 minute duration for the test without diesel, 5 minutes for the test with gasoil and 14 minutes for the 90s test). The duration of this plateau depends on the window breakage times of the vehicle. A similar phenomenon was also observed in the 90s test. The breakage of the rear window of the 90s vehicle occurred at 17 minutes and was followed by an increase in the flow of flames coming out of it. This time also corresponds to the sudden increase in HRR.

Smaller peak HRR are measured with the recent vehicles. These values are 6.1 MW and 4.6 MW for the tests with and without diesel, respectively, compared to 8.3 MW for the old vehicle. By readjusting the graphs in relation to the measured peak HRR, it can be observed that the main combustion phase (HRR > 2 MW) is slightly longer for the recent vehicles with a duration of 20 minutes against 16 minutes for the reference fire. Over this period, 4980 MJ and 4135 MJ are released during the two recent vehicle tests, compared to 3740 MJ for the test carried out in the 90s. Although the maximum HRR are lower for the recent vehicles, a greater amount of energy is released during the main combustion phase.

For the two tests with a 2/3 full tank, two different combustion dynamics were observed. During the 90s test, the failure of the diesel tank occurs before the full propagation to the rear bumper. The diesel spills to the ground and burns, encompassing the still intact fuel elements. HRR of the diesel and the rear fuel elements of the vehicle combined, resulting in a peak HRR of 8.3 MW. During the test on modern vehicle, the failure of the tank occurs after the spreading to the whole rear bumper of the vehicle and during the decay phase of the front combustion. The diesel in the tank spills to the ground and spreads...
over a smaller area. This is probably due to the absorbent nature of the tray on which the vehicle is. The slick surface, the advanced combustion of the rear bumper and the decay phase of the other parts of the vehicle do not lead to a significant increase in HRR. On the contrary, the heats produced seem to compensate each other, leading to the plateau visible on the HRR figure.

In order to compare the total energy released during the tests, only the first 48 minutes are observed. Over this period, the recent vehicles release 6216 and 5798 MJ without and with diesel, respectively, compared with 6085 MJ for the Laguna of the 1990s. Relative to the reference curve, the first test produce 2.1% more heat and the second 4.7% less. These values are close enough to consider that the energy available in a vehicle has little changed over time.

Mass losses are 310 kg for the test without diesel, 296 kg for the test with diesel and 275 kg for the old vehicle (90s). Therefore, 35 kg and 21 kg more masses are consumed during the tests compared to the old vehicle. For the first test, this difference would have been 61 kg if the diesel tank had been 2/3 full. However, it should be remembered that due to the evolution of the market, the models tested weigh approximately 200 kg more than the one studied in the 90s. These values seem to indicate that the increase in mass of the recent vehicles is mostly incombustible.

The heat released per unit mass of fuel was calculated for the two tests. It emerges that for one kilogram of fuel is released 21.7 MJ/kg, for the test without diesel, and 21 MJ/kg with diesel. This value was 23 MJ/kg in the test of the 90s. This difference, up to 10% for the test with diesel, may be due to the improved reaction to fire of materials used in recent vehicles. It is also recalled that a small amount of smoke leaked out of the calorimetric hood during the tests. Although these leaks appear to be relatively negligible, the loss of information implies a slight decrease in the heat of combustion.

Concerning the measured radiative heat fluxes. Joyeux [2] also carried out a measurement during the test of a passenger vehicle in the 90s. The sensor was placed at a distance of 0.7 m from the vehicle in the direction of the right front door. An average flux value of 25 kW/m² was obtained for the 6 minutes of full fire development. During the combustion of the diesel in the vehicle tank a maximum flux of 50 kW/m² was measured. Although the flux meters are placed 0.3 m further away in both tests, average values of 30 kW/m² (without diesel) and 25 kW/m² (with diesel) are measured during the 13 minutes of full combustion. These average values seem to assume that the surrounding thermal fluxes are close for recent vehicles. It is more difficult to conclude on the combustion of diesel fuel, during which the fluxmeter deteriorates after measuring 47 kW/m². However, this maximum recorded is close to the one recorded in the 90s (50 kW/m²).

Okamoto et al [5] studied the combustion of minivans using several radiative flux meters placed around the vehicle. They obtained radiative heat fluxes at 1 m from the front of the vehicle of 29.0 kW/m². The values measured for the two tests are significantly higher with 38 kW/m² (without diesel) and 33 kW/m².
(with diesel). However, it should be noted that Okamoto et al. conducted their tests in the open air and that no smoke accumulation above the test vehicle is possible. The value given in their study therefore only captures a part of the radiative flux emitted by the smoke produced during combustion.

CONCLUSION

In this article the combustion of two passenger vehicles studied experimentally was presented. The tests were carried out under a calorimetric hood allowing the measurement of the heat released over time. Measurements of temperatures and radiative fluxes around the vehicles as well as mass losses over time were also performed.

Despite the increase in the amount of plastic used in modern ICE vehicle [3], measurements showed that the maximum HRR did not drastically change with time, which corroborates the observations of Truchot et al. [4]. A maximum value of 6.1 MW for the Talisman test without diesel and 4.6 MW for the Talisman test with diesel was measured. This was 8.3 MW in the tests carried out in the 90s. Moreover, it has been observed that an early breakage leads to an increase in HRR and fire spread within the vehicle. It should be noted that the vehicles studied are more massive than the old ones, in this case approximately 200 kg. However, the Renault Talisman is the direct heir of the Renault Laguna.

The combustion times and the total energy released are close. The main difference is in the energy released during the full combustion which is more important for the recent vehicles. The peak HRR, although lower, is longer in time, thus increasing the overall energy released over this period. However, the heats of combustion estimated from the energy and mass loss (21.7 and 21 MJ/kg) are slightly lower than for older vehicles from the 1990s (23 MJ/kg).

The incident radiative fluxes measured around the vehicles are important with peaks between 29 kW/m² and 47 kW/m² during the two tests. These values remain close to those measured during tests in the literature (25 kW/m² on average and 50 kW/m² in peak).

AKNOWLEDGEMENT

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REFERENCES

Fire Due to Improper Maintenance

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ABSTRACT

Two case studies are presented, both involved car transporting trailers that caught fire 43 days apart in Australia in 2019. The investigation procedure is described together with the evidence found for the fire cause in both cases. The investigations revealed improper maintenance had caused both fires.

KEYWORDS: Fire investigation, trailer, maintenance, brakes

INTRODUCTION

Australia has a total land mass of 7,688,126 Klm², with 19,505,241 registered motor vehicles operating over 877,650 kilometres of roads. As to the total number of vehicle fires, according to Fire Rescue New South Wales 2021-2022 Annual Report, New South Wales, Australia’s most populous State, for the 2021-2022 year recorded 2,461 vehicle fires. Apart from personal transport vehicles in Australia, road transportation is used extensively to move freight. Heavy road transport vehicles in Australia are usually in B Double configuration, being one prime mover (tractor) and two trailers. The B Double configuration can consist of pantechnicon trailers, as depicted in Figure 1 below, flat-top trailers, tankers, and vehicle carrying trailers.

Figure 1  Prime mover and B Double trailers.

Despite this reliance on road transport, fire and emergency services generally do not investigate vehicle fires. The investigation of such fires is normally carried out by the vehicles’ insurer, or the cargo marine underwriter, via private fire investigators.

Being one of those private fire investigators, on average I investigate approximately one vehicle fire per week. My work is not confined to my home State of New South Wales. While I have worked in every State and Territory in Australia, most of my investigations are conducted in the eastern seaboard States of Queensland, New South Wales, Victoria and Tasmania.

This paper discusses two case studies from 2019 where vehicle carrying trailers in B Double configuration caught fire.
FIRE 1, 24 JULY, 2019

In July, 2019 I was asked to examine a B Double set of dual axle vehicle carrying trailers that had caught fire in northern New South Wales, whilst being towed by a 16 month old Volvo FM540 prime mover. The trailers were manufactured by J Smith and Sons of Gympie, Queensland. Between the two trailers, eight motor vehicles were being carried. All of these vehicles were being transported from Melbourne, Victoria to Brisbane, Queensland and were in second hand condition. This trip covered a distance of approximately 1,730 kilometres. The trailers were part of a large fleet of trailers, owned by a company that has Australia wide operations. The prime mover was owned by a sub-contractor to this company.

The prime mover and trailers left Melbourne, Victoria at approximately 05:00 hours. At about 19:45 hours and approximately 1,100 kilometres into the trip, the driver of the prime mover received a UHF radio message, from a truck passing in the opposite direction, to say smoke was coming from the trailers. The driver pulled to the roadside to investigate. On doing so, he found large amounts of smoke and flame coming from the A Trailers’ nearside front axle.

After uncoupling the prime mover and driving it away from the trailers, the driver, and other drivers, who had stopped to assist, used fire extinguishers to fight the fire. When Emergency Services arrived, the two trailers were damaged beyond repair, as were six of the eight vehicles being carried.

The examination of the trailers occurred 12 days after the fire. By this time the trailers had been moved to a holding yard, and as the prime mover was undamaged, it returned to service and was not available for examination. When examining a B double set of trailers I will always start with the A trailer and then move to the B Trailer.

The greatest fire damage to the A trailer was found to be at the axle set. Despite this concentration of fire damage at the axle set, the examination was started at the front of the A Trailer and worked towards the rear of the A Trailer. During this process the various systems of the trailer was checked, including the electrical and hydraulics, looking for evidence of failure.

Once the axle set was reached, I turned my attention to the wheel bearings, tyres and brakes. I found the only remains of tyres consisted of beading wire. I also noted that the wheel rims were of steel construction, rather than aluminum.
J. Smith and Sons always used BPW Transpec (hereafter BPW) axle sets, which were purchased from BPW as complete units and fitted to the trailer as a single unit. From past experience, I had found that if there is a wheel bearing failure in a BPW axle, it is common for the face of the wheel bearing hub cap to form a pronounced dome, due to heat generation. Normally, the face of these wheel hub caps are flat. I found no evidence of ‘doming’ of the hub caps.

However, as brakes were also a consideration, each of the of the brakes of this trailer had to be deconstructed for examination. During the process, I also examined the outer wheel bearings. I found all outer bearings where intact and free of damage.

Although the outer wheel bearings appeared normal, each wheel end was deconstructed. That is the remains of the aluminum wheel rims, the wheel hub and the brake drums were removed so that all components could be examined. Figure 5 depicts the deconstructed rear offside wheel end.
All four brake linings were free of damage and required no further examination. Examination of the front axle brake chambers revealed that the push-rod of the nearside brake chamber was bent at 90°. This brake chamber had deployed, via the spring brake, whereas the offside brake chamber had not. The guide spring of the spring brake operates at approximately 650 kPa. The bending of the push-rod is evidence that there was spring pressure applied at this brake during the propagation of the fire.

When I examined the rear axle brake chambers, I found the rear offside brake chamber had broken away from its mounting point on the axle and only the front section of the brake chamber, which houses the service brake, remained.
After deconstructing the remains of this brake chamber, I found that the push-rod had a distinct wear point. This had been caused by the push-rod moving against the bottom edge of the brake chamber mounting bracket. This also suggested that the brake chamber had been detached from its mounting point for a considerable time.

**Figure 7: Rear axle brake chambers**

The second fire occurred under almost identical circumstances as the first, but this time in the State of Victoria. The trailers were owned by the same transport company and were also manufactured by J Smith and Sons. During my examination of the trailers in this fire, I went through the same examination process, starting from the front of the A trailer and working to the back of the trailer. I found that the nearside brake chamber of the rear axle had broken away from its mounting point. All that remained of this brake chamber was the front section of the brake chamber and the push-rod.

**Figure 8: Wear point in brake chamber push-rod**

**FIRE 2 – 5 SEPTEMBER, 2019**

The second fire occurred under almost identical circumstances as the first, but this time in the State of Victoria. The trailers were owned by the same transport company and were also manufactured by J Smith and Sons. During my examination of the trailers in this fire, I went through the same examination process, starting from the front of the A trailer and working to the back of the trailer. I found that the nearside brake chamber of the rear axle had broken away from its mounting point. All that remained of this brake chamber was the front section of the brake chamber and the push-rod.
There was evidence that the brake chamber had been in this condition for a considerable period of time as the push-rod had worn away the bottom of the mounting bracket.

Examining the remaining section of the brake chamber and push-rod, I found the mounting bolts had torn away and the push-rod had been worn through to approximately half its normal diameter.
The offside brake chamber only consisted of the front section and push-rod. It was also loose on the axle mounting bracket.

I removed the remains of the offside rear brake chambers for further examination. While the push-rod was intact, there was evidence that cracking of the face of the brake chamber had been occurring around the mounting bolts.
CONCLUSION

The evidence gathered in both investigations had common points. Specifically, a brake chamber tearing away from its axle mounting point and the push-rods showing signs of frictional wear. I was of the opinion that the failure of the brake chambers in both cases were due to the same cause.

Although the trailers from both fires were owned by the same transport company, servicing of the trailers was carried out by another company. Service records revealed that all of the trailers had the brake chambers replaced in the months leading up to the fires. Further enquiries were made about the manner in which the brake chambers were replaced. I found that pneumatic impact wrenches were used to fit the brake chambers, instead of torque wrenches. Enquiries revealed that the servicing staff claimed it was difficult to use a torque wrench when working under a trailer. So a habit of using pneumatic impact wrenches was employed, as it was easy and fast.

The manufacturer, BPW Transpec requires brake chambers be fitted at 190 Nm. As pneumatic impact wrenches were being used, there was no accurate measurement of the torque. BPW Transpec confirmed that when brake chambers were fitted with a torque greater than 190 Nm, micro-cracking of the brake chamber mounting face occurred and could ultimately result in the brake chamber tearing away from the mounting plate of the axle.

The two trailers in this paper had brake chambers fitted using pneumatic impact wrenches. As a result cracking of the brake chamber mounting face occurred. In the case of the fire of 24 July, 2019 the offside rear brake chamber tore away from its mounting point and hung on the push-rod. In the seconds before the fire, the spring brake of the nearside front brake deployed. This caused the nearside front wheels to have greater drag, which ultimately resulted in fire. In the fire of 5 September, 2019 the rear offside brake chamber detached under a similar mechanism. With this fire it is not particularly clear on which wheel the fire occurred.

The failure of a brake chamber in this manner, ultimately leads to one, or more of the other brakes partially, or fully engaging. If this is not noticed by the driver, a fire will occur.

Since these two fires, workshop practices have been changed and no further fires have been reported.
These fires also demonstrate that a driver pre-start inspection is not always performed as diligently as they should. This is demonstrated by the evidence that the A Trailer in both fires had brake chambers torn away from the axle mounting point, possibly for days to weeks before the fire. Had the drivers been more rigorous with the pre-start inspections, the damaged brake chambers should have been discovered.

In Australia there is no mandatory requirement for tyre pressure and temperature monitoring systems to be installed on heavy vehicles.
An Analysis of Cabin EXHAUSTER Vents and Body Structure Pass-Throughs in Post-Collision Vehicle Fires

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ABSTRACT

This paper analyses real world post-collision vehicle fire incidents which caused serious injuries or death as a result of fire propagating into vehicle interiors through the cabin exhauster vents and body structure pass-throughs. Researchers have noted there is an opportunity to reduce vulnerability to fire penetration by minimizing the area of openings in the body structure [1]. In addition, the National Fire Protection Association recommends that penetrations in the barriers surrounding the passenger compartment should be protected [2].

Laboratory testing was utilized to establish the performance of the original equipment manufacturer (OEM) exhauster vent and pass-through designs utilized in the case study vehicles, as well as the effectiveness of alternate designs in delaying or preventing the propagation of a post-collision fire into the occupant compartment.

KEYWORDS: POST-COLLISION FIRE, EXHAUSTER VENT, PASS-THROUGH

INTRODUCTION

There are approximately 300,000 vehicle fires each year, accounting for one fifth of all fires in the United States. This is comparable to the number of annual house and apartment fires, but results in more fatalities than either, approximately 500 per year [3]. Nearly 3 out of 4 vehicle fires are caused by mechanical or electrical failures or malfunctions, but these fires only account for 11% of vehicle fire deaths. Collisions and overturns contribute to fires or fire ignition in only 3% of vehicle fires, however, these fires result in 3 out of 5 vehicle fire deaths [4].

It usually takes 10-24 minutes for emergency personnel to arrive at the scene after an incident occurs [3]. However, occupant death can occur rapidly, sometimes in as little as 1-3 minutes, once fire enters the occupant compartment [6][7]. In order to allow a sufficient length of time to permit escape or extrication, vehicles should be designed to resist propagation of fire into the occupant compartment.

The only United States Government regulation for fire testing of motor vehicles is Federal Motor Vehicle Safety Standard (FMVSS) 302: Flammability of Interior Materials. This standard was developed in the 1960s to address fires initiated in the vehicle interior by matches and cigarettes and applies only to materials inside the space occupied by the vehicle occupants. The FMVSS 302 test procedure uses a small pilot flame to ignite samples of materials in a benchtop fixture and specifies a limit on the speed of flame propagation. Today, less than 5% of fires originate in the vehicle interior and the vast majority of fires result from a source outside the occupant compartment [3]. Once an
external fire penetrates the occupant compartment, flames spread several times faster than allowed by FMVSS 302. As a result, FMVSS 302 is widely believed to be outdated [3].

In the case studies evaluated in this paper, fire was found to have propagated from an external source into the subject vehicles through exhauster vents and other pass-through openings into the occupant compartment. The body structures of modern vehicles are constructed of sheet metal and have numerous penetrations to accommodate cables, wires, hoses, ducting, and other components. These pass-throughs are typically sealed off using plastics, foams, and elastomeric materials. In some designs, metal plates are used to protect the openings.

Figure 1 2010s model sedan firewall HVAC and shifter cable pass-through

One type of pass-through of particular interest in some of the subject case studies is the cabin exhauster vent. Heating Ventilation and Air Conditioning (HVAC) systems in modern vehicles typically include cabin exhauster vents that allow air to flow out of the occupant compartment. Most vehicles are equipped with a pair of exhauster vents concealed at the rear of the occupant compartment or cargo space depending on the vehicle configuration. Examination of aged exhauster vents from several exemplar vehicles has shown the elastomeric louvres used to prevent backflow into the occupant space are often missing or deformed, and the elastomeric material is often degraded. This indicates that many exhauster vent designs are not suitable to last for the life of a vehicle.

Figure 2 New and used exhauster vents from a 2013 Sedan

There are a multitude of approaches to improving vehicle fireworthiness, and in particular the fireworthiness of exhauster vents and other pass-throughs. The use of more resilient and fire-resistant materials for the construction of pass-through seals can improve fire resistance. In the case of the exhauster vent, upgrading the materials not only improves fireworthiness but can also mitigate the effects of ageing and ensure vents operate as designed for the life of a vehicle. Flame arresters, which allow air flow but stop the transmission of flame, as well as intumescent materials, which expand when subjected to heat to seal openings, can also be successfully incorporated into exhauster vent and other
pass-through designs to improve fireworthiness without compromising vent or pass-through seal performance. In addition, minimizing the size of penetrations into the occupant compartment and providing shielding to protect the penetrations can improve fire resistance.

**METHOD AND RESULTS**

Real-world vehicle fires were investigated wherein it was determined that fire from a source external to the subject vehicle propagated into the occupant compartment through pass-throughs, causing injury or death to the vehicle occupants. The fire incidents involved varied accident circumstances, collision damage, and fuel sources.

**Case Study 1**
An early 2010s model sedan crossed the centerline of a highway and impacted a vehicle in an offset frontal collision that resulted in a fire originating in the engine compartment. Analysis revealed the fire propagated into the cabin of the accident vehicle through the HVAC and shift cable pass-throughs in the firewall. Figure 3 shows a photograph of the accident vehicle and an exemplar firewall. The driver was the sole occupant and was severely burned by the fire.

![Figure 3 Accident Vehicle and Exemplar Firewall Pass-Through](image)

**Case Study 2**
A 2000s pickup struck a highway embankment then rolled onto its roof and caught fire. Examination of oxidation patterns indicates the fire originated around the fuel tank and propagated into the occupant compartment through the cabin exhauster vent hole located on the rear wall of the cab. Figure 5 shows the accident vehicle and an exemplar exhauster vent on the rear of the cab. The driver was the sole occupant and was killed.

![Figure 5 Accident Vehicle and Exemplar Rear Exhauster Vent](image)
Case Study 3
A metal object struck the undercarriage of a 2010s model sedan on a highway and punctured the fuel tank causing a fire. It is the expert examiner’s belief the fire entered the occupant compartment through the exhauster vent located at the left rear fender. Figure 6 shows the accident vehicle and an exemplar rear exhauster vent. Three of the four occupants survived, and the fourth occupant died in the fire.

![Accident Vehicle and Exemplar Rear Exhauster Vent](image)

Case Study 4
A 2010s model sedan left the road and traveled through a fence before it came to rest at a pole. Hot components under the engine compartment caused a grass fire which ignited the vehicle. Investigation revealed the fire entered through the exhauster vents at the rear fender. Figure 7 shows the accident vehicle at the scene and an exemplar rear exhauster vent. Two of the four occupants were removed from the vehicle, and the remaining two occupants died in the fire.

![Accident Vehicle and Exemplar Rear Exhauster Vent](image)

Test Series
Burn testing has been conducted utilizing fuel sources representative of the fuels identified in the subject vehicle fires. This testing has been run utilizing partial vehicle clips obtained from exemplar vehicles to represent the area of fire propagation identified in the case studies, as well as sheet metal bench testing fixtures representing the pass-through openings in the subject vehicles. New OEM replacement exhauster vents and pass-through seals were tested, as well as aged exhauster vents obtained from exemplar vehicles and improved vent and pass-through designs.

Production Test Series 1
A burn test was conducted on an exemplar front clip from a vehicle equivalent to the Case Study 1 vehicle using brake fluid in a burn pan heated by a hot plate. The brake fluid was ignited from an external source, then moved into position under the firewall pass-throughs. Flames were visible in the occupant compartment approximately 351 seconds after the burn pan was moved into position against the firewall, shown in Figure 8.
Figure 8  Case Study 1 burn test set up and flame propagation at t = 351 seconds

Production Test Series 2
A burn test was conducted on an exemplar cab from a vehicle equivalent to the Case Study 3 vehicle using gasoline in a burn pan positioned underneath the exhauster vent and igniting it with an external source. Flames were first visible on the interior side of the exhauster vent at approximately 42 seconds after ignition. Figure 10 shows the vent completely fell out of the opening approximately 53 seconds after the fire was ignited.

Figure 10  Case Study 3 burn test set up and flame propagation at t =~53 seconds

Production Test Series 3
A burn test was conducted on an exemplar rear clip from a vehicle equivalent to the Case Study 4 vehicle using gasoline in a burn pan positioned underneath the exhauster vent and igniting it with an external source. Flames were first visible on the interior side of the exhauster vent at approximately 24 seconds after ignition, shown in Figure 11. The vent was completely engulfed and was melted out of the opening by approximately 40 seconds after ignition.
Production Test Series 4

A pair of burn tests was conducted using a steel panel benchtop fixture using straw positioned underneath the exhauster vent and ignited with an external source. The first test evaluated a new OEM replacement vent for the case study 5 vehicle and the second test evaluated an aged vent obtained from an exemplar vehicle equivalent to the case study 5 vehicle that was approximately 8 years old at the time of testing. Flames began coming through the new OEM vent approximately 68 seconds after ignition, and flames were observed coming through the aged vent 15 seconds after ignition. The benchtop testing is shown in Figure 12.

An additional burn test was conducted with a new OEM vent using a rear clip from an exemplar vehicle equivalent to the Case Study 5 vehicle using straw positioned underneath the exhauster vent and ignited with an external source. Flames were first visible on the interior side of the exhauster vent approximately 71 seconds after ignition, shown in Figure 13. This time is consistent with the burn through time observed using the benchtop fixture.
Improved Design Test Series 1

The firewall pass-throughs were improved by reducing the size of the HVAC pass-through opening in the firewall and using more fire resistant materials. The improved design replaces rubber grommets with welded steel plates in the firewall with holes sized no larger than necessary to accommodate the heater core and air conditioning lines. Split ring hinge collars were added to shield the heater core lines, and the OEM coupler was fitted on the AC lines. The shift cable pass-through was closed off with a steel plate fastened to the firewall that incorporates a steel tube to shield the cable. The improved design pass-throughs were subject to the same test procedure used to evaluate the OEM pass-throughs. The fuel in the burn pan was completely consumed by approximately 548 seconds, but some flammable components in the engine compartment continued to burn. The test was concluded approximately 732 seconds after the burning brake fluid was moved into position under the firewall and no flames were observed inside the occupant compartment during the test, shown in Figure 14.

Improved Design Test Series 2

The exhauster vent was improved by constructing a housing around the OEM exhauster vent interior. The housing was fitted with a commercially available flame arrestor type fire resistant vent assembly consisting of an aluminum honeycomb core with an intumescent coating encased with perforated sheet metal on one side and a fine stainless-steel mesh on the other. The improved design exhauster vent was subject to the same test procedure used to evaluate the OEM pass-throughs. The fire burned for
approximately 564 seconds and no flames were able to pass through the exhauster vent, shown in Figure 16.

As discussed previously, in Production Test Series 3 flames were visible in the occupant compartment approximately 42 seconds after the gasoline in the burn pan was ignited. Therefore, the improved vent design resisted the fire for a significantly longer time period than the production design and could likely have continued to resist fire for a longer period of time.

**Improved Design Test Series 3**
A new improved design vent was added to the test buck. An opening was cut on the opposite side of the vehicle from the OEM vent opening. A housing was installed fitted with a commercially available flame arrestor type fire resistant vent assembly consisting of an aluminum honeycomb core with an intumescent coating encased with perforated sheet metal on one side and a fine stainless-steel mesh on the other. The improved design exhauster vent was subjected to the same test procedure used to evaluate the OEM vent. The fire began entering the trunk compartment through a hole near the vent assembly at approximately 95 seconds and the fire spread to the edges of the alternative design vent at approximately 110 seconds, shown in Figure 17.

As discussed previously, in Production Test Series 4 flames were visible in the occupant compartment approximately 24 seconds after the gasoline in the burn pan was ignited. Therefore, the improved vent design resisted the fire for a significantly longer time period than the production design and could likely have continued to resist fire for a longer period of time. However, the burn testing revealed an additional hole in the body sheet metal that allowed fire to propagate into the compartment and spread to the interior side of the vent assembly.
Improved Design Test Series 4
The exhauster vent was improved by constructing a housing around the OEM exhauster vent interior. The housing was fitted with a commercially available flame arrestor type fire resistant vent assembly consisting of an aluminum honeycomb core with an intumescent coating encased with perforated sheet metal on one side and a fine stainless-steel mesh on the other. The improved design exhauster vent was subject to the same test procedure used to evaluate the OEM vent. The fire burned for approximately 221 seconds and no flames were able to pass through the exhauster vent, shown in Figure 18.

![Figure 18 Case Study 5 improved exhauster vent design and burn test at t= 221 seconds](image)

As discussed previously, in Production Test Series 5 flames were visible in the occupant compartment approximately 71 seconds after the straw was ignited. Therefore, the improved vent design resisted the fire for a significantly longer time period than the production design and could likely have continued to resist fire for a longer period of time.

CONCLUSIONS
Case studies and testing have shown the cabin pass-throughs and exhauster vents used in many vehicles fail to adequately resist the propagation of an external fire into the occupant compartment for a sufficient length of time to facilitate the rescue of vehicle occupants. In addition, exhauster vent assemblies were observed to deteriorate with age. Burn testing has shown that aged vents have a significantly reduced ability to delay the propagation of a fire, and actually have the potential to rapidly ignite and increase the speed of fire propagation into the vehicle interior. Finally, improved cabin exhauster vent and pass-through seal designs have demonstrated the ability to resist fire propagation for in excess of 10 minutes with no signs of degradation. The use of alternative pass-through and exhauster vent designs can significantly increase the amount of time available to rescue vehicle occupants and has the potential to eliminate fire propagation into the interior of a vehicle if the fuel source is consumed before fire penetration occurs.
REFERENCES


Fire safety of Zero Emission Buses depots: fire prevention and incident response

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ABSTRACT

Zero emission bus public transport, in particular through battery electric buses, is becoming more and more common in The Netherlands. Electric buses use battery packs, which contain thousands of lithium ion battery cells for storage of the required energy. Charging takes place in bus depots and also en route. In The Netherlands, and also abroad, in recent years serious fires have occurred in bus depots and on the road. These fires can have a direct impact on bus passengers, the driver as well as the surrounding area, depending on the local situation. They will also affect emergency response operations. To improve safety a thorough understanding of the fire safety risks of zero emission public transport is essential. Therefore three studies were conducted in recent years in our institute (NIPV – formerly IFV): a study of fire safety of zero emission buses in tunnels [1] a study to improve incident response in case of a battery fire of a zero emission bus [2] and a study to improve fire safety of bus depots [3]. In this paper we will present the results of these studies, with the emphasis on incident response.

KEYWORDS: fire safety, zero emission buses, bus depots, fire fighting

INTRODUCTION

In The Netherlands and in Europe, more and more zero emission buses are used for public transport. For the bigger part this concerns battery electric vehicles (BEV) and for a small part fuel cell electric vehicles (FCEV). Replacing internal combustion vehicles (ICE’s) with zero emission alternatives helps to reduce the carbon footprint and is as such in line with the ambitions for sustainability of the Dutch government. Additionally, the recent war in Ukraine has been a further stimulus for the reduction of fossil fuels.

Dutch public transport authorities grand permits to bus companies for public transport. In line with government policy, they increasingly require the use of zero emission (ZE) buses. Bus companies have to prepare a bid to be selected to operate bus lines. In their bids, they have to make clear how they will operate the bus line. Although safety and incident response are part of the operational procedures, they play a relatively minor role in the operator selection procedures, possibly because public transport has been using “tried and tested systems” over decades; systems that have undergone only very little changes. This is particularly so for the fuel (diesel) and propulsion systems used. Recent incidents with new zero-emission vehicles, however, have shown that this issue deserves more attention. Therefore the Energy Transition Team at NIPV conducts research in this area.

Table 1 shows some recent zero emission bus depot fires, involving multiple buses. From this table we conclude that bus depot fire do occur, involving several busses. These fire cause a lot of damage (busses and depot), have great impact on the environment (smoke), require a substantial effort of the fire and rescue service, and complicate the bus operations because less busses are available after the fire.
### Table 1: Multiple ZE-bus fires in bus depots [3]

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Location bus</th>
<th>cause</th>
<th>Involved buses</th>
<th>City, country</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery bus</td>
<td>In bus depot, outside</td>
<td>Unknown</td>
<td>6 busses</td>
<td>London, UK</td>
<td>2022</td>
</tr>
<tr>
<td>Unknown (probably ICE)</td>
<td>In bus depot, outside</td>
<td>Unknown</td>
<td>20 busses</td>
<td>Bromsgrove, UK</td>
<td>2022</td>
</tr>
<tr>
<td>Unknown (probably ICE)</td>
<td>In bus depot, outside</td>
<td>Unknown</td>
<td>3 busses</td>
<td>Walsall, UK</td>
<td>2021</td>
</tr>
<tr>
<td>H2 and ICE</td>
<td>In bus depot, inside</td>
<td>Hydrogen leakage of fuel tank</td>
<td>2 busses</td>
<td>Doetinchem, NL</td>
<td>2021</td>
</tr>
<tr>
<td>Battery bus and ICE</td>
<td>In bus depot, inside</td>
<td>Probably in ICE</td>
<td>40 busses</td>
<td>Dusseldorf, Germany</td>
<td>2021</td>
</tr>
<tr>
<td>Battery bus and ICE</td>
<td>In bus depot, under roof</td>
<td>During charging battery bus</td>
<td>25 busses</td>
<td>Stuttgart, Germany</td>
<td>2021</td>
</tr>
<tr>
<td>Battery bus and ICE</td>
<td>In bus depot, inside</td>
<td>Technical failure, not in the bus</td>
<td>9 busses</td>
<td>Hannover, Germany</td>
<td>2021</td>
</tr>
<tr>
<td>Battery bus</td>
<td>In bus depot, outside</td>
<td>unknown</td>
<td>4 busses</td>
<td>Haarlem, NL</td>
<td>2020</td>
</tr>
</tbody>
</table>

### METHOD AND RESULTS

To understand the safety risks of ZE buses, a literature study was done in 2016 [1]. We compared fire inducing mechanisms of ZE buses to those of buses with internal combustion engines (ICEs). For the incident response, in particular in confined areas such as tunnels, we derived various safety measures for the bus operator as well as the fire services to reduce the consequences of accident. We also conducted a study aiming to understand and assess the risks of en route charging (opportunity charging) of buses, which introduces extra hazards in the public area. We studied bus design and interviewed experts dealing with ZE buses. This resulted in important insights for fire services and bus operators on how to prepare for ZE bus fires in the public domain, as well as in advise for licensing authorities. Thirdly, we developed safety guidelines for design and construction of depots in which ZE buses are parked and charged. To this end, we also studied literature and design guidelines, (zero emission) bus depot fires and interviewed ZE bus stakeholders. In addition to fire safety measures (prevention), we also formulated emergency management / fire service guidelines.

### ZERO EMISSION BUSES AND BUS DEPOTS

We will subsequently describe the BEV busses and the hydrogen busses (FCEV). As much as possible, we will compare the safety risks of these ZE-busses to the traditional diesel busses.

**BEV buses**

The main difference between BEV buses and traditional diesel buses is the powertrain (engine) and fuel. While a combustion engine provides the propulsion for diesel buses, the propulsion for BEV buses comes from electric motors, for which the energy is stored in battery packs present in the vehicle. The energy (kWh) in 1 kg of the batteries is considerably lower than that of 1 kg of diesel. To obtain an acceptable range, a considerable volume and mass of batteries is necessary. The mass of electrically powered buses is therefore 2000-2500 kg higher than comparable diesel buses. The batteries can be installed in different places, such as on the roof, under the floor, in the front, on the back or a combination of these. Figure 1 shows some configurations of battery packs in buses.
FCEV buses

An FCEV bus is also an electrically powered bus, in which a battery pack is present. This package is smaller than in a BEV bus as most of the energy is stored in the form of hydrogen in high-pressure cylinders. The hydrogen cylinders are generally located on the roof. As with BEV buses, the battery packs can be in various locations in the bus (see Figure 2). These battery packs are charged outside driving hours in depots. Occasionally, the batteries are recharged through charging points on the route (“opportunity charging”).

As stated before, the energy content of a battery pack of an electric bus is lower than that of a diesel bus. A typical energy content for electric buses is 400 kWh (or 1.44 GJ). A 400 liter fuel tank of a diesel bus contains 4250 kWh (15.3 GJ) of energy, or more than 10x the energy content of a (fully charged) electric bus. However, battery packs also contain a large amount of other combustible material (battery casings, materials used to build modules and packs, electrical cabling, printed circuit boards). As a result, the total quantity of combustible material in a battery pack can come close to the value of a diesel tank. In addition to this, buses contain many (flammable) plastic materials. Because of these factors, it is to be expected that the total fire load of electric buses will not differ much from diesel buses. This notion is supported by experiments with passenger cars, which showed that the energy released during a fire of an electrically powered vehicle was only 10 to 15% lower than that of the otherwise identical diesel variant. With regard to the heat release rate (HRR), some experiments with passenger cars showed that for vehicles equipped with a diesel tank, the maximum value of the
HRR was up to 30% higher than for otherwise identical electric vehicles [7]. It is therefore to be expected that the maximum value of the HRR of diesel buses will be higher than for electric buses. The energy of an FCEV bus comes from the hydrogen. A bus with 35 kg H2 has an energy content of 1170 kWh. Adding 100 kWh in batteries gives a total of 1270 kWh. This is more than a BEV bus and less than a diesel bus. However, given the considerable quantities of combustible material in other places in the bus, the total quantity of combustible substances is not expected to differ much from that of diesel or BEV buses.

Bus depots
Three types of bus depots with facilities for electric charging or hydrogen refueling are used in the Netherlands (see also Figure 3):

- fully covered (inside, situations 1 and 2 in Figure 3);
- (Partly) covered (situations 3 and 4 in Figure 3);
- In the open air (outside, situations 5, 6 and 7 in Figure 3).

Depending on bus and fuel type there may be:
- electric charging through a pantograph;
- electric charging station through a plug;
- Hydrogen refueling units.

Figure 3  Types of depots with electrical and Hydrogen facilities

FIRE SAFETY RISKS OF ZERO EMISSION BUS DEPOTS

Fires in ZE-buses regularly find their way to the Dutch news headlines:
- 2022: two BEV-bus fires in Paris (single buses) and one bus depot fire with BEV buses in London;
- 2021: one bus depot fire caused by an FCEV bus in The Netherlands (Doetinchem) and three bus depot fires with BEV buses in Germany (Dusseldorf, Stuttgart and Hannover), two of which during charging;
- 2020: One bus depot fire with BEV buses in the Netherlands (depot in Haarlem).

The exact cause of the fires was not always known. Because of the limited number of (well documented) ZE-bus fires it is not possible to make a reliable statement about the probability of a fire in a ZE-bus compared to a traditional diesel bus. However, case studies show that the cause of the fires is often different. The majority of fires in diesel buses (70% [8], 95% [9]) are caused by the engine or in wheel arches, i.e. as a result of driving. Fires in electrically powered vehicles regularly occur when the vehicle is not in use. This also emerged in a study of passenger cars by [11] in which it was reported that out of 16 reported electric vehicle fires, 10 fires started while the car was stationary (4 parked, 6 charging). The remaining 6 fires were related to driving. In a Finnish study [11] it was stated that all (three) reported fires in BEV and FCEV vehicles, in a five year period, started during charging. Also fires in diesel buses mostly occur in older buses, whereas fires in battery powered buses occur in a relatively young fleet.

All this indicates that the charging process of electric buses is a significant fire risk for locations where charging takes place (i.e. bus depots with ZE-buses). This fire risk is not present in “traditional” diesel-bus depots, and therefore deserves special attention in fire safety for ZE bus depots. This notion is supported by studies from Australia [12] and the United Kingdom [13], both stating that lithium ion batteries cause typical fire risks. In particular mechanical, electrical or mechanical abuse may have a severe negative impact. Below we will address the fire risks for ZE bus depots. Causes, consequences, fire spread, fire suppression will be covered. Preventive and mitigating measures relevant for bus depots will be identified, based on literature and interviews.

**ZE-BUS FIRES IN DEPOTS**

**BEV buses**

Battery packs are made up of several modules and each module contains several battery cells. Overheating of a battery (cell) can lead to a so-called “thermal runaway”. A thermal runaway occurs if, in an exothermic (i.e. heat-generating) reaction, the heat produced cannot be sufficiently dissipated to the environment and accumulates internally, causing the temperature to rise and the reaction rate to increase exponentially. When this happens in lithium-ion cells, they will eventually break [14] leading to fire and the release of gases. The rising temperature can trigger the same process in adjacent cells leading to a chain reaction that spreads from battery cell, to battery module to battery pack and finally to fire of the vehicle [15].

![Event tree for a thermal runaway of a battery pack (based on [14, 10])](image-url)
Figure 4 shows the processes involved in a thermal runaway in more detail (see also [14, 10]). Crucial are the decomposition of the electrolyte and the occurrence of a defect in the separator of a battery cell. The separator provides electrical separation of the anode and cathode. If it becomes defective, for example due to metal deposits and dendrite formation (sharp metal deposits), a short circuit occurs, causing the cell to overheat. This can lead to further damage to the separator and decomposition of the electrolyte and cathode. When the electrolyte decomposes, gas is formed. The composition depends on the type of electrolyte, but in general it contains flammable and toxic components. The formation of gas leads to pressure build-up in the cell. This may cause the cell to break open and this gas to escape from the cell. The heat development can lead to overheating of neighboring cells and initiate the same process there (overheating and gas development), and so on. The pressure build-up caused by the gas evolution can cause the battery pack to burst, causing a sudden release of gases and the possibility of battery components being ejected. These gases can ignite explosively. The resulting flames and sparks can set a vehicle on fire and heat can (sometimes after a long time) ignite battery cells or modules that have not yet ignited.

The various causes as a result of which a thermal runaway can occur can be summarized as follows:

- Overheating of the cell, such as overcharging (for example, charging too fast), or problems with electrical connections between battery modules or packs. External heat sources can also cause this.
- Formation of metallic structures (dendrites, plating) as a result of overcharging or deep discharging. Use at low temperatures and aging of the battery can also have these consequences.
- Material / construction defects can also lead to separator defects as well as physical damage due to, for example, collisions or rough use of batteries.

Some causes can be directly related to driving, such as overloading or mechanical damage due to rough use or an accident. The factors that influence the quality of the batteries (charging method, temperature, ageing) can also occur when the bus is not in use, or predominantly occur when the bus is not in use.

The Battery Management System (BMS) in electric vehicles monitors (and detects) the functioning of the battery pack. In the event of deviations, such as a charging current that is too high, a discharge that is too large or a temperature of the battery that is too high, the BMS takes action. This can, for example, be active cooling during charging, switching off the charging process and possibly completely disconnecting the Li-ion battery.

Fires in lithium-ion battery packs have a slower fire development and longer burning time than fires in diesel buses. In addition, the composition of the toxic and corrosive substances that are released differs from that of a conventional vehicle. This affects firefighting. Fighting fire in the battery pack of BEV buses is also made more difficult by the shielding of the packs against water and impact. As a result, (extinguishing) water cannot reach the source of the fire. Finally, the process that causes a thermal runaway can keep itself going within the battery cells unnoticed from the outside. This can make it seem as if a battery pack fire has been extinguished, but the reaction and therefore heat development continues internally. As a result, water must be available for a long time (sometimes hours) to combat any flaming up flames. Special containers have been developed for passenger cars in which a car can be completely submerged in water for a longer period of time [16]. Such a solution does not (yet) exist for large vehicles, such as buses.

**FCEV buses**

The specific fire risk for FCEV buses comes from both the battery pack and the hydrogen. With regard to the battery pack, in principle the same risks are present as with a BEV bus. However, charging mainly takes place en route via the fuel cell and to a limited extent in depots. Also the energy content of the battery packs is also lower. The fire risks from batteries in depots are therefore smaller than for BEV buses. Nevertheless, a thermal runaway can still cause a bus fire with the same consequences as a thermal runaway in a BEV bus.
The risks posed by hydrogen originate from the hydrogen-containing elements in the bus and from the refueling installation, if located in the parking facility or depot. Two types of incidents should be considered:

- Release of gas (hydrogen) as a result of leakage (e.g. due to incorrect handling or corrosion) possibly leading to an explosive atmosphere if the combustible gas accumulates under roofs, for example.
- External heating of a gas cylinder leading to pressure build-up, opening of the safety valve (a Thermally activated Pressure Release Device or TPRD) and release of the gas, resulting in a jet fire. In this scenario, the hydrogen is not the cause of the fire.

Extinguishing a hydrogen jet is not possible, but the jet lasts only for a few minutes. If possible, the area heated by the jet can be kept wet. An explosion is instantaneous. Emergency response services will therefore mainly be occupied with combating / preventing secondary fires and providing first aid to victims.

**ZE-bus depots**

Battery fires are a fire risk for ZE-bus depots not present in depots with only diesel buses. The initiating events in a diesel bus that may cause a depot fire can generally be detected in an early stage (e.g. smoke coming from a burning cigarette in a bus). In electric buses, the “run-up” to the thermal runaway leading to the depot fire takes place inside the battery pack and only becomes visible when the battery pack breaks open, after which an exponential growth of the fire takes place. This results in an extremely fast spreading of the fire to (usually very closely parked) adjacent buses and the building, which makes an early intervention extremely difficult.

A fire that starts during non-driving hours, such as during (charging in) a depot, will also be noticed less quickly, because there will generally be fewer people in or near the bus. This increases the chance of developing a fire (during non-driving hours) in an electric bus compared to a diesel bus. Faulty or damaged charging equipment and vehicles hitting the charging point have also been identified as causes of fire of the charging locations [11]:

In FCEV buses, the hydrogen released by leakage can form a flammable hydrogen-air mixture if there is insufficient ventilation. If ignition sources are present, this can lead to a flash fire or, if the gas cloud is contained, to an explosion. Once a fire has started (whether or not as a result of a thermal runaway), the hydrogen in FCEV buses will form an additional risk. At 110 °C or when the blow-off pressure set point is reached the TPRD will open and a jet fire will occur. The jet will generally be aimed vertically upwards and will cause damage above the outflow point (e.g. the roof of the depot). Neighboring installations or buses will then not be damaged (unless fire spreads via the ceiling). A hydrogen flame is invisible unless there are particles (dust, for example) in the flame.

As outlined earlier, once a fire has started, the further development of a fire in a ZE-bus will not be very different from a diesel bus, as fire loads are comparable. Therefore, many aspects affecting fire in a diesel bus depot will equally apply in ZE-bus depots. Irrespective of bus type the following was found [16]:

- Bus equipment materials represent a very high fire load and are more flammable than, for example, trains. Reducing this fire load will take time.
- In a bus, the fire develops very quickly: within 1 to 2 minutes to a fully developed fire.
- The fire causes a lot of heat and smoke. Adequate extraction of smoke and heat is not possible.
- Both practical and numerical simulations show that once a bus is on fire, it is virtually impossible to save the building or other buses.
- If the fire starts in the engine compartment, fire-fighting systems installed in this compartment can significantly reduce the risk.
- External fire suppression systems (e.g. ceiling sprinkler) are ineffective for cooling the battery cells due to the metal (watertight) bodywork.
When there is a combination of several energy carrier(s) at a depot, the following is important:

- **Prevent cascading effects.**
  Cascading effects involve a chain of events that start small and grow larger. With a combination of energy forms, the cascading effects are the result of a fire in one type of energy carrier (for example a BEV bus or a fast charger), which spreads to the other type of energy carrier (such as hydrogen in an FCEV bus) [18].
- **Incident management will be more complex,** for example due to multiple hazards, locations and/or extinguishing techniques.

In a (fully) covered depot, heat from the fire will be more intense and smoke and toxic gases (e.g. HF) can accumulate. This requires (additional) protective equipment for the fire service and will make fire fighting more difficult [19].

The close proximity of the buses will not only cause a rapid fire spread, but will also make access to the fire-source much more difficult, possibly making it impossible to extinguish the fire. The (exact) location of the fire may also be more difficult to determine due to the smoke and heat development in the event of a fire in a covered parking facility.

As mentioned earlier, a thermal runaway can re-ignite a battery pack after it has (apparently) been extinguished. This requires a lot of water.

**SAFETY MEASURES: PREVENTION**

Fire prevention measures are measures that prevent fires to happen, or at least, reduce the fire probability. To make an inventory of the fire prevention measures, we studied scientific literature and reports from research institutes. We found two main categories for preventing ZE-bus fires: battery failure detection and immediate suppression and charge point detection.

Battery failure aims to identify as early as possible deviations from the (normal) battery operation window. In case a threshold is exceeded, immediate intervention measures come in place [20]. In the EU Cordis project, the bus battery, its environment and the charge infrastructure were studied. In addition, the Cordis researchers studied active fire suppression systems in the bus and the battery as well. They developed a fire safety concept for electrical and hybrid buses that includes fire detection, cooling of the battery and fire suppression. Tests demonstrated that even in the case of a relatively late activation of the fire suppression system, it is possible to prevent a thermal runaway. The battery failure is limited to the critical state, which means that bus passengers have substantial time and options for safe egress [21].

In most bus depots, bus get charged as well. The charge infrastructure could provide useful failure information as well. We studied the opportunities for retrieving useful failure data from the charge infrastructure [22].

Most charge point are equipped with a temperature sensor. In case the measured temperature exceeds a certain threshold (depending the chemistry and design of the battery but in general somewhere about 70 degrees Celsius), the charging process is interrupted. Applying such sensors in bus depot charge point, could also be useful preventing bus depot fires.

Collision barriers could prevent busses from colliding with the charge point. In addition, charge point may also be equipped with skewed sensors. These sensor create a signal in case the charge point is not in its original position anymore. Applying such sensors in bus depot charge points, could also be useful for early warning of possible bus depot fires.

Charge point operators receive signals from battery management systems in case of deviations due to too high currents and in case of too large discharging. This signal results in stopping the charging process. Bus depots operators may make appointments with the charge point operators regarding these early warnings, hence preventing for bus depot fires.
[23] conclude that parking garages that comply with the regulations and recommendation from electric car manufacturers may refrain from water-based fire suppression systems. Still, a sprinkler system prevent for fire spreading due to the fact that the sprinkler cools the environment and nearby cars/busses [1], but not to cool the battery cells.

In particular for hydrogen busses, hydrogen leakages can be detected before explosion levels are reached. This means that when such leakages are detected and reported to operators, operators may take the necessary action: alarming people in the bus depots, shut down the hydrogen systems and venting to prevent for reaching a critical explosion level.

SAFETY MEASURES: SUPPRESSION

Fire suppression measures are measures that either a) reduce the spreading of the fire, or b) control the fire or suppress/extinguish the fire. We studied literature and several bus depots that had already been realized in The Netherlands. The bus depot that we studied were Bus depot Westraven (Utrecht) and bus depot Breda.

Reduction of fire spreading
To reduce the spreading of the fire we came across to safety measures. Bus depots that had an quarantine area. This is an area at a distance from the bus depot, or an area equipped with fire suppression systems, where suspicious busses could be parked. Suspicious busses are for example busses that haven been involved in a (small) collision. Might the bus get on fire on the quarantine area, this will not spread to other buses or the whole bus depots because of the mutual distance to the bus depot or the fire suppression system intervention.

Another measure is that the bus depot itself was subdivided in several fire compartments. A fire compartment has a certain fire resistance meaning that the fire will be contained to this compartments for a prespecified amount of time, e.g. 60 minutes. This might give the fire and rescue services the opportunity to develop an intervention strategy and limit the fire spread to the involved fire compartment.

Control/suppress the fire
System that control the fire are systems that prevent the fire from getting bigger. Systems that suppress the fire are systems that extinguish the fire. There are systems that are integrated in the battery pack. These system get activated once a temperature threshhold is exceeded. An extinguish system directly puts the water on the battery cell (in the battery pack). Because of a relative intervention and colling directly the battery cell, only a small amount of water (12-13 liters) was sufficient to cool the battery cells effectively in the pack [21]. In addition to cooling the battery cell, it also prevents for the origination of explosive and toxic fumes.

Nowadays, a fire suppression system in the motor compartment of busses are mandatory. Again, early detection using sensors, is key. Next, an aerosol generator suppresses the fire within several seconds, hence reducing the reignition probability.

Finally, the fire and rescue might consider to enter the bus depot to suppress the fire. However, standard operation procedure for the Dutch fire brigade is to stay outside because of the large safety risks for fire personnel: large distances, difficult situational awareness and very limited possibilities to cool and suppress a battery fire in a zero emission bus. Based upon [24] the fire service needs to have adequate information from the bus depot operator regarding:

- Shut down the electricity from the charge infrastructure
- Charge point locations
- Temperature information in the charge point
- Data concerning the charge point: is a vehicle attached to the charge point? Is a vehicle being charged? Information regarding the failure/deviation?
ZERO EMISSION BUS DEPOT FIRE GUIDELINES

Now that we have identified a variety of safety measures, we are able to develop fire guidelines for zero emission bus depots in the Netherlands. To this end, for each of the phases of a fire, (origination, fire development and fire suppression) we will present five types of fire safety measures regarding:

- Bus design
- Bus depot building measures
- Installation systems in the bus depot
- Organisation of the emergency planning by the bus depot operator
- Measures that facilitate the fire service and rescue

In table 2 (matrix) below, we present the measures. In the upper row we made a subdivision of the 5 fire safety measures. In the most-left column, we made a subdivision of the three fire stages (origination, development and suppression). In the cells of the matrix we present the fire safety measures for bus depots in general. The measure that are in particularly related to zero emission are presented in red.

Table 2: Fire Safety Design guidelines for ZE- bus depots [3]

**CONCLUSIONS**

The studies showed that battery packs introduce an additional fire hazard not present with traditional diesel buses, in particular during charging. Recent fires with battery packs support this finding.

On the basis of bus fire statistic, however, it could not be borne out that, generally speaking, public transport with zero emission busses would be more dangerous than with traditional diesel buses, a conclusion certainly influenced by the absence of reliable statistics; after all the ZE-buses form only a small fraction of the total number of buses. Also the fact that on average ZE-buses are relatively new, will have contributed to this conclusion.
Furthermore the studies showed that, although much less “fuel” is present in ZE-buses than in diesel buses, the total heat released during a bus fire was not much lower for ZE-buses than for diesel buses. The same was found for heat release rate. This can be explained by the large volume of other combustible materials present in modern buses.

What was found to be significant though, was the development of the fire. Battery fires develop slowly as the battery heats up until a thermal runaway takes place at which moment an exponential growth occurs and the fire rapidly spreads to the whole bus. As much of this process takes place inside the battery, fire fighting is complicated: it is difficult to get water inside the (well shielded) battery and battery fires that appear to be extinguished can suddenly reignite again. Because of this, the fire fighting process may take a very long time and large volumes of water need to be present. Also, toxic gases can be released from the batteries, which can be a risk in confined areas like tunnels or garages.

In FCEV buses both hydrogen cylinders and batteries are present. Care should be taken to avoid a domino effects, e.g. that a burning battery pack triggers the pressure release device of a cylinder, resulting in a torch fire of hydrogen.

Unfamiliarity with the charging system and infrastructure may be a hindrance if fire fighters want to stop the charging process during a fire in a public area during opportunity charging.

The close proximity of large numbers of buses in a (covered) bus depot will seriously enhance the spread of fire and at the same time limit the possibilities for fire fighting. Making use of (open – no roof) fire compartments (with limited numbers of buses) that are separated by fire walls (and/or distance) will reduce this risk. In addition early detection systems are useful, like camera’s or heat detection. Also very effective can be well designed and coupled IT (data)-systems, like those present in the loading infrastructure, and battery management system, which can take preventive measures and initiate mitigating actions. From a more organisational point of view, we saw that public transport bus operators hardly prepare for dealing with their zero emission bus fires. They need to develop a safety management system (like for example is common on Dutch railways), including a) fire response plans, b) educating and training their personnel, and in particular their bus drivers and c) coordinate with safety regions (fire services) regarding their types of buses, operating procedures and emergency management plans.

REFERENCES


3. IFV, 2022, Ontwerprichtlijnen gericht op de brandveiligheid van stallingen en remises van zero-emissiebussen, CROW.


Development of toxicity assessment method for bus interior materials

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ABSTRACT

In recent years, fire safety requirements for bus interior materials have been increased and introduced into international regulations. Fire safety requirements for the burning rate, melting and dripping behaviour of interior materials already exist for many years. However, it remains unclear to what extent the release of smoke, combustion products and their toxicity should be limited. Therefore, a research and development project 82.0723 funded by BASt (Federal Highway Research Institute) was initiated to develop a simplified procedure for testing the toxicity and smoke development in case of fire of interior materials used in buses. The scope of the research included calculations to assess the toxicity of fire gases and the derivation of specifications for the formation of practicable limit values for smoke toxicity. Further investigations are needed to derive these limit values for smoke toxicity in order to be applicable for real fire scenarios in buses.

KEYWORDS: bus interior materials, toxicity assessment, smoldering

INTRODUCTION

Buses are used for passenger transport not only in local public transport as scheduled buses, but also for many years as coaches across Europe. Traffic accidents or technical defects can be the cause of fires in buses. The rapid spread of fire and smoke in particular constitutes a high-risk potential for passengers. Passengers often have only a few minutes to save themselves before irritating and toxic smoke products spread inside the bus [2]. In addition, time expires between the discovery of a fire and the possibility of stopping the bus. Particularly if people cannot save themselves quickly enough due to mobility or age restrictions, danger is imminent. This is illustrated by the most serious and devastating bus fire incidents of recent years: the bus fire on the A8 motorway near Garbsen near Hanover in 2008, in which 20 passengers lost their lives, or the tragic bus accident on the A9 motorway in Germany in 2017, in which the bus burst into flames after a traffic accident and claimed the lives of 18 people. Both travel groups consisted primarily of senior citizens [28], [29]. Another example is the school bus fire in Saxony-Anhalt, 2020. The fire broke out in the engine compartment, monetary damage amounted to 80,000 € (see figure 1).

With the increased use of plastics as a material for the bus and coach interiors due to their good and low weight, the question arises as to whether the safety level in relation to fires has decreased in recent years - especially in comparison with other means of transport. Because of the flammability of plastics and their ability to release large amounts of heat in the event of a fire, the main fire load in bus fires is often no longer the fuel on board but the plastics in the bus, which are also easy to ignite. However, in addition to the flammability of the materials for fire safety also the smoke production, smoke development and spread as well as their toxicity are also very important.
In recent years, a large number of fire safety aspects have been introduced into international vehicle technology regulations, such as fire detectors and extinguishing systems. Furthermore, the prescribed tests for burning velocity and dripping behaviour have been updated. It remains to be seen to what extent the toxicity of smoke gases in the event of a fire in bus materials have to be limited. In the national project FE 82.0377/2009 "Investigation of the formation, spread and toxicity of smoke in bus fires", it was shown that the procedure for determining the toxicity of smoke gases from the railroad sector and the method of determining the limit values are not sufficient for use in the bus sector. In addition, the materials used in buses have meanwhile been further developed against the background of changed regulations.

For the studies presented, national and international literature in the field of fire safety of buses was reviewed [2], [4], [7], [8], [9], [10], [11].

The subject of research continues to be how a simplified procedure for toxicity determination adapted to buses can be designed. Our ongoing study is based on the following questions: Which apparatuses or fire tests can be used to adequately examine the materials installed in buses (e.g. materials of ceiling, wall, floor and seats) with regard to the released smoke gas components? Should the materials be tested individually or as a composite, and under what combustion or ventilation conditions? How can toxicity be assessed and how can practicable limits be derived to limit smoke toxicity? What is the current state of research and how can research go beyond that?

**INITIAL SITUATION AND EXISTING FIRE REQUIREMENTS**

Bus fires occur relatively frequently. In Germany, there are no uniform fire statistics that can be used as a basis as in other European countries [3]. Therefore, an extensive study on bus fires in Germany was carried out as part of student research projects at Otto von Guericke University (OvGU). A selection of fires in Germany is given in Table 1. This selection was found through an online search using the keyword "bus fire".

**Table 1**  
Internet research on bus fires in Germany, online search with the keyword "bus fire"  
(excerpt) [8].

<table>
<thead>
<tr>
<th>date [reference]</th>
<th>short description</th>
<th>media information on the fire event</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 June 2019 [20]</td>
<td>coach, class trip, A2 highway</td>
<td>technical defect, bags and luggage also burned, no injuries, bus completely burned out</td>
</tr>
<tr>
<td>12 July 2019</td>
<td>fully occupied public bus, Deggendorf, Germany</td>
<td>technical defect, fire was extinguished</td>
</tr>
<tr>
<td>19 November 2019</td>
<td>coach, A3 highway</td>
<td>bus completely burned out, rear</td>
</tr>
</tbody>
</table>
The complete survey was carried out online on freely accessible press portals, websites of fire departments and police stations as well as websites of newspapers and radio stations. Systematic searches were carried out by means of search engines using various keywords and combinations. An overview is given in Table 2. The survey covers a total of 227 incidents from 2017 to 2020. One result of the research is that in the majority of cases, a fire breaks out in the rear part of the bus or in the engine compartment: in 128 of 229 researched fires, this corresponds to approx. 56 percent. If only fires without arson are considered, the figure is around 59 percent. The axle and wheel area (tires, brakes) and technical systems (air conditioning, heating systems) account for a smaller share.

Table 2  Number of investigated fire incidents in buses by fire origin [8].

<table>
<thead>
<tr>
<th>Location of fire</th>
<th>Number of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine</td>
<td>68</td>
</tr>
<tr>
<td>rear area, general</td>
<td>60</td>
</tr>
<tr>
<td>tires, brakes, chassis</td>
<td>25</td>
</tr>
<tr>
<td>external fire</td>
<td>5</td>
</tr>
<tr>
<td>interior</td>
<td>4</td>
</tr>
<tr>
<td>technical equipment such as air conditioning, heating, etc.</td>
<td>1</td>
</tr>
<tr>
<td>Not specified</td>
<td>54</td>
</tr>
<tr>
<td><strong>Total (without arson)</strong></td>
<td>217</td>
</tr>
<tr>
<td>Arson, criminal acts</td>
<td>12</td>
</tr>
</tbody>
</table>

The research also revealed that public buses were affected by fire incidents much more often than coaches: 59% of fire incidents involved a public bus. It was notable during the survey that, in the case of buses in operation, it was relatively common for technical monitoring equipment, passengers or attentive road users to alert the driving personnel to an irregularity, so that in many cases the vehicle could be stopped and the passengers could leave the vehicle in good time. The reports on the further course of the fire, however, often show a fire spreading to the interior and/or to large parts of the vehicle within a few minutes. The scientific survey on bus fires in Germany will be continued.

The regulations relevant for fire protection in buses are UN R 36 "uniform provisions concerning the approval of larger passenger vehicles with regard to their general construction", UN R 107, that
defines the requirements for vehicles of categories M2 and M3, and UN R 118 for fire protection requirements for materials [15] [18] [19].

The basis for the fire safety requirements for buses are the following categories of buses defined in the UN regulations:

- Category M2: Vehicles for the transport of passengers, which have more than eight seats in addition to the driver's seat and do not exceed a maximum weight of 5 tons.
- Category M3: Vehicles for the carriage of passengers with more than eight seats in addition to the driver's seat and whose maximum weight exceeds 5 tons.
- Class 1: vehicles with standing places for regular boarding and alighting
- Class 2: Vehicles for the transport of seated passengers, which have aisles or areas for the transport of standing passengers, which do not exceed the space of two double seats.

Vehicles of categories M2 and M3, whose capacity does not exceed 22 passengers plus driver, have two classes:

- Class A: vehicles designed to carry standing passengers, a vehicle in this class has seats and areas for standing passengers
- Class B: Vehicles designed to carry seated passengers; these vehicles do not have designated areas for standing passengers.

The prescribed fire tests of UN R 118 and other globally comparable standards for fire protection of road vehicles originate from the American standard FMVSS 302, which was developed in the 1960s. The following table (table 3) shows national and international regulations and standards as well as manufacturer standards on fire test procedures for interior materials.

Table 3 Fire test methods according to UN R 118 [14], [17], [18].

Fire tests according UN R 118

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<thead>
<tr>
<th>Appendix 6</th>
<th>Test procedure</th>
<th>Retrieved from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>determination of the horizontal burning rate of materials</td>
<td>Regulations/Standards</td>
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<tr>
<td></td>
<td></td>
<td>ECE R118 (Int.)</td>
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<td>ISO 3795 (Int.)</td>
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<td>FMVSS 302 (USA)</td>
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<th>Test procedure</th>
<th>Retrieved from</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Determination of the melting behaviour of materials</td>
<td>ECE R118 (Int.)</td>
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<td></td>
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<td>NF P92-505 (F)</td>
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<td>U.T.A.C. 18-502/2 (F)</td>
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<th>Test procedure</th>
<th>Retrieved from</th>
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<tr>
<td></td>
<td>Determination of the vertical burning velocity of materials</td>
<td>ECE R118 (Int.)</td>
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<td>EN-ISO 6941 (Int.)</td>
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</table>
In recent years, the regulations for the fire safety of buses have been adapted: new aspects of fire protection have been introduced into the international vehicle technical regulations, such as fire detectors and engine extinguishing systems. Furthermore, the prescribed tests for fire velocity and dripping behaviour were updated. First, UN R 107 was expanded to make fire detection systems mandatory in the engine compartment and where heaters are present. Then smoke detectors were made mandatory in areas not visible to the driver, such as toilets or in the driver's sleeping cabin. UN R 118 was expanded with regard to the requirements for electrical cables and insulation materials. Since the previous version of UN R 118 only required all materials to be tested horizontally, regardless of the installation situation (only curtains were tested in a vertical arrangement), the guideline has been expanded to the effect that the installation situation must now be included in order to test a more realistic scenario. As an alternative to performing the horizontal and vertical tests, testing in accordance with the requirements applicable to rail vehicles is permitted. In addition, the requirements for the passenger compartment now apply to the entire interior of the vehicle.

**STUDY METHODOLOGY AND PROCEDURE**

In order to methodically determine the fire smoke toxicity of materials used in buses, a suitable apparatus was selected and typical materials for bus interiors were identified. Since the focus was on the analysis of smoke gases, a research was carried out to find measuring equipment that could be coupled with an FT-IR spectrometer: (1) Smoke Density Chamber (SDC), which is an already standardised method for assessing toxicity in the rail vehicle sector, but does not allow control over the atmosphere in the chamber, (2) Cone Calorimeter [12], which in addition to determining the heat release rate is also a standardised method in the rail vehicle sector, but not for toxicity determination as well as the (3) DIN tube furnace, which allows thermal-oxidative decomposition at a continuous flow rate. Fire tests of the same groups of materials were carried out with all apparatuses in the entire research project. The present study reports on smoldering fire tests of polyurethane foam (PURblue) as well as on one textile (textile MB) used as upholstery fabrics. Further detailed smoke gas analyses during the DIN tube furnace tests of the other presented materials in table 4 can be found in literature as follows [8] and [14]. Bus seats, parts of the interior trim and flooring were identified as typical bus interior furnishings. These include polyurethane (PU), polyester (PE), acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), chipboard materials, polyamide (PA), polyethylene (PET), polypropylene (PP) as well as cotton, fleece, viscose, leather and imitation leather. In the large-scale study to investigate the smoke gas components, the following materials were tested in the DIN tube furnace, including four bus seat cover textiles and two different foams under smoldering combustion conditions:
Table 4  Sample selection of seat covers and upholstery from bus interiors (textile fabrics and foam).

<table>
<thead>
<tr>
<th>parameter</th>
<th>textile CD</th>
<th>textile LW</th>
<th>textile MB</th>
<th>textile RC</th>
<th>polyurethane foam (PURblue)</th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td><img src="image1.png" alt="image" /></td>
<td><img src="image2.png" alt="image" /></td>
<td><img src="image3.png" alt="image" /></td>
<td><img src="image4.png" alt="image" /></td>
<td><img src="image5.png" alt="image" /></td>
</tr>
<tr>
<td>top layer</td>
<td>66% polyester 28% wool 6% viscose</td>
<td>polyester/polyamide</td>
<td>100% polyester</td>
<td>70% polyester 30% wool</td>
<td>polyurethane foam + additives</td>
</tr>
<tr>
<td>base layer</td>
<td>60% polyester 24% viscose 15% cotton 1% elastane</td>
<td>polyethylene, Fleece</td>
<td>72% polyester 28% viscose</td>
<td>50% polyester 50% viscose</td>
<td>-</td>
</tr>
<tr>
<td>Results + discussion</td>
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<td>Presented in this paper</td>
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<td>Presented in this paper</td>
</tr>
</tbody>
</table>

The smoke gas components to be investigated, which are relevant for an evaluation of the toxicity of smoke from bus interior materials, were selected according to the following criteria:

1. smoke components typical for each fire: carbon dioxide and carbon monoxide.
2. smoke gases typical of combustion of materials used in bus interior furnishings: hydrogen cyanide, hydrogen chloride, formaldehyde, nitrogen oxides, benzene and ammonia.
3. smoke components which have a particular toxic effect on the human body or for which special medical measures must be taken: carbon monoxide, hydrogen cyanide and acrolein.

**FIRE EXPERIMENTS AND RESULTS**

For the studies of the selected bus interior materials under smoldering conditions, the DIN-tube method was modified for scientific purposes. The DIN-tube is originally used to decompose a building material under smoldering conditions so that the percent light attenuation caused by smoke production can be determined. In this present study the DIN tube method was used to study thermal oxidative decomposition without flame formation. Characteristic for a thermal oxidative decomposition is according to DIN 60695-6-1, oxygen concentrations between 5 vol.% and 21 vol.% by volume and temperatures below 500°C. This temperature range corresponds to an irradiance of smaller than 25 kW/m² and can be assigned to a self-sustaining smoldering fire. These experimental conditions can be achieved if the ring furnace temperature is set to 700°C, which means about 500°C on the sample [14]. The supply air into the DIN tube was realized at 5 l/min with ambient air and is kept constant during the experiments by a flow controller. For the analysis of smoke gas components an Ansysco FTIR spectrometer was connected to the collecting vessel. The real setup and a schematic representation of the experimental setup of the DIN tube furnace is given with figure 2.
Figure 2  Left side: real setup of the DIN tube furnace in laboratory and right side: schematic representation of the experiment with 1-3: light measuring section with voltmeter and computer, 4-4.1: DIN tube and furnace, 5: flow controller, 6-7: FTIR spectrometer and probe, 8-9: collecting vessel, 10: exhaust hood.

The specimen is placed in the quartz tube. At the start of the test, the ring furnace, which is kept at a constant temperature of 700 °C, is mounted and moves over the specimen at a feed rate of 10 mm/min. The duration of the experiment is 30 min. The following table 5 shows the tested samples of the cover fabric “textile MB” and the foam “PURblue” cut to size before the smoldering test and after the test. The samples are taken out of the conditioning before the test, cut to size of 1mm x 1mm x 30mm and weighed. After the test, the residues are weighed again to be able to determine the mass loss. The samples have a mass of approx. 1g at the start of the experiment.

| Table 5  | specimens before and after the smoldering fire tests in the DIN tube furnace (left side: textile MB (bus seat cover) and right side: polyurethane foam (upholstery bus seat)) |
|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------
| before smoldering | textile MB | polyurethane (PURblue) |
| after smoldering | ![Image](image1.png) | ![Image](image2.png) |

The concentration-time curves of measurable conspicuous gases from the gas analysis during the smoldering tests of textile MB in the DIN-tube furnace are shown below in figure 3. For the reproducibility of the test series, the material was tested in five tests under the same test conditions. In this series of tests, not only CO (approx. average of 750 ppm) and HCN (approx. average of 10 ppm) were found in the smoke gas, as expected, but also acrolein (approx. average of 10 ppm), formaldehyde (approx. average of 15 ppm) and sulfur dioxide (approx. average of 400 ppm) in high concentrations. The graphs include not only each individual test, but also the course of the mean value over all tests over time as well as a mean value over the concentration plateau, which arises due to the functioning of the DIN-tube furnace.
Figure 3  Selection of measured concentration during the DIN-tube furnace tests of textile MB with a) CO\textsubscript{2} concentration-time-curve, b) CO concentration-time-curve c) hydrogen cyanide-time-curve, d) acrolein concentration-time-curve e) formaldehyde concentration-time-curve f) sulfur concentration-time-curve

Using the same principle, figure 4 shows the evaluated concentration-time curves for the smoldering fire tests of the polyurethane PUR blue in the DIN-tube. During the smoldering of the PUR blue, strikingly high concentrations of HCN (approx. average of 50 ppm), acrolein (approx. average of 140 ppm, formaldehyde (approx. average of 50 ppm) and nitrogen oxides were analysed. Sulfur dioxide was only measurable in very low concentrations. The material was particularly conspicuous during the carbonization tests in that CO\textsubscript{2} was only measurable in absolutely low concentrations. The blue polyurethane foam was subjected to elemental analysis and thermogravimetric analysis (TGA) to provide information on thermal decomposition and decomposition reactions. The results of the TGA will be discussed in the oral presentation.
DISCUSSION AND CONCLUSIONS

In the present study, bus interior materials that meet updated fire safety requirements were experimentally investigated in order to be able to evaluate the smoke toxicity when these materials burn, hereby it should be noted that smoke gas production and smoke gas toxicity are not regarded in the updated regulations. For the assessment of smoke production, smoke gas composition and toxicity of smoke gas components, experimental studies were conducted in the DIN tube furnace under smoldering conditions with polyurethane foams and polyester-based textiles. The DIN-tube was used in Germany prior to European harmonisation of building product testing for the assessment of smoke gas toxicity of building products. During the thermal decomposition of the materials, the smoke gas
composition was continuously analysed by FT-IR spectroscopy. The analysis revealed noticeable high concentrations of toxic components including CO (carbon monoxide), HCN (hydrogen cyanide), sulphur dioxide (SO2), acrolein and formaldehyde as well as irritant components such as benzene and methanol and others. In summary, it can be said that the investigated polyurethane foam cannot be recommended as a bus interior material with regard to its fire behaviour and the smoke gases produced. The experimental results show that the disregard of heat release and smoke gas production as well as smoke gas toxicity allow the use of interior materials in buses that present very hazardous conditions to passengers in case of fires.

Experimental results as well as real fires reveal also the necessity to assess toxicity of the smoke gases when evaluating the bus interior materials as well as heat release rates. High heat release rates lead to a rapid-fire spread, which results in a high risk to passengers in the passenger compartment. If the transition of a fire to a fully developed fire takes place in the passenger compartment before the fire brigade can intervene, passengers who are injured in an accident or otherwise have limited mobility cannot be rescued by the fire brigade. High production rates of smoke gases can cause untenable conditions in a bus very rapidly because of the very limited space in the cabin. Reduction of visibility can prevent passenger from evacuation in an early phase in the fire. Further investigation is needed for the link between limits for heat release and smoke gas production as well as toxicity in small scale tests to the real situation in a bus cabin. The FED (Fraction Effective Dose) concept [13], [16], [17] is an efficient tool to link smoke gas concentrations in an enclosure to passenger safety with regard to toxic effect on the body when exposed to smoke gases for some time. Recommendations on how to proceed with development of future regulations for bus interior materials are given in [30].

REFERENCE LIST


15. Publications Office of the EU, UNECE Regulation No 107 of the Economic Commission for Europe of the United Nations (UNECE) – „uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction “, 2015.


19. UN Regulation No. 118. Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles, 2012.


Fire safe bus interior materials – flame retardants and the effect on smoke production and smoke gas toxicity

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ABSTRACT

The demands on bus interior products have increased with increasing sustainability, circularity and a reduction of harmful substances, today’s materials must be improved with regards of additives, such as flame retardants. A comprehensive study was made to evaluate the possibility to use phosphorous flame retardants (FRs) instead of the commonly used halogenated FRs compounded with ABS. The study showed that the fire performance could be improved with phosphorous FRs regarding heat release and smoke production. However, it was noted that the smoke production still was high, and that the smoke density was highest possible, i.e., no visibility through the smoke layer. Further testing of today’s bus interior materials showed that the high smoke density was achieved already after a few minutes of test time. Thus, it can be concluded that, in case of a fire, the visibility in the bus will be reduced and limit the ability of the passengers to safely evacuate. In addition, several toxic gases were detected in the smoke, both irritants and suffocating gases.

The bus fire regulation R118 for interior materials basically deals with burning rate and melting through a fine mesh. Critical fire parameters such as smoke production and smoke toxicity is not dealt with. The R118 regulation need to be improved with these critical parameters in order to have fire safe materials inside the bus.

INTRODUCTION

Accidents involving buses occur regularly around the world and the safety of buses must therefore be on a high level to prevent mortals. The fire safety of buses has increased during the years as fire regulations has been introduced. The introduction of UNECE R107, testing of extinguishing systems for engine rooms increased the safety and reduced the number of engine fires. However, a bus fire can originate from other parts of the bus and in case of a fire, the passengers must have enough time for evacuation, both in relation to open flames and flame spread inside the bus, as well as in relation to smoke production. If there is a rapid smoke production, the visibility in the bus decreases and the toxic effect from the smoke will hinder the evacuation. The material selection inside the bus will have a direct impact on the fire and smoke development in case of a fire. Using a low-performing material, will not only result in a burnout of the bus and risk the lives of the passengers, it will also have long-term effects on the environment, sustainability and economy [1] [2].

The regulation UNECE R118 [3] addresses the requirements and test methods for interior materials used on buses. The regulation has been amended several times to improve the fire safety, but the requirements are still low compared to other transport sectors such as railway vehicles [4] and ships [5]. In the regulation R118, basically three test methods are relevant for interior materials, the horizontal burning rate (Annex 6), the melting behavior (Annex 7) and the vertical burning rate (Annex 8). These methods are not very demanding, and a material can easily be developed and compounded, using the properties of additives, to fulfil the test requirements. The usage of additives, such as flame retardants, fillers and anti-dripping agents will give the material the required properties to fulfil the UNECE R118 tests. However, these might also contribute to a higher smoke production...
and toxic gas specie content. None of the test methods according to R118 deals with smoke production or gas specie content.

Acrylonitrile-butadiene-styrene (ABS) is commonly used material for a variety of applications, including interior parts for buses. However, ABS is a highly flammable materials which requires additives of flame retardants (FRs). Traditionally, brominated FRs are used, which are highly persistent in environment and accumulate in the food chain, intensifying their toxicity. As the brominated FRs, as well as other halogenated FRs, are active in the gas phase of a fire, there will be a production of toxic smoke. As the demands on circularity and less harmful substances increase from the industry, other FRs functioning with ABS must be identified [6].

**METHOD AND RESULTS**

A comprehensive study of fire performance was conducted to evaluate a range of phosphorous based flame retardants (PFRs), combinations thereof, and combinations with synergists [6]. As a first step, screening fire testing was conducted of 26 different compounds of ABS with PFRs and synergists using the UL 94 vertical testing method. As reference samples, pure ABS and ABS treated with halogen FR (HaloABS) were used. The 13 best performing PFR samples was selected for further testing with the cone calorimeter, according to ISO 5660-1, using a heat flux of 50 kW/m². The results showed that all PFR samples had improved fire performance with regards to heat release rate, i.e., a lower peak in heat release rate (pHRR). However, the smoke production (TSP) was higher for some PFR samples than for pure ABS. This confirms that the additives can increase the smoke production. Significantly highest smoke production was seen for the ABS with halogen FR. Noticeable is that this HaloABS is used today in bus interior products and approved according to R118.

Table 1 shows a summary of the test results of pure ABS, HaloABS and the best performing PFR ABS, compounded of 20 wt% AlPi and APP in a ratio of 1:1.

<table>
<thead>
<tr>
<th>Cone calorimeter, ISO 5660-1</th>
<th>Smoke chamber, EN ISO 5659-2, with FTIR gas analysis</th>
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<tr>
<td>t&lt;sub&gt;ign&lt;/sub&gt; (s)</td>
<td>pHRR (kW/m²)</td>
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<td>---</td>
</tr>
<tr>
<td>Pure ABS</td>
<td>37</td>
</tr>
<tr>
<td>HaloABS</td>
<td>36</td>
</tr>
<tr>
<td>PFR ABS</td>
<td>29</td>
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</table>

To further evaluate the smoke production of these samples, fire testing was conducted with the smoke density chamber according to EN ISO 5659-2, coupled with FTIR for gas analysis [6]. The irradiation level of 50 kW/m², without pilot flame was selected and considered to be a worst-case scenario. The results are presented in Table 1 and show a behaviour of smoke production similar to the results in the cone calorimeter, with a higher production from HaloABS and pure ABS. Both pure ABS and HaloABS ignited and had a very high smoke production as the smoke density (D<sub>s,max</sub>) reached the maximum value of 1320, which is the maximum value for the equipment to measure. The smoke density is a measure of the visibility through the smoke layer. This is an important parameter for the ability of people to evacuate a vehicle. A D<sub>s,max</sub> value of 500 indicates heavily reduced visibility through the smoke layer. Thus, at a value of 1320, there is no visibility through the smoke layer. Noticeable is that the D<sub>s,max</sub> for these samples was reached already after 218 s and 228 s. The PFR ABS showed another behaviour as the sample did not ignite. The D<sub>s,max</sub> of 926 was reached after 590 s, which is an improvement, however, the smoke density is still high and there is no visibility through the smoke. With the FTIR gas analysis, the toxicity of the smoke was evaluated. All three samples produced CO₂, CO and HCN. Pure ABS and HaloABS also produced NO₃, which was to expect as the samples ignited, thus resulted in a flaming combustion. HCl was detected in the smoke of HaloABS, also expected as the FR consisted of chlorine. The gas specie concentrations are here presented recalculated as a CIT values. This is the requirement parameter for materials used for interior products.
in railway applications. For interior materials the CIT at 4 min must be lower than 0.75 – 1.2, depending on operation category [4]. Thus, pure ABS and HaloABS has a critical CIT value.

In previous full scale fire tests of buses [1], harmful concentrations of gas species in the smoke were measured after 240-300 s. In an evacuation study by Hjohlman et al. [7], the evacuation time of the bus was determined to be approximately 125 s (the mean value of the measured time for evacuation in the two tests conducted in the study by Hjohlman et al.). The evacuation time related to smoke toxicity for railway vehicles is 240 s [4]. Based on these studies, it can be concluded that using the tested materials, considering the high smoke density and concentrations of gas species, evacuation can be critical.

To further evaluate the smoke production and smoke toxicity of common materials used for bus interior products, six materials were selected from a supplier of interior parts to different bus manufacturers [8]. Two products were FR treated ABS and the other four were FR treated ABS layered with polycarbonate (PC). All six materials fulfilled the requirements according to R118, which were expected as they are used in busses. However, noticeable was their fire performance besides the regulation criteria. When the materials were tested according to R118, Annex 7, the melting behaviour, several of the tested materials showed production of dark smoke. This is shown in Figure 1.

![Figure 1 - Testing according to R118, Annex 7 [8].](image-url)

Another noticeable fire behaviour was observed when testing according to R118, Annex 8, vertical burning rate. After ignition of the sample, the fire spread vertically in the sample with relatively large flames. As the temperature in the material increased, the material melted. This resulted in a large burning piece of the material which fell from the sample and created a “pool fire” of melted burning material under the sample. At the same time, the sample extinguished as most of the fire was located at the melted part. This is shown in Figure 2.

![Figure 2 – Fire development of Product 2 in R118, Annex 8 [8].](image-url)
Smoke density testing was conducted with the same test procedures as for the previously tested ABS samples (pure ABS, HaloABS and PFR ABS). Five of the six tested materials showed the same high smoke production as the ABS samples, with a $D_{s,max}$ of 1320. The time to reach $D_{s,max}$ was approximately 200 – 400 s, thus within the critical time for evacuation. Regarding smoke gas toxicity, all products showed the same general behaviour with an increase of CO$_2$, CO, NO$_x$ and HCN throughout the test and the highest concentration at the end of test. Two of the products showed a production of HCl and HBr, originating from the FR treatment. The concentrations of HCl and HBr showed a different behaviour, with a peak after some time into the test and then a decrease towards the end. The CIT value at 4 min, for the two products producing HCl and HBr, was slightly above or very close to the criteria.

CONCLUSIONS

The comprehensive study of PFRs compounded with ABS showed that there are alternatives to the commonly used halogenated FRs. The fire testing showed that using the phosphorus FR, a lower heat release, lower smoke production and reduced smoke gas toxicity could be achieved, compared with pure ABS and ABS treated with halogenated FR. However, the results generally showed a very high smoke density, with a value of 1320 in several cases, maximum for the equipment to measure, i.e., no visibility through the smoke layer. This dark smoke was produced for all tested samples already after approximately 200 s of testing in the smoke chamber, which is a critical time with regards to evacuation.

Further testing of commonly used bus interior materials, FR treated ABS and PC/ABS, showed the same rapid smoke production, reaching the maximum value after approximately 200 – 400 s. These materials are tested and approved according to the bus fire regulation R118. Thus, from a fire safety engineering point of view, the fire test methods used in R118 are not enough to select fire safe materials for buses. Important fire performance such as smoke production and smoke toxicity, are not included. The materials used in buses are designed to pass the R118-test methods, thus, to have a limited burning rate and not melt through a fine mesh. To fulfil the requirements, additives, flame retardants and anti-dripping agents are incorporated in the materials. However, these additives often increase the smoke production. The flame retardants slow down the burning, resulting in an incomplete combustion, producing a higher level of smoke and a higher concentration of toxic gas species. Generally, the tested products showed a very high smoke production with the smoke density at maximum for the equipment to measure, already after a few minutes of test time. Thus, it can be concluded that, in case of a fire, the visibility in the bus will be reduced and limit the ability of the passengers to safely evacuate. Further, several toxic gases were detected, both irritants (HCl and HBr) and suffocating (CO and HCN). The concentration of the species was high and comparing these with the requirements for marine applications as well as for railway applications, none of the here tested products can be used.

As a final conclusion, the R118 regulation for bus fire safety is not enough to select fire safe materials. The regulation only deals with ignition, burning rate and melting behaviour. Critical parameters such as smoke production and smoke gas toxicity is not dealt with, even though they strongly impact the ability of evacuation.

ACKNOWLEDGEMENT

The study was supported by the Swedish Centre for Chemical Substitution as well as Sweden’s strategic vehicle research and innovation partnership programme (FFI), via grant agreement 2019-03121.
REFERENCES


[3] ECE Regulation 118, Uniform technical prescriptions concerning the burning behaviour and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles, United Nations, 2019.


(Fire) statistics on incidents with alternative fuel vehicles in The Netherlands

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ABSTRACT

Since January 2021 the Netherlands Institute for Public Safety together with the 25 safety regions within The Netherlands register all incidents with alternative fuel vehicles the fire brigade attended to. Alternative fuels are alternative fuels for the traditional fossil fuels (to reduce the carbon footprint), such as LNG, CNG, hydrogen and battery electric. Data is collected about these incidents, which is stored in a self-developed database. Key data is published close-to-real time on our website. This data helps the fire service, policy makers and the industry to learn from these incidents. The paper will present the most important data collected and the first lessons learned from this (ongoing) research project.

KEYWORDS: alternative fuel vehicle, fire statistics, fire in electric vehicles, incident response

INTRODUCTION

The number of alternative fuel vehicles (AFV’s), such as battery electric vehicles (BEV), as well as fuel cell electric vehicles (FCEV), or CNG or LNG powered vehicles has increased significantly in recent years in The Netherlands and will continue to increase. All other things being equal (ceteris paribus), the number of incidents in which these alternative fuel vehicles are involved will increase as well.

Therefore it is important for us to learn from these incidents in order to get a better idea of the number and type of incidents involving AFVs, and particularly to learn from the mechanisms of such incidents and the response tactics. However, data on how many incidents with AFV’s that happen in The Netherlands was missing. In other countries, it was only seen that Finland has collected data between 2015 and 2019 [1]. In depth information on these incidents and the incident response was missing. Also a deskstudy from EV FireSafe showed 292 incidents with battery powered vehicles worldwide since 2010 [2]. This study however limited on incidents in which the battery pack was involved in the fire, whereas incidents in which the battery pack was not involved can bring valuable lessons.

Therefore, we concluded that the data on incidents with alternative fuel vehicles we were looking for was still missing worldwide: there was no dataset which compared incidents which AFV’s in a structured manner. Therefore the Netherlands Institute for Public Safety (Nederlands Instituut Publieke Veiligheid, NIPV) started a research program to collect data on incidents with AFV’s in The Netherlands. The data collected in this research should help us to get a better idea of the number and type of incidents involving AFVs, and particularly to learn from the mechanisms of such incidents and the response tactics.

To determine which data should be collected, we formulated the following questions to determine which data should be collected:
1. How many incidents involving alternative fuel vehicles occurred in 2021?
a. What was the nature of these incidents?
b. What were the characteristics of the vehicles involved in the incidents?
c. Which types of alternative fuel vehicles were involved in these incidents?
d. How many casualties did incidents involving alternative fuel vehicles claim?

2. What were the characteristics of the accidents involving alternative fuel vehicles in 2021?
   a. What were the characteristics of the locations where these accidents occurred?
   b. What was the role that the alternative fuel technology played in these accidents?
   c. What was the response to these incidents?

3. What were the characteristics of fires involving alternative fuel vehicles in 2021?
   a. What were the characteristics of the locations where these fires occurred?
   b. What was the role that the alternative fuel system played in these fires?
   c. How were these incidents fought?
   d. What was the involvement of charging infrastructure, if any?

RESEARCH QUESTIONS

With the above set of questions, we collected a large amount of data about incidents with AFV’s in The Netherlands. In this paper, we focus on the highlights out of this research project. Therefore the following four research questions are formulated:

1: How many incidents with AFV’s happened in The Netherlands?
2: What are the characteristics of the AFV’s involved in these incidents?
3: What role did the vehicle technology have in these incidents?
4: What can be learned from the incident response to these incidents?

SCOPE

This paper presents the data of incidents in the period from 1 January 2021 to 31 December 2021.

The scope of incidents included in the database is as follows:

> **Fuel**: this research considers the following fuels / vehicle technologies as indicators of an AFV being involved:
  
  - battery electric vehicle (BEV)
  - (plug-in) hybrid vehicle (P)HEV
  - fuel cell electric vehicle (FCEV)
  - Compressed Natural Gas (CNG),
  - Liquefied Natural Gas (LNG)
  - CNG or LNG in combination with petrol or diesel.

Any purely fossil fuel vehicles, such as petrol, diesel and/or LPG, are not part of the scope of this research.

> **Vehicle category**: in line with the definition given by the Netherlands Vehicle Authority in the mobility chain, a vehicle has four or more wheels. The research also considers motorbikes, trikes and microcars. A microcar is a motorized vehicle with a limited maximum speed and with more than two wheels. These latter three categories were added because of the relatively large battery capacity in the battery packs of these means of transport. Electric scooters, hoverboards, e-steps, e-bikes and similar vehicles are beyond the scope of this research due to their low battery capacity and the fact that they have fewer than four wheels.

> **Presence of the fire service**: only incidents which were physically attended by the fire service have been included. The reason for this is that we would like to know how the fire service took account of the special nature of an AFV in its action. Therefore, any incidents which were not physically attended by the fire service have not been included.
METHOD

Identifying incidents
Incidents are in this research defined as fires, accidents and other reported events (e.g. a leaking fuel tank) in connection with which the fire service is called in to fight the incident or create a safe situation.

Three approaches were taken in order to identify incidents involving AFVs.

> The first approach involved monitoring media coverage. Both social media and news reports were monitored by the NIPV in order to identify fires and/or accidents involving AFVs, using Obi4Wan to scan media messages.
> The second approach concerns contacts in the safety regions notifying the NIPV researchers, or giving them tips, about incidents involving AFVs.
> The third approach is linking the data from the Dutch GMS (Geïntegreerd Meldkamer Systeem (integrated control room system)) to data from the STAR (Smart Traffic Accident Reporting) database of the VIA traffic-specific ICT agency. VIA has been commissioned by the Dutch police and the Verbond van Verzekeraars (Dutch Association of Insurers) to record all traffic accidents in the Netherlands. This makes it possible to find out where and when traffic accidents involving AFVs attended by the fire service occurred.

Data collection method
To collect the data, we used a questionnaire. This questionnaire provides a structured and consistent approach to collect information on incidents involving AFVs. The questionnaire contained questions about vehicle information, cause of the incident, the involvement of the battery pack or gas tank, fire fighting tactics and procedures as well as if a submerging container was used to transport and/or submerge the incident vehicle. This questionnaire was then placed in LiveReports, a digital questionnaire system used by the fire brigade.

The questionnaire in LiveReports are used by the fire research teams (FRTs) of the safety regions and by NIPV researchers. The FRTs can either opt to physically investigate the AFV involved by themselves and to fill out the questionnaire afterwards, or to contact the fire engine commander, the officer in charge or the hazardous materials advisor to retrieve information about the incident and use this to fill out the questionnaire. In case a regional FRT did not have sufficient capacity to retrieve the incident information, a NIPV researcher, in cooperation with the regional FRT, retrieved the incident information from the fire engine commander, the officer in charge or the hazmat advisor involved. Subsequently, the NIPV researcher used this information to fill out the questionnaire, thus entering data into the database. PowerBI was used to make the data from LiveReports available in an Excel file after which NIPV-researchers analyzed the data in R version 4.0.3 and presented it in text, tables and graphs.

Criterion for including an incident in the database
The criterion for including an incident in the database is that the fire service must have been physically present at the scene of the incident. Whether or not the fire service was active is not relevant in this context. This criterion was chosen because the notion of ‘being active’ is hard to define. Any fire service turnout which is cancelled while on route to the incident is not included in the database because the fire service was not physically present at the scene.

Vehicle involvement
We have defined incidents as fires, accidents and other reported events (e.g. a leaking fuel tank) in connection with which the fire service is called in to fight the incident or create a safe situation.

> In an accident: the criteria for determining whether a vehicle was or was not involved in an accident are: the vehicle caused the incident, and/or the vehicle sustained damage.
In a fire: the criterion applied in the event of fire is that the vehicle contributed to the fire. An AFV which only sustained damage due to a fire, e.g. because another vehicle was on fire or because of a fire in a charging point, without the AFV having actually been on fire has not been included in the data collection since such an incident does not concern an AFV on fire. The same applies if the cargo in a vehicle was on fire: the incident is not included in the database. An example of this is the burning load of a refuse truck where the fire did not spread beyond the refuse.

Whenever it is doubtful whether an AFV was involved in an incident, the 'four-eyes principle' is applied. This means that two NIPV researchers ascertain whether the AFV was involved. If they are in doubt, they will ask the following question: did the fire service action initially target the AFV? If so, the incident ‘counts’ in the database; if not, it does not ‘count’. The following two examples serve to illustrate an ambiguous situation:

Example 1: A collision between a person and an electric bus where the fire service was called in to come and remove the person from under the bus does count. This is because the initial target of the fire service action was to rescue the person from under an AFV.

Example 2: A collision occurred between an electric car and a motor scooter with the scooter driver ending up in a ditch; the fire service was called in to provide medical assistance to the scooter driver on site and, if necessary, lift him out of the ditch. Since this was an incident where the target of the fire service action was not the AFV, the incident did not ‘count’.

Rationale
Although the greatest possible care was observed when collecting and processing the data presented in this report, it is possible that, in retrospect, conditions and data were found to be different from how they were interpreted at the moment when they were entered and when writing this report. The reason for this may be that long and thorough research revealed more information than was available at the moment when the initial conditions and data were entered.

It is also possible that some incidents occurred in the period under review which were not yet known to the NIPV. Wherever this report refers to incidents, this should be understood to mean: ‘the incidents known to the NIPV research team during the defined period.’

Limitations
Due to the nature of this research, an extensive research program which requires large demand of the research capacity of the NIPV, it was not possible to collect data about fossil fueled vehicle incidents in the same manner as data was collected incidents which involved an AFV. Therefore it was not possible to make an comparison of incidents which involved and AFV versus fossil fuel vehicles.

RESULTS
In this chapter, the data is presented to answer the research questions. First, the number of incidents is discussed. Next the characteristics of the AFV’s involved are presented. Third, the data about the role of the vehicle technology / fuel is presented. At last the data about the incident response is given.

Incidents
In 2021, as far as the NIPV has been able to ascertain, there were 221 incidents in The Netherlands involving AFVs which were attended by the fire service. These incidents can be broken down into:

159 accidents (71.9%)  
62 fires (28.1%)

One accident also led to a fire (0.45%).

In these 221 incidents, a total of 243 vehicles were involved. Of these 243 vehicles, 166 vehicles were involved in 159 accidents and 77 vehicles were involved in 62 fires.

The monthly breakdown of the fires, accidents and total number of incidents are shown in Figure 1
Of the 243 vehicles involved in an incident, 166 were in motion (in motion here means: the vehicle was travelling on a public road). The vehicle involved was stationary in 70 cases. For seven vehicles, it is not known whether the vehicle was in motion or was stationary.

When looking at the 243 vehicles involved, there were:
> 214 incidents where one AFV was involved
> five incidents where two AFVs were involved
> one incident where three AFVs were involved
> one incident where 16 AFVs were involved.

Vehicle characteristics
In this section we start by discussing the type of vehicles involved in the incidents. These are presented in Table 1: type of vehicles. In this table, the first column, which is the column most on the left, presents the type of vehicle. The second column, the one second from left, presents the number of vehicles involved in a fire. The third column presents the number of vehicles involved in accidents. The last, most right column, presents the total number of vehicles involved.

From Table 1 can be derived the passenger car is the type of vehicle which is the most often involved, 80.7%, in incidents with AFV’s in The Netherlands. Vans / light commercial vehicle make up for 10.7% of the AFV’s involved in accidents. When reflecting at the number of vans involved, 26, it is seen that most of them are involved in fires and a smaller number in accidents, just 5. This is caused by a distribution center fire in which 16 light commercial vehicles were parked. This fire caused all vehicles inside to burn down. The other type of vehicles make up for the remaining 8.6% of the total number of vehicles involved.

Figure 1: Breakdown of the incidents over the months of the year
In Table 2 the vehicle technology, the fuel, involved in incidents is presented. In the first column, the column most left, the categories of vehicle technology are given. In the second column, the number of fires that happened in the vehicle technology is presented. In the third column, the number of accidents that happened in the vehicle technology is presented. In the last column, the column most right, the total number of incidents that happened in the vehicle technology categories is given.

<table>
<thead>
<tr>
<th>Vehicle technology</th>
<th>Fire</th>
<th>Accident</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>47</td>
<td>86</td>
<td>133 (54.7%)</td>
</tr>
<tr>
<td>(P)HEV</td>
<td>23</td>
<td>71</td>
<td>94 (38.7%)</td>
</tr>
<tr>
<td>CNG</td>
<td>5</td>
<td>3</td>
<td>8 (3.3%)</td>
</tr>
<tr>
<td>FCEV</td>
<td>1</td>
<td>2</td>
<td>3 (1.2%)</td>
</tr>
<tr>
<td>Unknown</td>
<td>0</td>
<td>2</td>
<td>2 (0.8%)</td>
</tr>
<tr>
<td>LNG</td>
<td>1</td>
<td>0</td>
<td>1 (0.4%)</td>
</tr>
<tr>
<td>Combination of LNG and diesel, petrol or LPG</td>
<td>0</td>
<td>1</td>
<td>1 (0.4%)</td>
</tr>
<tr>
<td>Combination of LNG and diesel, petrol or LPG</td>
<td>0</td>
<td>1</td>
<td>1 (0.4%)</td>
</tr>
</tbody>
</table>

From Table 2 can be derived that BEV’s are most of the times involved in incidents with AFV’s, followed by (P)HEV’s. Two vehicles have an unknown vehicle technology. In these incident the first responder remembered an AFV was involved, but could not remember the exact vehicle technology involved.

**Role of the vehicle technology**
The vehicle technology / fuel can play a role in the incident. In this section, the role of the vehicle technology is first discussed for fires and then for accidents.

**Fires**
In 2021, 62 fires were recorded with a total of 77 alternative fuel vehicles involved. Of these 62 fires, information about the role of the vehicle technology in the fire, as well as the cause of it being involved, it presented. First the role of the battery pack and second the role of the gas tank are discussed. 71 vehicles contained a battery pack, 7 vehicles a gas tank. The sum of both, 78, is higher then the number of vehicles involved. This however comes from the involvement of 1 FCEV, which contains a battery pack and a gas tank.

![Figure 2: Involvement of battery pack in the vehicle fires.](image-url)
As is seen in Figure 2, in 50.7% of the 71 fires involving an AFV with a battery pack for propulsion, the vehicle battery was on fire. In the other cases, the battery was not on fire, and did not directly contribute to the incident. There were two incidents where it was not known whether the batteries were involved. Thermal runaway occurred in 33 of the 36 incidents where the battery was on fire. This thermal runaway occurred at the following moments in relation to the presence of the fire service (see table 3).

<table>
<thead>
<tr>
<th>Moment of thermal runaway</th>
<th>Frequency (number of times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to the arrival of the fire service</td>
<td>10</td>
</tr>
<tr>
<td>While the fire service was present</td>
<td>21</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
</tr>
</tbody>
</table>

From these 36 vehicles fires where the battery pack was involved, the fire research teams reported the following probable causes of these fires:

> There was a fire in a distribution center containing 16 vehicles; all 16 vehicles were affected by the fire. This caused the batteries to catch fire as well. The cause of this fire is not known.
> There were four cases of arson in which the battery caught fire.
> The battery became overheated once while a vehicle was being towed.
> Two incidents of failure in a battery pack.
> One incident of a technical defect while charging.
> There were five incidents with technical failures elsewhere in the vehicles, which set the vehicles on fire, after which the battery got involved in these fires.
> There were seven cases whose cause is not known.

Seven fires involved vehicles with gas tanks; only one of these gas tanks blew off it’s gas, hydrogen in this specific case. This caused the hydrogen gas to ignite in the garage where the vehicle, a bus, was parked, triggering a jet flame. The cause of the fire in this vehicle is, as far as could be ascertained, a leakage in the low pressure hydrogen system. The leaked gas exploded, causing the bus to catch fire.

**Accidents**

One of the 159 accidents resulted in fire breaking out. This caused the battery to become involved in the fire, leading to a state of ‘thermal runaway’. The thermal runaway occurred before the fire service arrived. As far as could be ascertained, the battery pack was not damaged in any of the 159 accidents to such an extent that this led to a risk of electrocution. No gas tank leaked or blew off during an accident.

**Incident response**

In this section, the most important data concerning the incident response is presented. This is again first done for the fires and second for the accidents. The data presented will be about the method of establishing the possible involvement of the vehicle technology / fuel in the incident (for example, the involvement of a battery pack in a fire), the extinguishing agent used and the process of vehicle recovery.

**Fires**

Where AFVs were involved in fires, the fire service used the methods listed in table 10 to try to establish the involvement of the vehicle technology.
Table 4 Method of establishing the involvement of the vehicle technology

<table>
<thead>
<tr>
<th>Established by means of</th>
<th>Frequency (number of times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuming</td>
<td>5</td>
</tr>
<tr>
<td>Boiling</td>
<td>2</td>
</tr>
<tr>
<td>Smoking</td>
<td>14</td>
</tr>
<tr>
<td>Hissing</td>
<td>5</td>
</tr>
<tr>
<td>Visually</td>
<td>27</td>
</tr>
<tr>
<td>Heat development</td>
<td>7</td>
</tr>
<tr>
<td>Thermal imaging camera</td>
<td>28</td>
</tr>
</tbody>
</table>

From Table 4 can be seen that an thermal imaging camera was used most of the times to establish the role of the vehicle technology, closely followed by a visual inspection. In case of a fire, smoking was one of the most observed indicators involvement of the vehicle technology.

The fire service carried out 40 extinguishing or cooling actions in fires involving AFVs. Table 5 shows how often each extinguishing agent and/or refrigerant was used.

Table 5 Extinguishing agent

<table>
<thead>
<tr>
<th>Extinguishing agent</th>
<th>Frequency (number of times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covering</td>
<td>1</td>
</tr>
<tr>
<td>High Pressure</td>
<td>17</td>
</tr>
<tr>
<td>Low Pressure</td>
<td>13</td>
</tr>
<tr>
<td>Medium Pressure</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>2</td>
</tr>
<tr>
<td>Foam</td>
<td>7</td>
</tr>
</tbody>
</table>

High and low pressured hoses were used most of the times. Foam was applied 7 times. In two incidents, multiple agents were used.

An analysis of the data of the recovery of the vehicles involved in accidents shows that as far as has been ascertained, submersion containers were used 20 times in order to remove a vehicle involved in a fire:

> In eleven cases, the vehicle was removed and immersed in water in the container at the towing companies location.
> In seven cases, the vehicle was transported in the submersion container, but this research could not ascertain if the vehicle was immersed.
> There were two cases where the vehicle was placed in the container as a preventative measure, but the container was not filled with water.

In the other 42 cases, the vehicle was removed in accordance with regular recovery protocols, it was handed over to the police or it is not known how the vehicle was recovered.

Accidents

Where AFVs were involved in accidents, the fire service used several methods to try to establish the involvement of the vehicle technology. The methods are shown in the left-hand column of Table 6. The right-hand column shows the number of times a certain method was used.
Table 6 Method of establishing the involvement of the different vehicle technologies / fuel types

<table>
<thead>
<tr>
<th>Method of establishing involvement</th>
<th>Number of times this has been applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>No signals observed</td>
<td>120</td>
</tr>
<tr>
<td>Smoke observed</td>
<td>2</td>
</tr>
<tr>
<td>Visually</td>
<td>82</td>
</tr>
<tr>
<td>Heat generation observed</td>
<td>1</td>
</tr>
<tr>
<td>Thermal imaging camera</td>
<td>46</td>
</tr>
</tbody>
</table>

The fire service carried out an extinguishing or cooling action in one accident involving AFVs. Low pressure hoses were used to extinguish the fire.

An analysis of the data of the recovery of the vehicles involved in accidents (n = 166) shows that most vehicles (n = 164) were handed over to the police or were removed by a vehicle towing company in accordance with regular practice. As far as could be ascertained, there were two cases where the vehicle involved was placed in a submersion container to remove it. The submersion container is a liquid-tight container in which a passenger vehicle can be placed. Submersion containers are used in the Netherlands to immerse lithium-ion batteries which are, or have been, on fire and which are or may be unstable. These batteries are submerged in water in these containers for a longer period of time in order to stop the actual or imminent thermal runaway process. In the Netherlands, submersion containers are used by vehicle towing company.

There were six cases where the fire service advised the vehicle towing company to park the vehicle involved in the accident at an “ample distance” from other vehicles and/or buildings. There was one case where the vehicle manufacturer was contacted to find out whether their remote reading of the on-board computer had shown an increased temperature in the battery pack. This was not the case.

In one case, the vehicle towing company asked the fire service personnel to remove the service plug, otherwise the operator would not transport the vehicle. Removing the service plug from the battery pack deactivates the high-voltage system.

ANSWERING OF RESEARCH QUESTIONS

In this chapter, the research questions are answered.

1: How many incidents with AFV’s happened in The Netherlands?
The fire service attended a total of 221 incidents involving a total of 243 AFVs in 2021. From these 221:
   > 62 were fires, involving 77 vehicles.
   > 159 were incidents, involving 166 vehicles. One accident also caused a fire to break out.

2: What are the characteristics of the AFV’s involved in these incidents?
Most vehicles involved were passenger cars (80.7%). Vans and light commercial vehicles accounted for 10.7% of the vehicles involved, and coaches and buses accounted for 5.3%. Lorries (1.6%), microcars (0.8%), one TukTuk (0.4%) and one Automated Guided Vehicle (0.4%) were the other vehicles involved.

Of these vehicles involved, 54.7% of the vehicles were battery electric vehicles, followed by 38.7% (plug-in) hybrid vehicles. The aggregate of the other alternative fuels accounts for 5.8%. In 0.8% of the cases it was known that an AFV was involved, but the vehicle technology / fuel type was unknown.

3: What role did the vehicle technology have in these incidents?
In case of vehicle fires, a total 71 vehicles contained a battery pack. In 50.7% of these cases the battery was involved in the fire. The battery was not involved in 46.5% of these fires. In two cases, it is still unclear whether or not the batteries were involved in the fire (2.8%). Seven vehicles with gas tanks were involved in fires. In one case (14.3%) the gas tank blew off due to the fire, causing the hydrogen gas to ignite.

There was one case where the vehicle technology contributed to an accident and the battery pack of the vehicle in question caught fire after the collision. There was not a single accident where the battery pack was damaged so badly that there was an electrocution hazard.

4: What can be learned from the incident response to these incidents?
For fires in vehicles, a high pressure system was used 17 times to fight the fire. Low pressure hoses were used 13 times, medium pressure hoses twice and foam seven times. Thermal imaging cameras were used 28 times to determine whether the battery pack was involved in the fire. The vehicles were immersed in submersion containers in 11 fires. Seven vehicles were transported in the submersion container, but it is not certain whether they were actually immersed. There were two cases where the vehicle was transported in the submersion container, but did not need to be immersed.

In case of accidents, a thermal imaging camera was used 46 times to check whether the battery pack was involved in the incident. There were two accidents where the vehicle was placed in an submersion container to remove it from the scene of the accident. There were another six cases where parking the vehicle at an ample distance from other vehicles and/or buildings was advised.

CONCLUSION
This research presents the first insights in incidents with AFV’s in The Netherlands. The most important conclusions about firefighting and accident response are presented in the two sections below in their respective order.

Firefighting
The data shows that the battery was involved in fifty percent of all fires. This means that firefighters will have to take into account that it will take a long time to handle the fire (extinguishing, cooling and removal of the vehicle, possibly using an submersion container), and that the vehicle towing companies should pay attention to contaminated cooling water.

That the battery pack is involved in fifty percent of all fires, means that it is not involved in the other fifty percent of the vehicle fires. Care must therefore be taken not to immediately submerge a BEV of PHEV involved in a fire as a precaution: after all, the battery pack is not involved in the fire in all cases. Careful consideration must therefore be given to whether submersion of the vehicle is necessary, which will only be the case once it has been established that the (lithium-ion) battery pack is involved in the fire.

Accident response
The data also shows that there was only one incident where the battery contributed to the accident (because a fire started and the battery became involved) and that there was not a single accident where the battery pack was damaged so badly that this gave rise to a risk of electrocution. This is useful information for the fire service as regards the possible hazard involved in such accidents. Based on these figures, the fire and electrocution hazards are relatively minor.

REFLECTION
This research was the first of its kind in The Netherlands by making numeric information available about incidents involving alternative fuel vehicles. It provides quantitative information about the
occurrence of accidents and fires involving alternative fuel vehicles, the locations of the accidents and fires, how the fire service responded and which equipment was deployed.

But this data is meaningless without further context. If, for example, the fire involving 16 vehicles in a distribution center, were removed from the data set, the figures for fires involving alternative fuel vehicles would change substantially. And furthermore, if a situation hardly every occurred in 2021 (e.g. fires involving AFVs in multi-story car parks), it does not mean that this incident scenario is not relevant enough to be taken into consideration. The data discussed here only reflects a specific year and the sample is too small to enable any trends to be identified. Fighting fires inside multi-story car parks remains a tricky business and fires involving electric vehicles take a different course than fires involving fossil-fueled vehicles. And what's more, only 5% of the Dutch vehicle fleet is electric. Any scenarios that do not or only rarely occur now could become more common in the future as the vehicle fleet grows.

As this research was the first of its kind in The Netherlands, it involved quote some challenges. Gathering data is easier said then done, and presenting it even more. At first, how do you collect incident data when you are not at the scene? We would therefore like to thank the fire research teams for their time and effort to collect the data for us. Second, how do we make sure we do not miss any incidents? We worked closely with the STAR-database to gather the accidents and kept improving our data filtering process in the ‘GMS’ to gather all fires. And thirdly, how to you process and store this data? Our Business Intelligence team was crucial is this process of setting up the data warehouse and the dashboards presenting their data. Their effort in supporting this research, regularly being confronted with privacy questions and software issues, was essential for this research to succeed.

REFERENCES


Fire suppression and manual firefighting of battery electric vehicle fires on ro-ro ships

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¹RISE Research Institutes of Sweden, Borås, Sweden
²Centro de Seguridad Marítima Integral Jovellanos, Gijón, Spain

ABSTRACT

The increased use of electric vehicles has raised a concern about firefighting measures including water spray fire suppression systems (often denoted “drencher systems”) and tactics and equipment used for manual firefighting on ro-ro cargo and ro-ro passenger ships. A test series involving testing of two pairs of geometrically similar internal combustion engine vehicles (ICEV’s) and battery electric vehicles (BEV’s) under as equal test conditions as possible were conducted to investigate the performance efficiency of the drencher system. In addition, manual firefighting equipment and tactics was evaluated on three BEV fire tests. It is concluded that a fire in the two types of vehicles is different but share similarities. However, a fire in a BEV does not seem to be more challenging than a fire in an ICEV for the drencher system design given in current international recommendations. Similarly, there are common (e.g., handheld fire extinguishers and hoses) and new (e.g., fire blanket and water-cooling device) manual firefighting equipment that effectively can be used to control or limit a BEV fire.

KEYWORDS: ICEV, BEV, sprinkler systems, water spray system, drencher system, manual firefighting, ro-ro spaces, ships.

INTRODUCTION

Electric vehicle (EV) deployment has been growing rapidly over the past ten years and will likely continue to grow. Basically, all car manufacturers in the world are introducing new fully electric or hybrid vehicles, partially in response to increasing efficiency and emissions standards. Large-scale free-burn fire tests [1, 2, 3] indicates that the peak heat release of a battery electric vehicle (BEV) fire is comparable to that of a vehicle with an internal combustion engine (ICEV), given similar sized vehicles. From these tests it is noted that the involvement and the time to involvement of the fuel tank and the battery pack of the vehicle have an influence on the fire growth rate and the severity of the fire.

However, there are limited information available about the fire suppression performance of sprinkler systems. Water spray systems (often denoted “drencher systems”) are typically installed on ro-ro cargo and ro-ro passenger ships. Roll-on/roll-off (ro-ro) ships are designed to carry wheeled cargo such as passenger cars, freight trucks, buses, and motorcycles, which are driven on and off the ship on their own wheels. The ships are large, with ro-ro spaces that extend the full length and width of the ship. The drencher systems consist of deluge sections with open water spray nozzles. The sections are manually operated in case of fire. Concerns have arisen whether these systems are able to control a fire in an electric vehicle and even if the design of the system in terms of water flow rates needs to be increased. Although the fixed water spray system is the premier alternative to fight vehicle fires in enclosed spaces, there can be situations when a manual intervention is efficient, e.g., early and fast suppression, or necessary, e.g., if the fixed system is malfunctioning. Similarly, concern has been
raised regarding manual firefighting equipment and tactics and alternative equipment has started to be
developed such as the Albero project mobile water spraying system\(^1\).

Within the LASH FIRE project, fixed and manual firefighting of BEVs has been investigated. The
objective of the fixed firefighting tests was to compare the fire suppression performance of a water
spray system for fires involving ICEV’s and BEV’s under as equal test conditions as possible. The
tests simulated a ro-ro space having a ceiling height of about 5 m and the system design in terms of
water discharge densities corresponded to the design recommendations in MSC.1/Circ.1430/Rev.2 [4].
The objective of the manual firefighting tests was to evaluate the effectiveness of existing and new
equipment on BEV fires.

**DRENCHER SYSTEM TESTS**

Two pairs of vehicles, i.e., a total of four vehicles were used in the tests. The pair of vehicles were
chosen to be as similar as possible, except for the powertrain, refer to Table 1. All vehicles were sport
utility vehicles (SUV’s). The make and model of the vehicles are not provided, but all vehicles are
considered representative of modern vehicles in the marketplace.

<table>
<thead>
<tr>
<th>Table 1. The vehicles used in the tests.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model year:</td>
</tr>
<tr>
<td>Type of vehicle</td>
</tr>
<tr>
<td>Curb weight, inclusive of driver [kg]</td>
</tr>
<tr>
<td>Drive</td>
</tr>
<tr>
<td>Fuel or type of battery</td>
</tr>
<tr>
<td>Fuel tank or battery capacity</td>
</tr>
<tr>
<td>Amount of fuel and charge level used in the test</td>
</tr>
</tbody>
</table>

ICEV1 and BEV1 was similar except for the powertrain. BEV1 was geometrically slightly smaller but
was about 30 % heavier than the ICEV1, mainly due to the weight of the battery pack. It is also noted
that BEV1 was built on a dedicated BEV platform with a simple flat rectangular battery pack design,
with battery modules positioned side by side between the wheel axles. ICEV2 and BEV2 was basically
identical except for the powertrain as the vehicles are designed using a modular platform that allows
different powertrains. The electric version is about 20 % heavier, mainly due to the weight of the
battery pack. The battery modules were primarily arranged in one pack beneath the area of the back
seat and in one pack beneath the area of the front seats.

**Vehicle arrangement**

Six steel sheet trays were positioned at the floor of the fire test hall, symmetrically under the four
water spray nozzles described below. Each tray measured 2500 mm (W) by 1000 mm (L) by
150 mm (H). The long sides of the trays were joined using bolts, long side-to-long side, to provide a
total area of 2500 mm (W) by 6000 mm (L), equaling 15 m\(^2\). The outer rim height of the trays was
150 mm, but the trays were designed with a lower rim height of 75 mm at the long sides that were
facing each other.

\(^1\) Dana-Meissner-Project-ALBERO-Results-October-2020-LASH-FIRE-webinar-14102020.pdf (lashfire.eu)
Prior the tests, the trays were filled with 75 mm of water to achieve an unbroken water surface. Four goose-necks at the short sides ensured a constant level of water despite water being discharged into the trays by the over-head water spray system.

The vehicle under test was positioned symmetrically in the tray. Each of the tires, respectively, was positioned on a small wood block that was 75 mm in height, making the vertical distance from underside of the vehicle to the water surface equal to the actual distance measured to a road surface. In addition, supports were placed at the jack brackets to prevent the vehicle from tilting or collapsing during a test. The intention was to improve the test-to-test repeatability by improving the stability of the vehicles. Figure 1 shows the arrangement.

The fuel tank was filled with unleaded 95-E10 to 90 % of the nominal tank capacity. This gasoline quality is a fuel which contains up to 10 % of ethanol, in accordance with the latest (from 2021) European specifications. A small (15 mm) circular hole was drilled at the bottom of the fuel tank, close to the longitudinal centreline of the vehicle. The hole was fitted with a rubber plug, which was disconnected at the start of the test to allow an outflow of fuel over the water surface of the fire tray. The outflow was immediately ignited with a torch.

The propulsion battery pack was charged to 90 % of its useable capacity. A small circular (22 mm for BEV1) and square (30 mm x 30 mm for BEV2) hole was drilled through the protective plate under the battery pack. This allowed the penetration of one of the battery modules at the rear, left hand side of the vehicle by a nail. The nail was pointed, had a diameter of 20 mm and was driven by a pneumatic cylinder placed inside the tray underneath the vehicle. The penetration depth was about 70 mm. Unless the combustion gases self-ignited they were ignited using electric igniters positioned close to the nail or by marshals that were placed at top edge of the rim of the fire tray.

**Deluge water spray system**

Four water spray nozzles were installed in a hydraulically balanced pipe-work, having a nozzle spacing of 3.05 m by 3.05 m. Each of the nozzles covered an area of 9.3 m². The flow rate of water was controlled via a diaphragm control valve connected to a compressed air supply. The control valve provided a constant pressure downstream the valve, irrespective of the inlet pressure. However, the desired water flow rate of 372 l/min to obtain a 10 mm/min discharge density was fine-tuned by an operator if required. The nominal operating pressure was 1.3 bar. Potable water was supplied from the public main. Figure 1 shows the spray pattern of the four nozzles.

![Figure 1](image_url)  
*Figure 1  The spray pattern of the four water spray nozzles used in the tests.*
Fire test procedure
The intent was to initiate fire in such a way that the liquid fuel or the battery pack was involved at the initial stage of the fire. This was made by a mechanical penetration of the fuel tank and the battery, combined with small fire ignition sources that ensured that fire ignition occurred. Although it can be argued that this type of fire ignition scenario is extremely rare, the approach was required to obtain a straightforward comparison of the two distinct types of vehicles. The application of water was manually initiated at a convective heat release rate of 1 MW, which corresponded to a total heat release rate of about 1.5 MW. This threshold was chosen to ensure that the fire had indeed involved the vehicle and at a time when continued fire growth was to be expected.

Water was discharged for 30 min. Thereafter, the fire re-growth was documented by allowing the vehicles to be completely consumed in the fire. The approach facilitated the handling (scrapping) of the vehicles after the tests and provided an indication of to what degree the fire was controlled by the application of water.

Instrumentation and measurements
The following measurements were undertaken during each test:
- The heat release rate.
- The gas temperature above the vehicle, at vertical distance from the water surface in the tray to the thermocouple of 5 m.
- The surface temperature on steel sheet screens to the sides of the vehicle. Two steel sheet screens were positioned at each long side of the tested vehicle. Each screen was sized 1 350 mm (L) by 1 800 mm (H) and had nominal thickness of 1 mm. The screens were positioned symmetrically with respect to the wheel axles and 100 mm apart. The horizontal distance to the side of vehicle was 500 mm. Each steel screen had a horizontal, 600 mm wide overhang that prevented water from wetting its back side.
- Plate Thermometer measurements. One Plate Thermometer was positioned along the longitudinal centerline of the vehicle, at a horizontal distance of 1500 mm, respectively, from the front and rear of the vehicle. The vertical distance measured to the center point of the water surface in the tray was 750 mm. The Plate Thermometer consists of a 0.7 mm thick Inconel 600 steel plate with a front face measuring 100 mm by 100 mm. A sheathed thermocouple is spot-welded to the plate that is insulated on the backside. The device is sensitive to heat convection, but compared to a conventional thermocouple, significantly more sensitive to heat radiation.

Results
Table 2 shows the heat release rate parameter results, as recorded prior or after the start of the application of water.

Table 2  Heat release rate parameter results, as recorded prior or after the start of the application of water, with the key parameters discussed above in bold.

<table>
<thead>
<tr>
<th></th>
<th>ICEV1</th>
<th>BEV1</th>
<th>ICEV2</th>
<th>BEV2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of test</td>
<td>Sept. 23, 2022</td>
<td>Sept. 21, 2022</td>
<td>Sept. 27, 2022</td>
<td>Sept. 29, 2022</td>
</tr>
<tr>
<td>Time to discharge of water [min:s]</td>
<td>01:12 (72 s)</td>
<td>12:40 (760 s)</td>
<td>00:58 (58 s)</td>
<td>16:45 (1 005 s)</td>
</tr>
<tr>
<td>Time to end of discharge of water [min:s]</td>
<td>31:12 (1 872 s)</td>
<td>42:40 (2 560 s)</td>
<td>30:57 (1 857 s)</td>
<td>46:45 (2 805 s)</td>
</tr>
<tr>
<td>Peak total heat release rate [kW]</td>
<td>7 978</td>
<td>2 944</td>
<td>5 324</td>
<td>1 975</td>
</tr>
<tr>
<td>Peak convective heat release rate [kW]</td>
<td>3 594</td>
<td>1 195</td>
<td>2 323</td>
<td>1 138</td>
</tr>
<tr>
<td>The maximum five-minute average convective heat release rate [MJ]</td>
<td>1 467</td>
<td>633</td>
<td>1 006</td>
<td>639</td>
</tr>
<tr>
<td>Total heat release [MJ] from fire ignition to end of water discharge</td>
<td>2 637</td>
<td>2 189</td>
<td>1 784</td>
<td>1 370</td>
</tr>
<tr>
<td>Total heat release [MJ] from fire ignition to the end of test</td>
<td>5 241</td>
<td>4 510</td>
<td>4 765</td>
<td>4 474</td>
</tr>
</tbody>
</table>
Figures 2 and 3, respectively, shows the heat release rate histories for each pair of vehicles.

**Figure 2** The total and convective heat release rate histories for ICEV1 and BEV1.

**Figure 3** The total and convective heat release rate histories for ICEV2 and BEV2.

Table 3 shows the temperature and heat flux measurement results as recorded prior or after the start of the application of water.

**Table 3** Temperature and heat flux measurement results as recorded prior or after the start of the application of water.

<table>
<thead>
<tr>
<th></th>
<th>ICEV1</th>
<th>BEV1</th>
<th>ICEV2</th>
<th>BEV2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Date of test</strong></td>
<td>Sept. 21, 2022</td>
<td>Sept. 23, 2022</td>
<td>Sept. 27, 2022</td>
<td>Sept. 29, 2022</td>
</tr>
<tr>
<td><strong>Mean water flow rate [l/min]</strong></td>
<td>372</td>
<td>373</td>
<td>371</td>
<td>374</td>
</tr>
<tr>
<td><strong>Peak gas temp. above the vehicle [°C]</strong></td>
<td>340</td>
<td>56</td>
<td>135</td>
<td>166</td>
</tr>
<tr>
<td><strong>Maximum average surface temp. on right hand side steel sheet screen [°C]</strong></td>
<td>407</td>
<td>149</td>
<td>277</td>
<td>165</td>
</tr>
<tr>
<td><strong>Maximum average surface temp. on left hand side steel sheet screen [°C]</strong></td>
<td>339</td>
<td>139</td>
<td>251</td>
<td>163</td>
</tr>
<tr>
<td><strong>Peak heat flux to the right of the vehicle [kW/m²]</strong></td>
<td>98</td>
<td>7</td>
<td>44</td>
<td>5</td>
</tr>
<tr>
<td><strong>Peak heat flux to the left of the vehicle [kW/m²]</strong></td>
<td>138</td>
<td>6</td>
<td>59</td>
<td>6</td>
</tr>
<tr>
<td><strong>Peak surface temp. on Plate Thermometer in front of the vehicle [°C]</strong></td>
<td>70</td>
<td>43</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td><strong>Peak surface temp. on Plate Thermometer behind the vehicle [°C]</strong></td>
<td>88</td>
<td>87</td>
<td>78</td>
<td>76</td>
</tr>
</tbody>
</table>

Figures 4 and 5, respectively, shows the mean surface temperature of the steel sheet screens to the sides of the vehicle. Note that the time scale extends to 60 min and not to 90 min as in the previous figures, in order to better capture the sequence of events when the water spray system was operating.
The fire scenarios
The fire ignition scenarios are considered unlikely but were necessitated by the desire to initiate the fire either in the gasoline fuel or in the battery pack and thereafter allow the fire to spread to other combustibles of the vehicle. Both fire ignition scenarios proved to work from the aspect that fire ignition was immediate in the flammable gases of the fuel spill fire as well as in the flammable gases escaping the battery pack, except for BEV2 where fire ignition occurred immediately but the presence of stable flames was a little delayed.

Thereafter, the fire scenarios of the two types of vehicles were quite different. The gasoline fuel spill fire in the ICEV tests developed rapidly and the application of water was initiated after around a minute. The fire in the battery pack of the BEV’s developed slower, involved other combustibles gradually and the application of water was initiated after more than twelve minutes and sixteen minutes, respectively.

The fires in the ICEV’s were initially suppressed, but the flowing gasoline fuel spill fire caused a larger damage to the fuel tank that resulted in an increase of the spill area and a peak heat release rate. Plastic fuel tanks in passenger vehicles are designed to meet international fire test requirements [5] and should withstand a spill fire test scenario for two minutes, which correlates well with the observations of the integrity in these tests. The peak heat release rate occurred during a period from between three and four minutes (ICEV1) and four and four and a half minutes (ICEV2). The peak heat release rate of ICEV1 was higher than that of ICEV2, which correlates with the larger quantity of gasoline used in ICEV1. After the burn-out of the spill fire after about six minutes (ICEV1) and five minutes (ICEV2), fire continued in combustibles as the tires, the plastics liners in the wheelhouses, undercarriage plastic
cover panels, inside the passenger compartment and inside the engine compartment. These combustibles are completely or partly shielded from the application of water from the overhead water spray nozzles. During this stage of the continued 30-min application of water, the heat release rate gradually decreased as these combustibles were consumed. Once the application of water was terminated, fire re-developed inside the passenger compartment, partly as the extent of damage to windows increased. Additionally, the paint and external front parts which were not involved in the fire due to the application of water started to burn. The post-application peak heat release rates were significant for both vehicles.

The fire in the BEV’s had involved other combustibles to a larger extent when the application of water was initiated. Even though these combustibles were completely or partly shielded from the application of water, the fire was promptly suppressed. The fire re-growth experienced in both BEV tests is primarily associated with the battery packs where the fire progressed from the rear part (where fire ignition took place) and towards the front part. However, contribution from the passenger compartment was also observed. The progress of the fire from battery module to battery module is captured by the heat release measurement, the most noticeable for BEV1, as regular peaks. For both BEV’s the fire in the battery pack burnt out during the 30-min application of water. Once the application of water was terminated, fire re-development was significantly slower in BEV1 (after about 18 min) than in BEV2 (basically immediately). The post-application fire re-growth involved unburnt combustibles as the paint and front part plastic panels as well as unburnt parts of the interior. The post-application peak heat release rates were significant for both vehicles.

The peak heat release rate was significantly higher for ICEV1 than for BEV1 as well as for ICEV2 compared to BEV2, which is associated with the short, but intense gasoline fuel spill fire. The maximum five-minute average convective heat release rate captures the severity of the fire over a longer period of time. The parameter value was the highest for ICEV1, more than twice as high than for BEV1 and BEV2. The value for ICEV2 was lower than that of ICEV1, as the vehicle was smaller with a smaller amount of liquid fuel.

The total heat release rate from fire ignition and to the end of water application was slightly higher for ICEV1 as compared to BEV1 and higher for ICEV2 as compared to BEV2. The same trend is observed for the total heat release rate for the entire test, which included the burn-out of the vehicles.

The performance of the water spray system
The performance of the water spray system was adequate for both types of vehicles. The application of water reduced the surface temperatures of the steel sheets screens, the Plate Thermometers and the heat radiation to a level that could limit or even prevent fire spread from a vehicle to adjacent vehicles. One concern can be raised, being that a flammable liquid spill fire could involve adjacent vehicles soon, a large fuel spill burns so intense and could spread under adjacent vehicles. The degree of fire control was established by terminating the water flow and observing the time to fire re-growth and magnitude of the fire. For both types of vehicles, the fire re-peaked to between 2 MW and 3 MW once the application of water was terminated. This is an indication that the heat release rate of the fires was indeed reduced by the water spray, despite that the fire to a large degree is shielded. Once the wetting and cooling of the body of a vehicle stopped, it was observed that damage to windows will occur or increase, paint will start to burn, and unburnt combustibles will ignite which contributes to fire re-growth.

The gas temperature was promptly reduced in the BEV tests and reduced to a level of 50 °C or less during water discharge. For the ICEV tests, a short peak reaching 340 °C (ICEV1) and 135 °C (ICEV2) was observed after the application of water was initiated, which relates to the increase of the gasoline fuel spill fire. After this stage, the gas temperature was reduced to less than 50 °C.

None of the Plate Thermometer surface temperatures peaked at any significant levels in any of the tests. It is observed that the peak temperature of the device facing the rear of the vehicle was
consistently higher than the device facing the front. This observation seems logical as the fire was started at the rear part of the vehicles.

Manual fire-fighting efforts were not part of the study but based on the tests it can be argued that an intentional premature termination of a drencher system should be avoided. When the water spray system is turned-off, resources should be readily available to manage a re-developing fire.

**MANUAL FIREFIGHTING TESTS**

In total three BEVs (same type in all tests) fire tests were conducted at Jovellanos Maritime Safety Training Centre located in Gijón, Spain, March 29 and 30, 2022. The first test was a free-burn test aimed to study the fire development without intervention. In the second fire test first response equipment was evaluated and in the third fire test manual intervention on a fully developed BEV fire was tested. The tactic to fight an ICEV or BEV fire can be divided into three stages; first response during the early or recipient fire development, manual firefighting with full protection during fully developed fires and post-extinguishment when the fire has decayed and is being fully under control. In all three tests the BEV was ignited with a propane burner placed on the ground under the traction battery. The burner was turned off when an intervention started. In the first response test the burner was reignited in between the tests. The temperature was measured at 4 places above the battery pack and at 4 places below the battery pack. The temperature at the burner, the engine, the passenger compartment, and the trunk compartment, were also measured. The experience of the firefighters was documented with video, observations, and de-briefing after the tests.

**First response tests**

This test was conducted in the open with one BEV surrounded by eight scrap cars to simulate a more challenging real situation onboard a ro-ro ship, see Figure 6 taken just after ignition. Three types of handheld fire extinguishers (two hand-held CO2 extinguishers, two hand-held ABC-powder extinguishers, and two hand-held foam extinguishers) and a fire blanket were tested.

![Figure 6](image)

*Figure 6 The black BEV in the middle after ignition surrounded by eight scrap cars.*

The extinguishing equipment was used during the early-stage fire development when the fire was sufficiently small for an early intervention by unprotected crew members. The handheld fire extinguishers were efficient in slowing or even terminating the fire development. This was supported by declining temperature measurements. The devices should be applied from the same direction (if two handheld extinguishers are used at the same time), preferably with fresh air flow in the back.

After the tests with handheld fire extinguishers, the fire was allowed to grow for 10 minutes. The fire growth rate was poor, most likely as a result of the prior extinguishing efforts and remaining extinguishing media. When the temperature was 550 °C above the battery, a fire blanket was pulled over the car and the temperature dropped to 300 °C in 7 minutes showing great efficacy in limiting and controlling the fire. The fire-blanket can also be used as a post-extinguishment measure, see below.
Manual firefighting tests

The aim of this test was to study the level of protection of the PPE (fire suit EN 469 level 2 together with gloves, boots, flash hood, long sleeved undergarment and Breathing apparatus), the suitable equipment (focusing on fire hoses) and the right procedure during extinguishment. The test was conducted in an indoor space aimed to simulate a ro-ro space with limited accessibility and visibility. The cars were placed with the BEV at the far left with a pillar in front and a scrap car on the right side of the BEV. A second scrap car was placed in front of the first scrap car to the right, see Figure 7.

Figure 7 The green BEV in the corner with two scrap cars.

At 9 min the fire was judged to be fully developed and manual intervention was prepared. The fire spread to the scrap car nearby. Two extinguishing operations were performed:

1. Two fire fighters equipped with one 25mm hose attached to a fogfighter.
2. One firefighter equipped with a 25mm hose attached to a fogfighter and one firefighter equipped with a 45 mm hose attached to a water mist lance.

The first operation started at 10 min after ignition when the temperature in the battery reached about 700 degrees, indicating a probable thermal runaway. The firefighters perceived that the extinguishing work with 25mm hose worked well, the course of the fire slowed down, but was not sufficient for extinguishment, see Figure 8.

Figure 8 Temperature development above and below the traction battery at the front passenger seat and left back seat.

The second operation was initiated at 13 min. At 19 min the fire in all cars was extinguished. The 25mm hose worked well and is much easier to use, i.e., lighter, and more flexible which ensures a
faster intervention. The water mist lance was perceived to be very efficient. It was used in the passenger compartment, under the car, or in the back-hood. It also works to some extent as personal protection. The water mist lance should be equipped with a valve. The 25 mm hose was used for protection, e.g., when water mist lance is applied in the compartment.

**Post-extinguishment**

One particular issue with BEVs is that they may re-ignite if the battery has not burnt out completely but is heated or damaged so that a thermal runaway may be initiated. For this purpose, the fire blanket as well as a water-based cooling device were evaluated. The advantage with these systems is that they can be left unmanned once they are put in place. The test with the fire blanket proved to be effective at extinguishing the fire and controlling it, see Figure 9, although there most likely was no thermal runaway at the time of application.

![Figure 9 The fire blanket is applied unto the BEV.](image)

To evaluate the Albero cooling device, three scrap cars were placed next to each other and the middle car was ignited using diesel. Some windows were smashed before the test and diesel was poured into the car. The Albero nozzles were placed on each side of the central scrap car. The Albero nozzles proved to have a good shielding effect that effectively limits the fire from spreading to adjacent vehicles. In addition, water is sprayed below the vehicles protecting the energy storage, see Figure 10.

![Figure 10 The fire blanket is applied unto the BEV.](image)

After the fire tests the fire fighters were decontaminated. For decontamination of firefighters, there is a need to work out a routine. Equipment for those who clean up needs to be available (respiratory protection and e.g., disposable overalls) as well as boxes with lids for contaminated clothing and equipment. It is also important that the undressing takes place in the correct order of which the breathing mask is the last part. The location for decontamination and the path to get there are important to consider as it may become contaminated.
Discussion
One particular fire behavior with BEVs is thermal runaway which is a thermal propagation and combustion in and between the cells of the traction battery. In the three tests with BEVs described in this section; video recordings, direct observations during the test, temperature measurements and dismantling of the traction batteries at a scrap yard after the tests was used to infer whether a thermal runaway occurred or not. There were minor jet flames and squeezing sounds captured on video and observed at the test site. The observed jet flames were minor and did not last for very long. Some squeezing sounds could be heard that lasted for longer. However, there are many pressurized parts such as tires, and springs that can cause a similar behavior. Temperature measurements above and below the traction battery reached above 700 °C in all tests with the highest values, above 1000 °C in the free burn test after more than 20 min fire without any intervention. Based on the pictures from the scrap yard it can be said with certainty that there was a thermal runaway in the free burn test. It is possible that thermal runaways started in the two other tests, but if so, it was terminated by the intervention. It is also possible that the intervention occurred before a thermal runaway had started and that the intervention then prevented it from happening. Most likely the other two BEV fires would have reached a thermal runaway without intervention.

CONCLUSION
Concerns regarding the performance of drencher systems in ro-ro cargo spaces on board ships have raised with the increased number of battery electric vehicles being transported. The objective of the tests was to compare the fire suppression performance of a water spray system for fires involving ICEV’s and BEV’s under as equal test conditions as possible. It is concluded that a fire in the two types of vehicles is different but share similarities. A fuel spill fire associated with an ICEV develops very rapidly, peaks high but burns out fast, whilst a fire starting in the battery pack of a BEV develops slower, is not as large but burn longer. The scenario of the fire in other combustibles, as the tires, exterior and undercarriage plastic parts and inside the passenger compartment is similar. The overall conclusion from the tests is that a fire in a BEV does not seem to be more challenging for the drencher system design given in MSC.1/Circ.1430/Rev.2 than a fire in an ICEV of comparable size. One concern can be raised, being that a flammable liquid spill fire could involve adjacent vehicles and could spread under adjacent vehicles.

Traditional and new firefighting equipment have been tested on a burning BEV. The fire was initiated with a propane burner below the traction battery. During the early fire development handheld fire extinguishers and a fire blanket were effective as first response measures in limiting or controlling the fire. During the fully developed BEV fire stage, extinguishment by fully equipped firefighters with hose and water proved to be effective at limiting and extinguishing the BEV fire. The 25mm hose worked well and was much easier to use (lighter and more flexible) than the standard 45 mm. However, 45 mm offers more cooling and faster extinguishment. Water mist lances proved to be very useful and efficient, e.g., in the passenger compartment or underneath the car. Fire blanket or portable water-cooling devices can be used as post-extinguishment measures. Overall, the fire development and resulting extinguishing of the type of BEV used in these tests did not differ significantly from a regular ICEV.

ACKNOWLEDGEMENT
The tests were conducted in the LASH FIRE project. The LASH FIRE project (www.lashfire.eu) is an international research project aiming to significantly reduce the risk of fires on board ro-ro ships by developing and validating effective operative and design solutions. LASH FIRE is addressing a total of twenty challenges covering the entire “fire protection chain”, it comprises both preventive and mitigating risk control measures in all stages of fires originating in ro-ro spaces. The project is running from September 2019 to August 2023. The project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 814975. The information in
this paper reflects only the author’s view and the Agency is not responsible for any use that may be made of the information it contains.

Martin Carlsson at Stena Teknik is also acknowledged for raising the demand and assisting in realizing the tests.

The vehicle manufacturers that sponsored the tests with vehicles are acknowledged.

Davood Zeinali, Kemal Arsavaa & Cristina Meliá from RISE Fire Research AS are acknowledged for the temperature measurements during the manual firefighting tests.

REFERENCES


5. Addendum 33: Regulation No. 34, Revision 3, “Uniform provisions concerning the approval of vehicles with regard to the prevention of fire risks”, United Nations, 12 November 2015
Large-scale tests of firefighting technologies for electric vehicle fires on board ro-ro ferries

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ABSTRACT

The results of 6 large-scale firefighting tests performed on electric and internal combustion engine vehicles are presented. The aim was to test practical firefighting technologies for electric cars on ro-ro ferries. For this purpose, an experimental test setup (approx. 12m × 7m) was constructed using two 40ft shipping containers, joined together and opened at both ends. The test setup intended to simulate the difficulties in deploying available firefighting technologies in the car deck environment due to the small spacing between and above the cars. Different firefighting technologies were tested individually and in combination, using fresh and salt water. The results show that several methods can limit the fire spread to neighbouring cars (fire blanket, water mist, water curtains). Other methods can be used to cool down the battery pack after the car cabin fire has been extinguished (extinguishing lance and battery piercing device) or terminate a thermal runaway event in the battery pack (extinguishing lance).

KEYWORDS: electric car fires, firefighting, large-scale tests

INTRODUCTION

The popularity of electric vehicles (EVs) has grown over the years as a potentially more sustainable substitute for internal combustion engine vehicles (ICEVs). In Denmark alone, the percentage of newly registered battery electric passenger vehicles has significantly increased by approximately 40% from the second quarter of 2021 to the second quarter of 2022, according to statistics provided by the European Automobile Manufacturers’ Association (ACEA) [1]. Most EVs run on a lithium-ion battery (LIB) with various anode, cathode, and electrolyte materials. Depending on the vehicles’ size and intended use, these batteries’ energy ratings can vary. The average battery capacity of a passenger EV is around 66kWh but could reach as high as 118kWh in more recent models [2]. Though EVs come with many advantages concerning environmental impact, the fire safety aspect of EVs can be considered more challenging due to their unique and unpredictable fire characteristics.

Ro-ro ferries with vehicle decks are an attractive solution for long-distance transport, reducing the number of kilometres driven and offering a break during the journey. Charging aboard ferries enables the EVs to be recharged during the trip without needing an additional stop before the destination. However, incidents have been reported where an EV has caught fire while charging on board these vessels [3]. An EV fire poses additional challenges for extinguishment, toxic emissions, and potential for re-ignition, especially after the battery packs have entered the thermal runaway (TR) process. Additionally, the battery compartments are often hidden away by vehicle structure, which means they may be less affected by sprinkler or water mist system activation. The ship's crew must attempt to fight the fire during the journey until the vessel reaches land. However, firefighting capabilities on board a vessel are limited regarding the available equipment on board and the training and experience the ship's crew has in fighting fires in general. These limitations, combined with the complexity and unpredictability of an EV fire, lead to a potentially dangerous and complex scenario to manage.
situation can be complicated because it could take hours to receive further assistance from the shoreside fire services.

Vehicle decks in ro-ro vessels are usually associated with lower ceiling heights, tight parking arrangements, and in some cases, obstructions at the ceiling level, such as pipes, cables and jet fans. These characteristics are unfavourable during a fire due to smoke accumulation at eye level (navigation) and when manoeuvring and using firefighting equipment. Despite the vehicle's decks being required to have optical smoke detection throughout the deck, it takes time before active measures are taken. Confirmation of fire, gearing up with firefighting clothes and equipment (including breathing apparatus) - these operational procedures allow the situation to escalate further before action is taken. It should also be noted that these vessels can carry large numbers of passengers, whose safety should be ensured during such scenarios.

Longer response times by the ship's crew could lead to the EV fire spreading to more than a single vehicle by the time the crew arrives at the scene. The longer time can lead to the fire being out of control and out of range and capabilities of the firefighters on board. Such a fire could not be considered a conventional scenario, even for a crew of professionally trained firefighters. Additional risks unique to EVs may also complicate the situation, e.g. using seawater against battery fires due to the added risk of electrocution for the firefighters and ignition of adjacent battery modules. Any water-based firefighting method uses seawater as the input media for a fire at sea.

The issue of fighting EV fires at sea has already been identified and investigated through funded European research projects [4][5]. Nevertheless, the usability of firefighting technologies in these challenging environments still requires further investigation. Therefore, The Danish Institute of Fire and Security Technology (DBI) investigated potential firefighting solutions suitable for ro-ro ferries under the scope of the project Electric Vehicle Fires at Sea: New Technologies and Methods For Suppression, Containment, and Extinguishing for Battery Car Fires On Board Ships (ELBAS) funded by the Danish Maritime Fund [6]. As a part of this project, a series of large-scale, live fire experiments were conducted at RESC - Rednings- og sikkerhedscenter in Korsør, Denmark. The aim was to practical test different types of existing and novel firefighting and extinguishment technologies against real-scale EV fires using sea and fresh water in an arrangement closely representing the parking arrangement in a vehicle deck on a ro-ro vessel. Assessing existing and novel firefighting techniques and providing training for shipping crew were primary objectives of these experiments.

**FIRE TESTS**

The main objective of the fire tests was to investigate the performance, usability, and applicability of different existing and novel firefighting methods to combat an EV fire on board ro-ro vessels. Several firefighting methods were used stand-alone and in combination with another throughout these tests. The test setup was designed and arranged to simulate the challenging environment in the vehicle decks of such vessels.

**Test setup**

In total, nine large-scale tests were performed in a test rig representative of a tightly parked vehicle deck on a ro-ro vessel, as shown in Figure 1. The structure surrounding the vehicles was made from merging two 40ft ISO stainless-steel containers with a stainless-steel plate at the ceiling and was open at the front and the back. The dimensions of the test setup are shown in Figure 2. The floor on which the vehicles were parked was made of 14mm thick steel plates with dimensions of 2m × 3m. The ceiling was insulated with 50mm thick Searox SL620, and directly above the EV, an additional layer of 50mm thick Saint-Gobain Isover Ultimate thermal insulation was used as additional thermal protection. The side walls of the structure were left uninsulated.
The mock-up's length and height are equivalent to a 40 ft ISO container (12.2m and 2.4m, respectively), whereas the width of the setup is 7.13m. This structure provided enough space to place nine cars in total in a matrix of $3 \times 3$, with the EV placed in the centre, surrounded by scrap ICE cars.

**Table 1** Overview of the EVs used during the tests

<table>
<thead>
<tr>
<th>EV model (year)</th>
<th>Battery capacity (kWh)</th>
<th>Location of the battery</th>
<th>Battery type</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV1 Renault Fluence ZE (2012)</td>
<td>22</td>
<td><img src="image" alt="Location of the battery" /></td>
<td>Lithium manganese oxide (LMO) [7]</td>
</tr>
<tr>
<td>EV2 Tesla Model 3 (2021)</td>
<td>55</td>
<td><img src="image" alt="Location of the battery" /></td>
<td>Lithium iron phosphate (LFP) [8]</td>
</tr>
<tr>
<td>EV3 Nissan Leaf (2011)</td>
<td>24</td>
<td><img src="image" alt="Location of the battery" /></td>
<td>LMO [9]</td>
</tr>
</tbody>
</table>

*Figures for the location of the battery (indicated by the black rectangles) were extracted from the Euro Rescue app on iOS*

Throughout the nine large-scale tests performed, EV1 was used seven times, and EV2 and EV3 were used once each. The seven EV1s and the EV3 were second-hand and in good condition. The EV2 was in bad condition, as the upper part of the car had already burned. To compensate for the damaged state of the EV2, the seats were replaced with new seats in good condition and a new makeup roof. However, the battery pack of the EV2 was tested and was in good condition before the tests.

**Car arrangement**

In all the tests, a single EV was surrounded by 8 ICEVs, as shown in Figure 3.
Figure 3  Vehicle, detection, and thermocouple arrangement for the tests, where car 5 in the centre is the EV (dimensions in millimetres)

The EV is denoted as car number 5, as shown in Figure 3, and the remaining cars (1-4, 6-9) are the ICEVs. All operating fuels (e.g., petrol, brake fluid) were discharged from the vehicles, the caps of the petrol cars removed, any gas-filled shock absorbers and airbags removed, and all tires depressurised before testing for safety reasons. The surrounding ICEVs were parked tightly, similar to the conditions on a vehicle deck. The gaps between the cars were 20 cm (+/- 5cm) from bumper to bumper and 40 cm (+/-5cm) from door to door. If the surrounding ICEVs were damaged (due to the flame spread) during some of the tests, the cars were shuffled around so that undamaged sides faced the EV before the tests.

Measurements and gas detection
Type K bead thermocouples were used for gas temperature measurements. Type K Cu disc thermocouples were also attached on the inside of the surrounding ICEVs (cars 2, 4, 6, 8 Figure 3) on the surfaces facing the EV. Plate thermocouples were attached to the outer surfaces of the ICEVs (cars 2, 4, 6, 8 Figure 3) surrounding the EV. To measure the temperature of the uninsulated walls of the structure four type K Copper disc thermocouples were attached to the inside surfaces of the side walls at heights of 2 m and 3 m inside the edges of the container walls.

Six Esylux Protector K 9V optical smoke detectors were installed on the ceiling directly above cars 1, 3, 4, 6, 7 and 9, 1m from the edge of the opened side of the structure in tests 1, 2 and 3. (Figure 3)

Investigated firefighting methods
In recent times, creative and different firefighting methods have been developed specifically to address the issue of EV fires. These methods can vary from water-based to non-water-based or direct battery cooling to defensive cooling techniques. Some of these methods have been tested in more favourable spacious outdoor environments. The cramped environment in a vehicle deck is far from these ideal conditions. The ELBAS tests, to some extent, included the added environmental and procedural challenges associated with firefighting at sea. Table 2 provides a list of tested firefighting methods and further details on all the experiments performed in this study. During experiments 4, 7 and 9, an additional battery pack from a hybrid car with a state of charge (SoC) of 120% was placed on the rear seats before ignition.
Table 2: Overview of the experiments performed

<table>
<thead>
<tr>
<th>Experiment ID</th>
<th>EV model</th>
<th>SoC</th>
<th>Extra battery/energy rating</th>
<th>Firefighting method(s) tested</th>
<th>Extinguishing media</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EV1</td>
<td>100%</td>
<td>No</td>
<td>Bridgehill fire blanket</td>
<td>Non-water-based</td>
</tr>
<tr>
<td>2</td>
<td>EV1</td>
<td>100%</td>
<td>No</td>
<td>E-extinguishing lance</td>
<td>Sea water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(MURER-Feuerschutz)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>EV1</td>
<td>100%</td>
<td>No</td>
<td>Battery piercing device</td>
<td>Freshwater</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(BEST from Rosenbauer)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>EV1</td>
<td>130%</td>
<td>Yes/ 0.76kWh&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jøni EV firefighter</td>
<td>Sea water</td>
</tr>
<tr>
<td>5</td>
<td>EV1</td>
<td>100%</td>
<td>No</td>
<td>DAFO/Albero water curtains</td>
<td>Sea water</td>
</tr>
<tr>
<td>6</td>
<td>EV2</td>
<td>100%</td>
<td>No</td>
<td>Water mist system (VID Fire-Kill)</td>
<td>Freshwater</td>
</tr>
<tr>
<td>7</td>
<td>EV1</td>
<td>100%</td>
<td>Yes/ 0.76kWh&lt;sup&gt;a&lt;/sup&gt;</td>
<td>E-extinguishing lance and water mist system</td>
<td>Freshwater</td>
</tr>
<tr>
<td>8</td>
<td>EV3</td>
<td>100%</td>
<td>No</td>
<td>Bridgehill fire blanket and water mist system (VID)</td>
<td>Freshwater</td>
</tr>
<tr>
<td>9</td>
<td>EV1</td>
<td>100%</td>
<td>Yes/ 0.76kWh&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jøni EV firefighter and DAFO/Albero water curtains</td>
<td>Freshwater</td>
</tr>
</tbody>
</table>

<sup>a</sup>The extra battery was at an SoC of 120% before the experiments.

The fire blanket was the only non-water-based method tested. In contrast, the remaining water-based methods provided direct cooling of the battery (E-extinguishing lance and BEST from Rosenbauer) and defensive cooling of the surroundings (Jøni EV firefighter, DAFO water curtains). Direct battery cooling methods have an advantage over defensive cooling methods regarding water consumption. EV fires require large amounts of water (around 1m³/kWh) [10] to fully extinguish and cool the battery to prevent TR or re-ignition. Using a large amount of water on a vessel at sea could lead to stability issues due to the added water weight on the ship. Therefore, direct battery cooling methods seem more favourable for such scenarios. However, due to their localised cooling mechanism, these methods are ineffective for extinguishing fires in other parts of the ignited car or neighbouring cars. They generally require a higher crew skill level. Therefore, these tests intended to combine defensive and direct cooling methods to investigate their effects on the EV fires on board ro-ro vessels. Combinations of two firefighting methods were tested on three of the nine tests (experiments 7, 8, 9 Table 2).

Methodology
Before ignition, the EVs were charged up to the SoCs given in Table 2, and the battery safety systems were bypassed. In experiment 4, the battery was overcharged before testing; see Table 2. The battery pack was then short-circuited to induce TR (via electrical abuse). This approach ensured that the battery pack acted as the initial ignition source of the EV fire instead of igniting the battery pack via external heat sources such as pool fires (thermal abuse). Nevertheless, during experiments 1, 6 and 8, the assistance of such a pool fire was required due to the battery pack not reaching TR after the attempted short-circuit.

After the EVs were ignited, the fire was allowed to develop naturally. The firefighting methods were used only 10min after the first smoke alarm was triggered. This 10 min period accounted for the average response time from the shipping crew based on previous experience.
RESULTS

Experiment 1
The fire blanket has the advantage of being a non-water-based method. However, this means it cannot provide cooling of the battery or surroundings. The main goal of the fire blanket is to contain the smoke and the flames within the boundaries of the blanket and potentially extinguish the fire by limiting access to O₂. Figure 4 shows the temperature evolution of the battery pack and the surroundings before and after the EV was covered with the blanket. Immediately after the blanket was deployed, a rapid decrease in the surroundings and the battery temperature was observed. However, the temperature of the battery pack soon started to increase after the initial temperature drop, highlighting the lack of cooling of the battery pack to prevent the propagation of TR.

Figure 4  Battery enclosure and smoke temperature measurements from experiment 1 show a temperature drop once the fire blanket is deployed. Temperature development shows that the blanket does not provide battery cooling. Nevertheless, it can keep the surrounding temperatures below 100°C.

In contrast, the surrounding temperatures stabilised below 100°C while the EV was covered. That indicated that flame spread to adjacent vehicles after the covering of the EV is highly unlikely and that the blanket could bring the fire under control.

Experiment 2
The extinguishing lance is designed to provide cooling directly on the battery. The lance should be hammered into the battery pack before the water supply is activated. One major advantage of such a lance is the low water consumption, which is an attractive onboard solution due to potential issues with added water weight on the vessels. Nevertheless, it is essential that the firefighters can locate the battery pack beforehand, which might not always be possible. Furthermore, the firefighters need additional training and are required to work close to the battery fire. There they are exposed to high heat, potential jet fires and possibly toxic gases.

During experiment 2, TR was achieved via short-circuit, but flaming combustion was not observed during the test. The absence of flames and thick vapour clouds in this experiment close to the EV made it easier for the firefighters to reach and locate the battery pack. The cramped environment inside the test setup hindered the movement when hammering in the lance. Once the lance had penetrated and the water was supplied, the cooling on the battery pack was substantial and immediate. The cooling effect of the lance can be identified when monitoring the temperature of the battery pack, as shown in Figure 5.
The battery temperature increased immediately after the short circuit and reached just above 300°C. A rapid decrease in the temperature was observed and stayed constant below 100°C for the whole duration of the experiment (highlighted by the shaded area in Figure 5). Similar observations were made by Sturm et al. [11], where a similar device was used against a battery pack of a larger SUV vehicle. Direct impingement of water on the battery pack provides control over the TR of the battery. Although, if flaming combustion is present, other methods should be used to extinguish the fire before using the lance. The presence of flames in the surrounding environment should be considered when this method is used.

Experiment 3
An automated battery piercing device (BEST from Rosenbauer) used in experiment 3 minimises the time spent by the firefighters near the battery fire. That limits firefighters’ exposure to the heat and toxic conditions surrounding the fire. The battery-piercing device has similar advantages to the extinguishing lance. Additionally, the device could be controlled remotely after it has been placed under the battery pack. The device, however, is not versatile and could only be used for battery packs located in the bottom of the car due to its design. Once the device has been placed, the piercing part can be deployed using pressurised nitrogen to penetrate the battery pack and inject the water. Due to the battery pack's location in EV1, the piercing device proved to be too short. Therefore, the tires were deflated to lower the battery pack before the experiment. Furthermore, the machine had to be placed under the car before the experiments and was activated 9 min from the first smoke alarm. Deploying the device and identifying the location of the battery during a fire could also be challenges that the firefighter must overcome during the fire.

The battery compartment was opened during the initial setup for short-circuiting purposes. Therefore, the casing of the battery pack was not fully sealed during the experiment. The cooling provided by the piercing device relies on the water being trapped within the battery pack’s casing. Due to the unsealed battery pack enclosure, the injected water leaked through, which resulted in a failed attempt by the
device. That can be observed in the temperature history of the battery compartment shown at 8.36 min, where the temperature only dropped about 50°C before the water started leaking out (Figure 6).

![Figure 6: Battery enclosure temperature during experiment 3 showing temperature control by the piercing device BEST failing likely due to the battery casing not being fully submerged in water.](image)

However, the cooling rate was far below the performance of the extinguishing lance. It was probably due to the battery compartment not being fully submerged in water. A sudden increasing trend was observed in the temperature of the battery compartment while water was still supplied through the device at 13:06 minutes. Once the temperature rose above the temperature before the device’s activation, it was assumed to have failed and the firefighters were called to control the fire manually. Even after the firefighters intervened, the battery compartment showed rapidly increasing temperature due to TR restarting after the battery pack was left unattended and additional firefighters’ intervention was necessary.

**Experiment 4**

A water-based defensive cooling method was tested during this experiment. The device consists of rails that can be pushed under and on each side of the EV (Figure 7(b)). The rails of the device are equipped with water mist nozzles, which act as water curtains next to the EV. The main idea behind this design is to control the flame spread to neighbouring cars. This method keeps the fire under control and prevents spreading.

![Figure 7: water curtains used in (a) experiment 4 and (b) experiment 5](image)
Figure 8 (a) Temperature measurements of the battery enclosure (b) Plate thermometer measurements from experiment 4, where an overcharged battery caused a swift fire spread to neighbouring cars. The cooling provided by the tested device was inadequate at that fire stage. The grey areas show the intervention by the fire brigade.

An overcharged battery pack was short-circuited, which led to an extremely violent fire. Temperatures exceeding 1000°C were observed near the EV within 10 min after the short circuit (Figure 8 (b)). The plate thermometer readings from cars 2 and 8 reached beyond 400°C within 3 min, indicating potential flame spread to those cars, which was also visually observed. Due to the fire's rapid growth, it was already out of control at the time of using the devices. Even though the devices were used well before the 10 min mark after the first alarm, this behaviour was not ideal for a device that primarily limits flame spread and containment. After the water supply was turned on from both sides of the EV, the temperatures rapidly increased, and the test compartment structure started to deform after the loss of insulation. At this point, the firefighters entered the scene with manual firefighting. The cooling provided by the device was inadequate to bring such a fire under control, which highlighted the importance of the response time, primarily due to the unpredictable behaviour of EV fires. The array of water mist nozzles installed on the rails of the device was only facing the EV, which did not provide cooling to the flames coming from the adjacent vehicles. Methods based on localised indirect cooling of the surroundings are far more effective when the fire has not spread to the surrounding cars due to the limited cooling provided.

Experiment 5

A device similar to the one tested in experiment 4 was used. It had a different design, as shown in Figure 7(b). The device generates a water curtain pointing upwards as opposed to the water curtain directed at the EV in the previously discussed device in experiment 4. The upward water curtain provides cooling on both sides, which can also provide cooling on nearby cars.

In this experiment, short-circuiting the battery pack failed to reach TR conditions; therefore, the ignition was assisted using a diesel pool fire placed under the EV. The temperature of the battery enclosure did not exceed 200°C during the experiment. Even after ignition via the pool fire placed under the EV. Nevertheless, the temperature inside the EV (measured at the roof) reached above 800°C 12 minutes into the fire. At the same time, temperatures measured by the plate thermocouples placed on cars 8 and 9 also increased rapidly. As shown in Figure 9, the temperatures on both sides and inside the EV dropped rapidly, with the activation of the water curtains indicating their cooling effect.
Figure 9  Temperature measurements inside the EV and from the plate thermometers during experiment 5

The upward cone released by the water mist nozzles could reach both sides of the EV and provide cooling, see Figure 9. However, the cooling on the inside of the EV will depend on the openings in the car. The windows of the EV during this experiment were left open, allowing the water droplets to reach inside the EV. This test showed that water curtain solutions can be effective, however they likely require fast deployment, before fire spread to secondary cars has occurred.

Experiment 6
Most vessels are equipped with a deluge sprinkler system covering the vehicle decks. Water, as an extinguishing agent, provides superior cooling upon impingement. Due to the hidden location of the battery packs in most vehicles, direct impingement of water droplets on the fire is unlikely. Water mist systems can also attenuate flame radiation and have proven more effective in preventing fire spread than sprinkler systems [12]. Therefore, a low-pressure water mist system (8 barG) was used in experiment 6. The deluge low-pressure water mist systems provide indirect cooling in the enclosure, despite the water droplets not reaching the battery packs. Water mist nozzles were installed under the ceiling of the test setup, as shown in Figure 10.

Figure 10  Layout of the water mist system (dimensions in millimetres)

The water mist system with a k factor of 23l/min at 1 bar [13] was set up at a water pressure of 8 barG with a supply water flow rate of 400l/min. A more modern EV2 than EV1 was used in this experiment; see Table 1. The car was in bad condition. Therefore, passenger seats were replaced to represent the available combustible material, and the car ceiling was restored. Despite the battery pack being in good condition before ignition, a short circuit could not achieve TR. Therefore, the battery
pack was ignited using a pool fire placed directly under the battery pack. When comparing the battery temperature against the temperatures measured at the ceiling level above the rear end and the front end of the EV (TC105 and TC106) plotted in Figure 11 (a), the smoke layer temperatures increase earlier than the battery enclosure temperature. The reason was that the pool fire consumed other combustibles before the battery pack entered thermal runaway.

![Figure 11](image)

The cooling effect of the water mist was observed in the smoke layer temperatures and in the temperature readings from the surrounding plate thermometers (Figure 11 (b)). All temperatures dropped rapidly directly after activation. The battery compartment temperature also decreased with the activation of the water mist because open windows on the EV allowed the water droplets to reach the battery pack. The temperatures outside the surrounding cars stabilised below 50°C within 2 min after the water mist system was activated.

**CONCLUSIONS**

A series of large-scale tests were performed using a similar methodology to initiate thermal runaway at the battery level. Battery short-circuiting was unsuccessful on four of nine occasions, indicating how different the battery response to identical electrical abuse can be. For the Renault Fluence (EV1), the thermal runaway was successfully initiated via a short circuit in five of the seven tests. Even though similar methods were used every time, each test led to different forms of fire development from non-violent vapour plumes to extremely violent, fast spreading fires, which grew out of control, spreading to neighbouring cars within 2½ min after the short circuit. These observations highlighted the unpredictable nature of EV fires. Therefore, fast response time from the vessel's crew is essential to reduce the potential risks.

Flame spread to adjacent vehicles was also observed during the tests. Initial flame spread to the cars parked on the sides was observed to occur at the window rubber seal on the side facing the EV. Depending on initial fire development, flame spread was observed within 3 minutes during experiment 4 (possibly due to the battery being overcharged) and within 10 minutes during experiment 6.

Both direct and indirect firefighting methods were tested on EV fires. The direct cooling methods in these experiments proved far more efficient regarding water consumption, cooling the battery down and stopping thermal runaway. The indirect techniques cooled the surroundings and may eliminate flame spread to the adjacent cars if deployed early enough. A combination of both types led to the successful extinguishment of the EV fire in all three tests. Prior knowledge about the battery pack's
location could be vital to reaching the battery pack, especially when using direct cooling methods. The challenge of manoeuvring larger firefighting devices within a tightly parked vehicle deck should be considered when selecting equipment. More compact and lighter devices have a clear advantage over larger ones due to the ease of handling. E.g. the E-extinguishing lance, the DAFO/Albero water curtain and the fire blanket had an advantage compared to the other methods. Fast initiation of the fixed firefighting systems already onboard (e.g. sprinklers, water mist) may be one of the best options, as this will likely reduce the risk of fire spread and control the EV fire, however this requires an update of the current procedures, and potentially use of automatically initiated systems rather than the standard manually operated systems.

Re-ignition of the battery pack was observed during experiment 3, a few minutes after the battery was cooled down using manual firefighting. It highlights the importance of safely handling an EV car for an extended period where the battery was involved in a fire.

REFERENCES


Fire Suppression Studies on Large Lithium-ion Batteries

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ABSTRACT

The Electrochemical Safety Research Institute (ESRI) at UL Research Institutes (ULRI) has carried out research on various fire suppressants for lithium-ion battery fires. In these studies, large lithium-ion battery modules used for EV or ESS applications have been taken into thermal runaway. The efficacy of a few fire suppressants have been studied. In addition to this, emission characteristics of lithium-ion cells and batteries have also been studied. The results of our studies will be presented orally.

INTRODUCTION

Lithium-ion batteries are used in a myriad of applications today ranging from consumer electronics to electric vehicles and grid energy storage systems. They are also becoming more prevalent in the aerospace and marine sectors. Globally, several fires and catastrophic events have been observed in the past few years due to lithium-ion batteries. Although the reasons for these events vary quite a bit, the end result is fire and smoke that are accompanied by catastrophic incidents such as injuries, loss of life and/or property.

The ESRI team has been working on studying lithium-ion cell and battery thermal runaway for a long time and as the size of the batteries and consequently the size of the fires and the damage have increased exponentially, it is imperative to find methods to not only mitigate the initiation and propagation of thermal runaway but also understand effective methods to suppress the fires. The added risk with lithium-ion batteries is the propensity to reignite after a fire has been initially subdued. This is because any heat festering within a battery pack can cause re-ignition of the cells and the other components in the battery pack.

EXPERIMENTAL

Studies have been carried out by the ESRI team on very small Li-ion cell modules (Figure 1) with cells in the 9P configuration and with several fire suppressants such as water mist, nitrogen gas at ambient and cold temperatures as well as with a commercial fire suppressant. The angle at which the suppressant is released, the time when it is released and the length of release were all variables used in determining the efficacy of a specific suppressant.

Figure 1. The Lithium-ion 9P modules used to study fire suppression at a very small scale.
Our next effort was to study larger modules that were received from the automotive industry. This work was performed in collaboration with the Automotive Research Association of India (ARAI). Both LFP and NMC modules were studied to understand the efficacy of fire suppressants on the fire and thermal runaway propagation events of these modules. The LFP modules were 12.8 V and 139 Ah (Figure 2a, b) and the NMC modules were 55.5 V and 96 Ah (Figure 2c, d). For the LFP modules, only water as suppressant was studied. For the NMC modules, water, nitrogen gas and a commercial aerosol fire suppressant were tested. Heating tapes were placed on a few cells in the modules to induce thermal runaway. The suppressants were released about 300 mm above the test article and between 4 to 9 minutes after the first observation of thermal runaway. The water spray was released at 30 liters per minute. A 30 L cylinder of nitrogen gas was released and a 250 g aerosol suppressant device was used for the tests. In the case of the nitrogen gas and commercial aerosol suppressant, the modules needed to be immersed in water to stop the reignition and control the fire and propagation. The water runoff or the water used for immersion of the modules from the suppression tests was analyzed to understand its toxicity, and the gases during thermal runaway was analyzed for the concentrations of oxygen, carbon monoxide, carbon dioxide, nitrogen oxides (NO_x) and volatile organic compounds (VOCs).

![Figure 2](image)

*(a) (b) (c) (d)*

*Figure 2. a) LFP module as received; b) LFP module without the cover; c) NMC module; d) NMC module without the cover.*

RESULTS

The summary of the results from the small 9P-cell configuration is given in Table 1.
Table 1. Summary of Fire Suppression Studies for the 9P Li-ion Modules

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$T_{\text{rupture}}$</th>
<th>$T_{\text{thermal runaway}}$</th>
<th>Propagation beyond cell 1</th>
<th>Flame outside box?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>$\sim 133 \degree C$</td>
<td>$\sim 210 \degree C$</td>
<td>Yes (all)</td>
<td>Yes; sustained fire</td>
</tr>
<tr>
<td>Water Mist Early (side)</td>
<td>$\sim 136 \degree C$</td>
<td>$\sim 200 \degree C$</td>
<td>Yes (all)</td>
<td>Yes</td>
</tr>
<tr>
<td>Water Mist Late (side)</td>
<td>$\sim 137 \degree C$</td>
<td>$\sim 197 \degree C$</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Water Mist Early (Overhead)</td>
<td>127</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Water Mist Late (Overhead)</td>
<td>134 °C</td>
<td>$\sim 194 \degree C$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>N$_2$ Early</td>
<td>$\sim 129 \degree C$</td>
<td>$\sim 190 \degree C$</td>
<td>No</td>
<td>Small or no sparks</td>
</tr>
<tr>
<td>N$_2$ Late</td>
<td>$\sim 133 \degree C$</td>
<td>$\sim 200 \degree C$</td>
<td>No</td>
<td>Small or no sparks</td>
</tr>
<tr>
<td>Stat-X Early</td>
<td>$\sim 127 \degree C$</td>
<td>$\sim 215 \degree C$</td>
<td>Yes (all)</td>
<td>Yes – at beginning and end</td>
</tr>
<tr>
<td>Stat-X Late</td>
<td>$\sim 137 \degree C$</td>
<td>$\sim 210 \degree C$</td>
<td>Yes (2)</td>
<td>Small sparks</td>
</tr>
</tbody>
</table>

From the studies on the small 9P modules (Table 1), it was observed that the angle at which the suppressant was sprayed as well as the time lag between the thermal runaway and the suppressant release were critical factors that determined whether the fire was suppressed and if propagation of the fire was observed.

The results of the tests on the larger automotive modules provided some interesting observations. It was observed that the efficacy of a fire suppressant depends not only on the nature of the suppressant but also on the timing and duration of its release. It was observed that in the case of the gas and aerosol suppressants, the suppressant needed to be present in the vicinity of the cells and a certain density of the suppressant was needed to be maintained for a relevant period to allow for the complete cooling of the cells. If that criteria was not met, reignition of the cells was observed and immersion in water was used to completely extinguish the fire as with the nitrogen gas and aerosol suppressant tests. In the case of water, spraying the water was efficient in suppressing the fire and the reignition. A summary of the results is provided in Table 2.

Figure 3 shows a picture of the NMC module after the commercial aerosol fire suppressant ran out and had to be immersed in a water tank to fully suppress the fire.

Table 2. Summary of Fire Suppression Studies for Automotive Li-ion Modules

<table>
<thead>
<tr>
<th>Test Article</th>
<th>Primary suppressant</th>
<th>Secondary suppressant</th>
<th>Events</th>
<th>Re-ignition after primary suppressant</th>
<th>Re-ignition after secondary suppressant</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMC Module</td>
<td>Water spray</td>
<td>-</td>
<td>Yes</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>LFP Module</td>
<td>Water spray</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NMC Module</td>
<td>Nitrogen</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td>N/A</td>
</tr>
<tr>
<td>NMC Module</td>
<td>Commercial Aerosol, Late release</td>
<td>Water spray</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>NMC Module</td>
<td>Commercial Aerosol, Early release</td>
<td>Water spray</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
The gas analysis for the LFP module, which did not experience a visible fire with flames, showed the highest levels of VOCs released and the lowest levels of carbon dioxide. Analysis of the water runoff showed high concentrations of contaminants such as HF, as well as fluorine in the form of fluoride other than HF and very large quantities of Li which indicates the possibility of compounds such as LiF or POF₃ being formed although this was not confirmed. Current studies involve the use of much larger NMC modules as single modules and modules in racks with the use of water and the commercial aerosol suppressant. The details of the results of these studies will also include gas composition analysis and analysis of the water runoff. The data from all these tests will be presented orally at the FIVE 2023 conference.

CONCLUSIONS

Research studies on a few different fire suppressants indicate that a critical density of the suppressant should remain in the vicinity of the hot lithium-ion cells for the relevant period of time in order to not only suppress the initial fire and prevent it from propagating but also prevent reignition of the cells. Although water seems to be the most efficient fire suppressant at this time, more tests on the larger energy storage modules will provide more data in order to make a decision on this.
Study on Water Injection Methodology Applied to Lithium-Ion Battery Fires

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ABSTRACT

This paper presents results from a set of tests demonstrating methods for first responders to inject water into the interior of a thermally damaged Li-ion battery or sub-units thereof. The purpose was to investigate the ability to limit or quench propagation of thermal runaway inside an automotive traction battery despite it being concealed by protective vehicle structures and sheets of metal.

The project behind this paper was a joint effort between different stakeholders such as first responders, actors in the automotive industry, and equipment manufacturers, with the Swedish Civil Contingencies Agency as project leader. The objective was to study the prospect of improving extinguishing operations, reduce the amounts of extinguishing water necessary to stabilize thermally damaged Li-ion battery units. The demonstrated method was intended to enable safer handling after incidents with battery electric vehicles, or E-Vehicles (i.e. vehicles with electrical drivetrain).

The results from the tests applying water injection methodology demonstrates that it can be possible to stop thermal runaway propagation in an automotive traction battery despite it being concealed behind vehicle structures.

KEYWORDS: lithium-ion battery, fire suppression, water injection, thermal runaway, electric vehicle

INTRODUCTION

Fully developed fire propagation in lithium-ion batteries are very rare [1] and an EV fire starts predominantly in the car rather than in the automotive Li-ion battery, also known as traction battery. At the same time, fire and rescue services experiences a lack of practical methods to interrupt thermal runaway and fire of a critically damaged automotive Li-ion battery systems, aka. a traction battery.

The fire suppression tactics implemented today on battery fires focuses on limiting the spread of the fire as well as applying large amounts of water onto the exterior of battery structure or the vehicle to provide cooling and extinguishing flames [2]. As an example, in a Tesla Emergency Response Guide, it is recommended that “copious volumes of water be used to fight a fire” of the battery [3].

One of the most distinctive novelties with traction battery fires is the risk factor of reignition. NTSB has documented several incidents where batteries later reignited after they had experienced a fire [4].

To reduce the risk level for reignition, the interior of the battery and its cells need to come down in temperature. For this purpose, E-Vehicles (i.e. vehicles with electrical drivetrain) that has experienced a severe traffic incident, such as heavy collisions and subsequent fires, are commonly stored in quarantine areas for a period of time as a safety measure. Additionally, the risk for reignition have motivated tow trucks to be escorted by fire trucks, as was the case after a high-speed crash incident in Mountain View, California, March 2018 [4].

The purpose of this project was to demonstrate a method to enable suppression of thermal events inside lithium-ion batteries even when it occurs behind protective vehicle structures. The present study
covered three test series involving fires in five fully charged “device under test” (DUT), i.e. three battery sub-packs, one stand-alone automotive battery pack and one complete E-vehicle. A heating plate, positioned in the middle of a battery module (defined as the “trigger-module”) was heated to cause thermal runaway. This then propagate to neighbouring battery modules. Thereafter, the physical structure of the DUT was breached using the tools tested so that water could be injected to the interior of the battery unit through an ingress hole. The overall results demonstrated that purpose-designed tools can be used to achieve water injection to suppress thermal runaway propagation in a large automotive Li-ion battery system.

In the final test on a burning E-vehicle much less water was used than previously reported in a fire test report by Exponent and The Fire Protection Research Foundation when conducting firefighting with traditional firefighting nozzles onto an un-obscured battery pack burning in a vehicle mock-up that required 442 gallons (1670 litres) of water[2]. However, the five fire tests conducted in this project should be primarily viewed as demonstrations on the methodology to perform water injection with purpose-designed tools onto the battery systems available in these five tests. A larger number of tests on variations of battery designs would be required to fully confirm the observations presented.

In terms of the personal safety of the operators conducting the tests, it was of key importance that before conducting the assigned methodology for water injection to suppress thermal runaway propagation, an on-site risk assessment was carried out in a similar manner as must be done by first responder commanders in a real vehicle fire scenario, with or without traction batteries.

BACKGROUND

The ever so important need for updated routines for first responders, personnel at car workshops and towing operations etc. push for innovative solutions when new technology present novel risk factors. The project behind this paper is another step on the road to enhance public understanding on how concealed battery fires can be suppressed more efficiently. The project was initiated in late 2021 by the Swedish Civil Contingencies Agency (MSB) whom, for more than a decade, has followed up on E-vehicle and traction battery safety and findings presented in research literature. This has been achieved by MSB projects and studies, and through interactions with the international community of first responders. [5] [6] Together with domestic partners within industry and the first responders’ community, and international partners such as CTIF, MSB continuously conduct efforts to collate and communicate the latest understanding on battery safety and how resources for civil contingencies should best act in the event of E-vehicle incidents in traffic, workshops and while parked, etc. As part of the project, MSB led a study on three series of tests on fully charged traction batteries and subunits thereof in the month of April 2022. The purpose was to demonstrate how a methodology for water injection could be used by first responders when an automotive battery experiences a fire that need to be quenched.

Previous studies have validated that the most effective suppression of a thermally propagating Li-ion battery is achieved when emergency coolant can be applied as close to the core of the heat source inside the battery and its cells, as possible [7] [8] . If only focusing on the cooling ability it is evident that water offer the highest specific heat capacity among single phase coolants. When adding its high heat of vaporization, the accumulated cooling ability of water further exceeds other coolants. Charlotte Roe et al. investigated immersion cooling for Li-ion batteries in 2022 and compared water-glycol with other single-phase coolant liquids and presented data confirming the outstanding cooling ability of water [9]. Furthermore, when choosing water as the fire suppression agent there are considerations on using fresh water with normal conductivity (40-800 μS/cm) or higher conductivity, e.g. salt water (55’000 μS/cm) [10]. One argument for using the former is previous test results from battery immersion tests showing little or no discharge when a 400 V battery pack was fully immersed into a freshwater bath for about 30 minutes [11] Discussions concerning discharging damaged batteries using salt water should be dismissed since it cannot be achieved at the site of the incident in a safe manner. The time it takes to fully discharge a battery varies too much between battery designs.
METHOD

The tests were conducted as a demonstrative study where the first series of tests implemented three different ways to ingress into a battery unit to inject water by an external supply. The delimitation of this approach was that the method should be a practically possible tactic of intervention after an on-site risk assessment by first responder commander who deems it to be necessary to conduct water injection to cool the battery interior. The second test series intended to observe the consequences of injecting water into a full-size battery pack undergoing thermal runaway propagation. The third test series studied the feasibility of conducting water injection safely into the interior of a traction battery inside a complete E-vehicle. The team conducting the test decided to use fresh water without additives for all tests, since water is the most readily available fire suppression medium for first responders.

The device under test (DUT) in all tests constituted of battery units with Li-ion battery cells containing cathode material with at most 60% Nickel contents. Electrodes with higher level of Ni and more energy dense materials are more reactive and acquires additional investigation beyond this project. Both prismatic and pouch cells were present in the battery units, but not cylindrical cells.

The level of SOC was set at 100% for all tests since it has long been known that higher charging level cause the electrode materials of Li-ion batteries to be more chemically reactive [12] [13].

In order to facilitate the initiation of thermal runaway and propagation within the DUT the battery units had been modified to exclude some safe-guard systems. Based on the accumulated experience within the project group it was concluded that provoking thermal propagation would otherwise be much too hard. The modifications had not impact on the cooling effect of the water injected.

The tools used to achieve penetration of the DUT for water injection and the equipment of the operators underwent a risk analysis specifically aimed to the conditions encountered during the tests. In two of the tests, tools that were purpose-designed for the task were used, while the third method relied on a set of tools commonly available in fire trucks (Figure 1). Full first responder PPE was used.

![Figure 1. (a) Cutting extinguisher (b) Insulated penetrating lance (c) An axe and a pipe with hose](image)

The cutting extinguisher (a) provided 58 l/min; while the insulated penetrating lance (b) provided 25 l/min flow of water; and the set of tools (c) provided 75 l/min.

The tests were conducted in a sequence of three test series:

i. Three stand-alone subpacks á 26 kWh
   - 100% SOC, four battery modules á 24 Volt, 6.54 kWh
ii. One stand-alone traction battery á 67 kWh
   - 100% SOC, twenty-four battery modules á 14.8 Volt, 2.8 kWh
iii. One full-size E-vehicle with traction battery á 75 kWh
   - 100% SOC, twenty-seven battery modules á 14.8 Volt, 2.8 kWh
Each test started by raising the temperature in the mid-section inside one or two battery modules (the “trigger-module”) of the DUT by means of a pre-test installed heating plate. This caused thermal runaway to start propagating between cells and battery modules. For all DUTs in all test series, the progression of propagation was monitored using thermocouples and an IR-heat camera.

In the first test series (i) water injection actions intended to begin when measured heat progression crossed over from the first to any neighboring battery module. In the second (ii) and third (iii) tests series, a timer started at the first indication of thermal propagation, and after 15 minutes water injection practice was performed. The period of 15 minutes was implemented to simulate the time for first responders to arrive at a scene of a vehicle fire.

Fire suppression actions were terminated when visual inspection indicated that thermal propagation had stopped. The criteria were that the IR-heat camera (aka, TIC-device) only showed stable temperatures below 50 °C on the surfaces of the DUT, and the rate of gas generation, flames and sizzling sounds were considered to be fading.

After a test was concluded an observation period of 15 minutes followed before the DUT were moved to a quarantine location. Standalone DUTs were quarantined for three days, while complete E-vehicle was quarantined for two days before visual inspection and voltage monitoring were conducted.

**Test Series i – Study on tools for water injection**

Purpose of this test series was to try out the three sets of tools that were used to inject water into the DUT and how safely it could be achieved, as well as demonstrate how the proposed method could counteract thermal runaway propagation in the battery unit selected.

Each subpack was equipped with a heating plate inside the “trigger-module” (marked as no.4 in Figure 2), and thermocouples to measure temperature for on-site monitoring of the progression of thermal propagation. Sensor 1. and 3. measured the temperature in the voids between modules, while sensor 2. 5. 6. and 7. measured surface temperatures.

![Figure 2](image)

*Figure 2 A heating plate was installed inside battery module marked 4. The DUT was equipped with Temperature sensors for on-site monitoring of the progression of thermal propagation. Lifting the complete subpack was done using a forklift.*

**Test Series ii – Study on conventional tools applied on battery pack**

The purpose of this test was to observe how the set of traditional tools (see Figure 1 (c)) available in fire trucks could be used on a full sized automotive stand-alone battery pack that experienced thermal propagation, as well as demonstrate how the proposed method could counteract thermal runaway propagation in the battery unit selected.
The battery pack was equipped with thermocouples (see Figure 3 and sensors 1-8) to monitor the progression of thermal propagation between battery modules inside the DUT. Two of the battery modules were equipped with heating plates but only battery module B was initially used as trigger-module. Although indications of thermal propagation were seen in the proximity of module B at first, the progression seemed to cease, and therefore trigger-module A was also heated until thermal propagation could be confirmed. Hence, the water injection practice was applied only after another 15 minutes based on the progression monitored in the proximity of module A. Consequently, the set of traditional tools (see Figure 1 (c)) to achieve water injection were applied on module A rather than the initial trigger-module B.

![Figure 3 The modules A and B were designed to act as trigger-modules by means of a heating plate. Thermocouples were installed in locations 1 to 8.](image)

Test Series iii – Study on complete methodology for suppression of battery fire
The purpose of this test series was to study how a purpose-designed tool could be safely applied to a complete E-vehicle experiencing ongoing thermal propagation inside its floor mounted battery pack, as well as demonstrate how the proposed method could counteract thermal runaway propagation in the battery unit selected.

The battery pack was equipped with the same number of thermocouples and heating plates as in Test Series ii and in the same locations. One difference was the additional three battery modules mounted in the tunnel section of the complete E-vehicle used for this test, see Figure 4.

![Figure 4 The battery pack was mounted under the floor of a complete E-vehicle in Test Series iii.](image)

Because the cutting extinguisher is a multipurpose tool it was chosen to be used in this test on the complete E-vehicle with a fire starting inside the battery pack.
The test started by overheating trigger-module B, and a 15-minute timer started when thermal propagation could be monitored inside the battery pack. After those 15 minutes battery fire had spread to the cabin of the vehicle. Therefore, the cutting extinguisher was first used to attack the flames inside the cabin from a safe distance. Thereafter, the backdoor was opened, and a fireman used the IR-heat camera to scan the vehicle’s interior for hot-spots. The vehicle’s Emergency Response Guide (ERG) was used for guidance to identify which surfaces were located close to the battery pack. To ensure better visibility and clearance from gases the firefighting personnel only worked from one side of the vehicle with the assistance of a PPV-fan (Positive Pressure Ventilation) to force all fire gases in the opposite direction. In order not to engage inside the vehicle and stay clear of the vehicle structure, an extension was added to the cutting extinguisher. Thereby its front piece nozzle could be applied directly onto the surface of the middle of the cabin floor structure guided by the heat signature detected by the IR-heat camera indicating hot-spots from the underlying battery pack. Then the cutting extinguisher could cut its way through all sheet metals that otherwise makes it impossible to inject water into the interior of the battery pack. All the time, the operator of the cutting extinguisher was supported by another fireman providing personal protection with a firefighting nozzle.

The test was terminated based on the same criteria as for the previous test series when visual inspection indicated no continuing thermal propagation and IR-camera temperature signatures were below 50 °C. After the observation period of 15 minutes the vehicle carcass was lifted 1 meter by a forklift and dropped a couple times to simulate the potential roughness of handling of an E-vehicle that has experienced a battery fire. However, no reignition occurred at that point or even later while the carcass was placed in a quarantine location for two days.

RESULTS

After each test, all battery modules of each DUT were checked for remaining voltage to identify the presence of stranded energy or residual energy. Those voltage measurements were conducted after the period of quarantine, i.e. three days after Test Series i and Test Series ii, and two days after Test Series iii.

A key factor was the assumption that in the extreme case of battery modules not being harmed, their voltage would stay intact; while the other extreme case would be that a completely burned-out battery module would show no residual voltage. Thereby the remaining voltage of individual battery modules were considered an indication of the extent of damage caused by the thermal runaway propagation.

**Test Series i (a) – Water injection using cutting extinguisher**

Visual inspection and voltage measurements conducted after the DUT had been quarantined for three days, demonstrated that water injection using a cutting extinguisher managed to provide enough cooling to the thermally propagating trigger-module and its neighbouring battery module to limit the spread to the remaining two battery module. The large surface to surface interphase between the two modules at the left of Figure 5 was expected to contribute to the direction of thermal runaway propagation. Conversely, the smaller surface to surface interphase between the trigger module and the next one to the right was expected to contribute to limitation of thermal runaway propagation in that direction. It was concluded that the flow of cooling water in the voids of the battery sub-pack not only suppressed the ongoing thermal propagation but also prevented further spread of the thermal propagation from the left side of the sub-pack to its modules on the right.
Test Series i (b) – Water injection using insulated penetrating lance
Voltage measurements and visual inspection performed on the DUT after it had been quarantined demonstrated that the insulated penetrating lance managed to provide sufficient amount of cooling fresh water to the trigger-module and its surrounding voids and neighbouring battery modules to prevent further spread of thermal propagation. In this test series only the trigger-module experienced loss in voltage. However, any conclusions on why thermal propagation did not manage to spread to the battery module below it was not formulated. Nevertheless, it can be noted that the ingress position for water injection differed between the test using tool (a) and tool (b).

Test Series i (c) – Water injection using axe and a pipe connected to hose
As for the two previous test series with purpose-design tools, the method of using an axe to create an ingression hole and then positioning a pipe with a hose for water injection into the interior of the battery demonstrated promising results by visual inspection and voltage measurements. In this test the thermal propagation managed to spread to the long-side neighbouring battery module and the voltage drop was larger for the two battery modules involved. The point of ingression was chosen using an IR-heat camera to identify based on the hottest spot on the sub-pack. An observable difference with performing ingestion with an axe were the intensity of the jet-flames emerging until the supply of water was connected and flooding could commence. This stood in contrast to the two purpose-designed tools, since they could supply flooding water immediately when ingestion hole was created.
Test Series ii – Study on conventional tools applied on a stand-alone battery pack

Trigger-module A initiated thermal runaway. 15 minutes after the first sign of thermal runaway propagation by thermocouples and sounds of popping and sizzling cells, the set of traditional tools (see Figure 1 (c)) was applied to area where the IR-heat camera indicated to be the hottest spot. At the moment when the axe penetrated the casing of the DUT, cascading jet-flames were released through that ingression hole. As soon as water was injected, using a pipe and a hose, the flames subsided, and the continuing flooding of water seemed to overcome the generation of heat from thermal runaway. The IR-heat camera showed how surface temperatures dropped and eventually reached below 50 °C, steadily decreasing. At that point, the test was concluded as done. Visual inspection and voltage monitoring demonstrated that thermal propagation had spread throughout the section with 12 battery modules, i.e. including trigger-module A and B. Of those 12 modules five contained residual energy.

Test Series iii – Study on complete methodology for suppression of battery fire

This test was a demonstration on how water injection could be applied in the event of thermal propagation happening to a battery pack mounted in a conventional E-vehicle. Applying water injection should be considered only after a first responder commander deems it to be necessary based on an on-site assessment. The test was initiated by overheating trigger-module B. The first sign of thermal propagation was soon seen in terms of smoke and within three minutes first visible flames appeared. At 15 minutes, the vehicle cabin was engulfed by fire and fire suppression actions was initiated by two firemen. The first one operated a cutting extinguisher and the second operated a
firefighting nozzle with intention to provide personal protection to his colleague, and an IR-heat camera to identify the hottest spots.

Figure 9 The use of this purpose-designed tool permits the operator to act from a safer distance when establishing an ingression hole for water injection. This picture was taken at a similar test in a previous project.

The procedure was conducted as presented in Method above, and the position of ingestion corresponded to the battery module number 16, see Figure 10. The period for fire suppression action was 10 minutes – from the first approach with the cutting extinguisher to the conclusion of the fire suppression action when temperature all surface temperatures had fallen below 50 °C, shown by the IR-heat camera. The extinguishing water consumption was calculated and amounted to a total of approximately 750 liters of which 240 liter was used by the cutting extinguisher for water injection into the battery pack. The cutting extinguisher was actively used for about 5 minutes and the supporting firefighting nozzle was actively used for about 4 minutes, sometimes simultaneously.

After two days of quarantine, the visual inspection and voltage measurements of the battery pack (removed from the E-vehicle) demonstrated that the injected water had spread through the voids of the battery pack and provided cooling water that managed to constraint the thermal propagation to such an extent that 17 of the battery modules still presented between 13 and 16 V as shown in Figure 10. Only five battery modules were completely drained of residual energy, while another five presented residual energy with voltage ranging from 3 to 10 V.

Figure 10 Out of 27 battery modules, 17 presented a voltage at 13 to 16 V after post-test quarantine. Five modules were completely drained, while another five carried residual energy corresponding to voltage between 3 to 10 V. The trigger-modules A and B were overheated when the test started. Number 16 was the battery module were the cutting extinguisher made ingestion and injected water.
DISCUSSION

The traction battery in an electric vehicle has a very high level of safety. Road vehicles are subject to regulations and international standards. These requirements and standards include isolation values, physical access to electrically conductive components, sealing requirements and shutdown of the high-voltage system in the event of a crash. UN vehicle legislation are type-approval requirements that must be met for a vehicle model to be sold on the market and are updated as technology evolves and based on needs identified in the market. For E-vehicles, there are specific requirements for electrical system and battery safety (e.g. ECE R100). They cover mechanical abuse such as vibration and crash tests, various types of electrical failure and thermal exposure, and various environmental factors, such as humidity and heat exposure onto the battery.

The physical testing conducted in the project was focused on suppressing fire in an E-vehicle by means of water injection into the thermally failing automotive traction battery. This methodology intends to provide cooling water to the voids inside the battery, preferably as close to the failing battery cells as possible. Before such actions can be implemented, the first responder commander acting on-site must assess the often complex situation. That should include to consider available indications whether the vehicle’s traction battery is indeed involved in the vehicle fire or not. Examples of such indications could be the presence of jet-flames as pressurized gases finds their way out of a burning battery, and smoke characteristics that deviates from what is experienced in a regular vehicle fire. There may be an opportunity to act in accordance with traditional routines before the battery pack becomes engaged in the fire, or possibility to permit the vehicle to burn out without any direct intervention if the surrounding circumstances allow. On the other hand, the option of water injection offers an opportunity to possibly reduce the time during which the burning carcass obstruct important infrastructure or present a hazard in rather confined space, e.g. indoor parking area. In addition to assessing the suspected occurrence of a battery fire, the tools used in these types of firefighting interventions should be designed for the intended usage and approved by the employer. Hence, the third set of tools cannot be recommended by the project behind this paper.

Visual inspection and voltage measurement relied on the assumption that damaged battery modules would be drained of their electrical energy to a varying degree of remaining voltage. This is a rough estimation, but it was concluded as sufficient for the type of demonstrative test series conducted. However, the extent to which the thermal propagation has progressed inside the DUTs before intervention with water injection is applied will influence the volumes of cooling water needed to quench ongoing thermal runaway and propagation inside the battery.

The key threshold to start water injection in Test Series i was how thermocouples inside the battery unit indicated the propagation of thermal runaway within the trigger-module and neighboring modules. The key threshold to start water injection in Test Series ii and Test Series iii was the simulated timeframe of 15 minutes for first responders to arrive at the scene of a vehicle fire. Hence, the two latter test series focused on the first responders’ timeframe to arrive at the scene, while the first test series focused on the level of thermal runaway propagation inside the DUTs by monitoring temperature profiles. The thermocouples used for this were installed for that purpose only and the temperature profiles acquired has not been used for post-test analysis.

All the three test series presented demonstrations exemplifying promising signs of quenching of Li-ion battery thermal runaway propagation by means of water injection. They all presented the opportunity that firefighting professionals could utilize water injection for potentially more effective suppression of thermally propagating Li-ion battery units despite them being obscured by one or more layers of sheet metal structures. The success for water injection will depend on the opportunity for the injected flow to spread through the voids of the battery system, and the results should be considered as limited to the physical set-up in these five demonstration tests.

In Test Series iii a complete E-vehicle fire was concluded as suppressed after 10 minutes of supplying a total of 750 liters of water of which only 240 liters used by the cutting extinguisher for water.
injection into the battery pack. The test team noted that this was much less than the 442 gallons (1670 liter) required to extinguish an un-obscured battery pack fire inside a mockup E-vehicle test conducted by Exponent and The Fire Protection Research Foundation, reported in 2013 [2]. It may also contrast the recommendations by Tesla Emergency Response Guide to apply “copious volumes of water” [3]. In comparison, the key change in methodology is the ability to use purpose-designed tools to provide means of ingression of water to the interior voids of an automotive battery pack despite it being obscured by vehicle structures. As demonstrated in Test Series ii creating the ingression hole may very well cause the initiation of thermal runaway in an undamaged battery module. Therefore, carefully evaluated routines need to be further developed by means of follow-up research, studies and tests inspired by the demonstrations presented in this paper.

CONCLUSIONS

The test team concluded that the results of all the five tests were very promising in terms of limiting the propagation of thermal runaway.

When using purpose-designed tools and fresh water, the demonstrations presented:

- good ability to safely inject water to flood the interior voids of the DUTs
- much less volumes of water than suggested by previous findings
- shortened duration of the fire suppression action
- no reignition of anyone of the tested battery units

It was observed that when ingression hole was created cascading flames could be emitted through the hole. Using purpose-designed tools, ingression was created at the same time as water was injected. This quenched the jet-flames immediately. As a contrast, when using traditional firefighting tools (exemplified in Figure 1 (c)) it took some additional actions to connect the water supply. Consequently, on basis of the conditions under which the three test series have been conducted, the test-team cannot recommend methods using tools that are not purpose-designed since such method is considered to be less safe for the operator.

Furthermore, the test-team concluded that although using IR-heat camera cannot fully distinguish the precise location of the core thermal failure inside the battery unit, it was the best available visual aid for the operator together with the information provided by the vehicle’s Emergency Response Guide. It provided the operator of the purpose-designed tool a better ability to inject water in the proximity of the core heat source inside the battery unit. With sufficient voids inside the battery unit water could spread and sufficiently quench the ongoing thermal runaway even if the ingression hole was not perfectly positioned.

Water injection methods shall be used only when the fire commander is convinced that there is a fire in the battery pack, the fire in the battery pack will not self-extinguish and such method can be used in a safe manner. The tools used should be purpose-designed and they, together with the method, need to be approved by the employer.

REFERENCES


Li-ion battery full scale thermal runaway test: environmental and personnel exposure influence in case of rescue operations

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ABSTRACT

Enhancing safety for emergency responders at electric vehicle traction battery fires is a key priority for the Public Authorities and the Manufacturers at a global level. Electrified vehicles are part of the global transport decarbonization strategies and require the development of new and specific skills and knowledge among the different stakeholders.

Lithium-ion batteries supplying energy to different EVs are designed satisfying stringent safety criteria and respecting specific Regulations, Codes and Standards, however, on the occasions an incident occurs, it presents a different challenge for rescue services.

In general, Li-ion battery thermal runaway is a critical safety issue for any electric vehicle. The ECE Regulation no. 100 in the revision 3 requires an advanced warning 5 minutes prior to the evolution of hazardous conditions for the vehicle occupants caused by thermal runaway. To achieve this 5 min. advanced warning, a robust and sensitive detection methodology is required followed by an appropriate management of the potential fire event evolution.

This paper presents a full view of the research activity conducted in an open environment with the scope to evaluate the gaseous emissions impact and the contamination of the residual water after the fire extinguishing operation, as well as the exposure for firefighters, during and after the fire as a result of a thermal runaway initiation on a fully charged lithium-ion battery pack with a nominal capacity of 37 kWh based on NCM pouch cells technology.

KEYWORDS: rescue services, Li-Ion batteries, thermal runaway, gaseous emissions, extinguishing

INTRODUCTION

The experimentation was shaped to evaluate and assess the behavior and the impact of a complete and fully charged battery in a controlled testing facility to support the rescue services in the management of a similar event. For the fire brigade the main goals were to define the safety measures, the tactics and management of the battery fire extinguishing procedures. The trial challenge was to go beyond the test evidence of the more common test conducted at cell and/or module level in a lab environment. The testing facility was selected to evaluate the interaction in case of a battery thermal runaway event with the surrounding environment common in case of an on-road accident scenario.

The paper also includes a section to display the extinguishing performance of a battery pack equipped with a so-called fireman access able to improve the cooling capabilities and the consequent reduction of the overall amount of the extinguishing agents.
TESTING FACILITY

The test was performed in a dedicated open area inside the Fire Station in Susa (Turin-Italy) within the Italian National Fire Corps – Turin Provincial Dept. The testing site is located on top of a hill area and it’s away from the residential zone (Figure 1).

![Figure 1 Testing facility - Fire Station in Susa (Turin – Italy)](image)

EXPERIMENTAL SET-UP

Device Under Test (DUT)
The Device Under Test (DUT) is the battery pack specified in Table 1. The battery pack has been designed with a vertical melting fuse, also known as fireman access, on the external side of the lateral wall between the HV connectors (out of the frame rails when it’s installed on the vehicle). The melting fuse size is 50x40 mm.

<table>
<thead>
<tr>
<th>Battery pack specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell level</strong></td>
</tr>
<tr>
<td>Rated Capacity</td>
</tr>
<tr>
<td>Rated voltage</td>
</tr>
<tr>
<td>Chemistry</td>
</tr>
<tr>
<td>Format</td>
</tr>
<tr>
<td>Energy density</td>
</tr>
<tr>
<td>Operating voltage</td>
</tr>
<tr>
<td><strong>Pack level</strong></td>
</tr>
<tr>
<td>Group mode</td>
</tr>
<tr>
<td>Modular group</td>
</tr>
<tr>
<td>Module configuration</td>
</tr>
<tr>
<td>Rated Capacity</td>
</tr>
<tr>
<td>Rated energy</td>
</tr>
<tr>
<td>Nominal operating voltage</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Package dimension</td>
</tr>
<tr>
<td>System weight</td>
</tr>
<tr>
<td>System energy density</td>
</tr>
<tr>
<td><strong>Fire initiation method</strong></td>
</tr>
<tr>
<td>The thermal runaway initiation has been originated by thermal propagation replacing one standard module with a trigger module.</td>
</tr>
</tbody>
</table>
The wiring harness incorporates the temperature sensors, and the power supply of the heater is passed through the sealing. Therefore, a part of the sealing foam has been cut out and the break-through spot has been sealed with a specific paste according to best practices.

The battery was assembled with a wiring harness for 15 modules. Therefore, one module (16 modules in total) is not connected to the wiring harness and data from this module was not readable, but fully charged. The trigger module was sensorized, and its data can be seen on the CANs communication bus.

**TEST DESCRIPTION**

A preliminary phase was dedicated to the set-up of the testing environment through the following tasks:

- battery pack positioning inside a container to collect the full extinguishing liquid
- preparation of the fire extinguishing Team and the two high pressure water lines
- electrical connection of the thermocouple to the datalogger
- position of a petrol genset set-up (220 V a.c.) and the two powerlines 12V d.c. through the dedicated power supply
- CAN signals recording through the CANcase Vector®
- Set-up of the instrumentation for the gas and extinguishing liquid sampling
- Preparation of two extinguishing water lines and firefighter Teams adoption of the Personal Protective Equipment (PPE).

After the preparation stage on the outdoor testing area, the effective test was started at 12:22 through the activation of the power supply of the electrical heater inside the battery module. The 220 V a.c. of the heater was deactivated at 12:30 when the first smoke release from the vent valve was visually detected. The activation of the rescue teams was delayed approx. 20 minutes to simulate a usual time lag from the emergency call activation to the firefighter arrival on the accident site. When the extinguishing operation was launched, the thermal runaway propagation was extended to the full pack showing visible and intense flame from both the vent valve and the melting fuse port. Table 2 shows the temporal sequence of events registered during the test starting from the activation of the heater inside the trigger module.

**Table 2  Timetable of the main events**

<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power-up of the thermal heater inside the battery module</td>
<td>12:22</td>
</tr>
<tr>
<td>First gas and smoke release from the venting valve (vent)</td>
<td>12:30</td>
</tr>
<tr>
<td>Initial visible flames and simultaneous end stop transmission from the battery</td>
<td>12:34</td>
</tr>
<tr>
<td>Start of the offensive fire attack through</td>
<td>12:50</td>
</tr>
<tr>
<td>End of extinguishing operation and battery pack monitoring (visual + thermos-camera)</td>
<td>13:03</td>
</tr>
<tr>
<td>Extinguishing water samples collection</td>
<td>13:00 ÷ 13:38</td>
</tr>
<tr>
<td>Draining with F500 extinguishing agent (50% concentration) through melting fuse and venting valve port</td>
<td>13:40 ÷ 13:41</td>
</tr>
</tbody>
</table>

**EXTINGUISHMENT ACCIDENT MANAGEMENT**

An offensive fire attack approach was adopted to extinguish the fire induced as a result of the battery cells thermal runaway. The fire attack strategy was implemented through two hose lines moved forward by two firefighters for each line, also known as the binomial method. The direct water jet, from one of the two hoses, was directed toward the melting fuse port on the battery pack. The binomial fire attack, coordinated by the Incident Commander, involved 4 firefighters in total (2 for each Team) with the following roles:

- exploration and attack (Team 1)
- water supply, protection water shield during the first approach and support (Team 2)
Team 1 started the offensive fire attack through a lance with adjustable flow rates set to 300 l/min. Then, after having identified the position of the melting fuse, the water flow rate was reduced to 150 l/min. to facilitate the battery flooding through the melting fuse hole. In parallel, Team 2 supported Team 1 in the approach phase through a wide spray jet (thermal shield) to protect both Teams from the smoke released during the movement versus the battery pack on fire. Then, Team 2 remained in standby. The overall water consumption was of 2500 liters: 1700 liters for offensive fire attack (extinguishing and battery cooling) and 800 liters for the defensive attack (wide spray jet) and hydraulic ventilation. After 5÷7 minutes from the first attack, a reduction of the fire dynamic was observed, but the interruption of the water injection emphasized a sudden temperature increase in the battery pack detected through the thermo-camera monitoring. Consequently, the Incident Commander decided to restart the water injection inside the battery pack. The complete fire extinguishing operation was achieved in approximately 15 minutes.

CHEMICAL SAFETY FOR FIRST RESPONDERS

The scenario was designed to reproduce as faithfully as possible, within the limits of the geography of the site and the arrangement of the battery itself, a real intervention by a team of firefighters with standard equipment.

To this end, the wind direction and the standard weather conditions in the area were checked, sensors and measuring instruments were positioned downwind of the battery, where the personnel in charge of the extinction approached upwind. The fire brigade involved in the extinguishing was equipped with full bunker gear, combined with SCBA and a 300 bar composite air cylinder.

Particular attention was paid to the first approach to the battery, carried out with the use of DMR nozzles to obtain the maximum cooling effect using water fractionated in tiny droplets.

Personnel outside the extinguishing maneuver operated at a safe distance with filtering masks and ABEK/NBCR filters. Finally, for the scenario monitoring, the CBRN Fire Brigade Unit was deployed on site in the remote case of undesirable developments with the release of toxic gases in such quantities as to require additional personal and collective protection equipment.

DATA ANALYSIS AND OBSERVATIONS

Thermal Imaging monitoring

During the test, the battery pack was also monitored with the use of thermal cameras, one in a fixed position and another on field operated by a firefighter. Since the measurement is based on the infrared energy emitted by the objects, the recorded temperatures will not be mentioned because of the impossibility to determine the emitting material. On the contrary, the observation of thermo-graphic video, and the comparison between what was taken and the general timescale, has allowed to highlight details invisible to a traditional shooting technology and to the human eye itself. The instruments used (Figure 2) were equipped with a MOS sensor capable of a resolution of 394x299 pixels, standing in position about 10 meters from the fire.

*Figure 2  Thermal Imaging Camera FLIR E54*
The time scale shows the battery pack firing at 12:35 (Figure 3). Already at 12:44 there was a copious release of vapors, particularly appreciable in the thermographic image. The emissions decrease almost disappears two minutes later, at 12:46 (Figure 3) probably due a temporary oxygen debt.

Figure 3 Thermal image after the thermal runaway initiation

In the next three minutes the situation evolves quickly, and the thermal runaway becomes more and more obvious. At 12:47 hot vapors are already visible that drag with itself splinters of material evidently at high temperature, and within a few seconds the flames flare up (Figure 4 and Figure 5).

Figure 4 Thermal image showing splinters projected (at 12:47) and first flames erupt (+10s)

Figure 5 Thermal image showing splinters projected (+67s) and battery pack totally engulfed in flames (+130s)
Interestingly, the expulsion of incandescent fragments continues until 12:53, and the energy with which they are thrown is clearly visible. Incandescent fragments pose a risk both to extinguishing personnel and to the possible spread of fire in the presence of flammable material in the vicinity. The extinguishing phase, started at 12:50 (Figure 6), clearly highlights the effectiveness of the technical solutions aimed at making possible the addressing of the extinguishing agent (water in this case) directly inside the battery pack.

Figure 6  Thermal image showing extinguishing phase (at 12:52) and fire under control (at 12:57)

Temperature and volume of the flames, after an initial peak, decrease rapidly, and after only 7 minutes, at 12:57 (Figure 6), the fire was under control. It is known that water is an extinguishing agent that can be used on lithium batteries, but in large quantities and with difficulty in penetrating the structure effectively. The situation remains stable even during the subsequent sampling and final extinguishing operations, performed with the addition of F500 micellar encapsulator agent, which allowed a rapid decrease in heat within about 15 minutes.

The penetration capacity of water mixed with the extinguishing agent F500 and its effectiveness on lithium battery fires makes it even more interesting to "inject" the mix inside the battery itself in case of fire. The F500 has been applied to get the battery pack inertization, consequently to the extinguishing phase with water. After the injection inside the pack the temperature detected through the thermal image was stable at 94°C for many minutes. Unfortunately, it was not possible to compare the full F500 extinguishing performance versus to water without any additive due to the availability of only one DUT.

Chemical analysis on emitted gases and extinguishing liquid

The set of chemical analysis carried out by the Department of Chemistry, Università degli Studi di Torino, aimed at the identification of the emissions released during the Li-ion battery fire test. The tasks performed are:

1) Sampling of the air during fire test
2) Sampling of the water used to extinguish the fire (total amount of water used 1.2 m³).

The analysis of air and water samples allowed the identification of the main volatile (VOC) and semi-volatile (SVOC) organic compounds released in the air and leached by the water, as well as of the inorganic contaminants leached in the water.

Sample preparation to evaluate volatiles organic molecules VOC in the emitted gases

The air samples taken during the fire test were as follows:

1) Background air before battery fire
2) SAMPLE 1, SAMPLE 2 AND SAMPLE 3 sequentially from battery fire start and before extinguishment collected, about 8 minutes apart (Figure 7 and Table 3). The samples were taken with 3 liters Tedlar® bags at a distance of about 3 meters from the battery under south side fire test. Determination of volatile organic compound content by modified USEPA TO-15 method was performed on these samples. The modification consists of using tedlar bags for air sampling instead of Silcosteel®-lined canisters. Through the aid of a collection cone, placed on the south side of the battery under test,
smoke was conveyed through a steel pipe to a sampling case depressurized by a vacuum pump at a flow rate of 600ml/min. Each bag was thus filled in 5 minutes.

Determination of volatile organic compounds (VOCs) was carried out according to USEPA method TO-15, which involves gas sampling in evacuated canisters made of Silcosteel® (Restek) or Silonite™ (Entech), cryo-concentration by "microscale purge and trap" for removal of moisture and CO₂, then analysis of VOCs by gas chromatography coupled with mass spectrometry. Method TO-15 was developed for the determination of trace VOCs (ppbv-pptv) in air samples, including polar VOCs sampling done in tedlar bags.

The analysis was carried out with a GC-MS system consisting of an Agilent mod. 6890 gas chromatograph and a mod. 5973 quadrupole mass analyzer, equipped with a mod. 7000 cryogenic gas preconcentration system (Entech) and a CP5Sil capillary gas chromatography column of 60 m, 0.32 mm inner diameter and with a stationary phase thickness of 1 mm. Calibration was carried out with TO-15 Restek standards with nominal concentration of one ppmv (BTEX, styrene, trimethylbenzenes, bromomethane) and with Ethyl methyl carbonate standard 1 ppmv prepared in canister and appropriately diluted. For these compounds the extended relative uncertainty is 5%. For identified compounds for which no standard is available, concentrations were determined using response factors of similar compounds. In this case the relative expanded uncertainty is 30%.

The background air sample contained negligible concentrations of VOCs compared to the three samples. Propane, isobutane and toluene were found to be present at concentrations below 0.1 ppbv, negligible concentration levels compared to those found in the air samples taken during the fire. The unidentified compounds represent less than 5% of the total mass of VOCs in the samples. The three air samples are characterized by the presence of similar compounds, but in different proportions. The concentration of VOCs is obviously also affected by the wind direction during sampling.

The following conclusions can be drawn:
1) Toxic VOC concentrations always remain below 1 ppmv and probably none exceed the respective TLV-TWAs. This is also due to conducting the test in an outdoor environment.
2) The sample containing the largest mass of VOCs is SAMPLE 3.
3) The classes of compounds present in the highest concentration are:
   ● Saturated aliphatic and branched olefinic hydrocarbons
   ● Aromatics, particularly toluene and styrene
   ● Cyclic siloxanes
4) The compounds in the saturated aliphatic and olefinic hydrocarbons category with branching are mostly derived from the thermal decomposition of polypropylene or ethylene-propylene. These compounds are contained in all samples, although SAMPLE 1 contains proportionately less of them.
5) All samples contain benzene, toluene, ethyl benzene and styrene. These compounds may result from the thermal decomposition of polystyrene, acrylonitrile/styrene copolymers, or ABS. The sample that contains the largest amounts of these is SAMPLE 3.
6) All samples contain volatile cyclic silicones, especially SAMPLE 3. These may result from thermal decomposition of silicone oils or rubbers.
7) The three samples contain significant amounts of ethyl methyl carbonate (especially SAMPLE 1). In SAMPLE 2, it is the VOC present in the highest concentration; in the other two, however, it is among the compounds present at higher concentration levels. Neither ethylene carbonate nor diethyl carbonate were detected.
8) SAMPLE 2 and SAMPLE 5 contain relatively high amounts of ethanol, which may result from the decomposition of ethyl methyl carbonate.
9) Traces of brominated organic compounds were detected in samples 3 and 5.
10) SAMPLE 2 contains relatively high amounts of acetaldehyde (not detectable in the other two samples).
11) Carbonyl sulfide (COS), which results from the decomposition of sulfur compounds, or the reaction below 900 °C of CO and S, is found in SAMPLE 1.
12) SAMPLE 3 contains traces of organic nitriles, especially acetonitrile and acrylonitrile.
Table 3  Sum of identified compound concentrations by class of chemical compounds in ppmv.

<table>
<thead>
<tr>
<th>CLASSIFICATION OF ORGANIC MOLECULES [ppmv]</th>
<th>SAMPLE 1 (8 minutes)</th>
<th>SAMPLE 2 (16 minutes)</th>
<th>SAMPLE 3 (24 minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aliphatic and Olefinic Hydrocarbons</td>
<td>2.51</td>
<td>1.78</td>
<td>4.15</td>
</tr>
<tr>
<td>Aromatics Hydrocarbons</td>
<td>0.1</td>
<td>0.13</td>
<td>0.71</td>
</tr>
<tr>
<td>Aldheydes</td>
<td>N.D.</td>
<td>0.55</td>
<td>0.06</td>
</tr>
<tr>
<td>Oxigenated (except aldehydes and carbones)</td>
<td>0.12</td>
<td>0.54</td>
<td>0.38</td>
</tr>
<tr>
<td>Organics Carbonate (battery cells solvents)</td>
<td>0.85</td>
<td>0.39</td>
<td>0.41</td>
</tr>
<tr>
<td>SiO</td>
<td>0.41</td>
<td>0.37</td>
<td>1.77</td>
</tr>
<tr>
<td>Alogenated</td>
<td>N.D.</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Nitriles</td>
<td>N.D.</td>
<td>0.07</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

Figure 7  Histogram of the concentrations sum of identified VOCs broken down by class of Compounds

Sample preparation for the determination of semi volatiles organic molecules (SVOC)
The water sample (100.0 mL ± 0.3) was extracted by Supelclean LC- 18 SPE Tube (Supelco) 500 mg SPE cartridge, then eluted with 1.5 mL ethyl acetate. Analyses were performed using a GC-MS system consisting of an Agilent 6890 plus Gas Chromatograph and an Agilent 5973 Network Quadrupole Mass Spectrometer, equipped with a CombiPal liquid autosampler from CTC Analytics. The optimized chromatographic conditions are as follows:
Chromatographic column: Agilent HP-5-MS 30 m long, 0.25 mm internal diameter and 0.25 μm stationary phase thickness.
Carrier gas: constant flow He (1 mL/min) Injection: splitless with pressure pulse (20 psi up to one minute), sample volume 1 μL, MMI injector in temperature programmed from 40 (0.1 minute) to 280 °C (ramp 700 °C/min) Column oven: 40 °C for 5 minutes then to 270 °C at 5 °C/min; final isotherm at 270 °C for 20 minutes.
Transfer line: 280 °C Mass spectrometer operated in scan mode on the range 29-600. The SPDE headspace extractions were carried out with a PDMS/activated carbon, 50 μm, 56 mm (SPNdl-1/AC-
50-56) extraction needle and 50 extraction strokes. The water sample (5.0 mL) was incubated at 60 °C in 20 mL headspace vials.
Calibration was performed by external standards for benzene, toluene, styrene, naphthalene, indane, ethyl methyl carbonate, diethyl carbonate, phenol, aniline, and bisphenol A. The other compounds were identified by searching the relevant mass spectra (background purified) in the Wiley275 and NIST17 mass spectra libraries by PBM algorithm (McLafferty). Identification is considered certain if the identification algorithm reports "match quality" better than 90 percent. Determination for compounds for which the standard is not available is semiquantitative (extended relative uncertainty of 50%).

**SVOC Results**

Compared with the test report on analysis by SPDE-GC-MS, a technique suitable for the analysis of volatile organic compounds (boiling points below 150 °C), the analytical technique used in this test report allows the determination of semi-volatile and more hydrophilic organic compounds (SVOCs).

The integrated sample contains the substances shown in Table 4. The masses of the various compounds are those in the integrated sample of fire extinguishing water (1.2 m³).

In this type of analysis, in contrast to that carried out by the technique for volatile compounds (SPDE-GC-MS), we note the presence of phenoles and bisphenoles, which are mainly derived from the decomposition of epoxy resins and polycarbonates. The main compound is bisphenol A, having a concentration of 8.9 mg/L in the quench water (total mass of 10.6 grams) and constituting about 35 percent of the mass of identified semivolatile organic compounds. The sum of phenols and bisphenols comes to 70% of the total mass of semi-volatiles. Consequently, one of the major impacts on the production of decomposition compounds during lithium battery combustion are the decomposition products of epoxy resins and polycarbonates.

In brief:
1) Large amounts of phenols and bisphenols are present (around 19 mg/L for a total mass produced during the test and migrated into the fire extinguishing water of 22 grams). These probably result from decomposition of phenolic resins and polycarbonates.
2) Ethyl Methyl Carbonate is present in significant amounts (the quantification is not correct because the present analytical method is not suitable for volatile substances).
3) Nitrogen compounds are present, particularly aliphatic and aromatic nitriles (which may result from the decomposition of polyamides (nylon) and NBR rubbers) and cyclic amides (decomposition of polyamides).

### Table 4 Classes of compounds present among SVOC compounds identified and quantified in the integrated sample of fire extinguishing water

<table>
<thead>
<tr>
<th>Class of Compounds</th>
<th>Concentration [mg/l]</th>
<th>Mass [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aromatic Hydrocarbon including PAH</td>
<td>0.69</td>
<td>0.83</td>
</tr>
<tr>
<td>Phenols</td>
<td>9.65</td>
<td>11.58</td>
</tr>
<tr>
<td>Bisphenols (decomposition of polycarbonate and epoxy)</td>
<td>9.44</td>
<td>11.33</td>
</tr>
<tr>
<td>Cyclic amides from nylon decomposition</td>
<td>0.43</td>
<td>0.51</td>
</tr>
<tr>
<td>Nitriles (decomposition of nylon and NBR)</td>
<td>1.54</td>
<td>1.85</td>
</tr>
<tr>
<td>Other Nitrogen containing organics (quinoles, aniline)</td>
<td>0.69</td>
<td>0.83</td>
</tr>
<tr>
<td>Carbonates (Li battery, electrolye solvent)</td>
<td>2.7</td>
<td>3.24</td>
</tr>
<tr>
<td>Plasticizers</td>
<td>0.2</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>30.41</strong></td>
</tr>
</tbody>
</table>

**Water Analysis**

Two liters of a blank sample from the firefighter’s tank (blank) and the extinguishing waters recovered immediately after the test (FEW) were analyzed by ion chromatography and by inductively coupled Plasma interfaced to a mass spectrometer. For the part involving ion chromatography the instrument used was a Metrohm 881 Compact IC chromatograph and the ICP MS instrument was a Thermo Scientific Icap Q C equipped with a Cetac Autosampler ASX-520 sampler. Water samples were
centrifuged at 4000 rpm then filtered Whatman Filter Paper, Grade 1, and acidified with ultra-pure nitric acid (for the ICP-MS analysis). Results from ICP-MS analysis are listed in Table 5.

Table 5 Results From ICP-MS analysis firefighter’s tank (Blank) and the extinguishing waters recovered immediately after the test (FEW)

<table>
<thead>
<tr>
<th>Be</th>
<th>B</th>
<th>Si</th>
<th>Al</th>
<th>Ti</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppm]</td>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppb]</td>
</tr>
<tr>
<td>Blank</td>
<td>&lt; 0.3</td>
<td>15.57</td>
<td>2.96</td>
<td>131.73</td>
<td>0.77</td>
</tr>
<tr>
<td>FEW</td>
<td>&lt; 0.3</td>
<td>37.77</td>
<td>12.47</td>
<td>22.100.86</td>
<td>18.69</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>As</th>
<th>Se</th>
<th>Rb</th>
<th>Zr</th>
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<tr>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppm]</td>
<td>[ppb]</td>
<td>[ppb]</td>
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</tr>
<tr>
<td>Blank</td>
<td>0.38</td>
<td>0.58</td>
<td>0.27</td>
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<td>&lt; 0.3</td>
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<tr>
<td>FEW</td>
<td>5.16</td>
<td>3.92</td>
<td>0.65</td>
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<td>0.09</td>
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<table>
<thead>
<tr>
<th>Mn</th>
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<tr>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppm]</td>
<td>[ppb]</td>
<td>[ppb]</td>
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<tr>
<td>Blank</td>
<td>40.04</td>
<td>741.28</td>
<td>19.84</td>
<td>214.99</td>
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<tr>
<td>FEW</td>
<td>12.902.52</td>
<td>1.750.11</td>
<td>4.163.29</td>
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<td>30.33</td>
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<table>
<thead>
<tr>
<th>Ag</th>
<th>Cd</th>
<th>In</th>
<th>Te</th>
<th>Cs</th>
<th>Ba</th>
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<tbody>
<tr>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppm]</td>
<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppb]</td>
</tr>
<tr>
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<td>&lt; 0.3</td>
<td>&lt; 0.3</td>
<td>&lt; 0.3</td>
<td>0.02</td>
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<tr>
<td>FEW</td>
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<td>&lt; 0.3</td>
<td>&lt; 0.3</td>
<td>0.93</td>
<td>0.03</td>
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</tbody>
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<table>
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<tr>
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<th>Pb</th>
<th>Bi</th>
<th>Th</th>
<th>U</th>
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<tbody>
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<td>[ppb]</td>
<td>[ppb]</td>
<td>[ppm]</td>
<td>[ppb]</td>
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<td>[ppb]</td>
</tr>
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<td>FEW</td>
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<td>&lt; 0.3</td>
<td>30.69</td>
<td>0.01</td>
<td>&lt; 0.3</td>
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</table>

As for the analysis by ion chromatography, the results are reported in the Table 6.

Table 6 Concentration of anion and cations in extinguishing waters.

<table>
<thead>
<tr>
<th>Concentration [ppm]</th>
<th>Blank</th>
<th>(FEW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorine</td>
<td>0.26</td>
<td>46.6</td>
</tr>
<tr>
<td>Chlorine</td>
<td>10.1</td>
<td>610</td>
</tr>
<tr>
<td>Nitrite</td>
<td>&lt;0.3</td>
<td>5.7</td>
</tr>
<tr>
<td>Bromine</td>
<td>0.1</td>
<td>28.5</td>
</tr>
<tr>
<td>Nitrate</td>
<td>1.2</td>
<td>105.3</td>
</tr>
<tr>
<td>Phosphate</td>
<td>&lt;0.3</td>
<td>17.1</td>
</tr>
<tr>
<td>Sulphate</td>
<td>169</td>
<td>144.4</td>
</tr>
<tr>
<td>Litium</td>
<td>0.01</td>
<td>46.6</td>
</tr>
<tr>
<td>Sodium</td>
<td>8.2</td>
<td>210</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.007</td>
<td>14.5</td>
</tr>
<tr>
<td>Potassium</td>
<td>1.11</td>
<td>267.7</td>
</tr>
<tr>
<td>Magnesium</td>
<td>21.5</td>
<td>140.2</td>
</tr>
<tr>
<td>Calcium</td>
<td>94.6</td>
<td>498.5</td>
</tr>
<tr>
<td>Strontium</td>
<td>1.9</td>
<td>3.25</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The effectiveness of the melting fuse to aid the fire extinguishment has been demonstrated. The direct cooling effect on the battery modules gives an advantage to: reduce the extinguish time, contain the amount used and avoid the re-ignition of the fire after many hours from the fire extinction. Toxic VOC concentrations always remain below 1 ppmv and probably none exceed the respective TLV-TWAs. This is also due to conducting the test in an outdoor environment.

Main contaminants are the following compounds/elements:
1) Air emissions of VOC are dominated by aliphatic and aromatic hydrocarbons (mainly benzene, styrene and C12 olefins), cyclic siloxanes and ethyl methyl carbonate. Hydrocarbons can form through
decomposition of polyethylene/polypropylene and polystyrene resins. Cyclic siloxanes from silicones and ethyl methyl carbonate are the solvent of the liquid Li-ion battery electrolyte.

2) VOCs in the water are dominated by ethyl methyl carbonate (with a quantity of nearly 130 grams released in the 1200 liters of water used), then other compounds are styrene, acrylates (derived from decomposition of polystyrene or ABS and polyacrylates, respectively). Phenol is also present, probably from decomposition of epoxies or polycarbonates.

3) SVOC in the water are dominated by bisphenols and phenols (with a total amount released in the water of 18-20 grams).

4) Inorganic compounds released in water are a) elements contained in the electrolyte and electrodes (Li, Co, Mn, Ni); b) Other elements (Al, Mg, K, Ca, Na). Aluminum and magnesium can be released from heat sinks used in the electronic circuits.

Overall, the main emissions derive from:
   a) plastic material decomposition
   b) solvents from the electrolytes
   c) elements from electrolyte and electrodes
   d) The decomposition products emitted suggest the presence of epoxies, polycarbonate, silicones, polyethylene/polypropylene.

Regarding the analyses of aqueous samples, the high concentrations of Lithium, Lead, Sodium, Magnesium, Nickel, Cobalt, Magnesium, Aluminum and Calcium as expected given the composition of the battery in question and the high concentrations of anions including Fluorine and Chlorine are noteworthy. As for sulfates there is to be noted a lower concentration of them due to the formation of insoluble compounds after battery combustion. The results of not many analyses in the literature (7-8) report similar values for some metals (Chromium and Lead) and considerably different ones.

As previously reported in the literature, extinguishing waters contain large concentrations of metals that, depending on the location of the event, can lead to contamination if not diluted or possibly collected before dispersal into the environment. As is also the case with fossil fuel cars, vapors released from combustion contain substances that can be harmful to humans. Rescue personnel should therefore use protective equipment until the fire is completely extinguished, as is the case in practice during this type of event and during the trials conducted in this test.

ABBREVIATIONS

ABS   (acrylonitrile butadiene stirene)
BTEX  Benzene, toluene, ethylbenzene, xylenes
CO    Carbon monoxide
COS   Carbonyl sulfide
DUT   Device Under Test
FEW   Fire Extinguishing Water
GC-MS Gas chromatography–mass spectrometry
N.D.  Not Detected
PBM   probability based match
ppmv  part per million in volume
TLV-TWA threshold limit value - time-weighted average
USEPA U.S. Environmental Protection Agency
SVOC  semi-volatile organic compounds
VOC   volatile organic compounds
REFERENCE LIST

1. W. Luo, S. Zhu, J. Gong, Z. Zhou Research and development of fire extinguishing technology for power Lithium batteries Procedia Eng, 211 (2018), pp. 531-537

2. Plus Victor Chomboa, Yossapong Laooualb


5. F. Larsson, P. Andersson, P. Blomqvist, B. Mellander - Toxic fluoride gas emissions from lithium-ion battery fires Sci. Rep., 7 (1) (2017), 10.1038/s41598-017-09784-z


7. Vinay Premnath- Southwest Research Institute - Detailed Characterization of Emissions from Battery Fires – Sept. 30th, 2021


Analysis of combustion gases and fire water run-offs from passenger vehicle fires

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ABSTRACT

In the IEA Global EV Outlook 2022, Norway, Iceland, and Sweden were reported to have the highest electric car shares of the new car market: 86%, 72% and 43%, respectively. Electrification of the transport sector has multiple benefits but has also raised some concerns. Fires in electric vehicles are reported almost daily in the media and social media channels. However, if the traction battery catches fire, it can be difficult to extinguish since the battery pack in an electric vehicle is generally well protected and difficult to reach. To cool the battery cells, firefighters must prolong the application duration of suppression agent. This results in the use of large amounts of water, that potentially could carry pollutants into the environment. In this work, the analysis of extinguishing water from passenger vehicle fires are reported. Three large-scale vehicle fire tests were performed, the vehicles used were both conventional petrol fuelled and battery electric. Tests were performed indoors at RISE, Borås and the test setup allowed analysis of both combustion gases and extinguishing water. Results show that all analysed extinguishing water was highly contaminated. Additionally, the ecotoxicity analysis of the extinguishing water showed that the extinguishing water was highly toxic towards the tested aquatic species, independent of the traction energy of the vehicle.

KEYWORDS: electric vehicle, large-scale fire test, extinguishing water, ecotoxicity

INTRODUCTION

Fire tests on single battery cells and battery packs are more frequent than large-scale vehicle fire tests. Large-scale vehicle fire tests require additional safety measures and are much more costly compared to cell/module/pack testing. Tests on battery packs and battery modules provide information on risks associated with the battery and support engineering of a fire safe battery design, whilst large-scale fire tests give a holistic view on vehicle fires. A handful of large-scale fire tests on battery electric vehicles (BEVs) have been performed and can be found in for example work by Watanabe et al. [1], Lam et al. [2], Truchot et al. [3], Lecocq et al. [4], and Willstrand et al. [5]. A typical passenger vehicle fire lasts for 60 – 90 min and has a total heat release (THR) of an average of 5.9 GJ [5]. The THR will depend on the vehicle size and materials used in manufacturing the vehicle. For example, plastics used for seating/upholstery etc. amount to ~ 20% [6] of the total weight of a passenger vehicle and will considerably affect the combustion behaviour.

All fires release toxic gases, and the quantity and composition depend on the material composition of the combustibles, gas temperature, and the oxygen availability [7]. Gases found in vehicle fire emissions include (but are not limited to) carbon monoxide (CO), nitrous oxides (NOx), sulphur dioxide (SO2), hydrogen halides (HX) and hydrogen cyanide (HCN), which all are classed as asphyxiant or irritant gases. Polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), dioxins and a range of metals/metal oxide particles are also found in vehicle fire effluents.
An overview of substances found in the combustion of ICEVs and BEVs can be found for example in Willstrand et al. [5] and Lönnmark & Blomqvist [8]. Additionally, the environmental impact of the fire will depend on the size of fire as well as if any suppression media is used. In 2016, Kärman et al. [9] studied the environmental impact from different firefighting tactics and use of different suppression media, such as foams and additives. All tested foams and additives were toxic against water living organisms and the most environmental benign firefighting tactic was to not extinguish the fire at all. However, for some fires this option is not feasible. Instead, a quick response and little usage of water would result in a more environmental benign firefighting operation.

The extinguishing water from vehicle fires contain a variety of toxic combustion products. The concentration and type of compounds will depend on many factors, such as the material combusted, the fire scenario, suppressant used, and the volume of water/suppressant used. In a study by Lönnmark & Blomqvist [8], it was found that extinguishing water from internal combustion engine vehicle (ICEV) fires were severely contaminated and contained a high concentration of suspended substances and a high organic content. The analysed water also contained inorganics such as lead (Pb), copper (Cu), zinc (Zn), and antimony (Sb). For BEVs the addition of battery specific metals (such as lithium (Li), manganese (Mn), cobalt (Co), nickel (Ni)) and various fluorinated compounds can be expected. Fluorochemicals in lithium-ion batteries are found in the binder material, electrolyte salts, electrolyte additives and fluorinated derivatives of the electrolyte [10]. Many of the fluorinated compounds are used improve the performance and lifetime of the battery. Therefore, substitution of these compounds, without having deteriorating performances of the battery, may be difficult. Note that fluorinated compounds are also found for example in tubing and hoses (PVDF and PTFE), electronics, anti-static coatings, as well as in the air conditioning refrigerants.

METHODS & MATERIALS

Three large-scale vehicle fire tests and one battery fire test were performed in the large fire hall at RISE, Borås. Advanced flue gas reduction and water purification systems are used to minimise exhausts to the environment upon testing in the fire hall. All tests were ignited using a propane burner (30 kW) at test time $t = 5$ min.

Test objects
The tested vehicles comprised of one BEV where the battery pack had been removed (test 1, reference test, free burning), one complete ICEV (test 2, petrol, 40 L) and one BEV (test 3, SOC 90%, NMC, ~ 50 kWh). Additionally, a separate battery fire test (test 4, SOC 90%, NMC, ~ 50 kWh) was performed using the battery pack that had been removed from test 1. The battery pack was shielded above it to reduce direct water exposure from the sprinkler system to the battery pack casing (representing the protection of the chassis). The ICEV, BEV and battery pack fire tests applied a sprinkler system for water application (see further “collection of extinguishing water”). All vehicles as well as the battery were brand new (manufactured in 2021) and came from the same manufacturer, which enabled a good comparison between the tested vehicles.

Heat release rate
To calculate the heat release rate (HRR), an industry calorimeter was used. The calorimeter collects combustion products through the hood and extracts them through a large exhaust duct. A set of guide plates and a sufficient length of the duct (~ 30 m) have been used to decreases the air turbulence in the exhaust duct. Equations used for the calculation of HRR can be found in reference [5].

Collection and analysis of extinguishing water
To reduce uptake of existing contaminants from the fire hall and to enable collection of the extinguishing water, a large steel tray ($5.0 \times 2.0 \times 0.15$ m), equipped with a water outlet connected to a pump, was positioned under the vehicle/battery pack to collect water from the sprinkler system used (see below) (see Figure 1). For safety reasons the extinguishing water was pumped to an adjacent hall for sampling.
For water application, to enable extinguishing water collection, a system that could deliver water homogeneously for all tests and that could be operated remotely was required. A sprinkler system was considered as the best alternative. The sprinkler heads used in the tests were upright TYCO model Series TY FRB, Quick Response, Standard Coverage (glass bulbs were removed to enable remote operation of the system). Each of the sprinkler heads covered an area of 9.3 m². The vertical distance from the deflector of the individual sprinkler heads and the bottom of the large tray was 2.85 m. The sprinkler system was operated to give a water discharge density of 10 mm min⁻¹, corresponding to 93 L min⁻¹ per sprinkler head and a total flow rate of 372 L min⁻¹ for the whole system. The sprinkler system was active for 30 min during each test, resulting in a total of 11 160 L of water used per test. The distribution line of the pipework had a solenoid valve that was remotely operated when the fire size reached a convective heat release rate of 667 kW, corresponding to a total heat release rate of ~1 MW. For the battery pack fire test, the activation time was set to 30 s after venting. The sprinkler system was scheduled to be active for 30 min during each test. However, in the BEV test, activation was performed in two steps, see further results section “Heat release rate”.

The large tray beneath the vehicle was exchanged to a new tray between test 2 (ICEV) and test 3 (BEV). The pump tray and the connected hose were not exchanged between the tests. Therefore, background water sampling (blank samples) was performed before each test to evaluate any remaining contamination from previous tests or from the fire hall itself. Blank samples were taken by flushing the whole test setup with clean tap water for a minimum of 10 min before each test. The water used for flushing (at t = 10 min) was taken as the blank sample.

The collection of extinguishing water for all tests started when the sprinkler system was started. A heavy-duty pump was used to pump the water from the pump tray at a flow rate of ~ 2 L s⁻¹. One liter of water was collected for sampling each minute for the time that the sprinkler system was active. At the end of the test, 0.5 L of the water left in the large tray was also taken for analysis. In total, two samples from each test were analysed: (1) 0-30 min and (2) sample taken from the large tray at the end of each test.

Chemical analysis of the extinguishing water
The extinguishing water was analysed for 16 PAHs, VOCs, inorganics & anions. For analysis of the inorganic species, water samples were filtered (0.45 µm) before determined by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) and ICP Optical Emission Spectrometry (ICP-OES). Water-soluble contents of fluoride, chloride and bromide was analysed using ion chromatography (IC) with a conductivity detector.

For analysis of VOC, water samples (100 ml) were extracted with dichloromethane (DCM) after addition of internal standard bis(2-ethylhexyl) phthalate (DEHP-d). The extracts were evaporated to 0.2 to 0.5 ml followed by GC-MS. Detected compounds were identified using NIST library of mass spectra and the concentrations were determined in equivalents of internal standard DEHP-d. Another part of the samples (10 ml) was analysed by headspace GC-MS after heating at 95°C for 30 min. The compounds detected were identified by NIST library of mass spectra and the concentrations were determined in equivalents of internal standard benzene-d. The PAH concentration in the water samples was analysed by GC-MS, using 16 external standards after extraction with DCM.
Biological characterization of extinguishing water

Biological characterisation was performed by an external laboratory, Toxicon AB. Samples taken from the large tray at the end of each test were frozen and sent to Toxicon for analysis. pH, salinity and conductivity were measured before characterisation, and were buffered if needed. Microtox analysis was performed on all samples according to SS-EN ISO 11348-3:2008 (mod.) “Determination of the inhibitory effect of water samples on the light emission of Vibrio fischeri (Luminescent bacteria test)”. Growth inhibition rate (ErC_{10} and ErC_{50}) of Pseudokirchneriella subcapitata (Green algae) was evaluated on water samples from the ICEV and BEV test according to SS-EN ISO 8692:2012 “Fresh water algal growth inhibition test with unicellular green algae”. Half maximal effective concentration (EC_{50}) for Daphnia magna (Crustacean) was determined for samples from the ICEV and BEV using SS-EN ISO 6341:2012. “Determination of the inhibition of the mobility of Daphnia magna Straus (Cladocera, Crustacea) - Acute toxicity test”.

RESULTS

This section presents the results regarding HRR and the chemical analysis of the extinguishing water.

Heat release rate

The HRR was calculated for all four tests and results are presented in Figure 2.

![Figure 2. Calculated heat release rates and total heat release for each test. Blue shading indicates the sprinkler system active period/s. Note that the x-scales are scaled differently.](image)

Test 1, reference test   THR: 5.0 GJ
Test 2, ICEV   THR: 6.1 GJ
Test 3, BEV   THR: 5.7 GJ
Test 4, Battery pack   THR: 0.8 GJ

Test 1 was a free burning test whereas the remaining tests had the sprinkler system active (sprinkler active period is indicated in blue in Figure 2). For test 3 (BEV), the sprinkler system was activated in two steps, upon the first activation of the sprinkler system the HRR drastically decreased (as well as battery surface temperatures). To eliminate the risk of having the sprinkler system active without having thermal runaway, it was decided to turn off the sprinkler system 10 min after activation. A dry period of 15 min followed, where the fire was allowed to grow. A second activation of the sprinkler
system was initiated after 15 min and was left active for another 20 min in order to keep the water amount at the same volume for all tests. The THR for each test is presented in Figure 2.

**Extinguishing water**

Table 1 presents the inorganic and anions analysed. Mercury, cadmium or arsenic was not found for any of the water samples analysed. In table 2 the biological characterisation of the extinguishing water is presented. PAHs were only detected for the ICEV and BEV, at a concentration of 13 and < 2.5 µg L\(^{-1}\) respectively. VOCs were only found in the extinguishing water from the ICEV at a concentration of 2600 µg L\(^{-1}\).

**Table 1. Concentration of inorganics and anions (mg L\(^{-1}\)) for water samples (0 – 30 min). Number in brackets indicate the concentration found for respective blank test (i.e., measurement uncertainty). Values have been rounded.**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Reference test</th>
<th>ICEV</th>
<th>BEV</th>
<th>Battery pack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentration (mg L(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>n.a.</td>
<td>1.50 (0.009)</td>
<td>0.02 (0.02)</td>
<td>1.20 (0.06)</td>
</tr>
<tr>
<td>Boron</td>
<td>n.a.</td>
<td>1.30 (&lt;0.05)</td>
<td>0.20 (&lt;0.05)</td>
<td>0.80 (&lt;0.05)</td>
</tr>
<tr>
<td>Lead</td>
<td>n.a.</td>
<td>0.07 (&lt;0.0005)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cobalt</td>
<td>n.a.</td>
<td>0.01 (&lt;0.0001)</td>
<td>0.03 (&lt;0.0001)</td>
<td>0.02 (0.002)</td>
</tr>
<tr>
<td>Nickel</td>
<td>n.a.</td>
<td>0.02 (0.0006)</td>
<td>0.08 (0.0005)</td>
<td>0.05 (0.01)</td>
</tr>
<tr>
<td>Chromium</td>
<td>n.a.</td>
<td>0.006 (&lt;0.0003)</td>
<td>-</td>
<td>0.0007 (0.0004)</td>
</tr>
<tr>
<td>Copper</td>
<td>n.a.</td>
<td>0.09 (0.0024)</td>
<td>0.03 (0.01)</td>
<td>0.009 (0.02)</td>
</tr>
<tr>
<td>Tin</td>
<td>n.a.</td>
<td>0.007 (&lt;0.0003)</td>
<td>0.0002 (&lt;0.0003)</td>
<td>-</td>
</tr>
<tr>
<td>Vanadium</td>
<td>n.a.</td>
<td>-</td>
<td>-</td>
<td>0.003 (&lt;0.02)</td>
</tr>
<tr>
<td>Zinc</td>
<td>n.a.</td>
<td>2.50 (0.01)</td>
<td>0.70 (0.004)</td>
<td>-</td>
</tr>
<tr>
<td>Antimony</td>
<td>n.a.</td>
<td>0.10 (0.0012)</td>
<td>0.20 (&lt;0.0002)</td>
<td>0.008 (0.002)</td>
</tr>
<tr>
<td>Lithium</td>
<td>n.a.</td>
<td>-</td>
<td>4.10 (&lt;0.04)</td>
<td>32 (0.2)</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>n.a.</td>
<td>0.50 (0.01)</td>
<td>0.01 (0.0015)</td>
<td>0.03 (0.002)</td>
</tr>
<tr>
<td>Manganese</td>
<td>n.a.</td>
<td>0.09 (0.003)</td>
<td>0.14 (0.008)</td>
<td>0.11 (0.01)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anions; values presented are corrected towards the blank samples (mg L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoride</td>
</tr>
<tr>
<td>Chloride</td>
</tr>
<tr>
<td>Bromide</td>
</tr>
</tbody>
</table>

**Table 2. Biological characterization of extinguishing water, effective concentrations for the tested aquatic species. Tabulated values have been rounded.**

<table>
<thead>
<tr>
<th></th>
<th>ICEV</th>
<th>BEV</th>
<th>Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective concentration (% vol/vol)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microtox (EC(_{50}), 15 min)</td>
<td>1.8</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Green algae (E(_{50}), 72h)</td>
<td>2.5</td>
<td>6.5</td>
<td>Not tested</td>
</tr>
<tr>
<td>Crustacean (EC(_{50}), 48 h)</td>
<td>14.0</td>
<td>30.5</td>
<td>Not tested</td>
</tr>
</tbody>
</table>

**DISCUSSION**

The THR for the tested vehicles were in the range of 5.0 – 6.1 GJ, indicating that the traction energy (i.e. petrol or lithium-ion battery) does not dictate the total amount of energy released. The peak HRR for the reference test, i.e., vehicle without traction energy was ~ 2500 kW. The highest peak HRR was
found for the ICEV, having two peaks around or above 3500 kW. The peak HRR for the BEV was ~3000 kW and for the battery pack ~2500 kW.

The active burn time for the reference test and ICEV test was around 90 min, whereas the BEV had a burn time of ~100 min. The longer burn time could be attributed to the slower propagation in the battery pack compared to the fast combustion of the petrol as the tank burst (40 L of petrol burned in ~5 min compared to the 20 min burn time for the battery pack). Additionally, the combustion (and venting events) of the free-standing battery pack was visibly much more intense than for the BEV (Figure 3). A plausible reason for this is that the gas vents and chassis were efficient in deflecting the jet flames underneath and towards the back of the vehicle, resulting in visibly shorter flames. Furthermore, the time to initiate thermal runaway in test 4 (battery pack) was substantially longer than for test 3 (BEV). The battery pack did not show any major venting events before the test time of 60 min (initiating burner power output was the same for all tests, 30 kW).

![Figure 3. Photographs of a) thermal runaway for the BEV and b) thermal runaway for the battery pack.](image)

**Comparison of inorganics towards surface water guidelines**

Each analysed inorganic specie was compared to existing guideline values for surface waters found in references [11–23]. For all tests, where the sprinkler system was active, the concentration of aluminum, copper, cobalt and fluoride was above the surface water guideline values. Additionally, for the ICEV: molybdenum, antimony, zinc, lead and chloride; for the BEV: zinc, antimony and chloride; and for the battery pack, nickel was also found in concentrations above the guideline values for surface water.

Mercury, lead, cadmium and copper are often highlighted as the more severe environmental pollutants due to that they are bioaccumulating (valid for Hg, Pb, Cd) and highly toxic for aquatic organisms. Mercury and cadmium were not found in any of the analysed water samples. Lead was only found in the water from the ICEV (65 µg L⁻¹); the recommended guideline value for lead is in the range of 3–30 µg L⁻¹. Copper was found in all tests; the highest concentration of copper was found in the extinguishing water from the ICEV (90 µg L⁻¹) and then for the BEV (25 µg L⁻¹) and lastly the battery test (9 µg L⁻¹). The guideline value for copper in surface water range between 9–90 µg L⁻¹. The surface water guideline values for chloride range between 120–640 mg L⁻¹. The analysed concentration of chloride range between 35–250 mg L⁻¹. For fluoride, the recommended guideline values range between 0.12 [17] – 0.50 [13,19] mg L⁻¹. The fluoride concentrations in the analysed water ranged between 8–70 mg L⁻¹, well above the recommended values.

**Biological characterization**

In the Microtox analysis (*Vibrio fisheri*), the inhibition of bacteria luminescence (EC₅₀ and EC₂₀) was studied. For 15 min of exposure, a vol/vol % of 0.35 – 0.75 (EC₅₀) and 1.8 – 4.0 (EC₂₀) was required which indicate that the tested extinguishing water had high toxicity towards *Vibrio fisheri*. For green algae (*Pseudokirchneriella subcapitata*), EC₅₀ is presented in Table 3 (high toxicity for both samples). The no-observed-adverse-effect level (NOAEL) was 0.2 and 0.7 % vol/vol (72 h exposure) for ICEV and BEV, respectively.

For crustacean (*Daphnia magna*), EC₅₀ are presented in Table 3 (high toxicity for ICEV and
intermediate toxicity for BEV). The NOAEL 24 h exposure was 3.1 and 25 % vol/vol for ICEV and BEV, respectively. For a 48 h exposure, the NOAEL was 3.1 and 12.5 % vol/vol for ICEV and BEV, respectively. The criteria for acute toxicity based on EC50 was taken from reference [22].

CONCLUSIONS

The extinguishing water from the BEV and the battery pack contained higher concentrations of lithium and fluoride than the extinguishing water from the ICEV. Lithium has no surface water guideline in Sweden, whereas fluoride is toxic to water living organisms at the found concentrations (dilution effects were not considered in this work).

For the ICEV, lead was found in much higher concentrations than for the BEV. Lead was found for the ICEV test both in the combustion gases (published elsewhere) as well as in the extinguishing water. Furthermore, PAHs and VOCs were found to a higher degree for the ICEV than for the BEV. The biological characterisation indicates that all extinguishing water analysed in this work were highly toxic towards the tested aquatic species. The analysed extinguishing water from the ICEV had somewhat higher toxicity to the tested aquatic species than the extinguishing water from the BEV.

The analysed compounds presented in this report are only representative for a small number of tests. As vehicle type, battery chemistry, fire scenario etc. are varied, the pollutants and concentrations of these will most likely be subjected to variations.

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REFERENCES


Fire Performance of a Cryogenic UN-T75 Storage Tank: Phase II – LNG

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ABSTRACT
The Department of Transportation (DOT) Federal Rail Administration (FRA) awarded a contract to Southwest Research Institute (SwRI) to conduct research and testing in the interest of ISO storage tanks for Liquefied Natural Gas (LNG) service. In Phase I of the project, SwRI fire-tested an LNG tank filled with liquid nitrogen (LN2) and demonstrated the performance of the pressure relief valve system. In Phase II, this test was repeated with the same type of tank filled with LNG. In addition, several types of data were collected during the experiment to understand how the fire exposure affects the internal and external heating of the tank. This information will be used in future computer modeling efforts to predict performance with different tanks and fire scenarios. This paper provides a summary of the test results observed in the Phase II testing, conducted on June 29, 2022.

KEYWORDS: LNG, Pressure Relief Device, Transportation

INTRODUCTION
The railroad industry is actively working on alternative fuels to diesel, including LNG and compressed natural gas (CNG). The safety performance of these alternate fuel tank cars under accident induced fire conditions has not been verified and is a cause for concern. The FRA is interested in methods and approaches, both analytical and experimental, which can evaluate the thermal safety performance of LNG/CNG means of containment (tanks, ISO tanks, etc.) under fire conditions. The purpose of the first phase of this project was to conduct fire testing of an ISO tank filled with LN2, located on top of a flat rail car and exposed to a propane pool fire.

The purpose of the second phase of the project was to repeat the first test with LNG inside the test tank.

The primary objective of the test program was to evaluate the pressure relief system installed on the test tank. The secondary objectives were to collect data (temperature and pressure) to understand how the fire exposure affects the internal and external heating of the tank. This information can be utilized in future analytical work to predict performance with different tanks and fire scenarios.

TEST ARTICLES LNG ISO

Test Tank
An ISO UN-T75 storage tank, outfitted for LNG service, was procured from Cryogenic Vessel Alternatives, Inc. (CVA). The model number of the tank is CVA-12K-114-ISO and measures 12.2-m long, 2.6-m high and 2.4-m wide (40-ft long, 8.5-ft high and 8-ft wide). Note that CVA is now a part of Taylor Wharton. Figure 1 provides selected photographs of the tank that was used in this
experiment. The test tank was filled with 9500 gal of LNG, provided by Airgas USA, LLC, on June 28, 2022. This resulted in a starting fill level of nominally 78%.

Figure 1 Photographs of Test Tank.

Flatcar for ISO Tank Installation
The FRA was able to identify a project partner in the Florida East Coast Railway (FECR), which was able to donate a flatcar for this project. This car consisted of two flatcars connected together, in order to safely travel across the country by rail. One of these cars was utilized for each phase of the project (one per fire test). The car was taken off the rail line at the Transload Operations location for Hondo Railway. The cars were disconnected and transported by truck to the remote test site, located in Sabinal, Texas. Figure 2 shows two photographs of the flatcar prior to arrival at the remote site.

Figure 2 Photographs of Donated Flatcar.

SAFETY PLAN
Historical events were reviewed and the standoff distance parameters were previously discussed for those events. There were two primary events in the last 20 years, where a large LNG tank failed catastrophically. It should be noted that the tank designs for these two events were different from the design tested in this project. However, due to lack of other available data, these events can be used to conservatively estimate potential effects from a significant failure of the tank during a fire test.
Tivissa, Catalonia (Spain)
On June 22, 2002, an LNG road tanker exploded in Tivissa, Catalonia (Spain). Results from the accident investigation have been published [1] and are summarized below.

- **Overpressure:** Investigators calculated the explosion had an equivalent mass of 30 kg (66 lb) of TNT.
- **Sound Pressure Level:** ~122 dBA at SwRI Remote Site fence line, based on estimated overpressure [2].
- **Shrapnel:** Tank front end = 125 m (410 ft) away, Tank back end = 80 m (262 ft) away
- **Fireball:** Radius = 75 m (246 ft), Height = 13 m (371 ft), Duration = 12 s, Estimated heat flux of 16 kW/m² at 198 m (650 ft) (two bystanders received 1st and 2nd degree burns)

Murcia (Spain)
On October 20, 2011, an LNG tanker exploded in Murcia, Spain. Results from the accident investigation have been published [3,4], and are summarized below.

- **Overpressure:** Investigators calculated the explosion had an equivalent weight of 41 kg (90 lb) of TNT.
- **Sound Pressure Level:** ~123 dBA at SwRI Remote Site fence line, based on estimated overpressure.
- **Shrapnel:** Secondary fragments up to 200 m (656 ft) away
- **Fireball:** Radius = 66-79 m (218–258 ft), Height = 100 m (328 ft), Duration = 9.4 s, Estimated heat flux of 55 kW/m² at a distance of 91 m (300 ft) (pine needle pyrolysis)

Based on the summarized historical data, in-house calculations and consultation with SwRI’s safety department, it was decided to perform the Phase I test with LN2 in the test tank. However, based on the successful performance of the pressure relief system in the first test, the second test was conducted with LNG inside the test tank and test planning at the SwRI remote test site was conducted with the assumption that the tank could fail catastrophically.

**FIRE SOURCE CHARACTERIZATION**

It was agreed between SwRI and FRA to consider a real accident scenario in order to determine the test duration. The following sections provide more detail about the assumed scenario, the calculated burning duration of the scenario (with safety factor) and the fire source to be used in the experiment for this duration.

**Accident Scenario**
The accident scenario considered was a central ISO tank exposed to a 18.3 × 6.1-m (60 × 20 ft) LNG spill/fire by two adjacent ISO tanks. Each ISO tank has a capacity of approximately 37,854 liters (10,000 gallons) of LNG. Therefore, the time was calculated for 75,708 liters (20,000 gallons) of LNG to evaporate (over a 20 s spill time) and burn (over the remainder of the calculated duration), based on literature values of published regression rates. This time was then used to calculate the required amount of liquid propane needed to provide this test exposure.

**Burning Duration Calculations**
The Federal Rail Administration provided a summary reference [5] on the topic of LNG regression rates in a series of large-scale experiments and recommended the rate to be used in this calculation. The amount of propane required was calculated based on an exposure area of 12.2 × 4.0-m (40 × 13-ft) (nominal footprint of ISO tank on flatcar) and for a test duration of up to 73 min. Based on these calculations [6], the required amount of propane for this experiment was approximately 30,283 L (8000 gal).

**Final Fire Source Configuration**
The fire source consisted of a 12.2 × 4.0-m liquefied petroleum gas (LPG) burner. A 50-mm diameter piping array was installed in the steel burner pan. The array had eight branch lines and each branch line had (11) 3-mm diameter holes. The piping array was installed in the burner pan with the holes
pointed downward, which allowed the LPG to diffuse more evenly through limestone rock layer contained in the burner pan. LPG was fed to the burner array at the corners from a buried pipe. An LPG supply system consisting of a 30,283 L (8000 gal) LPG tank, pump loop, and flow meter was setup approximately 274-m (900-ft) away from the test area. An emergency stop button was routed to the adjacent control room to allow test personnel to safely stop the flow of LPG to the burner, in case of an emergency.

TEST INSTRUMENTATION

Several types of instrumentation were utilized in this experiment. Internal instrumentation included (24) gas/liquid/surface temperatures measured inside the test tank, as well as the internal tank pressure, the annular space tank pressure and the pressure relief discharge pressure.

Externally, 18 surface thermocouples (TCs) were provided to measure exterior tank surface temperature and provide boundary layer temperatures at the same nominal locations as the heat flux measurements. An additional 18 TCs were used to characterize the total heat flux from the fire and into the tank at several locations. Directional Flame Thermometers (DFTs) were used to measure the heat flux into the tank. The DFT was originally developed for measuring temperatures and heat fluxes in pool fires [7]. The DFT is conceptually similar to the plate thermometer but consists of two 3-mm thick, 120 × 120-mm Inconel plates with 25-mm thick ceramic fiber blanket in between. An advantage of the DFT over the plate thermometer is that the heat transfer through a DFT can be calculated with an inverse heat transfer code such as IHCP1D [8]. The use of these devices in fire experiments has been standardized in ASTM E3057 [9].

Incident heat flux was measured at two ground-based (1-m above grade) targets. Instruments were also provided at some distances from the tank to measure blast pressures, if any, resulting from catastrophic tank failure. Figure 3 provides schematic locations of the various external test instrumentation.

![Figure 3 External Tank Instrumentation Sketch.](image-url)
TEST RESULTS

SwRI’s Fire Technology Department performed a fire test of an LNG cryogenic tank (filled with LNG) secured on top of a flat car on June 29, 2022, at SwRI’s remote test site in Sabinal, Texas. The tank was exposed to the LPG fire source for a total of 56 min, followed by continuous burning of the LNG through the pressure relief connections and numerous other leakage points in valve cabinet. This continued for an additional two days. The following sections provide selected photographs of the setup, testing and post-test conditions, a summary of the video observations, a summary of the test data, and post-test observations and recommendations.

Selected Photographs
Figures 4-6 show the test setup, pre- and post-test condition of the tank and flatcar.

<table>
<thead>
<tr>
<th>LPG Supply Tank, Pump and Bypass</th>
<th>ISO Tank Valve Cabinet</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO Tank (West Side)</td>
<td>ISO Tank (East Side)</td>
</tr>
</tbody>
</table>

*Figure 4 Selected Setup and Pre-Test Photographs.*
Figure 5 Selected Testing Photographs.

Figure 6 Selected Post-Testing Photographs.

Data Summary

Figure 7 provides a summary of the temperature and heat flux data, as determined from the DFTs, centrally located on each side of the tank and over the fire source. Figure 8 shows the incident heat flux data, as determined from the copper disc calorimeters. Figure 9 and Figure 10 show the internal tank temperatures in the center as well as at the ends of the tank for the first few hours of the test. Figure 11 shows the internal pressure and level data in the tank over the first few hours of the test and Figure 12 shows the annular space pressure and pressure relief pipe pressure for the early part of the test. Figures 13-15 show selected data over the extended post-test duration.
It can be seen from reviewing Figure 7 that the fire exposure to the tank was not uniform and this was likely affected by the wind conditions. This resulted in a more severe exposure on the East side of the tank, as compared to the West side. The peak incident heat flux to the East side of the tank was 225.2 kW/m² and the peak incident heat flux to the West side of the tank was 32.1 kW/m². The peak incident heat flux from the fire source to the bottom of the flatcar was 105.7 kW/m².

Figure 8 shows the incident heat flux to targets 23-m away in the North and West directions. The peak incident heat flux to these targets was relatively low and the peak in the North direction was 2.68 kW/m² and the peak in the West direction was 1.27 kW/m². It was likely higher in the North direction for a longer duration due to the continued burning in the valve cabinet area after the fire exposure was terminated. Unfortunately, there was not a similar measurement taken on the East side of the tank, which would have likely been the highest radiative heat flux due to the non-uniform exposure on the tank from the fire source due to the ambient wind conditions.

Figure 9 shows the internal tank temperatures throughout the tank changed relatively consistently over the duration of the fire exposure. The internal temperature increased from approximately -215 °C to -165 °C.

![Temperature Graph](image1)

![Heat Flux Graph](image2)

![Center – East - DFT](image3)

![Center – West - DFT](image4)

![Center – Fire Source - DFT](image5)

*Figure 7 Selected DFT Heat Flux Data.*
Temperature Graph

Heat Flux Graph

North Copper Disc Calorimeter

West Copper Disc Calorimeter

Figure 8 Incident Heat Flux to Downfield Targets Data.

Figure 9 Internal Temperatures in Center of Tank.
Figure 11 shows the internal tank pressure increase from 345 kPa (50 psig) to 1.24 MPa (180 psig) over the fire exposure duration. The tank liquid level was also measured during the test and reflected by the IT-L series in Figure 11. Unfortunately, after approximately 110 min, this signal is unreliable, likely due to overheating. Additional data processing will be necessary to estimate how the liquid level changed over time.

The pressure relief valves (PRVs) seemed to operate at the correct nominal pressure. As can be seen in Figure 11 and 12, the first large increase on the PRV-P channel occurred at an internal tank pressure of approximately 807 kPa (117 psig), which coincides with the stated set pressure of 793 kPa (115 psig).
From this point in the test, the PRVs continued to open and close as necessary based on the internal pressure. Figure 12 also shows the annular space pressure between the inner and outer tank. Based on this data as well as the fast internal tank pressure rise during the fire exposure, it is likely the vacuum in the annular space was lost within a few minutes of the fire exposure.

![Figure 12 Annular Space Pressure and Pressure Relief Discharge Pressure.](image)

![Figure 13 Post-Test Internal Tank Temperature Data.](image)
In Figures 13-15, selected post-test data are presented to show how the temperatures stabilized as the tank burned off its contents. In Figure 15, it can be seen how half of the temperatures increase more rapidly since they are located above the liquid level and how the other half are only starting to increase after approximately 30 hours.
SUMMARY

The following subsections highlight a few conclusions from the testing activities during Phase II of the project.

- An ISO Tank, filled with LNG, was exposed to a LPG fire for approximately 56 min, after which time, the LNG continued to burn through the pressure relief valve and leakages in piping cabinet for an additional 48 hours.
- There was no BLEVE or other catastrophic failure observed during the test.
- Based on the internal pressure rise and vacuum pressure measurement, the vacuum likely degraded relatively quickly into the fire exposure. The pressure inside the inner tank increased to a peak of approximately 180 psig.
- The PRV system worked properly. The pressure valves began operating at approximately 114 psig. The valves intermittently reseated and close and reopened before fully opening for the majority of the test duration.
- There was additional venting after the fire exposure stopped and this continued for more than two days. The pressure in the tank was at atmospheric level in the morning of July 1, 2022.

FUTURE WORK

The following list highlights several topics that plan to be explored in more detail during Phase 2 of the project.

- Additional data analysis of Phase II results.
- Additional comparison between modeling calculations (virtual testing analysis methods) and experimental test results.
- Additional validation work between test data and modeling calculations after Phase 2 test is performed.
- Integration of phase change into the modeling calculations.
- Evaluation of crashworthiness through calculation.
- Evaluation of effects of tank rupture in various scenarios.

REFERENCES


Fire propagation and temperature distribution in the vicinity of CNG fuel tanks during a bus fire

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ABSTRACT

This paper presents the results of two compressed-natural-gas (CNG) -fueled buses in a burn test. The burn test was designed to mimic bus depot fire accidents.

The rate of development of the fire from the engine compartment to the fuel tank area, time to fill the whole passenger compartment with smoke and the time to open the TPRD (temperature-triggered pressure relief device) were of interest in relation to the time for the fire brigade to arrive to establish a safety perimeter.

The discharge of CNG and the evolution of the fire dynamics after opening the TPRD mounted on the fuel tanks were observed. The temperature on TPRDs as well as inside the bus were measured. Several cameras recorded the spread of fire and smoke both from outside and inside a bus.

Measured data are crucial for safe and efficient rescue operations and the evaluation of threats imposed on the surrounding environment.

KEYWORDS: cng, natural gas, bus, fire-test, jet-fire

INTRODUCTION

Compressed natural gas is an alternative to gasoline and diesel in private and public transportation systems with proclaimed environmental benefits. Nowadays, CNG buses are commonly found in the public transport fleets of many cities and urban agglomerations worldwide. Natural gas is a mixture of gaseous alkanes (methane, ethane, propane, and butane). The main component is methane in a concentration range of approximately 80-95 % by volume. Natural gas is flammable with flammability limits from 5 to 14.3 volume percent in air. CNG is stored onboard the bus in several cylindrical pressure vessels, usually mounted on the bus roof, under pressure up to 200 bar. In the event of fire, the pressure inside the fuel tanks increases as the temperature of the surrounding environment increases. To avoid vessel rupture, a pressure relief device is mounted on each vessel. The pressure relief device is temperature-triggered (TPRD) and is non-reclosable. Once opened, the entire contents of the vessel is released into the surroundings. After triggering the TPRD, gas under high pressure flows through a very small opening (on the order of millimeters) to the surroundings, resulting in a supersonic flow. Thus, compared to gasoline or diesel-fueled buses, both cloud fires and jet fires of significantly bigger size or length may evolve. During operation in the urban environment or at depots, buses are very often close to other vehicles and buildings. When the CNG pressure cylinder is being discharged, there is a high probability of causing significant damage in the relatively large perimeter. Berends and Sloetjes reported a case of a CNG bus fire, where a 15 to 20 meters long jet fire developed. Another incident occurred in April 2022 in Italy. CNG bus caught fire and jet fire of significant length developed on the left side of the bus. [2].
The issue of the vessel's local overheating or malfunction of the TPRD leading to the pressure vessel rupture [3] also cannot be completely omitted. This can be caused by improper design (e.g. covers or shielding of TPRDs), an insufficient number of TPRDs for long vessels, or by cooling TPRD during rescue operations.

The aim of the burn test was to determine the specific fire risks connected to a CNG-fueled bus fire in a context of its daily operation, evacuation of passengers in case of the bus fire and rescue operations. Emphasis was placed on a function of TPRD and the consequences of accidental natural gas discharge from fuel tanks. The burn test was designed to mimic two accidents that occurred in 2019 at a bus depot in the Czech Republic. In the first case, only one bus was destroyed, thanks to the immediate action taken by depot personnel. However, twelve buses were destroyed or heavily damaged during the second fire accident. In both cases, the fire ignited in the engine compartment. Fire at a bus depot presents a serious threat in terms of physical damage to the fleet and financial loss. The probability of a fire spreading from its origin is usually very high due to the small distances between parked buses.

EXPERIMENTS AND METHODS

Experimental setup
The test was carried out outdoors; with an average temperature of 7.7 °C. Average wind speed was 2.8 m/s, with a maximum of 8.3 m/s. Two CNG buses were positioned one meter apart from each other (see Fig. 1). Bus number one was ignited with 18 liters of heptane in an 80 × 80 cm pan placed under the engine compartment (see Fig. 2). Based on bus fire statistics, the engine compartment is one of the most common bus ignition locations in operation and at depots.

Figure 1 Experiment scheme
To monitor the fire growth and thermal conditions for TPRD activation, temperatures inside ignited bus number one and on the TPRDs were measured. K-type thermocouples (unshielded, 0.5 mm bead) were used. Figure 3 shows the location of four thermocouple trees inside the bus. The gas temperature was measured at three different height levels: 1.4 meters – head of a sitting person, 1.8 meters – head of a standing person, and 2.2 meters – ceiling temperature.

Figure 1 shows the locations of the thermocouples mounted on the TPRDs. They were mounted on the rear side of all pressure vessels on bus number one and at the front, middle, and back of the vessel closer to the origin of the fire on bus number two. To ensure that the temperature of the TPRD body was measured, TPRD thermocouples were mounted using high-temperature cement.

**Figure 2 Experiment photo**

**Figure 3 Thermocouple scheme**

**CNG fuel system**

Each bus was equipped with four composite pressure vessels (TYPE IV) mounted on the roof of the bus and covered with a fiberglass shell. The volume of each vessel was 240 liters. The initial pressure of natural gas in the vessels was 75 % of the maximum working pressure of 200 bars, which corresponds to a pressure of approximately 150 bars (25 kg of compressed gas in each vessel). Each vessel was equipped with a multifunctional valve on the front and rear sides of the vessel. Each valve was fitted with two TPRDs. Using the TPRD as a pressure relief device on a CNG fuel tank is required by UN Regulation No. 110. The valve in the front part of the vessels was fitted with a TPRD with an orifice 7 mm in diameter, resulting in an outflow area of 38 mm². The valve in the rear part of the vessels was fitted with TPRDs having four orifices, each 6 mm in diameter, resulting in a total
outflow area of 113 mm². TPRD orientation (direction of the gas outflow) on the tested bus is shown in Figure 4. Orientation of TPRDs varied between vessels, even on the same bus.

![](image)

**Figure 4** TPRD orientation

### RESULTS AND DISCUSSIONS

**Fire spread**

The development of the fire over the first bus and the spread of the fire to the second bus were very fast. This was partly due to a strong wind blowing in the direction away from the ignited bus to the second bus and also due to the relatively large ignition source (80 × 80 cm heptane pool). About two minutes after ignition, the rear left window on bus number one broke, resulting in a steep increase in temperature inside the bus due to improved fire ventilation (see Fig. 8). This led to the rapid advance of a smoke layer inside the bus. It took only two minutes for the smoke to first be detected in the rear part of the bus until all of the interior of a bus was engulfed in smoke (see Fig. 5).

Around four minutes after ignition, the fire was at maximum intensity. Temperatures oscillated between 800 and 1000 °C depending on changing ventilation conditions due to multiple window breakage. A sharp increase in temperature could be observed on all thermocouples along the bus length in a short period of time, showing very fast fire development. Six minutes after ignition, the fire inside the bus started to slowly decrease in its intensity as the combustibles were burning out, and the fire traveled from the rear to the front of the bus. The lowest temperatures were measured at the thermocouple tree in the middle part of a bus, where the fire load was the lowest (Fig. 2a). The test ended after 30 minutes from ignition.
Figure 5 Smoke spread

TPRD activation

About four minutes after ignition, the flames reached the CNG vessel on bus number two. During the next 50 seconds, the temperature on the surface of the TPRDs under the cover began to increase. Five minutes after ignition, a sudden increase in temperature could be observed on all TPRDs on bus number two (see Fig. 8). This indicates the opening of the TPRD and the burning of the discharging natural gas. Additionally, the flame color changed from deep orange to bright orange or even white confirming the combustion of the natural gas. Shortly after activation, a sudden decrease in temperature could be seen (see Fig. 8). This occurs due to TPRD cooling by gas expansion during its release. Natural gas being released from a high-pressure environment to a low-pressure one through a small orifice undergoes expansion. This expansion is accompanied by significant heat consumption. As a result, TPRD is cooled down even though it is engulfed in flames. Hasalová et al. [4] found that even relatively intense fire sources are not able to exceed the cooling effect due to gas expansion. Cooling the TPRD may result in a significantly lower gas release rate and a prolonged outflow time.

On bus number two, intense and rapid fire in the vicinity of the pressure vessels did not allow significant TPRD cooling due to expansion and gas outflow could continue with high outflow intensity. TPRDs temperature as seen in Fig. 8 increased sharply again short time after TPRD opening. At the maximum intensity of the natural gas leak, a jet-fire extending up to a distance of twenty meters to the left side of the bus number two was observed (Fig. 7). However, the size of the jet was strongly influenced by the wind. There was no other observed increase in the temperature of the TPRDs on bus two. It can be concluded that all the vessels in bus two discharged at a similar time. There was no influence of the fiberglass cover because the cover was destroyed by the very high intensity of the fire before the gas discharge started. The gas release ended about seven minutes after fire initiation. From this point, the temperature of the TPRDs decreased to approximately 700 °C, indicating that the flaming of natural gas had ended.

Different natural gas discharge behavior was observed on bus number one. Compared to bus number two, the cooling of TPRDs due to gas expansion had a strong effect, leading to the TPRDs’ ‘solidifying’ and resulting in a lower methane discharge rate. Although bus number one was the one where the fire was set, the TPRDs were activated about 50 seconds later than on bus number two, around six minutes from fire initiation. The beginning of the natural gas outflow is clearly indicated in Fig. 8 by a sudden increase in temperature. However, the peak value is around three times lower compared to bus 2 (Fig. 8). This was caused by several factors. Relatively strong wind pointed the fire plume toward bus number two and particularly its roof. The area of the pressure vessels was engulfed
in flames, leading to high temperatures and suppression of the expansion cooling effect. For bus number one, the flames reached only the back and left sides of the fiberglass cover of the pressure vessels when the gas discharge began. The fiberglass cover, which remained undamaged at that point, held the natural gas under the cover and protected the vessels against the direct influence of flames. Burning occurred only through leaks under the cover. The discharging natural gas was burning with a significantly lower intensity. The surface temperature of the TPRD decreased below 150 °C and remained almost constant until about 19 minutes after ignition. At that time, the temperature of the TPRD increased to above 400 °C, indicating the second ‘activation/reopening’ of the TPRD. At that stage, the fire was already in the decay phase. However, jet fires were clearly observed from the TPRD outlets in various directions. One TPRD outlet was pointed directly into the passenger compartment (Fig. 6). The length of the observed jets did not exceed three meters.

Figure 6 inner jet-fire

Figure 7 jet-fire maximal length
Figure 8 Temperatures during the experiment
CONCLUSIONS

Even though emphasis is nowadays given to other types of alternative fuels, CNG buses are still in operation world-wide and incidents with serious outcomes may occur.

The burn test showed very rapid fire propagation in the event of a bus fire. It took two minutes from the initiation of the fire until the first smoke was spotted inside the bus. It took another two minutes until the whole bus cabin was engulfed in smoke, leaving less than four minutes from the onset of the fire for the evacuation of passengers. The maximum gas temperatures reached values up to 750 °C when no burning of natural gas was present and around 1000 °C during natural gas release.

Burn test results corresponds well with the fire incidents reported in the literature. Jet fire of up to 20 meters can develop to any side of the CNG bus. Time when the jet develops cannot be predicted and fire jets can occur long after the fire initiation depending on the dynamics of fire spread over the bus and can occur even after fire-brigade arrive on scene.

Another issue that needs to be taken into account in case of CNG bus fires is “solydifing” of TPRDs. It was observed during small-scale experiments as well as during experiments with passenger cars [4] and was observed in the bus test burn as well. Solydifing of TPRDs does not increase the risk of the explosion of the vessel, because at least minimal outflow from the vessel is ensured. However, it may pose significant risk to intervening personnel as the intensity of jet fire can increase suddenly even a very long time after the fire initiation (even when other combustibles are consumed and fire is in the decay stage).

Although all parts of the CNG system may be compliant with ECE R110, there are no requirements for the performance of the CNG bus after the approved CNG system is mounted. This experiment confirmed the dynamic and hardly predictable behavior of a gas release and fire resulting from many factors: the size and location of the vessels, the type of TPRD, the material of the vessel cover, the material of the bus roof, etc. Some recommendations for enhancing the safety of the CNG system as a whole have previously been formulated [3] and are supported by the results of this experiment. To conclude general recommendation that jet fires of length up to 20 meters can occur during any time of rescue operation can be given.

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REFERENCES


[6] UN ECE Regulation No. 110, Uniform provisions concerning the approval of I. specific components of motor vehicles using compressed natural gas (CNG) in their propulsion system; — II. vehicles with regard to the installation of specific components of an approved type for the use of compressed natural gas (CNG) in their propulsion system

[7] UN Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV)
Hazards of EVs in the built environment and firefighting tactics

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ABSTRACT

Vehicles have changed significantly over the years. Modern vehicles present new hazards due to the incorporation of larger quantities of combustible materials (e.g., fuels, plastics, synthetic materials, etc.) into their designs and the popularization of alternative fuel (e.g., electric) vehicles. Concerns regarding their unique hazards, burn characteristics, and typical burn duration continue to be raised in the fire community. Compared to older vehicles, modern vehicles burn differently. Modern parking structures have optimized space requirements for vehicle parking and storage and often implement automated retrieval features and car stacking, which presents unique hazards as well. Thus, it raises the question if the safety infrastructure of these parking structures and vehicle carriers have kept pace.

Similar concerns have arisen among the fire service communities. There are a number of situations in which emergency responders may encounter EV incidents or crashes, including submersion, a collision, downed energized power lines laying on the EV, an exposure to an external hazardous material incident, or a vehicle over an embankment, for example, which often involve fire and/or significant damage to the vehicle. In all these events, first responders are called upon to conduct an initial size-up, rescue trapped victims, extinguish fires, assess the remaining state of charge, and determine means for vehicle removal, while trying to guard against stranded energy induced electric shock and mitigate a li-ion battery thermal runaway or reignition event.

The Fire Protection Research Foundation conducts a variety of research projects relating to the hazards posed by emerging technologies and the general push for electrification on the built environment and fire brigades. This paper covers current knowledge of the fire hazards of electric vehicle and goals, methods and preliminary findings of three distinct research activities: 1) Assessment of EV firefighting techniques and technologies and the impact on stranded energy 2) Classification of modern vehicle hazards in parking structures – Phase II and 3) Lithium-ion Battery Electric Bus Fire Risk Management and Prevention.

KEYWORDS: Electric vehicles, electric buses, fire hazard, first responder tactics, parking structures

INTRODUCTION

The electrification of all end-use sectors is a major part of global efforts to reach net-zero emissions by 2050. This includes passenger vehicles, delivery vans, public transportation buses, and heavy duty vehicles. Vehicle and battery manufacturers have pledged to invest $860 billion globally into the electric vehicle transition by 2030 [1]. In 2021, the number of electric vehicles on the road was triple that of three years ago, with over 16.5 million electric cars on the road. Through this exponential growth, Europe set a record for the highest electric car penetration rate, China sold more electric cars in 2021 than existed globally in 2020, and substantial growth was seen in the United States and other parts of the world. Adoption continues to accelerate as financial incentives are released by governments, new models and sizes are released on the market, and the battery capacities and ranges are increased.
This growth and adoption, however, is not limited to the passenger vehicle industry. The vehicle electrification initiatives also target delivery vans, public transportation buses, and heavy duty vehicles, as the transportation industry contributes approximately one-quarter of all energy-related greenhouse gas (GHG) emissions and buses produced 1.1% of total GHG emissions from the transportation sector annually, according to the United Nations Environment Program (UNEP) and US Environmental Protection Agency (EPA), respectively. To push the commitment to decrease greenhouse gas (GHG) emissions, improve air quality and reduce noise in cities, governments throughout the world have provided lucrative monetary incentives to encourage shared mobility and clean, sustainable, and fuel-efficient transportation. One of the outcomes of these incentives has been the increased use of electric buses for intercity, intracity, and school public transportation.

Vehicles have undergone a substantial transformation in their design over the last few decades. Government efficiency standards, in the US, Europe and China, are influencing the trends in modern vehicle design. Global efficiency goals have pushed automotive manufacturers to leverage increase the use of plastics and other synthetic materials to produce lighter and more fuel-efficient vehicles. Likewise, environmental goals have led to increased use of alternative fuel vehicles, such as battery electric, hydrogen fuel cells, liquified natural gas (LNG), among and other emerging technologies. With so many changes to materials and fuel sources used in the design of vehicles today, it has been confidently hypothesized that modern vehicles will behave differently in a fire.

Historically, fire protection strategies for the built infrastructure (e.g., parking structures, bus depots, etc.) were based on the hazards posed by traditional vehicle technologies, such as internal combustion engine vehicles (ICE). As the vehicle market landscape evolves to increasingly include more alternative fuel vehicles, and be dominated by battery electric vehicles, questions emerge regarding whether existing protection strategies are still appropriate based on the hazard characterization of battery electric vehicles of all scales. While parking structures developing into large, out of control events have historically been rare, they are on the uptick, as evidenced by the recent fires at Liverpool’s Echo Arena (UK) and at the Stavanger Airport (Norway) which involved hundreds of vehicles and resulted in severe structural damage. These incidents have raised concern regarding the probability of a single vehicle fire developing into conflagrations in a parking garage setting.

Similar concerns are raised from an emergency response perspective, as the distribution of vehicles on the road are increasingly electric. Fires in vehicles are not uncommon. However, a growing number of these responses require first responders to mitigate incidents involving hybrid and electric vehicles efficiently and effectively. With the global goals of vehicle fleets being predominantly electric by 2030, the need for up-to-date firefighter training and guidance becomes more critical as high-voltage vehicles are exponentially placed in service. In order to provide this much-needed education, more research and testing was required on the current battery systems being utilized by vehicle manufacturers to arrive at the best response methods.

A significant amount of research has been conducted by the Fire Protection Research Foundation (FPRF) and others regarding cellular and modular battery fire propagation, heat release, gas analysis, and cooling and extinguishment on lithium-ion batteries in electric vehicles, stationary Energy Storage Systems (ESS), and warehouse storage applications. This paper details a summary of the hazards posed by electric vehicles in the built infrastructure and during emergency response and summarized on-going research at the Fire Protection Research Foundation that is aiming to fill outstanding knowledge gaps.

**EV Hazards Compared to Other Vehicles**

Both ICEV and EV contain a large quantity of flammable materials, including the power system or fuel (liquid petroleum fuel or battery) and flammable plastic components [2, 3]. Vehicles more than 15-20 years old show a significant difference in average curb weight and plastic content, when compared to modern vehicles. The average US vehicle in 2018 contained 91% more plastic by weight
than the average vehicle in 1970, regardless of fuel source (e.g., EV vs ICE). This equates to a potential increase in chemical energy in a fire of approximately 2,300 MJ [4].

The composition of the vehicle body for both ICEV and EV were fairly consistent, with a high percentage of plastic content. The available test data has confirmed the heat release rate (HRR) was largely driven by the combustion of the vehicle body [5]. But since the vehicle body composition is relatively consistent between passenger EVs and ICEVs, the fuel source (e.g., fuel tank or li-ion battery pack) drives the differences in HRR. Literature indicates that the heat release rates of EVs are often slightly lower than ICEVs, however, they are generally in comparable ranges. It should be noted that vehicle HRR was found to be highly dependent on the test conditions such as the vehicle size, the type and placement of the ignition source, ventilation conditions and the configuration of the vehicle, fuel source of the vehicle, and its surroundings, as HRR above 7 MW were found in vehicle fire tests from every decade since 1970 [4].

General conclusions when comparing HRR data between ICE and EV vehicles is that the EV’s do not necessarily present a greater hazard than ICE’s, but simply a different hazard. Limited test data also revealed that the peak HRR from burning gasoline in an ICE vehicle occurred around the same time or earlier than involvement of the EV batteries. Since the composition of the vehicle’s bodies are similar, the fuel tank in an ICE and the batteries in an EV really drive the main distinguishing characteristics and difference between ICE and EV fires, such as an ICE posing a pool fire scenario and EVs posing a potential jet fire scenario. While the fire intensity and total energy released from vehicle fires of varied ages has remained relatively constant, the changes in construction materials have reduced the time to...
ignition, increased the probability of spread, and the fuel sources have altered the behavior of fire development, which increases the hazards in built infrastructure such as parking garages and bus depots [4].

**FIRE SPREAD**

Historical data has shown that a fire spreading to multiple vehicles was rare. Between 1995 and 1997, 98% of parking structure fires involved less than four vehicles, and none involved more than seven. By contrast, 14% of parking structure fires involved more than five vehicles in 2014 [6]. Past regulations assumed that fire spread from one vehicle to another would not occur, and if it did, the fire department would arrive in time to control it [7]. However, the densely packed fuel loads in parking garages or bus depots heightens the risk of fire spread among electrified vehicles given the changes in material composition, increase in vehicles dimensions, and tighter parking arrangements. Although limited, available test data has shown rapid fire spread between vehicles in a parking garage configuration, on the order of 10-20 minutes. However, once two or more cars are involved, the time to ignition of additional vehicles is reduced dramatically.

If the fire spreads and more vehicles become involved, the prolonged high-temperature exposures on the load-bearing structural elements can threaten the integrity of the structure. Incident experience suggests that the majority of fire incidents in electric buses have spread beyond the vehicle of origin. And at the Liverpool incident, the constant high temperature exposures caused significant spalling of the concrete, which typically occurs when the internal temperature exceeds 374°C (705°F) [7]. This created large penetrations in the floor which contributed to vertical fire spread. The ceiling level temperatures experienced from an inferno of modern vehicles can also cause failure of structural steel. Once it exceeds its critical threshold of 538°C (1000°F) the load bearing capacity is reduced to half and may compromise the structure. As seen in the Stavanger Airport fire in Norway (2020), these conditions can lead to structural collapse of a multi-story parking structure. This is changing the hazard profile of vehicle fires and their impact on infrastructure such as parking garages.

**EV FIRE MITIGATION STRATEGIES**

Although the available literature on fire suppression and firefighting strategies for EV’s is still limited, EV fires are generally harder to suppress due to the challenge of internally cooling the battery pack, the long duration of the fire event, and their potential for reignition. Past FPRF research found that for the suppression of an EV fire, water is still considered as most effective, and a significant amount of water is required to extinguish and cool the battery [8]. While less suppressant can be used if it is directly applied to the battery pack, it is difficult to get direct water streams onto the battery packs to achieve sufficient cooling.

Alternative applications of water have also been studied by RISE through internal and external applications of water sprays and mists on EV fires. It found a water-based suppression inside the battery compartment to have lasting cooling effect and positive impacts on stopping thermal runaway propagation. In line with the findings of other studies, external water applications require long duration suppression, yet still showed minimal cooling effects and failed to stop propagation within the battery pack [9]. Thermal and atmospheric impact will be focal points within the context of fire development and possibilities of rapid extinguishment, potential cooling effects and potential fuel enrichment resulting in explosivity. Further study is warranted for determining if and how best to apply agents to lessen the overall amount of water required and if the use of these agents contributes to re-ignition due to the increase in solution conductivity.

While FPRF testing has primarily focused on water-based extinguishment, a 2014 study by DEKRA in Germany assessed the use of water additives for the control and extinguishment of lithium-ion batteries used in EVs. The two agents tested showed promise in reducing surface tension and allowing
deeper penetration into battery compartments. In the NTSB investigations it was found that a foam or wetting agent was used at most of the incidents at some point during the total response [10].

As an alternative to water-based tactics, fire blankets to smother EV fires are gaining traction, although limited in the literature to date. A vehicle studies company, Centro Zaragoza, examined the impact of fire blankets on smothering an EV fire and preventing battery reignition [11]. Results have shown a positive impact on reducing temperatures and toxic gas release, however reignition still occurred, though extended coverage time was hypothesized to limit the probability for reignition. The role and effectiveness of fire blankets have been identified as a knowledge gap, worthy of additional testing to study their effects in isolating EV fires and reducing risk to first responders.

**KNOWLEDGE GAPS**

While a substantial body of literature on battery and EV hazards has been developed over the last decade, EV battery technology has seen significant changes regarding architecture, power, and the increased use of high-kilowatt hour (kWh) batteries over the last couple of years.

The fire service has been left with little insight on how to safely and effectively manage firefighting activities and stranded energy hazards during and after an EV fire incident. Battery re-ignition post incident has become more common when faced with a high-kilowatt hour battery containing a significant state of charge. This information is lacking from the overall body of scientific literature, meaning guidance for assessing the hazards of stranded energy with respect to mitigating the overall incident is also lacking. The diversity of response situations encountered by first responders necessitates different approaches, which should be guided by sound research on how to deliver water most effectively and efficiently to the battery pack. Alternatively, allowing the vehicle to burn and consume much of the stranded energy, reducing the potential for re-ignition and/or the severity should the battery catch fire again may be preferred. A study of the intersection of these two issues was needed produce much valuable data to inform operational procedures for first and second responders to EV incidents.

Likewise, engineers, designers and facility managers have been left with limited guidance on appropriate and effective protection strategies. Additionally, test data to be utilized through sound engineering analyses or assessments to inform decision making have also been lacking.

While past studies have helped move the needle forward on our understanding of the hazards and impact of protection strategies, more work is needed to further clarify recommended protection strategies in facilities and clear guidance on how first responders should tactically handle electric vehicle fires. The following areas were identified as needing additional research:

- The factors and conditions contributing to vehicle-to-vehicle fire spread.
- Further assessment on the effectiveness of sprinkler protection on modern vehicle fires in normal parking configurations, as well as car stackers.
- Impact of vehicle fires on concrete spalling.
- Hazard assessment of bus depots with electrified bus fleets and charging infrastructure.
- Assessment of the effectiveness of various EV firefighting techniques and technologies and their impact on the stranded energy risk.

**ONGOING RESEARCH FROM THE FIRE PROTECTION RESEARCH FOUNDATION TO ADDRESS KNOWLEDGE GAPS**

In response to these gaps, the Fire Protection Research Foundation has initiated a number of studies to provide further guidance. These are summarized below:
Assessment of EV firefighting techniques and technologies and the impact on stranded energy

Fire departments respond to a high percentage of fires involving passenger highway vehicles every year. In 2020, firefighters responded to vehicle fires at a frequency equating to one vehicle fire every 3 min and 3 seconds, accounting for 15% of all reported U.S. fires and 18% of the associated fire deaths [12]. Although fire statistics of electric vehicles are not yet captured holistically, scientific literature and fire incidents have shown that electric vehicles pose unique risks and challenges to emergency responders. As the EV market continues to grow in lockstep with the net-zero emissions goals, the potential for responders to encounter crashes and/or fires from these vehicles will grow proportionately.

There are a number of situations in which emergency responders may encounter EV incidents or crashes. These scenarios may include submersion, a collision with one or more vehicles or a stationary object, downed energized power lines laying on the EV, an exposure to an external hazardous material incident, or a vehicle over an embankment, for example, which often involve fire and/or significant damage to the vehicle that may preclude access to manual disconnects for the high voltage battery system or cause extensive battery damage. In all these events, first responders are called upon to conduct an initial size-up, rescue trapped victims, extinguish fires, assess the remaining state of charge, and determine means for vehicle removal, while trying to guard against stranded energy induced electric shock and mitigate a li-ion battery thermal runaway or reignition event. As battery energy storage efficiency increases, the size and capacity of EV battery modules will likewise increase, resulting in a proportionally larger risk to all parties involved with an EV emergency event.

A report from the US National Transportation Safety Board found that firefighters lacked the necessary training and guidance to respond effectively to EV incidents containing lithium-ion batteries.

In response, the Fire Protection Research Foundation initiated a study to develop the information necessary for improving efficiency and safety during response to high-voltage lithium-ion battery EVs by determining the effectiveness of current firefighting techniques, evaluating new technologies and practices, and determining the impact of suppression activities and risks associated with stranded energy and re-ignition. The outcomes of this research will provide an evaluation of the performance of suppression tactics for EVs through a large-scale testing effort.

The large-scale fire test methods employed through this project to develop qualitative and quantitative data to inform best practices and develop training programs, can be summarized as follows:

1) Cell Level Testing: Cell level tests will be conducted on lithium-ion batteries from three distinct manufacturers of the latest model and chemistry type to evaluate the repeatability of critical cell temperatures, gas production, and mass loss measurements across cells from different EVs forced into thermal failure under ambient conditions and their sensitivity to heating rate applied for use in subsequent scaled testing.

2) Module Level Testing will be conducted to evaluate:
   a. Cell to cell propagation rate to establish baseline fire hazard at the module level, and the scaled effects of state of charge, failure method, and test environment (i.e., ambient air or enclosed).
   b. Thermal runaway propagation control approaches, including the resulting effect of surface cooling at different water flow rates applied to the bottom and side of a scaled pack enclosure and quantitatively compared to volume filling suppression approaches using water and water additives.
   c. The effect of flame control by means of a thermal blanket on gas production and failure propagation.

3) Cold Flow Pack Level Testing
   a. Cold flow tests utilize battery pack shells and vehicle mock-ups to identify and quantify fire department tactics that result in water ingress into battery packs. Suppression streams are defined by approach orientation, height, distance, stream
type, pressure and flowrate. Cold flow tests will be quantitatively compared based on the total water delivered to the target and water delivery efficiency.

4) Pack Level Fire Testing
   a. Pack-scale fire tests will be conducted utilizing fully populated EV packs and vehicle mock-ups. Baseline measurements of the unsuppressed fire (e.g., HRR, cell, module, and pack temperatures, heat flux, gas production details, and total mass loss) will be gathered. Structural failures in the pack resulting from cell thermal runaway that allow for unplanned water ingress will be investigated. Based on data collected from the cold flow pack testing, at least two candidate suppression approaches will be selected and tested at the pack scale.
   b. Post-test analysis evaluate thermal runaway propagation and overall damage within the pack; flame extension outside the pack observed during testing; measured HRR, total heat release (THR), heat flux to exposures, and stranded energy.
   c. Additional testing will be conducted to evaluate and compare the effect of fire blankets based on time and duration of deployed.
   d. A final set of pack level tests will seek to develop a transitional or combination attack plan, merging active cooling and flame suppression approaches to minimize the total energy and exhaust gases released from the failure event.

5) Full-Scale Electric Vehicle Testing: Based on the findings from the previous tests, the following four full-scale electric vehicle tests will be conducted:
   a. Free Burn
   b. Full-scale EV fire test will be conducted applying a water-only suppression approach developed based on the findings of the pack-scale suppression efficiency analysis.
   c. The combination or transitional attack approach applying both active suppression and fire blanket approaches developed from results of Test Series 2 shall be applied.
   d. The final full scale vehicle test shall be appropriated to examining a water-based suppression scenario where a limited, or delayed, water supply necessitates highly efficient and deliberate fire suppression.

Protection against hazards of electric vehicles and electric buses in parking structures and bus depots
As the electrification trends continue, the fire protection systems and strategies in our built infrastructure, such as parking garages and bus depots, must keep pace with the evolving hazards of the vehicles present in these facilities. An essential element of designing fire protection systems is understanding the design fire. The design fire specifies the heat release rate that should be used in the design of the system response. Designing for the maximum credible event or consequence has also been gaining traction in other literature. A significant amount of work has been developed to determine the statistical basis for this maximum credible event (MCE). If a rich enough dataset of previous events exists, then statistical estimates can be made about the MCE. However, for sparse datasets, like for electric vehicles and electric buses, various approaches are explored for defining the statistical bases for accidents. One approach is to use statistically parameterized and validated models to generate a consequence prediction space. A key element of this approach is the need for validated models for the underlying physical phenomena that couple to define the consequence space. For the parking garage or bus depot accident scenario, a critical question is “what role does the battery system play in the hazard evolution?”. Specifically, how does the heat release rate and/or flammable gas evolution rate for a battery-powered vehicle or bus failure contribute to the hazard evolution. Thus, it is critically important to acquire data on the burning characteristics and gas generation rates of battery-powered vehicles and buses.

The Fire Protection Research Foundation has two active research projects that are working to make demonstrable progress on defining the EV design fire and establishing fire protection and risk mitigation strategies for parking structures or bus depots by:
   - Establishing additional full-scale vehicle test data to support and clarify the design fire for a battery electric vehicle.
• Compiling available data on the burning characteristics and gas generation rates of battery-powered vehicles and buses to validate models and generate model additional scenarios better understand past incidents and characterize other potential consequences.
• Establishing evaluation criteria to classify the hazard of electric vehicles.
• Establishing a hazard mitigation framework for assessment of the hazard posed by electrified vehicles to indoor facilities, like bus depots and parking structures.

A summary of these two projects and their high-level objectives and methods are provided below:

1) **“Classification of Modern Vehicle Hazards in Parking Structures – Ph. II”** which aims to quantify the fire hazard and spread characteristics of modern vehicles (electric and ICE) to inform fire protection requirements for parking structures.

In light of the number of large-scale experimental studies of full EV’s still being limited in the public domain, the "Classification of Modern Vehicle Hazards in Parking Structures – Ph. II” study focuses on contributing to the overall body of test data for electric vehicle hazard characterization in comparison to internal combustion engine vehicles in the context of parking structures and systems in our communities today. This study includes an international review of trends in parking structures and emerging parking systems to clarify the characteristics of the existing and future stock of parking garages and vehicle distribution (ICE vs EV) that would impact the design and installation of fire protection systems (e.g., spacing between cars, ceiling height, construction type, presence of car stackers, etc). Since applicable codes and standards have been updated to provide additional protection measure in parking structures, as a result of recent incidents, a review of statistical data on the experience of vehicle fire events in sprinklered versus unsprinklered garages is also being conducted. Following the baseline literature review and data analysis effort, an EV and an ICE test specimen will be procured fully characterized and burnt under a calorimeter to obtain baseline hazard data, such as HRR, heat flux, temperature, gas measurements, etc. This test data will be compared against the established evaluation criteria to assess the fire hazard characteristics and potential for fire spread between modern vehicles.

2) The **“Lithium-ion Battery Transit Bus Fire Prevention and Risk Management”** project is developing a guide to lithium-ion battery transit bus fire prevention and risk management with recommended practices for original equipment manufacturers, battery companies, transit agency facilities, and vehicle maintenance. This project is comprised of qualitative and quantitative elements, including conducting a literature review to assemble qualitative and quantitative data and using models of various types and levels of sophistication to organize and communicate quantitative data. The baseline information and modeling results are then used to develop a Hazard Mitigation Analysis (HMA) methodology and guide for qualitatively and quantitatively assessing the safety of bus depots or other vehicle storage facilities.

Full-scale fire test data for electric buses is even more limited than for passenger electric vehicles. A lot of the hazard characterization data for electric buses is coming from incident experience at this time. As the technical test data and literature on this topic expands, it is important in the meantime to establish a framework for assessing, quantifying, and improving the level of safety at electric bus depots and other applicable indoor facilities. This strategy is particularly important for newer technologies, like electric buses, for which standards are relatively immature and where new technologies are being integrated rapidly and in novel ways. It is recognized that as technologies mature, test data combined with the data of past failures, can be used to update standards to minimize the reoccurrence of any previously experienced failure type or support the development of best practices for fire service response and management. Scenario planning, supported by HMAs, may anticipate possible failure types for these less mature technologies, with the goal of mitigating these potential failures with engineered or response solutions.

While there are many ways to construct an HMA, this study utilizes the bowtie methodology as it allows for significant information to be conveyed in one diagram, but also allows for that same
data to be condensed down immensely to focus on single threats or consequences. Each barrier may be condensed to a color, or relative strength, for ease of review while also containing large amounts of data and analysis regarding effectiveness. The model may also be converted to tabular form as needed. Barriers may be rated quantitatively based on effectiveness and relevance while threats and consequences may be evaluated based on likelihood and impact. In some cases, some consequences may feed into threats of greater magnitude or of another type, which can be viewed in multiple ways. Figure 3 provides an illustration of a general bow-tie methodology for a given hazard analysis [13].

Confidence in the output of a hazard mitigation process requires an evidence-based approach to recommendations. The evidence can be based upon existing data either in the literature, generated from validated models supplied from industry consensus and expert opinion, or produced via test data and field failures. The methods of this project include collection and organization of the data necessary to begin building out the bowtie models and providing guidance for how safety and design professionals can evaluate EV bus depots and complete the HMA process to inform implemented hazard mitigation strategies.

CONCLUSIONS

The presentation will summarize the findings from past FPRF projects on the hazards of modern vehicles, including EVs, and the knowledge gaps that led to the on-going research activities around vehicle electrification. It will also explain the project methods and preliminary findings from the on-going “Assessment of EV firefighting techniques and technologies and the impact on stranded energy” study, “Classification of Modern Vehicle Hazards in Parking Structures – Ph. II” study and the “Lithium-ion Battery Transit Bus Fire Risk Management and Prevent” study that are available at the time of the conference.

REFERENCES


Fire safety in semi-automatic parking facilities

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ABSTRACT

This paper investigates fire safety in semi-automatic parking facilities (garages). A semi-automatic parking facility is a parking facility where larger or smaller areas have a system for automatic car stacking or close parking of cars on the same level. The paper is based on a project initiated to increase the knowledge about semi-automatic parking facilities and fire safety in these facilities. Information about semi-automatic parking facilities in Norway and abroad was collected through surveys, interviews, and literature studies.

KEYWORDS: parking facilities, car stacking, fire safety, interviews, regulations.

INTRODUCTION

Automatic car stacking systems can increase the capacity of a parking facility by dense parking of cars on one level (Figures 1 and 2) or stacking of cars on several levels (Figure 3). For the sake of simplicity, we will use the term “car stacker” for both systems where cars are placed on several levels and systems on just one level. The car stacking gives a higher fire load inside the parking garage. A semi-automatic parking facility is a conventional parking garage which users can access where an automatic car stacking system has been installed. The stacked cars are not isolated from the users by solid walls. Due to the abovementioned features, semi-automatic parking facilities may impose higher fire risks for users and challenges for fire services. However, information about fire risks in semi-automatic parking facilities or car stackers is scarce in the open literature, and information about relevant safety regulations in different countries can be difficult to find and understand without contacting local experts.

This project was initiated to broadly address the risks, experiences, prevention, preparedness, and regulations related to fire in semi-automatic parking facilities. The situation in Norway was in particular focus, but information from other countries was used as a supplement. The overall goal was to provide a report that contributes to more knowledge about semi-automatic parking facilities and how to mitigate risks related to fire inside them.

METHODS

To learn about events and potential risks in semi-automatic parking facilities, interviews were conducted with several fire and rescue services who have experience and/or competence in complicated and at-risk buildings. The fire and rescue services contacted were located in larger towns in Nordic countries.

A literature study was also conducted, and fire authorities and fire safety experts in several countries were contacted about regulations related to semi-automatic parking facilities and the experiences they may have with fires in such facilities. The investigation of regulations focused on requirements for sprinklers and smoke ventilation. The literature study and contacts covered eight countries: Denmark, Finland, France, England, Germany, New Zealand, Singapore, and Sweden.
A producer of automatic car stacking systems was consulted, and a field study was arranged. In the field study, project participants visited a semi-automatic parking facility in a Norwegian town. The local fire brigade, people involved in assessing the fire safety, and users of the parking facility were also present.

RESULTS AND DISCUSSION

Types of automatic car stacking systems
All the commercially available automatic car stacking systems found in the mapping work involve parking a car onto a platform, which a mechanical system can then move. The platform can typically be 260 cm wide and 560 cm long [1]. The stacking systems we found in Norway have the platforms aligned horizontally, but stackers with tilted cars exist [2]. The systems can be very simple, with a single platform sliding between two areas to allow cars to park behind it, like in Figure 1. Other systems that park cars on one level can have a fleet of platforms that can move sideways to give way to the innermost parking spaces. This is sometimes called fleet parking, and an example is shown in Figure 2. For both these systems, the innermost parking spaces can be ordinary parking spaces without any platforms, but they can only be accessed when the platforms in front are available or the system moves the platforms to give access. The systems can also be more complex, like systems where the floor has been excavated to allow for underground parking in a section of the parking garage. For such a system, a person passing by may not be able to see that there is an underground level.

Figure 1 Car stacking with just one platform that can slide between two places in order to let other cars access the ordinary parking spaces behind it.

Figure 2 Car stacking on one level with several sliding platforms arranged so that all parking spaces can be accessed.
The systems on one level can be without any side walls, but the commercial systems with stacking over several levels found in this work had wire fences around the automatic stacking systems. The presence of such fences can restrict the access of firefighters. When there are walls around the systems, the users will typically have a key to open it, and a platform for them to park on will be provided by the system. The driver will drive onto the available platform, leave the car, walk away from the platform, and the door will be closed before the system moves the platform with the car.

The systems can be equipped with chargers for electric vehicles (EVs), and it is also possible to install EV chargers after the system is installed.

Finding parking spaces in urban areas can be tricky, and these automatic stacking systems are very useful for increasing the available parking spaces in densely populated areas. It is therefore expected that more of these systems will be installed in large towns and cities in the near future and that new creative solutions for increasing the number of parking spaces per area may arise.

## Guidelines, regulations, and experiences

The literature review, interviews and contacts gave no examples of fire-related incidents in semi-automatic parking facilities. This is not very surprising, as fires in parking facilities are rare and semi-automatic parking facilities are a relatively new concept.

Construction works in Norway must fulfil the requirements of the building code, which is commonly known as TEK17 [3]. The building code mainly provides functional requirements. This building code also has a guideline, VTEK17, [4] that provides acceptable solutions (i.e. solutions deemed to satisfy the functional requirements) which are optional to follow. Sprinklers are not mandatory for parking garages in Norway, i.e. this is not a requirement in TEK17.

The VTEK17 provides acceptable solutions for parking garages, but these apply to the building itself and do not specify requirements for automatic car stacking systems. VTEK17 states that fully automatic parking garages, which are closed and not accessible to the public, must have automatic sprinklers which can operate for a minimum of 60 min. It is not specified if this is also valid for semi-automatic parking garages. Furthermore, VTEK 17 § 11-8 says that automatic sprinklers must be installed when the total area of levels with open connection is over 800 m². In the same paragraph, it is also specified that emergency exits must be available from each level. Based on this acceptable solution, it seems unsuitable to define internal levels inside a semi-automatic parking system as separate levels. Hence, according to the guidelines, a rather large parking facility with car stacking systems may be constructed without automatic sprinklers in Norway. However, it is specified that parking facilities with an area above 400 m² must have smoke ventilation.

An overview of regulations for parking facilities in eight countries outside Norway is given in Table 1. When investigating laws and guidelines in other countries, it was apparent that semi-automatic parking facilities are rarely described. France, Germany, New Zealand, and Singapore have regulations for
Fully automatic parking facilities, i.e., parking facilities with car stacking systems which are closed off from the public. In Germany, it is specified that parking facilities with more than 20 parking spaces for cars must have automatic extinguishing systems. In Singapore, fully automatic parking facilities are divided into three categories based in height and area, and automatic sprinklers are required in all categories except the category for the smallest and most open parking facilities [5].

Table 1 Overview of regulations for parking garages in eight countries outside Norway.

<table>
<thead>
<tr>
<th>Country</th>
<th>Are there general requirements for sprinklers and smoke ventilation in parking garages?</th>
<th>Do the regulations specify requirements for facilities with automatic car stacking?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark [6, p. 9]</td>
<td>Guideline (acceptable solutions): Sprinklers and smoke ventilation are sometimes indicated, depending on the area of the parking garage and how it is used.</td>
<td>No, these are not included in the guidelines. Fire safety must be documented by analysis.</td>
</tr>
<tr>
<td>Finland</td>
<td>The requirement for smoke ventilation depends on the fire load. Sprinklers are not required.</td>
<td>No</td>
</tr>
<tr>
<td>France</td>
<td>Not answered</td>
<td>Sprinklers are required for fully automatic parking facilities if there are more than three levels [7].</td>
</tr>
<tr>
<td>Singapore</td>
<td>Not answered</td>
<td>For fully automatic parking facilities only [5].</td>
</tr>
<tr>
<td>Sweden</td>
<td>Guideline (acceptable solutions): Sprinklers for fire sections over 5000 m² (sum of the area on all levels connected). This applies to all types of buildings.</td>
<td>No</td>
</tr>
<tr>
<td>Germany</td>
<td>Automatic extinguishing systems must be provided for all parking garages with more than 20 parking spaces. Smoke ventilation is mandatory in many states.</td>
<td>For fully automatic parking systems only</td>
</tr>
<tr>
<td>England [8]</td>
<td>Venting of heat and smoke, depending on the type of building in which the parking facility is located</td>
<td>No</td>
</tr>
<tr>
<td>New Zealand [9]</td>
<td>Sprinklers if the gross area is over 5000 m².</td>
<td>Yes, sprinklers.</td>
</tr>
</tbody>
</table>

Concerns of the fire and rescue services
Lack of regulations, lack of overview and lack of access to inspection were important topics during the interviews. If the owner of an ordinary parking garage decides to install a system for the automatic movement of cars in a fleet parking or a stacking system, they can do it without any application process or requirements for upgrading of fire safety measures. There is no system that ensures that the fire services become aware of the system that is present. Some of the fire services who were familiar with these types of installations were first made aware of them by coincidence. Based on internal investigations, some fire services had created their own overview of how many semi-automatic parking facilities there were in their regions. A better overview of where the semi-automatic facilities exist and access to inspect them was desired by several of the interviewed fire services. One way to improve the overview would be to require a building application before such a system could be installed.

One concern that was mentioned by several fire services was fires in EVs, since these can be hard to extinguish and sometimes easily reignite. In a report on fire safety when vehicles powered by alternative fuels are parked in closed spaces [10], it was recommended that underground parking facilities are designed in a way that makes it possible for the fire services to tow ignited EVs to an area where it is easier to prevent fire spread, such as an area without combustible material close by. In a semi-automatic parking facility with fleet parking, it will be challenging to get access to tow out a car unless the fire service can override the automatic parking system and make the system clear the way...
up to the ignited vehicle. In an automatic car stacker, both cars below ground and higher levels can be difficult to access, and cars on the ground level can be shielded by wired fences, as shown in Figure 4.

Figure 4: Automatic car stacking system on three levels. The ground level and underground level are shown, while only the bottom of the platforms on the top level are visible. The ground level is shielded with a wire fence.

Concerns were also raised regarding accessibility to extinguish cars on higher levels or in the middle of a fleet of parked cars. For fleet parking, the cars may be so closely packed that a firefighter cannot walk in between them with a hose. The system would also need to stop moving platforms before a firefighter could enter, and the firefighter would need some way of finding out whether the system is immobilized or not.

For semi-automatic parking facilities under or at the base of a heavy building, concerns were raised regarding the ability of the structure to hold the load. If it takes a long time for the fire services to reach the facilities, the structural integrity of the stacking system may be heavily reduced.

**Increased fire load and risk for fire spread**

The purpose of creating a semi-automatic parking facility or upgrading an ordinary parking facility to a semi-automatic one is to increase the maximum number of cars parked in the system. Inherently, the fire load can be much higher in a semi-automatic parking facility than in an ordinary parking facility. In addition, the system also introduces new elements that can increase the fire load or risk of fire spread, such as the hydraulic system and the reduced space between cars.
In the field study, a semi-automatic parking facility under a residential building block was visited. When the systems for stacking cars were installed, inhabitants took the initiative to have fire safety evaluated. People who were involved in this evaluation were present at the field study and said that the existing sprinkler system had been considered insufficient. They had therefore upgraded the sprinkler system to improve fire safety.

The increased risk of fire spreading for stacked cars was investigated experimentally in England in 2009. Two tests were conducted with two cars placed in a mock-up stacker. The fire started in the lower car. One test was conducted with sprinklers installed [11] and one without any extinguishing [12]. The driver’s window of the lower car was open, but otherwise, all windows were closed. In the test without sprinklers, the fire spread to the car above within 6 minutes, and the inside of the upper car was burning within 9 minutes after the lower car was ignited. The maximum heat release rate was 8.5 MW, which was reached within 12 minutes. For the other test, eight sprinklers were installed at strategic positions: four above the top car and four lower in the rig. The fire was started similarly as the first test, and the fire spread to the upper car within 11 minutes after ignition. 13 minutes after ignition, the first sprinkler was activated. Only three sprinklers were activated over the duration of the test. After the test with sprinklers, most of the combustible material in the lower car had burned, but the upper car had only external damage. The sprinklers managed to significantly reduce the temperature of the fire, despite only a few sprinklers activating. In the same test series, tests were also conducted to investigate fire spread between cars on the same level. In one test set-up, a fire was started inside a car where the driver’s window was open, and the fire spread easily to a car parked beside it and from there over a vacant parking space to another car. However, in a similar test with sprinklers installed, the fire did not spread to any of the cars. These tests demonstrate how sprinklers can be very effective in limiting fire from spreading horizontally, but vertically they can have less impact.

In addition to the increased fire load caused by denser parking of cars, there has also been a general increase in fire load for cars over the last decades. Newer cars are bigger and contain more plastic materials [13], and they also have a higher maximal heat release rate [14]. Also, EVs and hydrogen cars bring new concerns regarding fire load and extinguishing efforts required.

CONCLUSIONS

Several types of automatic car stacking systems for increasing the parking capacity of a parking facility exist. Such parking facilities help utilize the area more efficiently and may become more popular and show up in new creative forms as communities become more urbanized.

No examples of fire-related incidents in semi-automatic parking facilities were uncovered in this research. Still, there are many aspects that give rise to concern for fire safety, and the main impacts are listed below.

- Increased fire load
- Higher risk for fire spread
- Restricted accessibility for fire and rescue teams

It is therefore recommended to assess how the installation of an automatic car stacker or fleet parking system affects the overall fire safety of a parking garage before the installation is conducted and to evaluate the load-bearing capacity of the load-bearing structures.

Since the presence of automatic car stacking systems in a parking facility increases the fire risk, it would be helpful for fire services to know where these installations are located and to have access to inspect them. In Norway, it is not required to send an application before installing a car stacking system in an existing parking garage. There is no system that ensures that the Norwegian authorities are notified when the systems are installed.
Requirements and acceptable solutions in Norway and several other countries are based on the total area of a fire compartment or fire section or the total parking garage area. The total area is not an ideal parameter to establish the guidelines on when cars are packed more closely than in traditional parking garages, such as during stacking or fleet parking. Parameters such as the fire load density or the number of parking spaces may be more suitable, either alone or in combination with the total area.

ACKNOWLEDGEMENT

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REFERENCE LIST

Fire safety engineering case study of an electric vehicle car park fire

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ABSTRACT

The risk of electric vehicle fires increases significantly as this market is in great expansion. At the same time, there is a need to deepen the current knowledge on this type of incident to prepare adequate fire safety measures. A method for formulating the fuel and related effluents based on available experimental results of internal combustion engine and electric vehicle fires is proposed and applied to a generic case study. The objective is to verify the respect of the tenability conditions during a fire involving internal combustion engine and electric vehicles in a car park, and to observe the differences in terms of smoke extraction efficiency for these two types of vehicles.

KEYWORDS: electric vehicle, car park, heat release rate, toxicity, fire safety engineering

INTRODUCTION

For reasons of limited space, especially in city-centers, car parks are often built underground and on several levels. Their structure can vary in dimensions and geometry but are usually made in incombustible materials such as concrete. Thus, the fuel load in underground car parks originates mainly from the vehicles and materials present there, and frequently with a high density leading to the possibility of large fires. Recommendations and practices [1][2][3][4][5] have been introduced in France, the Netherlands and the United Kingdom to take into account the additional fire risk associated with electric vehicles (EV), especially regarding charging stations, sprinklers, smoke management, and dedicated firefighting procedures, but they are based on limited research. When a fire occurs in an underground car park, it differs from open-air fire due to the ventilation conditions that can affect the fire development, the upper layer stratification and the temperature. Because of the relatively low ceiling and compartmentation in such structures, the hot gases can rapidly accumulate and increase temperature and toxicity issues for users and emergency services, while the heated structure could enhance the radiation imparted to materials at proximity. If the fire intensity, the temperature and visibility conditions are crucial for the structural behaviour of the building, the fire effluents are also of main concerns for the safe egress of users and the efficient intervention of the firefighters.

With the expansion of the electric vehicle market [6], the probability of electric vehicle fires increases significantly. It thus becomes necessary to develop tools and quantitative data to address fire safety concerns. EVs are mainly equipped with large lithium-ion battery packs, which represents a change in the type of risk, especially in the case of enclosed structures such as car parks.

Large-scale tests of electric vehicles are expensive and seldom published [7]. Due to the lack of tests, it is difficult to verify if the structural designs are resilient to electric vehicle fires. Thus, it seems necessary to develop the current research on this type of incident. Valuable experimental studies are nevertheless available in the literature [8][9][10][11][12][13][14][15][16][17][22][23]. These studies are of great interest for evaluating the fire behaviour, and the fire effluents for both conventional and electrical vehicles. From the cited studies, it is concluded that the risk of EV fires is comparable and may not be significantly more hazardous than traditional vehicles (ICEV – Internal Combustion Engine Vehicles)
in terms of peak heat release rate (pHRR), total heat release (THR), and the resulting heat of combustion related to the mass of fuel burned. However, an additional risk comes from the characteristics, in terms of combustibility and toxicity, of the venting gases from the battery, which are released after its thermal runaway and in particular the hydrogen fluoride (HF). For fire safety engineering purposes, a design fire curve can be derived for quantifying a given fire scenario for such vehicles, which represents the time evolution of the HRR for the adequate THR. It must be associated with representative fuel characteristics in terms of heat of combustion and fuel stoichiometry, and to the release yields of effluents.

Numerical simulations are commonly used in fire safety engineering for evaluating the environing conditions, both thermal and toxic, for a given fire scenario and building type, especially with the CFD code Fire Dynamics Simulator (FDS) [25]. For instance, a comparative numerical study of the smoke clearance and temperature conditions in a car park was conducted based on various tests carried out on conventional and electric vehicle fires in [15]. However, the fuel used for the modelling was a simple hydrocarbon and was similar for both vehicles. In a more recent publication [24], an electric vehicle fire in an underground car park was simulated to assess the safety conditions for the public but the study was not based on experimental HRR nor used a representative fuel. The simulations showed that in the event of an electrical vehicle fire, no additional risk was observed in terms of thermal effects compared to an internal combustion engine vehicle fire.

The type of fuel used as input in the numerical simulations of an electric vehicle fire must be representative of the materials of the vehicle and those of the battery to accurately predict the thermal and toxic conditions. However, it is generally difficult to compare the toxic effects of the various combustion gases emitted by electric and internal combustion engine vehicles. Moreover, the effluent’s yields may vary with time. Indeed, the full set of the different quantities of combustion gases emitted are rarely quantified and detailed, even if valuable studies provide part of the effluent yields [9][11], and in particular the HF emissions which can be toxic for the public or the emergency services.

For this, a method for formulating the fuel and these effluents based on experimental results is proposed in this article. It is applied to a generic case study related to an underground structure. The objective is to verify the respect of the tenability conditions during a fire involving internal combustion engine and electric vehicles in a car park, and to observe the influence these two types of vehicles.

**NUMERICAL SETUP**

**Fire Dynamics Simulator**

The numerical simulations are performed with the Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS) version 6.7.9 [27]. FDS is a computational code in fluid dynamics that incorporates a combustion model and a model for the description of turbulent flows (Large Eddy Simulation). This code allows 3D modelling of the computational domain. It considers heat transfer at walls, ventilation conditions for the removal of hot gases, and air intakes. The Navier-Stokes equations are solved in the limit of low Mach number, thermally driven flow with an emphasis on smoke and heat transport from fires. The radiative heat transfer is included in the model through the solution of the radiative transport equation for a grey gas. The default sub-models of FDS are used for the gas phase radiation exchanges. The default grey gas model is based on soot spectral bands. The grid used for the radiative transfer equation solver is the same as for the fluid solver. The default value of 100 solid angles is chosen in FDS. The combustion model with primitive and lumped gas species definition, to solve a transport equation for each species to be tracked, was also used. The default Deardorff model is used for the LES sub-grid modelling. The thermal characteristics of the structural elements are integrated into the numerical model in terms of density, thermal conductivity, heat capacity and emissivity. Then, the 1D heat transfer at walls is simulated with the given thermal characteristics of the system components.

**Underground car park**

A generic floor representative of a level of an underground car park is modelled with an area of approximately 2000 m² and a capacity of 63 vehicles (Figure 1). In the numerical model, mesh cells of
0.250 x 0.250 x 0.125 m (x,y,z) are used. The car park door is represented with an opening of 7.00 x 2.25 m (w x h). Two pedestrian access doors are considered for evacuation. The mechanical smoke extraction is provided in accordance with the requirements of the French Technical Instruction n°18 relating to covered car parks [26]. The air inlet is provided by a fan with a 3.375 m² area and a flow rate of 11.8 m³/s. The air exhaust surface is of 2.25 m² with a flow rate of 15.8 m³/s. The initial fire source is applied on the upper face of an obstacle representative of a car with dimensions 4.0 x 2.0 x 1.0 m (L x w x h) and located in the upper right part of the car park (see Figure 1). No fire spread to adjacent vehicles is taken into account in this generic study.

**Figure 1** Overview of the generic covered car park modelled with FDS - location of the fire source (red), the air inlet (green) and the smoke exhaust (blue)

### METHOD FOR FUEL AND EFFLUENTS

In FDS, it is necessary to integrate a combustion equation that specifies the nature of the fuel as well as its associated effluents. The input data are then the effluents’ yields, fuel chemistry and heat of combustion. The methodology used to evaluate the complex fuel stoichiometry in the case of an electric or an internal combustion engine vehicle is based on the toxic data of the various combustion products emitted during tests that are available in the literature. From the different production rates \( \nu \) of the effluents emitted (mainly Soot, \( \text{H}_2\text{O} \), \( \text{CO}_2 \), \( \text{CO} \), and \( \text{HF} \)) and the oxygen consumption yield \( \nu_{\text{O}_2} \) as given in Equation (1), it is then possible to determine the chemistry of a fuel that can represent as faithfully as possible the fuel mixture of an electric vehicle as a whole (vehicle and battery).

\[
\begin{align*}
C_aH_bO_cCl_dF_e + \nu_{\text{O}_2}\text{O}_2 & \rightarrow \nu_{\text{CO}_2}\text{CO}_2 + \nu_{\text{CO}}\text{CO} + \nu_{\text{Soot}}\text{Soot} + \nu_{\text{H}_2\text{O}}\text{H}_2\text{O} + \nu_{\text{HCl}}\text{HCl} + \nu_{\text{HF}}\text{HF} \\
\end{align*}
\]

Each stoichiometric coefficient \( \nu_X \) of each specie \( X \) in Equation (1) can be expressed from the mass yields (in grams of specie \( X \) / gram of mass lost) and the ratio of the molecular weight of both specie \( X \) and the fuel as presented in Equation (2). However, the molecular weight of the fuel \( M_{\text{Fuel}} \) is itself dependent on the amount of each atom \( (a, b, c, d \text{ and } e) \) and hence of the stoichiometric coefficients. However, the ratio of two different combustion products \( X \) and \( Y \) is only dependent on their respective molecular weight and mass yields as expressed in Equation (3). Note that by measuring the heat of combustion \( \Delta H_c \) (in MJ/kg), it is also possible to gain knowledge of \( \nu_{\text{O}_2}/M_{\text{Fuel}} \) as proposed by Equation (4).

Hence, by measuring the heat of combustion and the respective mass yields of each specie, it is possible to estimate each stoichiometric coefficient and then the fuel chemistry. However, from the measurements of the different effluents during the tests, it is not possible to distinguish the products of combustion from the vehicle itself and from the battery or the fuel tank.
\[ v_x = y_x \frac{M_x}{M_{\text{fuel}}} \]  
(2)

\[ \frac{v_x}{v_y} = \frac{M_x}{M_y} \]  
(3)

\[ \Delta H_c = 13.1 \times v_{O_2} \frac{M_{O_2}}{M_{\text{fuel}}} \]  
(4)

It has to be noted that some data may not either be measured or presented in the literature for each effluent. For example, in [8], the mass yields of water vapour were not provided. For this example, this issue can be addressed by performing an analysis of the stoichiometric coefficient ratio between water vapour and carbon dioxide \( \frac{v_{H_2O}}{v_{CO_2}} \) that can be obtained for various compounds.

This can be achieved thanks to Equation (5) and by knowing the amount of carbon and hydrogen \((a\) and \(b\) respectively) as well as the carbon monoxide and soot yields (that can be translated into stoichiometric coefficient \(v_{CO}\) and \(v_{\text{Soot}}\)). Such analysis shows that this ratio ranges between 2.0 (for methane) and 0.4 for materials hydrocarbons compounds releasing large amount of soot such as polycarbonate, polystyrene or benzene [19-21].

\[ \frac{v_{H_2O}}{v_{CO_2}} \approx \frac{b}{a-v_{CO}-v_{\text{Soot}}} \]  
(5)

The different fuel chemistries derived are synthesised in Table 1. Soot and HCl emissions from the EV and ICEV fuels are comparable and the type of vehicle seems to have a limited influence on their yields. Regarding CO emissions, the EV fuel appears to release 75% less than ICEV fuel. This relatively small difference is consistent with the findings of [22]. HF emissions are severely irritating to humans even at low concentrations and both EVs and ICEVs produce HF. From the fuels derived in our study, the HF emissions from the EV fuel are twice those from the ICEV one, in consistency with the significant quantities of HF found in reported fire tests. Fluorine can originate from the battery cell but also in the air conditioning system or flame retarded materials. The fuels determined based on the experimental results of [8] are used to the practical case of fire safety engineering study described in the previous section.

<table>
<thead>
<tr>
<th>Fuel type - Formula</th>
<th>HoC (MJ/kg)</th>
<th>Effluent yields (g/g fuel)</th>
<th>CO</th>
<th>Soot</th>
<th>HF</th>
<th>HCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV - C_{1.38}H_{2.47}O_{0.41}Cl_{0.006}F_{0.008}</td>
<td>30.25</td>
<td>0.04550</td>
<td>0.01090</td>
<td>0.00630</td>
<td>0.00630</td>
<td></td>
</tr>
<tr>
<td>ICEV - C_{1.70}H_{2.88}O_{0.21}Cl_{0.009}F_{0.004}</td>
<td>36.15</td>
<td>0.06010</td>
<td>0.01115</td>
<td>0.00310</td>
<td>0.00910</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Fuel type for the fire scenario investigated.

FIRE SCENARIOS

Different scenarios are considered in terms of initial vehicle as fire source in terms of HRR curve and fuel stoichiometry. The first one results in an electric vehicle, the second one involves an internal combustion engine vehicle. These first scenarios use HRR and stoichiometry of the different fuels evaluated using the effluent measurements derived from the experimental data of Lecocq et al. [8].

In the study of Lecocq et al. [8], the HRRs were evaluated for two electric vehicles and two internal combustion engine vehicles, from two different constructors. During these tests, the charge status of the battery was 100% for the electric vehicles, and the fuel tank was full for the internal combustion engine vehicles. The peak heat release rate and the total heat release rate for the four vehicles were comparable as well as the heat of combustion related to the mass of fuel burned. Thus, that the risk of EV fires is comparable and may not be significantly more hazardous than more traditional ICEV in terms of pHRR, THR, and the resulting heat of combustion related to the mass of fuel burned. However, the fire
propagation can be influenced by test conditions and by the ignition method that is used. The characteristics of the fire scenarios considered are synthesized in Table 2. For fire safety engineering purposes, a design fire curve can be derived for quantifying a given fire scenario for such vehicles, which represents the time evolution of the HRR for the adequate THR. It must be associated with the fuel characteristics in terms of heat of combustion and fuel stoichiometry, and to the release yields of effluents. From the four tests provided by Lecocq et al. [8], different HRR curves can be derived with a unique set of parameters to represent the initial fire growth and its decrease. The maximal HRR reached in the plateau phase is the one from the experiments, and the horizontal plateau is limited by the decay phase which starts when 50% of the total fire load has been consumed. The fire growth can be assessed using the following equations for the fire growth and decrease:

\[
HRR_{\text{growth}} \propto \left(\frac{t}{\alpha}\right)^2
\]

(6)

\[
HRR_{\text{decrease}} \propto e^{-t/\beta}
\]

(7)

With \(t\) the time in seconds, and the parameters \(\alpha\) and \(\beta\) constant parameters with respective values of 300 s and 12.5. The growth rate \(\alpha = 300\) s is representative of a medium fire kinetics in standard fire safety engineering studies [31]. The decay is observed when 50% of the THR is achieved with a decay rate \(\beta=12.5\) s. The unique set of parameters \(\alpha\) and \(\beta\) is used to evaluate the simplified HRR curves for the four fire tests of [8], as indicated in Figure 2. The generic fire curves for the EV and the ICEV are derived using the unique set of \(\alpha\) and \(\beta\) parameters and the maximum pHRR of each type of vehicle from the two constructors.

![Figure 2](Evolution of the Heat Release Rate for the EV and ICEV fire scenario from [8] (straight lines) and from the simplified curves (dotted lines) - generic EV and ICEV curves.)

The fire scenarios from Table 2 are then simulated using FDS. These scenarios allow investigating the influence of the fire curve, of the fuel type and of both the fire curve and fuel type on the usual quantities evaluated in simulations such as gas temperature, extinction coefficient, and effluent concentrations.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>HRR profile</th>
<th>Fuel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 a</td>
<td>EV</td>
<td>EV generic</td>
</tr>
<tr>
<td>1 b</td>
<td>EV</td>
<td>ICEV generic</td>
</tr>
<tr>
<td>2 a</td>
<td>ICEV</td>
<td>EV generic</td>
</tr>
<tr>
<td>2 b</td>
<td>ICEV</td>
<td>ICEV generic</td>
</tr>
</tbody>
</table>

Table 2 Fire scenario investigated.

A criterion for the quality of the mesh resolution is given in the FDS reference guide [28] and in the literature [29], for simulations involving buoyant plumes. The non-dimensional \(D^*/\Delta x\) ratio is proposed to estimate the quality of the mesh, where \(\Delta x\) is the size of the grid cells and \(D^*\) the characteristic fire diameter. It is recommended that \(D^*/\Delta x\) to range between 4 and 16. According to the experimental results from [8], the peak heat release rates for the vehicles considered were comprised between 4.5 and
5.8 MW, associated in the simulation with a surface of the vehicle of 4 x 2 m (8 m²). Hence, considering that the mesh is fine when D*/ Δx is taken at 16 (highest value of the recommended range), the mesh size should be of 0.15 to 0.25 m. Thus, the grid size used in this study (0.25 to 0.125 m) can be considered sufficiently fine to accurately capture the combustion and turbulence phenomena. No sensitivity analysis was hence performed regarding the fine mesh size selected in this application.

RESULTS

Quantities analysed
The influence of the fuel type is analysed in terms of gas temperature, soot extinction coefficient and effluent concentrations, in particular CO and HF emissions during the vehicle fires. Usual criteria exist to evaluate the compatibility of the smoke exhaust system together with a safe evacuation of users and later intervention of the rescue services such as firefighters. These criteria are synthesised in Table 3. In this paper, all of these criteria are observed at head height for the public (i.e. 1.875 m). For the rescue services, these criteria would have been evaluated at 1 m from the ground. Because the influence of some effluents is more dose related, no unique values for HF and HCl concentrations are used as criteria but their influence is rather provided by the FEC evolution.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Users</th>
<th>Rescue services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas temperature</td>
<td>40°C</td>
<td>100°C</td>
</tr>
<tr>
<td>Soot extinction coefficient / Visibility of light-emitting sign</td>
<td>0.4 m⁻¹ / 20 m</td>
<td>1.6 m⁻¹ / 5 m</td>
</tr>
<tr>
<td>CO concentration</td>
<td>150 ppm</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 Criteria for the gas temperature, soot extinction coefficient and CO concentration.

Additionally, the overall toxicity of combustion during the fire scenarios considered through the calculation of the fractional effective doses (FED) at exits in the car park based on ISO 13571-2020 [32]. The concept of Fractional Effective Dose (FED) and Fractional Effective Concentration (FEC) relate to the manifestation of physiological and behavioural effects in exposed subjects and is dependent on both the concentration of the asphyxiant gas and exposure time. It supposes that the asphyxiant gases have a cumulative effect, and the irritant gases have an instantaneous effect at tenability level. Carbon monoxide (CO) and hydrogen cyanide (HCN) are the only asphyxiant gases considered. CO₂ is considered for its effect and not only as an aggravating factor for hyperventilation as in previous revision of the model. Irritants are also considered through their dose effect. The general aspect of the model is given in Equation (8), where \( C_i^n \) is the average incremental concentration, expressed in \( \mu L/L \) of the class-specific toxic gas \( i \), AF is the assessment factor applied to calculate the incapacitation threshold based on the respective non-lethal threshold concentration, \( \Delta t \) is the chosen time increment, expressed in minutes and \( k_i \) is the effect-based toxic load constant. For asphyxiants, the model considers the effect of CO, CO₂ and HCN as in Equation (9). For irritants, the parametrization of the equation is taken from [33].

\[
X_{FED}^{(FEC)} = \sum_{i=1}^{N} \sum \frac{(C_i^n x AF_i)^n}{k_i} \Delta t
\]

\[
FED_{tox} = \sum \frac{([CO x 3])^{1.77}}{0.498 \times 10^8} \Delta t + \sum \frac{([HCN x 3])^{1.64}}{0.109 \times 10^6} \Delta t + \sum \frac{3}{0.114 - 1.14\% CO_2} \Delta t
\]

Numerical results and analysis
The different quantities detailed in the previous section are presented in the following figures for the fire scenario considered at 5, 10 and 15 minutes of fire. These times correspond respectively to the early evacuation period of the car park of the users, and to the fire conditions related to the HRR’s plateau encountered later by the rescue services during their intervention.

Regarding the gas temperature in Figure 3, it is observed that the criterion is reached at exit 2 in 5 minutes for every fire scenario, while exit 1 is still safe until 15 minutes. Only slight differences appear
between the four scenarios although the temperature is hotter in the areas away from the fire source for scenarios 2a and 2b.

<table>
<thead>
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</tbody>
</table>

**Figure 3** Gas temperatures at man height – Values hidden under the criterion of 40°C.

The visibility in terms of soot extinction coefficient in Figure 4 shows that the criterion is reached at exit 2 in 10 minutes for every scenario, while exit 1 is still safe until 15 minutes for scenarios 1a and 1b. As previously observed for the gas temperatures, the visibility criterion is lost in the areas away from the fire source for scenarios 2a and 2b.

<table>
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</tbody>
</table>

**Figure 4** Soot extinction coefficient at man height – Values hidden under the criterion of 0.4 m⁻¹ (visibility of 20 m).
The CO and HF concentrations are shown in Figure 5 and Figure 6 respectively. A concentration of CO up to 150 ppm is evaluated at exit 2 for the scenario 2, whereas it is not the case until 10 minutes for scenarios 1. After 15 minutes, exit 1 experiences CO concentrations lower than 150 ppm for scenarios 1 but this criterion is reached for scenarios 2. Regarding HF concentrations, conditions are quite comparable until 5 minutes for every fire scenarios. However, higher HF concentrations are observed after 10 minutes for scenarios 1a at 2a, involving EV type fuel. Interestingly, the HF concentrations are more important in the car park for scenario 2a than for scenario 1b and for scenario 2a than scenario 1a.

![Figure 5 CO concentration at man height – Values hidden under 150 ppm.](image)

![Figure 6 HF concentration at man height – Values hidden under 10 ppm.](image)
FED and dose of asphyxiants are presented in Figure 7 at 10 and 15 minutes. Values up to 1.0 are reached in 15 minutes for scenarios 1a and 2b involving EV type fuel. However, FED and asphyxiant at exit 1 are lower than 1.0 until 15 minutes. Note that the FED and dose of asphyxiants values follow the trends of HF release.

<table>
<thead>
<tr>
<th>FED</th>
<th>Asphyxiants</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 min</td>
<td>15 min</td>
</tr>
<tr>
<td>1 a</td>
<td></td>
</tr>
<tr>
<td>1 b</td>
<td></td>
</tr>
<tr>
<td>2 a</td>
<td></td>
</tr>
<tr>
<td>2 b</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 7  FED and dose of asphyxiants at man height – Values hidden under 0.1.*

**CONCLUSION**

The tenability conditions were evaluated during a fire involving vehicles in an underground car park through a method for formulating the fuel and related effluents based on available experimental results of internal combustion engine and electric vehicle fires. A design fire curve was derived for quantifying a given fire scenario for such vehicles, that represents the time evolution of the HRR for the adequate THR with a unique set of parameters to represent the initial fire growth and its decrease. Four different fire scenarios were then simulated using FDS to investigate the influence of the fire curve, of the fuel type and of both the fire curve and fuel type on the usual quantities evaluated in simulation such as gas temperature, extinction coefficient, and effluent concentrations.

The gas temperature showed that the criterion considered for a safe evacuation of users was reached at exit n°2 in 5 minutes for every fire scenario, while exit n°1 was still safe until 15 minutes. Only slight differences appeared between the four scenarios although the temperature was hotter in the areas away from the fire source for scenarios 2 involving the HRR curve of ICEV vehicle. Thus, whereas the pHRR for the two types of vehicles were comparable, it appeared that the consequences of EV fires was not significantly more hazardous than more traditional ICEV in terms gas temperatures. The soot extinction coefficient for the four fire scenarios showed that the criterion for visibility was reached at exit n°2 in 10 minutes for every scenario, while exit n°1 was still safe until 15 minutes for scenarios 1. However, the visibility criteria was reached in the areas away from the fire source for scenarios 2.

Values of CO concentrations up to 150 ppm were evaluated at exit n°2 for the scenarios 2, whereas it was not the case until 10 minutes for scenarios 1. After 15 minutes, exit n°1 experienced CO concentrations lower than 150 ppm for scenarios 1 but this criterion was reached for scenarios 2. Regarding HF concentrations, conditions were quite comparable until 5 minutes for every fire scenario.
However, higher HF concentrations were observed after 10 minutes for scenarios 1a at 2b, involving EV type fuel. This conclusion was also drawn regarding the FED and dose of asphyxiants at 10 and 15 minutes, where values up to 1 were reached in 15 minutes for scenarios 1a and 2b involving EV type fuel. Thus, the fuel type has a greater influence than the fire curve regarding the concentration of eflluents.

From this generic numerical work, it appears that using EV vehicle as fire source is not leading to gas temperatures and visibility conditions more severe than for a more classical ICEV fire as used in fire safety engineering study. However, HF concentrations are higher for EV type fuel, and the FED and dose of asphyxiants values of 1 are then reached in less than 15 minutes. Thus, it appears of importance to considerate this effluent in fire safety studies dealing with closed geometries such as an underground car park when EV fuel is used.

It has to be noted that the conclusions drawn from these simulations are dependent on the chosen hypothesis and inputs. First, the HRR curves are closely related to the ignition scenario used in [8] (ignition occurs inside the car) and it can be debatable to use such data to simulate the spread from one vehicle to another. This is why no fire spread to adjacent vehicles was taken into account in this generic study. Note that no explosion or projection related to the battery was observed during EV fire tests in the tested conditions. Second, fluorine can originate from the battery cells but also from the air-conditioning system for example. As observed during the tests in [8], both EVs and ICEVs produce HF but the emission attributed to the combustion of the battery pack appears at approximately 35 minutes after ignition when a first and similar peak for both EV and ICEV is observed around 15 minutes. The HF yields are not constant during the fire. Even if the HF emissions are higher for EV, the toxic threat for such vehicles may arise at the later stage of the fire. The methodology for estimating a fuel chemistry is generalizable to any experiment or to extract several fuel corresponding to different stages of a fire. However, the approach of using a generic fuel describing the whole duration of a vehicle fire leads is quite common in fire engineering studies but leads to increase the simulated toxic threat as it increases the toxicants yields at the beginning of the fire. It has to be reminded that as for the HRR, the HF emissions are also dependent on the mode of ignition and fire spread inside the vehicle when first experimentally characterised.

While the HRR behaviour of vehicles is continuously studied for decades [16], the nature of the combustible fuel release by the combustion of the vehicles is seldom studied or discussed. As new materials or usage (plastics, air conditioning fluids, more electronics, etc.) are introduced in vehicles, fuel/toxicants release needs to be updated so the risk analysis and fire engineering studies stay relevant. This paper proposes an approach to generate generic fuels based on experimental fire results. It should be of prime importance to keep up performing experimental campaign - maybe at European level – as more and more EV are developed and put on the market, with an emphasis on both the HRR and the fuels/toxicants through for example FTIR measurements. Also, the fire load of charging stations can be added in such studies, as well as the effect of sprinklers on visibility, etc. No fire spread to adjacent vehicles was considered in this study, but the consequences of multiple vehicle fires should also be investigated and especially the criterion for the fire to spread from one vehicle to another, especially in case of explosion or projection from battery packs.

REFERENCE LIST

2. NEN 6098 Smoke control systems for powered smoke exhaust ventilators in car parks.
3. NEN 2535 Fire safety of buildings - Fire alarm systems - System and quality requirements and projection guidelines.


12. LCPP, “Etude de l’impact de feux de véhicules électriques (RENAULT) sur les intervenants des services de secours”, Fort de la Briche Saint Denis (91) BSPP, 2 avril 2012.


27. FDS (Fire Dynamics Simulator) general web site https://pages.nist.gov/fds-smv/


Submerging container and its possible alternatives: a comparative assessment study

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Arnhem, The Netherlands

ABSTRACT

The number of electric vehicles in The Netherlands increases rapidly. With this, the number of incidents involving the battery pack of these vehicles also increases. We examined the current used practice of submerging containers to mitigate fires in electric vehicles and compared the submerging container with other available techniques on the market.

INTRODUCTION

The number of battery electric vehicles (BEV) in The Netherlands is rapidly increasing over the past years and will continue to do so even more rapidly in the years to come. With this increase, the number of electrical vehicle incidents also increases. These BEV incidents come along with other types of risks in comparison to internal combustion engine vehicles (ICE). Especially the ‘thermal runaway’ of the battery pack requires a different fire suppression tactic compared to ICE to fully extinguish the fire.

One of the tactics used in The Netherlands is submerging (of the battery pack) an electric vehicle into dedicated containers. These so-called submerging containers have been used multiple times to extinguish the fire in the battery pack. This method of extinguishment also has it drawbacks, for example, battery pack has to be damaged in order for the water to reach the battery cells. This gave rise to the discussion whether or not the use of submerging containers is the best available technique to extinguish fires in the battery pack of an electric vehicles or that other more suitable methods are available. To give clarity in this discussion we answered four research questions:

1. In which situations is a submerging container currently used in The Netherlands?
2. How does a submerging container control/suppress BEV incident?
3. Which alternatives are available and how do they work?
4. How do these alternatives assess in comparison to the submerging containers for the response?

METHOD

In order to answer research question 1 and 2, interviews were held with towing companies as well as with fire brigades regarding the use of a submerging container. These interviews were held by mail, telephone as well as by MS Teams. To answer research question 3 and assist in the answering of research question 4, a study in Dutch and international literature is held, as well as interviews with several research institutes in other European countries.

The scores in research question 4 are given with the use of expert opinion (intersubjectivity), where possible supported by literature. For this several researchers and applied professors of the Dutch Institute for Public Safety together came to a judgement on the different alternatives which have been found in research question 3.
As an aid to come to the judgement of the different alternatives for the submerging container, three scenario’s are described.

Scenario 1a: Fire in an electric vehicle in which the battery pack is indisputably involved in the fire. The vehicle in this scenario is easily accessible.

Scenario 1b: Fire in an electric vehicle in which the battery pack is indisputably involved in the fire. The vehicle is parked in a parking structure.

Scenario 2: Fire or an accident in which there is suspicion by the first responders that the battery pack might be damaged (either mechanical, thermal or electric), but it is unknown if the battery pack has an increasing temperature and possibly goes into thermal runaway.

We based this judgment on seven criteria, which are given in Table 1:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety of firefighting personal</td>
<td>The matter in which the application of the technique brings firefighting personal at risk, for example the exposure to smoke or high temperature. The time firefighters are close to the vehicle as well as the required number of firefighters to apply the technique is of influence for this criterium.</td>
</tr>
<tr>
<td>Safety of towing company personal</td>
<td>The matter in which the application of the technique brings towing company personal at risk, for example the exposure to smoke or high temperature. The time towing company personal are close to the vehicle as well as the required number of towing company personal to apply the technique is of influence for this criterium.</td>
</tr>
<tr>
<td>Cooling effect</td>
<td>The matter in which the technique slows down / stops further propagation of the thermal runaway in the battery pack</td>
</tr>
<tr>
<td>Additional damage to the vehicle</td>
<td>The additional damage the vehicle gets as an extra as a result of the technique on top of the damage already there to the vehicle as a result of the fire.</td>
</tr>
<tr>
<td>Impact on the environment</td>
<td>The pollution of air / ground / water as a result of the use of the technique, to nature and size.</td>
</tr>
<tr>
<td>Deployment time</td>
<td>The time it costs to apply the technique from the moment it is decided to do so.</td>
</tr>
<tr>
<td>Practical usability</td>
<td>The ease to use a technique in the correct manner. Hereby is looked at the availability, the level of skills needed and the amount of special actions required of the technique to be used.</td>
</tr>
</tbody>
</table>

We judged the criteria using a five-point scale (--, -, +, + and ++), where -- was a high negative influence and ++ was a high positive influence by the alternatives on incident response to the electric vehicle. The judgement was done by the ‘ceteris paribus’ principle, meaning that the use of the alternative was the only changing factor, where other circumstances remained the same.

The judgement is done in a group discussion for each of the seven criteria per scenario. This judgement led to a score per criteria per alternative. The total score of the seven criteria per alternative resulted in the best available technique per scenario.

**RESULTS**

With the use of interview results, the literature study and expert opinion, we answered the four research questions.

**RQ1: In which situations is a submerging container currently used in The Netherlands?**

the procedure for the use of the submerging container in The Netherlands is that the container is brought to the scene in case of manipulation (damage by heat or an accident) of the battery pack. The vehicle is then transported in the container and stored in the container at the tow yard. If the battery pack is unstable, the container is then filled with water.
Until this point in time, the submerging containers are only used at the request of the fire brigade at fires and traffic accidents involving electric vehicles [2]. In 2021, in the Netherlands, the submerging container was called to the incident scene 22 times. The battery electric vehicle was actually submerged in the container 11 times.

**RQ2: How does a submerging container bring the incident under control?**

From multiple research it is shown that the (long-term) cooling of a battery pack is de most effective way of stabilizing the thermal runaway [3], [4]. The submerging container is able to stabilize the temperature and therefore prevent for further propagation by having the ability to cool the cells, the battery casing and/or surrounding carrosserie for a long period of time. Next to that, the water washes out a large proportion of the dangerous gases.

The cooling effectiveness of the submerging container mostly depends upon the possibility for the water to penetrate the battery pack. This is less easy than it looks as battery packs are designed to be water resistant [5]. Openings in the battery pack, such as ventilation openings, a removed service plug or damage due to fire enable water to enter the battery pack and apply cooling at the cell level.

**RQ3: Which alternatives are available and how do they work?**

The alternatives for the submerging containers can be categorized in three phases:

> Extinguishment: fully extinguish the fire in the battery pack (and the vehicle)
> Suppression: cooling / suppression of the fire in the battery pack
> Transport: technique for (safe) transport of an vehicle involved in an incident.

The different alternatives are given in Table 2, the most left column. And “X” marks the activity in which alternative can be used for.

**Table 2 Submerging container alternatives and their applicability to incident management activities**

<table>
<thead>
<tr>
<th>Method</th>
<th>Extinguishment</th>
<th>Suppression</th>
<th>Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submerging container</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Aerosol container</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Cobra Coldcutter</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-Extinguishing Lance</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobile sprinkler</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mobile submerging unit</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire blanket</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Transportation blanket</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BEST battery extinguishing system</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Extinguishing bag</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire-access in battery pack</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Let the vehicle burn out</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**RQ4: How do these alternatives score in comparison to the submerging containers for the response?**

To answer this research question, the three scenario’s as mentioned in the methodology section are used. Based on literature, we described the alternative and it’s operation. Based upon group assessment using expert opinion, we assessed the alternatives on the seven criteria.

**Scenario 1a: Fire in an electric vehicle in which the battery pack is indisputably involved in the fire. The vehicle in this scenario is easily accessible.**

Long term cooling of the battery pack is necessary to stop the thermal runaway [6]. The vehicle is already total loss in this scenario. As soon as the fire brigade has extinguished the burning vehicle, the battery pack has to be cooled over a long period of time in order to stop the thermal runaway.

The group assessment of the experts shows that an fire access in the battery pack is the best available technique to extinguish an EV-fire with the battery pack involved. If this fire access is not available, the submerging of an electric vehicle in a submerging container is the best available technique to
To extinguish an EV-fire with the battery pack involved. Third best is to let the vehicle burn out, however, this is only a suitable option if the surrounding environment of the incident allows this to be an option (for example, this is not an option in a city centre).

Scenario 1b: Fire in an electric vehicle in which the battery pack is indisputably involved in the fire. The vehicle is parked in a parking structure.

In this scenario, it is necessary to transport the BEV outside of the parking structure in order to fully stabilize the situation. As the process of transporting the vehicle out of the structure takes a long period of time, which was for example the case in the fire in The Singelgarage in The Netherlands [7], it is necessary to cool the battery pack of the vehicle until the vehicle can be transported.

The group assessment of the experts shows that also in this situation a fire access in the battery pack is the best available technique to stop the fire in the battery pack. If this fire access is not available, it is assessed that the BEST battery extinguishing system is the best available technique to cool the battery pack of the vehicle until it can be transported. Once the vehicle is out of the parking structure and is out on the street, scenario 1a becomes applicable, thus submerging the BEV in a container.

Scenario 2: Fire or an accident in which there is suspicion that the battery pack is damaged (either mechanical, thermal or electric), but it is unknown if the battery pack has an increasing temperature and possibly goes into thermal runaway.

Because of the damage to the battery pack, it is necessary to transport the electric vehicle in a safe manner. In this scenario, the cooling of the vehicle is not necessary. In case the battery pack starts to increase in temperature, scenario 1a will be applicable.

The group assessment of the experts shows that the use of a submerging container solely for transportation, so without it being filled with water, is the safest way of transport. If the battery pack temperature rises/ goes into thermal runaway, the container can be filled with water to submerge the battery pack and contain the incident.

CONCLUSIONS

The submerging container is widely used in The Netherlands to contain fires involving the battery pack of an electric vehicle. The submerging container is the best available technique if an fire access in the battery pack is not available. The container scores in comparison with the other alternatives high on cooling effect, impact on the environment and is relatively practical in situations where the EV can easily be reached. In case the vehicle is parked at a hard-to-reach place and it takes time to facilitate the safe recovery of a vehicle, for example in a parking structure, the BEST battery extinguishing system is seen as the best available technique to suppress the fire until recovery is possible. Next to that, the submerging container is seen as the best available technique for the safe transport of the vehicle.

REFERENCES


Bench-scale fuel fire test for materials of rechargeable energy storage system housings

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ABSTRACT

The automotive sector increasingly demands safety technologies such as flame-retarded materials used for electric vehicles. Suitable materials are needed for the fire protection of a Rechargeable Energy Storage System (REESS) - including battery, housing and control electronics - against an external source of damage such as a fuel fire outside the car, and also against internal technical failure of the REESS such as an internal fire and (in the worst case) thermal-runaway of the entire battery system. To meet the requirements, the flame retardancy of the REESS housing materials is of great importance.

Here we report the flame retardancy behavior of thermoplastic and thermoset composites in the event of an external fire, investigated by a bench-scale fuel fire test which simulates the fire treatment of the UNECE-R100-8E at component level.

KEYWORDS: electric mobility, flame resistance, bench-scale fuel fire test

INTRODUCTION

The safety of the traction battery (rechargeable energy storage system (REESS)) of electric vehicles is of great importance. In addition to damage to the battery cells due to an external damaging event, such as a fire caused by an accident with a fuel-powered vehicle, the battery itself can become a source of danger due to internal failure. The traction battery housing therefore fulfills an important safety function. In order to reduce weight and costs, housings made of fibre-reinforced plastics are under development.

To assess the fire resistance of REESS under the influence of fire, large-scale fire tests on partial or complete systems are currently mandatory. According to the United Nations Economic Commission for Europe (UNECE) Regulation No. 100, also "fire resistance" tests according to Annex 8E (UNECE-R100-8E) are required.

In the UNECE-R100-8E test for vehicles or components, the vehicle or REESS is currently exposed to a gasoline pool fire by direct flame treatment for 70 s followed by 60 s of indirect flame treatment. After the thermal treatment, the REESS is observed for at least 3 h to confirm that the temperature decreases and no dangerous processes resulting in an explosion have been initiated during the fire exposure. In addition to the gasoline pool fire, a structure consisting of many individual gas burners may now also be used for flame treatment. According to UNECE-R100-8E, the heat flux of the gasoline pool fire is about 25–50 kW m⁻² and temperatures of 700–900 °C are reached during the direct fire exposure phase and 300–800 °C during the indirect fire exposure phase.

The UNECE-R100-8E test is not applicable for materials and products in material development phase and optimization phase of processing processes. The use of materials and the costs both for the construction of the test object and the conducting of the test are too high. To be able to use suitable
flame and fire protection tests during material development and process optimization, a cost-efficient bench-scale fuel fire test was developed at Fraunhofer ICT with the support of the Fraunhofer ICT working group Flame, Fire and Explosion Protection. ([www.ict.fraunhofer.de/de/komp/Flamm-Brand-Explosionsschutz](http://www.ict.fraunhofer.de/de/komp/Flamm-Brand-Explosionsschutz))

Further descriptions and application examples can be found in the literature [1–7].

**SETUP OF THE BENCH-SCALE FUEL-FIRE-TEST FFEP 20-001.01**

A laboratory fire test stand for evaluating coatings, developed by Rütgers Organic GmbH, was modified. Instead of using a Teclu gas burner, gasoline (60 mL, Super 95 E5, DIN EN 228, ROZ 95) in a steel pan (170 × 170 mm²) was used to create a fuel fire with a burning time of about 130 s. The real burning time of the fuel is influenced by test specimen tested and therefore, varies between 100 s and 130 s. The distance between steel pan and surface of the test specimen is about 300 mm. Test specimens of 190 × 190 mm² were fixed in a steel test specimen holder, which has a flame-exposed area of 180 × 180 mm². The temperature of the back surface of the test specimen was measured (surface thermo sensor form B & B Thermo-Technik, K type, -50 °C to 650 °C) and recorded in increments of 1 s. Figure 1 shows the setup of the bench-scale fuel fire test.

![Figure 1: Bench-scale fuel fire test; drawing taken from fire dynamics simulator (FDS).](image)

**TESTING**

The bench-scale fuel fire test is carried out in a fire shaft (3 × 3 m²) with active ventilation. The test specimens used are stored for at least 7 days in a standard climate (23 °C, 50% relative humidity). Several test specimens are tested for each material. The test specimen is firmly clamped into the test specimen holder, positioned in the test bench and the surface thermo sensor is placed in the middle of the test specimen reverse side surface. The surface thermo sensor is freely movable and presses with its own weight on the test specimen surface to prevent surface contact losses in an event of specimen
deformation. The test starts by filling the steel pan with 60 mL of gasoline and igniting it. The temperature is recorded until at least 5 minutes after extinguishing of the gasoline fire. The fire behaviour of the flame treated specimen surface is recorded with a video camera.

TEST CRITERIA OF THE BENCH-SCALE FUEL FIRE TEST

The bench-scale fuel fire test is not yet validated to the UNECE-R100-8E test but allows to study several important burning characteristics.

(1) **Temperature of the reverse side of the specimen:** The inside temperature of an REESS is of particular importance. If the battery cells become too hot, a thermal-runaway can be triggered. It is assumed that a temperature above 80 °C leads to an irreversible damage of the battery cells, e.g. by the decomposition of the electrolyte. Above 120 °C, the thermal-runaway is most likely initiated. The REESS housing should protect the inside from high temperatures during an accident. In the bench-scale fuel fire test, the temperature of the reverse side of the specimen is an important test criterion. The test specimen reverse side temperature should not rise above 120 °C (test criteria class B) or even better not rise above 80 °C (test criteria class A).

(2) **Ignition of the reverse side of the specimen:** The protection of the critical components, systems, and sensors inside a REESS from open fire is a main feature of the REESS housing. Therefore, housing materials should not show any breakthrough of the flame. In the bench-scale fuel fire test, the test setup does not allow an easily ignition of pyrolysis gases released from the specimen reverse side. Ignition of the reverse side of the specimen indicates that the flame has penetrated the specimen from the pool fire side. Ignition of the reverse side of the specimen should be classified as a failure criterion.

(3) **Self-extinction:** A burn-through of the housing and flame propagation within the vehicle must be avoided after the fire treatment of the REESS. Therefore, materials for the REESS housing with low after-flame time and self-extinction properties are preferable. The test specimen should show self-extinction property and not continue to burn after the fire treatment.

(4) **Structural integrity:** During and after an external fire, the REESS housing should not show a loss of load bearing capacity as well as no disintegration, e.g. by the formation of holes and falling down of reinforcing fibre layers. However, the current test setup of the bench-scale fuel fire test only allows a visual observation of the specimens during the test and an organoleptic evaluation of the specimens after the fire treatment. Strong disintegration is to be considered as a failure criterion. The application of additional mechanical stress, e.g. simulating the mass of the REESS inside components is under development.

(5) **Mass loss:** The mass loss of the test samples helps to understand the flame retardant behaviour of the housing material. It indicates how much material is lost by both the decomposition of material and dripping of, e.g. molten parts and detachment of, e.g. loose char layers or fibres, as well as the formation of protective layers, e.g. caused by a flame retardant. The mass loss is determined by weighing the samples before and after the fire test.

DOCUMENTATION OF THE BENCH-SCALE FUEL FIRE TEST

For the documentation of the bench-scale fuel fire test the listed parameters of Table 1 are used.
Table 1 Table for documentation of the bench-scale fuel fire test.

<table>
<thead>
<tr>
<th>Number of test specimens</th>
<th>[Example]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>[plate]</td>
</tr>
<tr>
<td>Thickness / mm</td>
<td>[3]</td>
</tr>
<tr>
<td>Fiber reinforcement</td>
<td>[carbon fiber]</td>
</tr>
<tr>
<td>Fiber amount / mass%</td>
<td>[50]</td>
</tr>
<tr>
<td>Flame retardant amount / mass%</td>
<td>[ATH] [20]</td>
</tr>
<tr>
<td>T&lt;sub&gt;reverse side&lt;/sub&gt; classification**</td>
<td>[not classified (＞120 °C)]</td>
</tr>
<tr>
<td>T&lt;sub&gt;max, reverse side&lt;/sub&gt; / °C</td>
<td>[230/252]</td>
</tr>
<tr>
<td>t&lt;sub&gt;Tmax&lt;/sub&gt; / s</td>
<td>[124/118]</td>
</tr>
<tr>
<td>Ignition of the reverse side of the specimens</td>
<td>[no]</td>
</tr>
<tr>
<td>Self-extinction</td>
<td>[yes]</td>
</tr>
<tr>
<td>After burn time / s</td>
<td>[0]</td>
</tr>
<tr>
<td>Structural integrity</td>
<td>[remains]</td>
</tr>
<tr>
<td>Mass loss / %</td>
<td>[0.9 ± 0.36]</td>
</tr>
</tbody>
</table>

* ATH = aluminium hydroxide (flame retardant)
** class A (≤ 80 °C), class B (≤ 120 °C) or not classified

CONCLUSIONS

The bench-scale fuel fire test is a cost-efficient pre-evaluation method for developing materials and manufacturing processes for REESS housings prior to a standard fire test according to UNECE-R100-8E. The fire behaviour of the materials and their changes due to the pool fire allow an assessment of the usability. Changes in the mechanical properties of the components can also be determined after the fire test. The reverse side temperatures provide information about the insulation behaviour of the materials and thus, an initial assessment of the internal temperatures to be expected in a REESS housing. This makes it possible to estimate the thermal loads on the batteries contained and, if one knows the properties of the battery system, to predict its possible behaviour or damage.

REFERENCES


Firewall Design in Buses to Mitigate the Propagation of Engine Fires

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INTRODUCTION

This paper describes the results of research\(^1\) that was conducted due to National Highway Traffic Safety Administration’s (NHTSA) safety concerns related to engine fires in buses in general, and the partition (often referred to as the "firewall") between the engine compartment and the passenger compartment in motorcoaches (rear-mounted engines), medium-size buses (forward-mounted engines), and school buses in particular. The research examined the following.

- The ability of the partitions to mitigate the propagation of fire originating in the engine compartment into the passenger compartment.
- An accounting of openings or gaps in partition designs that could allow fires to propagate and noxious gases to flow into the passenger compartment.
- Conformity of firewall designs to identify benchmarks in terms of their ability to mitigate propagation of engine fires into passenger compartments.
- Practical considerations and design constraints for improved partitions to mitigate propagation of engine compartment fires into the passenger compartments.

METHOD AND RESULTS

The research involved the following three tasks.

Task 1: Literature Review—A literature review was conducted to identify research projects, tests reports, case studies, incident data analyses and related documents that provide insights into the different factors that contribute to the propagation of an engine fire into the passenger compartment of a motor vehicle. Some of the publications that were reviewed explore various strategies for preventing, delaying, or minimizing the likelihood of engine fire spread that leads to injuries or fatalities of occupants in the passenger compartment. The literature review involved the following sets of documents.

- Applicable standards, practices and regulatory requirements
- Reports of relevant research archived by the Motor Vehicle Fire Research Institute
- Pertinent investigative reports and articles on school bus fires
- Other germane publications found in the open literature

Task 2: Firewall Documentation—The second task involved documenting the engine compartment partition designs for selected motorcoaches, medium-size buses, and school buses. The resulting documentation included photographs, LiDAR scans, measurements of the size and location of openings in the partition, cataloging materials used for cables or ducting or other items associated with each opening, etc. After initial desk review of vendor drawings, it was therefore decided to focus on obtaining the information via site visits. Six different sites were visited and 16 buses (model years from 1994 to 2021) were examined, as follows.

3 motorcoaches, all with rear-mounted engines
2 transit buses, both with rear-mounted engines (one hybrid)
5 medium-size buses, all with forward-mounted engines
6 school buses (3 full-length, 1 reduced length and 2 medium-size), all with forward-mounted engines

For each bus surveyed, several summary statistics are reported. These include the total estimated firewall area, the total penetration area (sum of the areas of all penetrations in the firewall of a given bus), the total penetration fraction (ratio of total penetration area and firewall area), total number of penetrations, and the average area per penetration. The firewall area varied between 0.45 to 4.93 m², the total penetration fraction varied from 0.9 to 11.8 percent and total number of penetrations varied from 1 to 62. Table 1 provides an overall summary of these statistics for each bus surveyed. This list is sorted by total penetration fraction from lowest to highest. The rear-mounted engine buses have the lowest penetration fraction and the school buses and medium-size buses have higher penetration fractions.

Table 1: List of Visited Sites and Buses for Which the Firewall was Documented

<table>
<thead>
<tr>
<th>Bus ID</th>
<th>Bus Type</th>
<th>Engine Mounting Position</th>
<th>Firewall Area (in²)</th>
<th>Total Penetration Area (in²)</th>
<th>Total Penetration Fraction (%)</th>
<th>Total Number of Penetrations</th>
<th>Total Number of Penetrations</th>
<th>Average Penetration Area (in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020 Gillig hybrid 35-ft. transit bus</td>
<td>Transit</td>
<td>Rear</td>
<td>3968</td>
<td>34.5</td>
<td>0.9</td>
<td>1</td>
<td>34.5</td>
<td>26</td>
</tr>
<tr>
<td>2009 Gillig 35-ft. transit bus</td>
<td>Transit</td>
<td>Rear</td>
<td>3247</td>
<td>11.1</td>
<td>1</td>
<td>34.5</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>1994 MCI 102-DL3</td>
<td>Motorcoach</td>
<td>Rear</td>
<td>7228</td>
<td>106.6</td>
<td>1.5</td>
<td>6</td>
<td>17.8</td>
<td>7</td>
</tr>
<tr>
<td>2013 MCI D4555, Cummins ISX engine</td>
<td>Motorcoach</td>
<td>Rear</td>
<td>7228</td>
<td>106.6</td>
<td>1.5</td>
<td>6</td>
<td>17.8</td>
<td>7</td>
</tr>
<tr>
<td>2009 Prevost X3-45, Detroit engine</td>
<td>Motorcoach</td>
<td>Rear</td>
<td>7648</td>
<td>121.6</td>
<td>1.6</td>
<td>7</td>
<td>17.4</td>
<td>7</td>
</tr>
<tr>
<td>2008 IC Maxxord DE3200-4-2</td>
<td>Medium Size Bus</td>
<td>Forward</td>
<td>1335</td>
<td>40.6</td>
<td>3.0</td>
<td>26</td>
<td>1.6</td>
<td>6</td>
</tr>
<tr>
<td>2008 Champion Cutaway, GM engine</td>
<td>Medium Size Bus</td>
<td>Forward</td>
<td>1370</td>
<td>46.5</td>
<td>3.4</td>
<td>26</td>
<td>1.6</td>
<td>6</td>
</tr>
<tr>
<td>2016 Moverbird MB-11 School bus</td>
<td>School Bus (Medium Size)</td>
<td>Forward</td>
<td>756</td>
<td>30.0</td>
<td>4.0</td>
<td>7</td>
<td>4.3</td>
<td>7</td>
</tr>
<tr>
<td>2017 Lion 360 school bus</td>
<td>School Bus (Full Length)</td>
<td>Forward</td>
<td>1244</td>
<td>56.1</td>
<td>4.5</td>
<td>15</td>
<td>3.7</td>
<td>15</td>
</tr>
<tr>
<td>2016 Van-Car Type B wheelie</td>
<td>School Bus (Medium Size)</td>
<td>Forward</td>
<td>906</td>
<td>55.8</td>
<td>6.2</td>
<td>5</td>
<td>11.2</td>
<td>5</td>
</tr>
<tr>
<td>2014 Starcraft Prowler</td>
<td>Medium Size Bus</td>
<td>Forward</td>
<td>831</td>
<td>60.5</td>
<td>7.3</td>
<td>5</td>
<td>12.1</td>
<td>5</td>
</tr>
<tr>
<td>2011 IC full length school bus</td>
<td>School Bus (Full Length)</td>
<td>Forward</td>
<td>1733</td>
<td>127.5</td>
<td>7.4</td>
<td>62</td>
<td>2.1</td>
<td>62</td>
</tr>
<tr>
<td>2006 IC School Bus (Short)</td>
<td>School Bus (Reduced Length)</td>
<td>Forward</td>
<td>1479</td>
<td>110.3</td>
<td>7.5</td>
<td>33</td>
<td>3.3</td>
<td>33</td>
</tr>
<tr>
<td>2004 IC School Bus (Long)</td>
<td>School Bus (Full Length)</td>
<td>Forward</td>
<td>1467</td>
<td>155.0</td>
<td>10.6</td>
<td>34</td>
<td>4.6</td>
<td>34</td>
</tr>
<tr>
<td>2021 Ford E-450 para-transit bus</td>
<td>Medium Size Bus</td>
<td>Forward</td>
<td>695</td>
<td>78.6</td>
<td>11.3</td>
<td>9</td>
<td>8.7</td>
<td>9</td>
</tr>
<tr>
<td>2021 Ford Cutaway para-transit van</td>
<td>Medium Size Bus</td>
<td>Forward</td>
<td>1135</td>
<td>154.1</td>
<td>11.8</td>
<td>10</td>
<td>13.4</td>
<td>10</td>
</tr>
<tr>
<td>Averages</td>
<td></td>
<td></td>
<td>2642</td>
<td>81.2</td>
<td>5.2</td>
<td>15</td>
<td>12.2</td>
<td>15</td>
</tr>
</tbody>
</table>

The high-level observations from the documentation of firewalls in the surveyed buses are as follows:

- Rear-mounted transit buses and motorcoaches have the fewest visible penetrations and lowest total penetration fraction.
- Full length school buses (forward-mounted engines) have the highest number of visible firewall penetrations and highest total penetration fraction.
- Medium-size buses have nearly the same total penetration fraction as full-length school buses with one third of the number of penetrations.

Task 3: Engineering Assessment—In the final task, a detailed engineering assessment was made of the partition designs documented in Task 2. The methodology for conducting this evaluation involved the following steps.

- Define a firewall design that can serve as a benchmark for the different types of buses and/or engine configurations (rear versus front mounted) that were documented in Task 2.
- Evaluate the documented firewalls from the site visits using the following approach.
  - Rate the firewall against the benchmark for the different mechanisms identified in National Fire Protection Association standard 556 by which engine fires can affect the health and safety of people in the passenger compartment.
  - Determine how the firewall design can be improved to meet the benchmark specifications and assess the practicality of the improvements and identify constraints for implementation in existing and new buses.
- Identify potential defense-in-depth measures (added layers of fire protection) and/or compensatory measures to reduce the risk for fatalities and injuries due to an engine fire.

Table 2 provides a list and legend for the buses that were analysed against benchmark design. Figure 1 shows a summary of the benchmark evaluation for motorcoaches and transit buses. Figure 2 and Figure
show a summary of the benchmark evaluation for school buses and medium-size buses, respectively. It is evident from the prevalence of red colored cells in Figure 2 and Figure 3 that firewalls in buses with forward-mounted engines have a much inferior benchmark rating than firewalls in buses with rear-mounted engines. The orange colored cells labeled “N” (or “Y”) refer to cases where the rating is probably “N” (or “Y”) but could not be determined with certainty. The orange colored cells labeled “C” refer to large quantities of loose exposed electrical cables, wires and connectors located under the dashboard of SB5 and MB2. Figure 2 also shows that the medium size school buses (SB5 and SB6) are slightly better in meeting benchmark criteria than full size school buses.

### Table 2. List of Buses With Fully Documented Firewalls

<table>
<thead>
<tr>
<th>ID</th>
<th>Bus Description</th>
<th>Year</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1</td>
<td>MCI 102-DL3 motorcoach</td>
<td>1994</td>
<td>NHTSA VRTC, East Liberty, OH</td>
</tr>
<tr>
<td>MC2</td>
<td>MCI D4505 motorcoach</td>
<td>2013</td>
<td>Greyhound Maintenance Center, Dallas, TX</td>
</tr>
<tr>
<td>MC3</td>
<td>Prevost X3-45 motorcoach</td>
<td>2019</td>
<td>Greyhound Maintenance Center, Dallas, TX</td>
</tr>
<tr>
<td>TB1</td>
<td>2009 Gillig diesel transit bus</td>
<td>2009</td>
<td>First Transit, Brownsville, TX</td>
</tr>
<tr>
<td>TB2</td>
<td>2020 Gillig hybrid transit bus</td>
<td>2020</td>
<td>First Transit, Brownsville, TX</td>
</tr>
<tr>
<td>SB1</td>
<td>IC full length school bus</td>
<td>2004</td>
<td>NHTSA VRTC, East Liberty, OH</td>
</tr>
<tr>
<td>SB2</td>
<td>IC short school bus</td>
<td>2006</td>
<td>NHTSA VRTC, East Liberty, OH</td>
</tr>
<tr>
<td>SB3</td>
<td>Lion 360 full length school bus</td>
<td>2017</td>
<td>Applus+ IDIADA, Adelanto, CA</td>
</tr>
<tr>
<td>SB4</td>
<td>IC full length school bus</td>
<td>2021</td>
<td>Navistar / IC Bus, San Antonio, TX</td>
</tr>
<tr>
<td>SB5</td>
<td>Van-Con Type B medium size wheelchair bus</td>
<td>2016</td>
<td>Applus+ IDIADA, Adelanto, CA</td>
</tr>
<tr>
<td>SB6</td>
<td>Microbird MB-11medium size school bus</td>
<td>2016</td>
<td>Applus+ IDIADA, Adelanto, CA</td>
</tr>
<tr>
<td>MB1</td>
<td>Champion medium size bus</td>
<td>2008</td>
<td>First Transit, Brownsville, TX</td>
</tr>
<tr>
<td>MB2</td>
<td>IC Maxxforce DT3200 medium size bus</td>
<td>2008</td>
<td>Navistar / IC Bus, San Antonio, TX</td>
</tr>
<tr>
<td>MB3</td>
<td>Starcraft Prodigy medium size bus</td>
<td>2014</td>
<td>Applus+ IDIADA, Adelanto, CA</td>
</tr>
<tr>
<td>MB4</td>
<td>Ford medium size para-transit bus</td>
<td>2021</td>
<td>FirstGroup, Tampa, FL</td>
</tr>
<tr>
<td>MB5</td>
<td>Ford E-450 medium size para-transit bus</td>
<td>2021</td>
<td>FirstGroup, Tampa, FL</td>
</tr>
</tbody>
</table>

### Figure 1. Benchmark firewall comparison for motorcoaches and transit buses

<table>
<thead>
<tr>
<th></th>
<th>MC1</th>
<th>MC2</th>
<th>MC3</th>
<th>TB1</th>
<th>TB2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward-mounted engine</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Single wall construction</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>No thermal insulation</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>HVAC penetrates firewall</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Cowling in passenger area</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Openings with grommets</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Unprotected openings</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Other hazards</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Firewall area (in²)</td>
<td>7228</td>
<td>7228</td>
<td>7648</td>
<td>3247</td>
<td>3968</td>
</tr>
<tr>
<td>Area of penetrations (in²)</td>
<td>106.6</td>
<td>106.6</td>
<td>121.6</td>
<td>34.5</td>
<td>34.5</td>
</tr>
<tr>
<td>Penetrated/firewall area (%)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Number of penetrations</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

### Figure 2. Benchmark firewall comparison for school buses

<table>
<thead>
<tr>
<th></th>
<th>SB1</th>
<th>SB2</th>
<th>SB3</th>
<th>SB4</th>
<th>SB5</th>
<th>SB6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward-mounted engine</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Single wall construction</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>No thermal insulation</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>HVAC penetrates firewall</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Cowling in passenger area</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Openings with grommets</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Unprotected openings</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Other hazards</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>C</td>
<td>N</td>
</tr>
<tr>
<td>Firewall area (in²)</td>
<td>1467</td>
<td>1479</td>
<td>1244</td>
<td>1733</td>
<td>906</td>
<td>756</td>
</tr>
<tr>
<td>Area of penetrations (in²)</td>
<td>105.6</td>
<td>110.3</td>
<td>56.1</td>
<td>127.5</td>
<td>55.8</td>
<td>30.0</td>
</tr>
<tr>
<td>Penetrated/firewall area (%)</td>
<td>10.6</td>
<td>7.5</td>
<td>4.5</td>
<td>7.4</td>
<td>6.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Number of penetrations</td>
<td>34</td>
<td>33</td>
<td>15</td>
<td>62</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The following conclusions can be drawn from this study.

- Engine fires are much less likely to spread to the passenger compartment in buses with a rear-mounted engine compared to buses with a forward-mounted engine because firewalls in buses with a rear-mounted engine are not in direct contact with the passenger compartment and have far fewer penetrations with a much smaller total penetrated area.
- Furthermore, buses with a rear-mounted engine have much better benchmark ratings than buses with forward-mounted engines.
- The proximity of a forward-mounted engine to the driver and the primary exit raises the importance of the firewall’s ability to mitigate fire spread from the engine to the passenger compartment in a school and medium-size bus. Firewall design features that can mitigate the spread of flames and gases have been identified, as follows.
  - Apply a thermal-resistant intumescent coating on the engine side of the firewall.
  - Periodically inspect the cowling and perform repairs as needed or replace deficient or inadequate cowling with a fire-resistant design.
  - Penetrating items such as electrical cables and tubing routed through a pipe flange that is screwed to the sheet metal of the firewall instead of through an unprotected opening in the firewall. Fill annular space around the penetrating items with fire-resistant sealant.
  - Use HVAC system components and ductwork made with metal components (in lieu of plastic parts) and install a fire damper to prevent toxic smoke from flowing into the passenger compartment.
- Defense-in-depth and compensatory measures are identified that have the potential to enhance fire safety. Examples are the implementation of frequent and rigorous preventative engine inspection, maintenance and repair programs and development of updated instructional materials to facilitate safe egress in the event of a bus fire.

<table>
<thead>
<tr>
<th></th>
<th>MB1</th>
<th>MB2</th>
<th>MB3</th>
<th>MB4</th>
<th>MB5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward-mounted engine</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Single wall construction</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>No thermal insulation</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>HVAC penetrates firewall</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Cowling in passenger area</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>Openings with grommets</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Unprotected openings</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Other hazards</td>
<td>B</td>
<td>C</td>
<td>N</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Firewall area (in²)</td>
<td>1370</td>
<td>1335</td>
<td>831</td>
<td>1135</td>
<td>695</td>
</tr>
<tr>
<td>Area of penetrations (in²)</td>
<td>46.5</td>
<td>40.6</td>
<td>60.5</td>
<td>134.1</td>
<td>78.6</td>
</tr>
<tr>
<td>Penetrated/firewall area (%)</td>
<td>3.4</td>
<td>3.0</td>
<td>7.3</td>
<td>11.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Number of penetrations</td>
<td>6</td>
<td>26</td>
<td>5</td>
<td>10</td>
<td>9</td>
</tr>
</tbody>
</table>

Figure 3. Benchmark firewall comparison for the medium-size buses
New Initiation Methods for Thermal Propagation Tests of Traction Li-Storages

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ABSTRACT

Li-Ion technology is nowadays state of the art in electrical traction batteries. It promises high energy density and reliability but in case of a cell failure leading to an internal short circuit, a considerable amount of heat will be released. There are cases where the heat generated by internal short circuits is sufficient to turn all of the chemical energy stored in a cell into heat. Such cases are called a thermal runaway. In addition, the heat released in the cell can be transferred to neighbouring cells and trigger a thermal runaway in them as well. In this case, one speaks of thermal propagation, which in the worst case can spread to all cells in the battery. For thermal propagation testing of battery storage systems, a new ISO standard ISO 6469-1 was developed and published in November 2022 which describes how propagation test is carried out. To initialize the first cell, we have developed an initiation cell based on an electrically initiated thermite reaction, which generates the same amount of heat over time as the target cell used in the battery storage system. Thermite reactions are typical representatives of binary particle systems, which consist of a metal-oxide and a metal. Besides the concentrations of metal and metal-oxide, the burning velocity and therefore, the time-dependent heat development can be controlled by many other parameters like particle size or porosity, heat and mass transfer and the reaction kinetics or the casing. In this work, we developed a thermite replacement cell till a final technical demonstration of the cell to imitate the thermal propagation of a Li-Ion battery.

KEYWORDS: battery storage systems, thermal runaway, thermite replacement cell

INTRODUCTION

Li-Ion technology is nowadays employed for e-mobility as energy storage in electrical traction batteries [1][2]. Organic solvents with inorganic lithium salts are used in these batteries. The motivation for this technology is related to its high energy density and reliability and the long range that can be achieved in relation to the volume and weight of the battery. In the event of a fault, high energy densities in electrical storage systems lead to the release of considerable amounts of heat. Faults include short circuits that can occur inside or outside a battery cell [3]. There are cases where the heat generated by short circuits is sufficient to turn all of the chemical energy stored in a cell into heat. Such cases are called a thermal runaway. During a thermal event, hot gases and particles escape from the cell, which can combine with air to form a combustible mixture. In addition, the heat released in the cell can be transferred to neighbouring cells and trigger a thermal event in them as well. In this case, one speaks of thermal propagation, which in the worst case can spread to all cells in the battery storage [4]. For thermal propagation testing of battery storage systems, a new ISO standard ISO 6469-
1 AMENDMENT 1 was developed and published in November 2022 [5]. This amendment to ISO 6469-1 describes how the propagation test is carried out. To initialize the first cell, three different methods are suggested that the test engineer can use: (i) an internal heat element which needs to be implemented inside a cell, (ii) an external heater, which needs to be installed outside of a cell or in between of two cells, (iii) the widespread nailing method. Unfortunately, all of these methods are subject to various limitations in terms of their applicability to all of the battery storage variants under consideration, and the undoubtedly best initialization method has not yet been invented. We have therefore developed an initiation cell based on an electrically initiated thermite reaction, which generates the same amount of heat over time as the target cell used in the battery storage system. Our thermite cell replaces or is exchanged for the target cell in the battery storage. We designed the replacement cell in such a way that unlike an actual battery cell, it does not release any gas or particles to the outside during thermal discharge.

Most of thermite reactions fulfil these conditions [6]. They are typical representatives of binary particle systems, which consist of a metal-oxide ($M_{x2}O_{x3}$) and a less noble metal ($M^1$). Once initiated, the metal reduces the metal-oxide ($M_{x2}O_{x3}$) to form the more stable metal oxide ($M_{x1}O_{x5}$) and resulting metal ($M^2$) under release of a huge amount of energy in form of heat, light or sound [7]. Those reactions are also known as solid-state reactions, because the educts and products are mostly in the solid phase. Some of them also react only in the solid phase. Couples of $M^1$ and $M^2$-oxides can be chosen on the basis of their position in the electrochemical series or their Gibbs energy from the Ellingham diagram of the oxidation of elements with pure oxygen [8]. Besides the concentrations of metal and metal-oxide, the burning velocity and therefore, the time-dependent heat development can be controlled by the particle size, the melting, the evaporation and the decomposition of the particles, the heat of reaction, the heat and mass transfer and the reaction kinetics [9]-[11]. In the case of the replaced battery cell, also the battery casing plays an important role, its construction, stability, thermal behaviour (thermal conductivity and capacity) and mass.

In this work, we developed a thermite replacement cell to initiate the thermal propagation of a Li-Ion battery. The process was supported by modelling of the thermal battery cell behaviour to choose and adjust a matching thermite and to develop a suitable casing for the cell ending with the final technical demonstration of the cell.

EXPERIMENTAL AND MODELLING RESULTS

The heat release, reaction time and surface temperature of a PHEV2 battery cell (54 Ah, $U = 3.6$ V, length x width x height = 148 x 91 x 26.5 mm$^3$, aluminium casing), used as a model battery cell, should be simulated. The data of the model cell were determined in a calorimeter experiment in which the cell was triggered using the nail method. The released thermal energy reached 504 kJ, with a maximum surface temperature of $T_{\text{max}} = 841$ °C and a reaction time of 11.39 s.

In the next step, a suitable thermite system to simulate the heat release rate and the burning rate should be selected. For this purpose, the source strength and the necessary burn-off temperature were first determined using model calculations by solving the 1-dimensional heat conduction equation with a propagating Gaussian function as the source term. Due to the thermal conductivity of the cell, the Thermite system has a specific amount of heat of at least 800 kJ/kg at a propagation speed of 50-100 mm/s in order to achieve the required temperature profile and the amount of heat released. Figure 1 shows the measured temperature profile in comparison with the model calculation with the specified data.
The amount of heat released and the adiabatic combustion temperature for various thermite reactions were then calculated by means of thermodynamic calculations, and the burning rate and burning behaviour were investigated experimentally. Of the thermite systems examined, the aluminium/iron(III) oxide (Al/Fe$_2$O$_3$) thermite showed the most suitable properties for this application. In addition to a theoretical reaction heat of $Q = 3989$ kJ/kg and an adiabatic combustion temperature of $T_{ad} = 3140$ K, the combustion rate can be set over a wide range via the fuel/oxidizer ratio. In addition, the thermite reacts with almost no gas phase development and the components are REACH harmless. The theoretically calculated adiabatic combustion temperature and burning rate as a function of fuel concentration for Al/Fe$_2$O$_3$ is shown in Figure 2.

The concentration ratio Al:Fe$_2$O$_3 = 40:60$ was selected. For the necessary energy to be released of approx. 500 kJ, 125 g of the thermite mixture are then required. Since the material is in the form of a compact mixture, faster burning rates are observed even when using smaller amounts due to the high heat release. In addition, the combustion temperature had to be reduced. Both parameters could be reduced by adding inert material (20 wt% aluminium oxide). A housing with the geometry of a PHEV2 cell was then constructed and the housing material was selected on the basis of further model calculations in such a way that the thermal conductivity of the thermite replacement cell corresponds to that of a battery cell. A suitable housing material was thus found to be inexpensive structural steel. Finally, the developed thermite replacement cell with an electrical ignition was also examined in a calorimeter test and the results compared with those of the previously characterized PHEV2 battery.
The results of the experimentally determined surface temperatures and released amounts of heat are shown in Figure 3. The amount of heat converted in the thermite replacement cell was $Q = 465 \text{ kJ}$.

![Figure 3: Measured quantity of heat (left) and temperature at the surface (right) for a PHEV2 battery cell (gray) compared to the results for the thermite replacement cell.](image)

**CONCLUSIONS**

The heat energy released during a thermal runaway in a PHEV2 type Li-ion battery cell due to an internal short circuit is enormous. It is approx. 500kJ and could be determined using the nail method in a calorimeter test. In order to investigate the behaviour of a battery storage system due to a thermal runaway in one or more cells, an electrically initiated replacement cell with thermite filling was developed. The required specific amount of heat and propagation speed of the heat source to be used could be determined on the basis of modelling calculations. Preliminary investigations showed that an aluminium/iron(III) oxide thermite is very well suited due to the solid reaction without the formation of a gas phase. Aluminium oxide was added as an inert substance to moderate the burning rate and temperature. The amount of heat released by the thermite replacement cell constructed with the geometry of a PHEV2 battery cell was approx. 465kJ in the calorimeter test. The amount of heat released and the temperature profile on the surface correspond well with that of the PHEV2 battery cell.

**REFERENCES**

B. Kennedy, D. Patterson, S. Camilleri, Use of lithium-ion batteries in electric vehicles, Journal of Power Sources, 2000, 90, 156-162.


Mingyi Chen, Jiahao Liu, Yaping He, Richard Yuen, Jian Wang, Study of the fire hazards of lithium-ion batteries at different pressures, Applied Thermal Engineering, 2017, 125, 1061-1074.


https://www.iso.org/standard/73574.html, 24.08.2022


On the effect of ventilation conditions in naturally ventilated car parks on fire safety

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ABSTRACT

Ventilation conditions are an essential factor in the development of car park fires. This study investigates if larger open wall areas can affect fires in naturally ventilated car parks such that a reduction of the fire resistance of the main load-bearing system is warranted. A set of ten fire simulations with different wind conditions (direction and force) were carried out. Two generic car parks were examined, one with a 21% open area fraction and one with a 41% open area fraction. A simplified structural analysis for all scenarios was, furthermore, conducted to investigate the effect of different open area fractions on the collapse time of individual steel beams. The results of this study indicate that the fire resistance of the main load-bearing structure should not be reduced from R30 or R60 to R15, even if the wall surfaces have a larger open area fraction.

INTRODUCTION

On January 7th, 2020, a fire broke out in a car parked on the ground floor in the car park at Stavanger airport Sola [1]. The fire damaged several hundred vehicles and led to a partial collapse of the car park. The Norwegian Directorate for Civil Protection (DSB) and the Norwegian Building Authority (DiBK) initiated a research project investigating the fire resistance of main load-bearing systems in naturally ventilated car parks.

The following main rules apply to the load-bearing systems in car parks in the Nordic countries Norway, Sweden, Denmark, and Finland: R 30 – R 60 for car parks with two floors, R 60 for car parks with three and four floors, and R 60 – R 90 – R 120 for car parks with more than four floors. However, in Norway, the main load-bearing system may, under certain conditions, be constructed with a fire resistance of minimum R 15 A2-s1,d0 [incombustible material] if the car park is designed with more than 1/3 open wall area. However, the scientific basis for this reduction of the fire resistance based on the open area fraction is lacking. The present paper aims to address this issue.

METHOD

A fire-spreading model based on the model from Markert and Giuliani [2] has been developed. The car model is built of blocks of polycarbonate, polypropylene, rubber, polyurethane foam, and polyvinyl chloride. The fire spreading in the model (i.e., the ignition of an adjacent car) is governed by 37 temperature measurement points distributed strategically around each car and a given ignition temperature of 450°C, the ignition temperature of polycarbonate. The fire development for every single car (i.e., the heat release rate) is based on the reference curve from the Steel Research report EUR 18867 [3].

This model was used to simulate fire spreading in two generic car parks. Both car parks have the same layout (see Figure 1). However, one car park has an open area fraction of 21%, while the other has an open area fraction of 41%. The north side is, in both cases, completely enclosed. Three different wind speeds and two different wind directions have been investigated.
For each fire/wind scenario, a simplified structural analysis has been conducted based on Eurocode 1, part 1-1 [4] and Eurocode 3, part 1-2 [5]. Each time, the structural analysis has been conducted for an R 15, R 30 and R 60 design. The structural analysis includes no cascading effect once the first structural member fails.

**RESULTS**

The fire simulations have shown that a larger open area fraction, and thus better ventilation, can limit the extent of fire spread, i.e., the number of cars to which the fire spreads (see Figure 2). However, increased ventilation and, thus, increased wind velocity in car parks leads to the fire spreading faster in the wind direction downstream of cars already burning. Note that the fire will become ventilation controlled if many cars are involved. The model uncertainty will increase for ventilation-controlled fires, as it depends on predefined heat release curves for individual cars.

For very high wind velocities (e.g., 11 m/s), the open area fraction plays a smaller role in the confinement of the fire spread to fewer cars since the high wind velocity leads to good ventilation even for low open area fractions (21 % in this study).

A faster fire spread in the wind direction may result in more cars burning simultaneously, compared to a more enclosed car park, where the flow rate is lower. Several cars burning simultaneously may cause greater thermal stress on the support system and potentially an earlier structure collapse. Figure 3 shows the heat release rate (HRR) for a scenario with a wind speed of 11 m/s. The fire reached a higher maximum heat release rate in the car park with a larger open area fraction than in the more enclosed car park, even though the same number of cars were involved throughout the total fire duration.
The simulations have shown that a larger open area fraction can negatively affect the fire spread if the wind direction is unfavourable for a given car park design. The investigated car park had a completely closed northside. Wind from the south leads to an increased air supply for the fire, while the enclosed northside restricts the capability to ventilate smoke out of the car park (see Figure 4).

A simplified structural analysis showed that an increased open area fraction both entails a positive and a negative effect on the structure's load-bearing ability in a fire, depending on whether wind conditions are favourable or not. The effect of different open area fractions is observable when comparing parking houses with the same fire resistance (see Figure 5). For scenarios without wind, not shown here, the effect of changing the open area fraction is first visible once the fire has reached a certain size and becomes ventilation controlled.

However, a car park with an open area fraction of less than 1/3 of the total wall area cannot have a fire-resistance rating of R 15 in Norway. Hence, a comparison needs to be made between a more enclosed car park with R 30 and a more open car park with R15. In this case, regardless of wind conditions, the structural analysis showed that expanding the open area fraction from 21 % (i.e., less than 1/3) to 41 % (more than 1/3) has a smaller effect on the collapse time than reducing the fire resistance from R 30 to R 15. The difference is even more pronounced in reducing R 60 to R 15.
from west

from south

3 m/s

11 m/s

Figure 5 The fraction of collapsed beams over time for different fire/wind conditions, based on a simplified structural analysis of load-bearing structures with different fire resistance. Note for 11 m/s wind from the south and a R30 resistance no beam collapses within 60 minutes.

CONCLUSIONS

To investigate the effect of ventilation conditions in naturally ventilated car parks on fire safety, CFD simulations, and theoretical analysis were carried out in this study. It was found that the fire resistance of the load-bearing structures should not be reduced from R30 - R60 to R15, even if the wall surfaces have more than 1/3 open area fraction.

In what way open wall surfaces impact a car park fire is highly dependent on the fire scenario and wind conditions. These two factors cannot be controlled. Dimensioning the fire resistance of the main load-bearing system in a car park based on the open area fraction of wall surfaces (more than 1/3 of the area) is therefore considered unreliable.

REFERENCES


Battery fires: triggering and stopping of thermal runaway on cylindrical lithium-ion batteries studied with Accelerating Rate Calorimetry

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ABSTRACT

In this study, an adapted thermal test was performed, where the self-heating of the cell without adiabatic conditions was analysed and cooling by pressurized air was used to stop the thermal runaway chain of chemical reactions. For all investigations, an Accelerating Rate Calorimeter (ARC) was utilized, providing, if desired, adiabatic test conditions, precise temperature, and temperature rate measurements, as well as a safe environment to study battery fires. Critical temperatures of battery fires triggered by thermal abuse and conditions to stop the reaction have been successfully determined.

KEYWORDS: Thermal runaway, lithium-ion battery, stopping of runaway reaction, battery fire extinguishing

INTRODUCTION

Cylindrical lithium-ion batteries (LIB) of type 21700 have multifaceted usage applications, such as consumer goods, battery electric and hybrid electric vehicles. In consequence, their safety and the conditions provoking a thermal runaway are of utmost importance. There is a knowledge gap, with regard to controlling and stopping of the cascade of reactions during thermal runaway, hence a study on commercial cylindrical cells is of particular interest and allows to gain a better understanding without having to deal with sample manufacturing variations impacting the results and allowing to repeat experiments for validation and for numerous parameters. The Accelerating Rate Calorimeter (ARC) is a device that allows to perform battery safety test in a controlled atmosphere while acquiring precise temperature and temperature rate data. It allows for isothermal and adiabatic operation and has small heat losses and advanced control systems to stabilize those conditions. The device is made to withstand a battery fire and explosion, the heating system is calibrated for temperatures of up to 350 °C, data acquisition is possible even over 1000 °C. Thus, battery safety tests can be conducted with this device to understand and quantify safety relevant events for lithium-ion batteries and their performance beyond normal operation.

SAMPLE INFORMATION

This study was carried out on commercial cylindrical type 21700 cells from suppliers. Electrical measurements were performed to characterize capacity, internal resistance, and impedance by means of a Biologic BCS 128-815 impedance analysis system. The results were averaged over all 210 cells of this type of the same batch that have been acquired. The cell chemistry was characterized with ICP-OES employing an iCAP 7600DUO from Thermo Fisher Scientific. To prepare this analysis, the cell was discharged and opened in a glovebox under argon atmosphere to access anode and cathode active
material. The metal, oxygen and carbon content were determined with three separate samples of each anode and cathode for validation. The electrolyte was investigated using a GC-MS of type Clarus 690 Arnel 4019 by Perkin-Elmer. Hence, the electrolyte has been extracted from a cell after formation using a centrifuge under argon atmosphere. Both ICP-OES and GC-MS are validated with internal standards. To characterize the separator, FTIR spectroscopy was performed on a Nicolet™ iST™ 5 FT-IR-Spectrometer from Thermo Fisher Scientific. Microscopy revealed a spherical cathode and flake-like anode structure of the active material. The other given cell information has been obtained from the materials safety data sheet.

**Table 1** Electrical and chemical cell properties

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Mean capacity in mAh at C/3</th>
<th>Anode</th>
<th>Electrolyte salt</th>
<th>Max. discharge current rate</th>
<th>Binder</th>
<th>Cathode chemistry (ICP-OES)</th>
<th>Separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>21700</td>
<td>4893 ± 26</td>
<td>graphite with 1.4 % silicon</td>
<td>Lithium hexafluorophosphate (LiPF₆)</td>
<td>2C (continuous), 3C (pulsed)</td>
<td>Polyvinylidene fluoride (PVDF)</td>
<td>LiNi₀.₈₄Co₀.₁₂Al₀.₀₄O₂</td>
<td>Polyethylene (PE)</td>
</tr>
</tbody>
</table>

**Table 2** Electrolyte composition analyzed by means of GC-MS, cells after formation

<table>
<thead>
<tr>
<th>Dimethyl carbonate (DMC)</th>
<th>Ethylene carbonate (EC)</th>
<th>Fluoroethylene carbonate (FEC)</th>
<th>Ethylmethyl carbonate (EMC)</th>
<th>Diethyl carbonate (DEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>67 mass %</td>
<td>15.7 mass %</td>
<td>8.7 mass %</td>
<td>8.6 mass %</td>
<td>0 mass %</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL SETUP**

Thermal runaway and fire behavior was evaluated using an Accelerating Rate Calorimeter of type ARC-ES by Thermal Hazard Technology. This calorimeter is made for small and medium battery cells, and perfectly sized for the cells investigated in this research, allowing fewer thermal losses and less thermal inertia than larger calorimeters. Remote operation, a blast box and door sensor protect the operator, fume extraction assures no dangerous gas accumulation, and the pressured air-cooling system can chill the cell down when needed.

A modified Heat-Wait-Seek (HWS) experiment was used that consisted of a normal step heating process, where a heating step size of 5 K starting at 50 °C was applied to the cell and each interval has a following waiting phase to establish thermal equilibrium and a subsequent seek phase where the calorimeter is looking for self-heating of the cell. If a self-heating rate of more than 0.02 °C / min is detected, the calorimeter switches to exothermal operation and follows the self-heating of the battery providing adiabatic conditions. While normal HWS tests run until the cell reaches thermal runaway, in this case the heating was stopped when a set temperature was reached. Consequently, no adiabatic conditions were kept inside the calorimeter anymore and it was observed if the cell went into thermal runaway only from its self-heating and the remaining heat in the system. If the cell did go into thermal runaway at the given temperature, the test was repeated with an immediate pressurized air cooling, activated upon reaching the critical temperature. Therefore, from below of the cell, pressurized air was introduced into the calorimeter with a pressure of p = 5 Bar. For that purpose, the calorimeter is equipped with a pressurized air supply - the cooling operation is done automatically in the “cool” mode.

**RESULTS**

With the Heat-Wait-Seek (HWS) test in the ARC [1], thermal abuse was studied, and temperature rates of exothermal reactions were evaluated and compared for different cathode materials and states of charge (SOC) of 0, 30, 60, 80 and 100 % [2, 3]. This allowed to determine several critical temperatures given below for a SOC of 100 % that are averaged each over at least two experiments [4].
Table 3  
Critical temperatures from Heat-Wait-Seek tests until thermal runaway at SOC 100 % [4]

<table>
<thead>
<tr>
<th>Temperature of cell venting</th>
<th>Temperature of rate</th>
<th>Temperature of rate</th>
<th>Temperature of rate</th>
<th>Temperature of rate</th>
<th>Temperature of rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>133 °C</td>
<td>141 °C</td>
<td>149 °C</td>
<td>160 °C</td>
<td>168 °C</td>
<td>178 °C</td>
</tr>
</tbody>
</table>

Based on those critical temperatures that were used as heating stop or cooling start points, the adapted HWS test was performed, as described above. Thereby the temperatures for all four possible outcomes were found: thermal runaway or no thermal runaway for stopping of heating and for pressurized air cooling at the highest possible of the critical temperatures. Each result was validated by at least a second experiment with a new cell and all experiments were done with cells at SOC 100 %.

Table 4  
Temperatures obtained in modified HWS test for both stopped and unstoppable TR

<table>
<thead>
<tr>
<th>Thermal runaway</th>
<th>Heating stop or cooling</th>
<th>Temperature</th>
<th>Temperature rate at temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Stop heating</td>
<td>141 °C</td>
<td>0.5 °C / min</td>
</tr>
<tr>
<td>NO</td>
<td>Cooling with p = 5 Bar air</td>
<td>168 °C</td>
<td>5 °C / min</td>
</tr>
<tr>
<td>YES</td>
<td>Stop heating</td>
<td>149 °C</td>
<td>1 °C / min</td>
</tr>
<tr>
<td>YES</td>
<td>Cooling with p = 5 Bar air</td>
<td>178 °C</td>
<td>10 °C / min</td>
</tr>
</tbody>
</table>

Successful inhibition of thermal runaway

It can be concluded from table 4 that TR was inhibited when the parameters were:
- heating until 141 °C (corresponds to a rate of 0.5 °C / min) and heating was stopped
- heating until 168 °C (corresponds to a rate of 5 °C / min) and immediate cooling was applied

The following temperature curves in figure 1 were recorded at the centre of the cell for those two cases:

Figure 1  
Temperature over time plot for inhibited thermal runaway, on the left for stopped heating at 141 °C, on the right for immediate pressurized air cooling at 168 °C

In the case of the stopped heating one can witness an immediate cooling accompanied by a short self-reheating of the cell. Then a subsequent slow cooling by heat dissipation until the end of the experiment is registered. In the case of immediate pressurized air cooling, the temperature is steeply rising until the critical temperature and then rapidly decreasing as soon as the cooling is on. No fire occurred in both cases and the cells did not go into thermal runaway during or after the experiment.

Unsuccessful inhibition of thermal runaway

It can be viewed in table 4 that TR did occur when the parameters were:
- heating until 149 °C (corresponds to a rate of 1 °C / min) and heating was stopped
- heating until 178 °C (corresponds to a rate of 10 °C / min) and immediate cooling was applied

The below temperature curves in figure 2 were recorded at the centre of the cell for those two cases:
Figure 2  Temperature over time plot for non-inhibited thermal runaway, on the left for stopped heating at 149 °C, on the right for immediate pressurized air cooling at 178 °C
In both cases the cells went into thermal runaway from self-heating and reached about 550 °C.

Observation of the cell state
A picture showing one cell after successful inhibition of thermal runaway by cooling and another for an experiment with cooling, in which runaway was not stoppable, are given below.

Figure 3  Pictures of samples after the experiment, on the left for an inhibited runaway reaction and on the right for a cell destroyed after unsuccessful inhibition of thermal runaway

One can observe that the cell on the left shows only little damage from heating and traces of electrolyte from venting. This cell is not usable anymore as the current interrupt device was triggered. It is noticeable, that the cell did not burn and there is no structural damage.
The cell on the right however, underwent thermal runaway and was in a fully evolved fire. The jelly roll was partially ejected and the positive terminal was separated from the cell and is severely deformed. In a battery pack, a propagation of TR to a neighbouring cell is very likely for the latter cell.

CONCLUSION

Critical temperatures of battery fires triggered by thermal abuse have been successfully determined. Conditions from which the reaction is stoppable were found and show the potential window of actions of emergency cooling to prevent a battery fire. Moreover, it was revealed that immediate pressurized air cooling can stop the runaway reaction until a certain temperature and temperature rate that was found to be 168 °C and 5 °C / min for the studied NCA type 21700 cell. A cell of this type that is only heated to 141 °C and 0.5 °C / min will not go into thermal runaway from self-heating. The inhibition of a battery fire for an overheated cell by cooling can also be achieved using other extinguishing agents such as water, as long as the cell can be accessed and a comparable cooling rate as in the experiment is obtained.
ACKNOWLEDGEMENTS

We want to thank Dr. Thomas Bergfeldt from the chemical analysis group of IAM-AWP for performing the ICP-OES analysis. In addition, we want to thank Dr. Freya Müller from IAM-WK for the GC-MS analysis. Our gratitude goes to the Helmholtz Association for the funding of this research in the programme Materials and Technologies for the Energy Transition (MTET).

REFERENCES


