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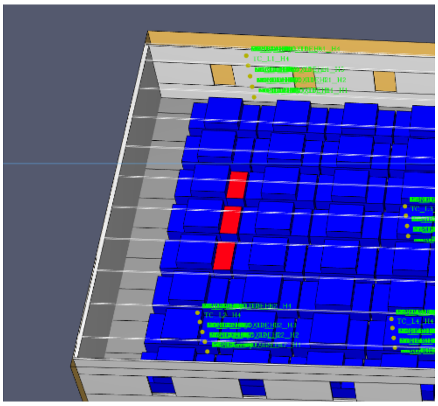
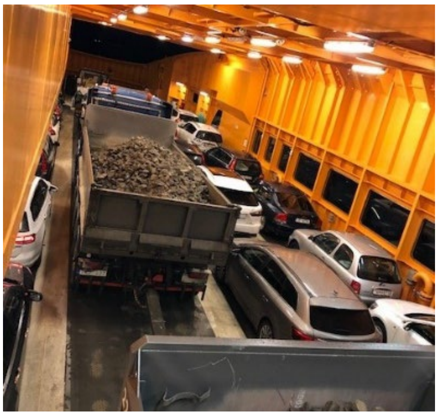

BREND 2.0 - Fighting fires in new energy carriers on deck 2.0

Jonatan Gehandler, Anna Olofsson, Jonna Hynynen, Alastair Temple, Anders Lönnermark, Johan Andersson, Julia Burgén, Chen Huang

RISE Report 2022:47

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Abstract

The project BREND investigated risk with alternative fuel vehicles inside ro-ro spaces. BREND 2.0 is a continuation and has in particular investigated two of the major risks identified in BREND, namely the risk of toxic gases from electric vehicle fires and the risk of a pressure vessel explosion for fire exposed biogas or hydrogen vehicle tanks. Simulations of electric vehicle fires inside a ro-ro space based on real input fire data has been performed. Field experiments that investigate the conditions that can lead to pressure vessel explosion were made with fire exposed biogas and hydrogen tanks. Recommendations are given about how ro-ro space fires in alternative fuel vehicles, or indeed any vehicle fire, can be managed.

Key words: New energy carriers, alternative fuel vehicle, battery, alternatively powered vehicles, electric vehicle, pressure ship, biogas vehicle, CNG vehicle, hydrogen vehicle, fire, explosion, manual firefighting, tactics, risk, ro-ro ship

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Content

Preface

The recently (in 2019) completed project BREND investigated how fires in alternative fuels (e.g., gas and batteries) for vehicles should be handled in ro-ro spaces, focusing on manual fire extinguishing. BREND identified a need for more research on how the risks of fire in alternative fuel vehicles (AFVs) should be assessed, as there were only a limited number of incidents and conducted fire tests. This project, BREND 2.0, focuses on some of the greatest uncertainties identified in BREND. These uncertainties include pressure vessel explosion of fire-exposed compressed gas containers and the risks of being exposed to toxic smoke from electric vehicle fires.

The project has actively collaborated with industry, authorities, and the public sector through established networks. A reference group with an advisory function was also established for the project. The reference group's participants were mainly based on the participants in BREND, and its role was to provide input and advice, for example regarding which fire scenarios are to be simulated and to elaborate the resulted recommendations. Thanks to the reference group:

- Södra Älvsborgs Räddningstjänstförbund (Joel Jacobsson)
- Räddningstjänsten Storgöteborg (Jonas Olsson, Christopher Hoff)
- Svensk Sjöfart (Carl Carlsson)
- Stena Teknik (Martin Carlsson, Lisa Gustin)
- Destination Gotland (Stellan Högström, Sofia Wikberg, Daniel Pantzarfelt)
- Wallenius Marine (Urban Lishajko, Peter Jodin, Per Westerdal)
- Färjerederiet (Anna Junvik, Henrik Benderius)
- Safetygruppen (Calle Ortner)
- Transportstyrelsen (Mattias Hörnquist, Saeed Mohebbi)
- Trafikverket (Henrik Modig, Ulf Lundström)
- Energigas Sverige (Mattias Hanson)
- Myndigheten för samhällsskydd och beredskap (Yvonne Näsman)

The project has had a steering group that included Haukur Ingason (RISE), Anders Lönnermark (RISE), Franz Evegren (RISE) and Lisa Gustin (Stena Teknik) with a role to support in decision-making, priorities and ensure that the project delivers the desired benefit in a scientific way.

Trafikverket (The Swedish Transport Administration) are acknowledged for funding of the BREND 2.0 project. The fire tests presented in this paper have also been sponsored by TUSC Tunnel Underground Safety Centre. The fire tests with biogas and hydrogen tanks will be presented in greater detail in a separate scientific paper.

A technical report from conducted computer simulations is published under the title “BREND 2.0: Fire simulation technical report”.

A quick guide on the formulated recommendations is published separately under the title “BREND 2.0: Quick guide”, and also available in an Appendix of this report.

List of abbreviations and terminology

AFV	Alternative fuel vehicle
BA	Breathing apparatus
BEV	Battery electric vehicles
BREND	Project acronym for *Fire in new energy carriers on-board (Brand i nya energibärare på däck)*
CNG	Compressed natural gas
CTIF	International association of fire & rescue services
EMSA	European maritime safety agency
EV	Electric vehicle
E-TOX	Project acronym for *Toxic gases formed in the event of a fire in electric vehicles*
FDS	Fire dynamics simulator
FEC	Fractional effective concentration
FED	Fractional effective dose
FFFS	Fixed firefighting system
FOI	Swedish defence research agency
Gas vehicle	Gas vehicle in this report is a vehicle using, e.g., CNG, LPG, LNG or H_2 as fuel. CNG and H_2 are the main gaseous fuels investigated in this report.
HEV	Hybrid electric vehicles
HF	Hydrogen fluoride
HGV	Heavy goods vehicle
HRR	Heat release rate
H_2	Hydrogen (compressed gas)
LNG	Liquified natural gas
LPG	Liquid petroleum gas
PCC	Pure car carrier
PCTC	Pure car and truck carrier
PHEV	Plug-in hybrid electric vehicles
PPE	Personal protective equipment

Ro-pax	Ro-ro passenger ship - means a passenger ship with ro-ro spaces or special category spaces. A passenger ship is a ship which carries more than twelve passengers.
Ro-ro	Roll-on/roll-off
Ro-ro space	Space not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship in which motor vehicles with fuel in their tanks for their own propulsion and/or goods (packaged or in bulk, in or on rail or road cars, vehicles (including road or rail tankers), trailers, containers, pallets, demountable tanks or in or on similar stowage units or other receptacles) can be loaded and unloaded normally in a horizontal direction. (Definition from SOLAS)
SOLAS	International Convention for the Safety of Life at Sea
SSF	Project acronym for Safe and Suitable Firefighting
TUSC	Tunnel and underground safety centre
TPRD	Temperature-activated pressure relief device

Summary

The automotive industry is switching to new energy carriers such as biogas, hydrogen, or batteries. There are different types of ships that carry vehicles, they are so called ro-ro ships. The vehicles carried onboard are in ro-ro spaces. The project BREND investigated risk with alternative fuel vehicles inside ro-ro spaces. An issue with ro-ro spaces is that toxic fire smoke can accumulate inside the enclosure and the pressure from explosions are maintained for longer distances than in the open. BREND 2.0 has investigated two of the major risks identified in BREND, namely the risk of toxic gases from electric vehicle (EV) fires and the risk of a pressure vessel explosion for fire exposed biogas or hydrogen vehicle tanks.

Toxic gases are found in combustion products for all type of vehicle fires. For EVs, the presence of hydrogen fluoride (HF) in combustion gases when li-ion batteries burn has sparked a major concern due to the toxicity of HF, despite the fact that these batteries rarely initiate vehicle fires and are difficult to ignite. Simulations of electric vehicle fires inside a ro-ro space based on real input fire data has been performed. EV fires result in higher emission of HF that is produced, compared to internal combustion engine vehicles (ICEV) on fire. HF is very dangerous to inhale, but studies outside this project have shown that the risk for a potential skin uptake of HF is low and it is unlikely that adverse health effects are caused during smoke diving from HF for firefighters wearing standard personal protective equipment. The “runner” (unprotected first responder) has a possibility to extinguish the fire during the initial stage (5-15 min from ignition, depending on the ignition source and ventilation conditions) if it is possible to stay out of the smoke. Several compounds in combustion gases, from both EV and ICEV fires, are highly toxic in addition to HF, and the risk of exposure should be related to the combined impact of these gases rather than the isolated levels of individual species.

In the event of a gas vehicle fire, gas tanks containing high pressure compressed biogas or hydrogen are equipped with a temperature-activated pressure relief device (TPRD) that should release the gas. However, incidents have occurred nationally and internationally were the tank ruptured in a pressure vessel explosion instead. Field experiments that investigate the conditions that can lead to pressure vessel explosion were made with fire exposed biogas and hydrogen tanks. Based on these experiments it is concluded that a local fire exposure for an extended period, above 15 min, on the gas tank can result in a pressure vessel explosion. However, such fires are rare since vehicle fires normally develop into a fully developed fire by that time, which should activate the TPRD. It is also found that application of water on the tank further lowers the risk of a pressure vessel explosion since the tank then is cooled, and thus protected.

Recommendations are given about how vehicle fires onboard ships can be managed. Most likely the initial vehicle fire will be like any vehicle fire regardless of the fuel. In fact, liquid fuels are more likely to initiate or contribute to the fire at an early stage. Therefore, the chances for a successful intervention, either by the runner, fixed firefighting system, or by the fire team intervention, during the initial fire development is even better for alternative fuel vehicles, given early detection and trained and prepared crew. However, the crew needs to be prepared for different fuel-dependent hazards that may occur so that risks are kept at a minimum. Training and post-extinguishment not to be forgotten.

Sammanfattning

Sverige har som mål att ha en fossiloberoende fordonsflotta 2030 och därför behöver fordonsindustrin ställa om till nya energibärare såsom biogas, vätgas eller batterier. Det finns olika typer av fartyg som fraktar fordon, de är så kallade rorofartyg, där fordon kan rulla på och rulla av. Fordonen som transporteras ombord befinner sig i rorolastutrymmen. Ett problem med rorolastutrymmen är att giftiga brandgaser kan ansamlas inuti utrymmet och trycket från explosioner kan upprätthålla längre avstånd än i det fria.

BREND 2.0 är en fortsättning på det projektet *BREND – Brand i nya energibärare på däck* som avslutades 2019. BREND undersökte hur bränder i fordon med alternativa bränslen (till exempel gas och batterier) ska hanteras i rorolastutrymmen på fartyg. Fokus var på manuell brandsläckning och tester genomfördes för olika typer av system och taktiker. Detta projekt, *BREND 2.0*, fokuserar på några av de största osäkerheterna som identifierades i BREND: tryckkärlsexplosion av brandutsatta behållare för komprimerad gas och riskerna att utsättas för giftiga gaser från elfordonsbränder.

Giftiga gaser finns i förbränningsprodukter för alla typer av fordonsbränder. Vad gäller elbilar har förekomsten av vätefluorid (HF) i förbränningsgaser när litiumjonbatterier brinner utlöst en stor oro på grund av dess toxicitet, trots att dessa batterier sällan initierar fordonsbränder och är svåra att antända. Datorsimuleringar av elfordonsbränder i ett rorolastutrymme baserat på verkliga indata från brandtester har utförts i olika typer av ventilationsförhållanden (dvs. olika typer av rorolastutrymmen). Elbilsbränder resulterar i högre utsläpp av HF som produceras, jämfört med brand i förbränningsmotorfordon (ICEV). HF är mycket farligt att andas in, men studier utanför detta projekt har visat att risken för ett potentiellt hudupptag av HF är låg och det är osannolikt att negativa hälsoeffekter orsakas vid rökdykning för brandmän som bär personlig skyddsutrustning (larmställ, handskar, skor, andningsapparat etcetera) av standardtyp. När det gäller inandning av förbränningsgaser (d.v.s. utan andningsapparat) är flera föreningar i förbränningsgaser, från både EV- och ICEV-bränder, mycket giftiga förutom HF, och risken för exponering bör relateras till den kombinerade påverkan av dessa gaser snarare än de isolerade nivåerna av enskilda gaser. ”Löparen” (den oskyddade första insatspersonen på ett fartyg) har möjlighet att släcka branden under den initiala brandutvecklingen (5–15 minuter från antändning, beroende på antändningskälla och ventilationsförhållanden) så länge det är möjligt att hålla sig utanför brandgaserna.

I händelse av brand i gasfordon är gastankar som innehåller högtryckskomprimerad biogas eller vätgas utrustade med en temperaturaktiverad tryckavlastningsanordning (TPRD) som ska släppa ut gasen. Däremot har incidenter inträffat nationellt och internationellt där tanken spruckit i en tryckkärlsexplosion i stället för att TPRD har löst ut. Fältförsök som undersöker de förhållanden som kan leda till tryckkärlsexplosion gjordes med brandexponerade biogas- och vätgastankar. Baserat på dessa experiment dras slutsatsen att en lokal brandexponering under en längre period, över 15 minuter, på gastanken kan resultera i en tryckkärlexplosion. Sådana bränder är dock sällsynta eftersom fordonsbränder normalt utvecklas till en fullt utvecklad brand vid den tiden, vilket borde aktivera TPRD. Det visar sig också att

applicering av vatten på tanken ytterligare minskar risken för en tryckkärlexplosion eftersom tanken då kyls och därmed skyddas.

Rekommendationer ges om hur fordonsbränder ombord på fartyg kan hanteras. Troligtvis kommer den första fordonsbranden att vara som vilken fordonsbrand som helst oavsett bränsle. Faktum är att flytande bränslen är mer benägna att initiera eller bidra till branden i ett tidigt skede. Därför är chanserna för ett framgångsrikt ingripande, antingen av löparen, fast brandbekämpningssystem, eller av brandteamets ingripande, under den inledande brandutvecklingen ännu bättre för alternativa bränslefordon, givet tidig upptäckt och utbildad och förberedd besättning. Besättningen behöver dock vara förberedd på olika bränsleberoende faror som kan uppstå så att riskerna minimeras. Träning och eftersläckning inte att förglömma.

1 Introduction

Sweden aims to have a fossil-independent vehicle fleet by 2030 and therefore the automotive industry needs to switch to new energy carriers such as biogas, hydrogen, or batteries. Sweden currently has approximately 50,000 CNG or biogas vehicles and according to data from the International Energy Agency, there were around 10 million electric cars globally in 2020[1]. There is also an increased interest in electrolysis and renewable hydrogen in Sweden as well as abroad. Fuel cell vehicles propelled by hydrogen are expected to increase in the future and can e.g., be used as a complement to the battery in electric vehicles to get a longer range. Electric vehicle (EV) is a term that includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs). There is a lot of research and experience on fire risks with fossil fuels, but more research is needed to understand the new fire risks that arise in vehicles with these new energy carriers.

There are different types of ships that carry vehicles, they are so called ro-ro ships, where vehicles can roll on and roll off. Ro-ro passenger (ro-pax) ships carrying vehicles and passengers, vehicle carriers that only carry vehicles, sometimes referred to as Pure Car Carrier (PCC) or Pure Car and Truck Carrier (PCTC) and there are the smaller road traffic ferries, e.g., operating between islands in the archipelagos of Sweden. The vehicles carried onboard are located in a ro-ro space: ro-ro spaces are a type of cargo space and ro-ro spaces include special category spaces and vehicle spaces. According to the International Convention for the Safety of Life at Sea (SOLAS) vehicle spaces are cargo spaces intended for the carriage of vehicles with fuel for their own propulsion. Ro-ro spaces are spaces not normally subdivided in any way and normally extending to either a substantial length or the entire length of the ship for vehicles (defined as above) and/or goods. Special category spaces are enclosed vehicle spaces above and below the bulkhead deck, into and from which vehicles can be driven and to which passengers have access. Special category spaces may be accommodated on more than one deck provided that the total overall clear height for vehicles does not exceed 10 meters. Special category spaces are the most frequent type of closed ro-ro spaces on ro-pax ships. These different ships also have different deck (space) conditions that affect the fire development, from closed spaces to open spaces, and weather decks. A weather deck is a deck which is completely exposed to the weather from above and from at least two sides. An open ro-ro space is either open at both ends or has an opening at one end and is provided with adequate natural ventilation effective over its entire length through permanent openings distributed in the side plating or deckhead or from above, having a total area of at least 10 % of the total area of the space sides. A closed ro-ro space is neither open nor a weather deck. Closed and open ro-ro spaces are required to be equipped with a fixed extinguishing system, often a deluge system, that becomes an important response strategy in case of fire. Weather decks on the other hand do not have to be equipped with any fixed firefighting installations but can be equipped with water monitors, manually operated or possible with remote control options. Figure 1 to Figure 3 show a variety of conditions onboard ro-ro ships.

[1] https://www.iea.org/reports/electric-vehicles [Accessed 2022-01-12]

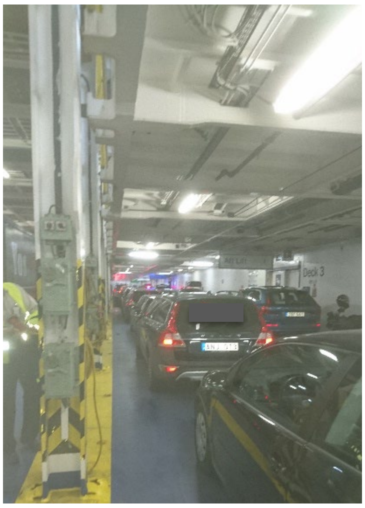

Figure 3. Closed ro-ro space on a ro-ro ship.

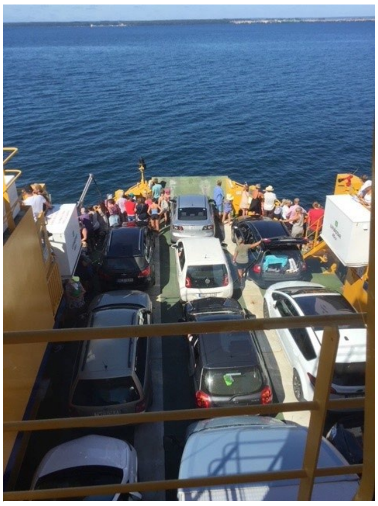

Figure 2. Traffic ferry with passenger mixed with cars.

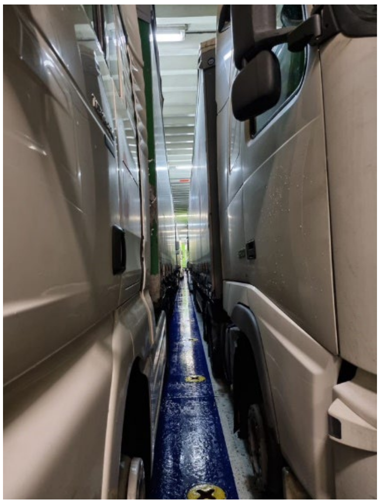

Figure 1. Tight between the vehicles onboard.

These different types of ships, with corresponding spaces and systems, have different possibilities to fight vehicle fires, also including the capacity of the crew; which can be from well-manned crew to smaller ferries with as little as only two crewmembers on duty. This means that different fire response strategies must be applied.

In this report the term *gas vehicle* is used as a general word meaning a vehicle using for example CNG, LPG, LNG or H_2 as fuel. Similarly, the term *gas tank* refers to the energy storage of gas vehicles. CNG, H_2 and EV are the main alternative fuel vehicles (AFVs) investigated in this BREND 2.0 project.

1.1 Background

The recently completed project BREND (TRV 2018/9494) [1] investigated how fire in vehicles with new energy carriers (including gas vehicles and EVs) should be handled on ro-ro ships, with a focus on manual firefighting. In order to be able to carry out a manual firefighting operation, the fire team onboard needs to carry out a risk assessment to determine which tactics and methods they should use. BREND conducted a literature survey, simulations, and workshops, which contributed to new knowledge about the risks that fire in vehicles with alternative fuels can entail onboard a ship. One of the conclusions in the BREND project was that the greatest risk of damage to life, health and the environment arises in the event of a fire in gas-powered vehicles. Tanks for gas vehicles can cause a jet flame in the event of a fire, but they can also explode if the pressure relief device (a melt fuse that is activated at temperatures around 110 °C) does not release.

The new risks associated with new energy carriers have also been brought to attention in other areas, and special attention has been paid to enclosed spaces such as underground parking garages and tunnels. RISE operates the platform TUSC (Tunnel and Underground Safety Centre), which is a research network about fire safety in underground facilities. The results from BREND include much of the previous research conducted within the research platform TUSC, but new knowledge has emerged since BREND ended, e.g., a project that investigated the risks of gas tanks exposed to local fire, relatively far from the thermally activated pressure relief device (TPRD) [2]. Vehicle gas tanks are tested as standard with a fire that often encloses the entire tank, but many fires are, at least during a development phase, local and can give a more local fire exposure towards the tank. In seven out of eight fire attempts, the safety system worked as intended, while the tank in one attempt exploded as a result of the local fire. One factor that has also been pointed out as the reason why vehicle gas tanks have sometimes exploded is that the extinguishing agent has cooled the fuse and thus prevented it from releasing. Both BREND and the TUSC-funded project in 2019 [2] have particularly pointed to a need for more knowledge about the function of the fuses, under what conditions they work and what consequences a working or non-working fuse in the event of a fire in a ro-ro space has.

For electric vehicles, one of the conclusions from BREND was to avoid the fire gases as much as possible due to the uncertainty about how toxic they are. This conclusion can lead to a delay in firefighting actions, which can have major consequences for the ship and its passengers and crew. There is a great need for more research in this area, in order to be able to improve the risk assessment in manual firefighting and reduce the risk of harmful exposure to personnel in a rescue operation. RISE, have completed or, is currently involved in several projects dealing with toxic substances in the event of fire and the safety of rescue workers with regards to electric vehicles. One project is called E-TOX [3] which aimed to raise the level of knowledge regarding toxic gases formed in the event of a fire in electric vehicles compared to conventional vehicles and to investigate how this affects rescue efforts. Also, the project “Safe and Suitable Firefighting”, a just finalised RISE project studied the Personal Protective Equipment for firefighting onboard, with a focus on the fire suit. The project investigated the standards and requirement that exist to examine which requirements are relevant for the firefighters’ outfit and protection onboard.

1.2 Aim

The BREND 2.0 project will improve the risk assessment in the event of fire in gas and electric vehicles on a ro-ro ship. The recommendations for risk assessment in BREND will be further developed for safer and more efficient manual firefighting. BREND 2.0 aims to raise the level of knowledge about manual firefighting risks in relation to fire-exposed gas cylinders and the risk of toxic gases from fires in battery electric vehicles.

1.3 Method

BREND 2.0 was divided into 4 work packages as follows, which are further described in sections below:

1. Project management
2. Preparatory analysis and requirements
3. Simulation and fire testing of selected scenarios
    a. Gas vehicles
    b. Electric vehicles
4. Recommendations regarding risk assessment and dissemination of result

1.3.1 Project management

The work package included administrative tasks such as finances, project management, contact with the reference group and the steering group as well as status reporting. This work package had an overall responsibility to take the project forward within budget and time frame.

1.3.2 Preparatory analysis and requirements

The work package compiled information and results from previous research. The study has primarily been compiled based on already ongoing research at RISE but has also been supplemented with searches within scientific databases and journals. The literature study aimed to describe what has been done before and to provide an overview of the area. The results have, among other things, been used as a basis for decisions about which fire scenarios to analyse.

For gas vehicles, special research results from the TUSC project "CNG vehicle containers exposed to local fires" [2] was compiled and analysed based on the conditions on a ro-ro ship.

For electric vehicles, the results from BREND [1], RO5 [4] and E-TOX [3] in particular was used to compile research on toxic gases in the event of fire in electric vehicles or individual lithium-ion batteries, as well as ventilation conditions and other important conditions on ro-ro ships.

Furthermore, research on the need for protective equipment was compiled, which also includes analysis of the protective equipment that is available and that is used today in the event of a fire on a ship. This was mainly done through the Safe and Suitable Firefighting project [5] that was ongoing at the same time as BREND 2.0 and the project conducted workshops together.

1.3.3 Simulation and fire testing of selected scenarios

This work package is divided into gas vehicles and electric vehicles.

Work package 3A - Gas vehicles: Fire experiments was carried out to create new knowledge about how gas tanks behave in different situations, e.g. in case of extinguishing operation. The experiments were built on the experiments carried out with methane tanks within the recently completed TUSC project [2]. In this project the special focus was on characterization of Temperature-activated pressure relief device (TPRD) and the inclusion of water application. It was relevant to study different types of gases and the exact set-up was based on an analysis of the scenarios produced as a result of the workshop with reference group in the beginning of the project. Identified risks were analysed based on the safety of personnel.

Work package 3B - Electric vehicles: Computer simulations was used to simulate the gas concentrations that can be expected at different positions in a ro-ro ship when different vehicles (BEV and ICEV) are on fire. Results from full-scale fire tests in the finalized E-TOX project [3] as well as information on ventilation from the RO5 project [4] have been used as a basis for the simulation models. The models were developed in the software Fire Dynamics Simulator (FDS) which is built on open-source code and free to use. FDS is specially developed to simulate the spread of smoke and heat in the event of fires and is used extensively in research and commercial situations. The models were used to calculate concentrations of different toxic substances in different places on deck under different ventilation conditions (i.e. different types of ro-ro space) and was used as a basis for developing the risk assessment.

1.3.4 Recommendations regarding risk assessment, firefighting response, and dissemination of results

In work package 4, the results from work package 2 and 3 was analysed to form the basis for updated and developed recommendations regarding risk assessment and firefighting response.

The first workshop was held in the beginning of the project with the purpose to present the result from work package 2: the latest research regarding risk associated with alternative fuel vehicles (AFV) with focus on gas vehicles and electric vehicles. The workshop was done in cooperation with the project Safe and Suitable Firefighting. The workshop also presented the relevant standards for the personal protection equipment for firefighting and some user perspective of the equipment. The workshop concluded what the research should focus on within BREND 2.0 (and Safe and Suitable Firefighting).

The second workshop was planned and conducted when the results from the experiments and computer simulations was analysed, with the purpose to form the basis for further developed recommendations regarding risk assessment and firefighting response. A workshop was held with reference group, which ensured connection to real conditions onboard ro-ro ships, relevant risk assessment and dissemination of results to end users.

A final seminar for knowledge dissemination and project result was carried out in February 2022, also this was made together with Safe and Suitable Firefighting.

2 General risk picture for AFVs

This chapter aims to describe the overall risk of AFVs in terms of likelihood and severity, in comparison with conventional vehicles. In previous reports, RISE have investigated the risk of new energy carriers in enclosed spaces such as tunnels and garages [6], and ro-ro spaces [7]. Hazards related to a conventional vehicle on fire are heat, smoke, and toxic gases, another hazard is projectiles related to small explosions of e.g., tires or airbags. AFVs share many of these conventional hazards but each fuel has its particular risk picture. AFVs typically concern gas vehicles and electric vehicles.

A gas is defined here as a substance which at room temperature does not have a definite shape or volume. Gaseous fuels can be handled in three different ways, in compressed form, in pressure-condensed form or as cryogenic gas, i.e. so strongly cooled that the gas is condensed into liquid form. Compressed gases (e.g., CNG and hydrogen) are handled in pressure vessels under high pressure, with maximum pressure in the range of 200-700 bar. Pressure condensed gases (e.g., LPG) have the property that the gas condenses when it is compressed. This means that the pressure vessel contains the product in a liquid phase and a gas phase. The pressure in the vessel varies with the ambient temperature but is often in the order of 5 bar at 20 °C. A liquefied gas (cryogas) is a gas that is cooled below its boiling point and in this way can be stored in condensed form in the pressure vessel (e.g., LNG with a boiling point of -162 °C). The pressure vessel is very well insulated (much like a thermos) to minimize heat leakage into the vessel. The small heat flow that nevertheless leaks into the vessel means that a small part of the gas is constantly evaporated, which increases the pressure inside the vessel and if no gas is consumed, it means that some gas needs to be vented out through a safety valve ("boil-off") to avoid reaching too high pressure. The opening pressure for the safety valve is adapted to the dimension of the pressure vessel but is often around 5-15 bar [8].

Based on the previous research projects, BREND 2.0 focused on the risk of toxic gases from traction battery fires, and the risk of pressure vessel explosion or jet flames from compressed natural gas (CNG) or hydrogen (H_2) vehicles, see further chapter 3 and chapter 4 in this report.

Based on available statistical data from the EV producer Tesla (global statistics of their EVs), and national statistics from Sweden, Finland, and Norway about fires in EVs, a recent RISE report concludes that fires including or starting in the traction battery are rare and exceptional [9]. However, it is still uncertain how ageing will affect the fire-safety of EVs. Statistics from rescue assignments in cars in Norway, from Direktoratet for samfunnssikkerhet og beredskap (DSB)[2] have the same conclusion, it is rare that the battery is the cause of a fire in an electric car. The statistics show that during 2016 to 2019 there was a total of 3260 car fires; 2651 fire in diesel/petrol cars, and 60 fires in electrical cars, 12 fires in hybrid cars and 11 in gas cars. Additional to this there were 450 unknown fires in passenger cars.

For gas vehicles, the likelihood of fire is argued to be similar to conventional vehicles, although the fuel is less likely to initiate fires since it is stored more safely.

[2] Branner i personbiler | Direktoratet for samfunnssikkerhet og beredskap (dsb.no)

Consequently a U.S. Department of Transportation study [10] of 135 accidents involving CNG powered vehicles between 1976 and 2010, concluded that ignition could, in almost all cases, be attributed to other sources than the CNG tank or fuel storage system.

A pressure vessel explosion is a fairly unlikely event which, in the event of fire, has happened two times in Sweden, to the best of the author's knowledge, once following a fire in a passenger car in Kramfors [11] and once following a fire and extinguishment with foam of a bus outside Gnistängstunneln in Gothenburg [12]. During this period Sweden has had around 50 000 gas powered vehicles. The fire tests reported above show that it is not easy to design a fire test that will result in a pressure vessel explosion. Although difficult conditions were created and maintained for a considerable time, only one out of in total 15 tests resulted in a pressure vessel explosion.

Jet flames are more common than pressure vessel explosions. In Sweden, there is one documented damage from a jet flame on adjacent buildings and vehicles. There is also one case where a firefighter got the jet flame directly on him, but without injuring himself [13].

Overall, the number of fires for AFVs compared to conventional vehicle fire are currently lower (normalised for the number of vehicles), although consequences can be more severe or problematic, see chapter 3 and chapter 4 about consequences from pressure vessel explosion and toxic gases from EV fires in ro-ro spaces.

3 Risks with fire exposed compressed gas containers

Gaseous fuels may be stored in different ways. The risks of various gaseous fuels stored as compressed (e.g., CNG, hydrogen), pressure condensed (e.g., LPG) or liquified (e.g., LNG) in enclosed spaces have been reviewed in previous projects [e.g., 1, 8]. The focus of the BREND 2.0 project is on storage of CNG and H_2. CNG and H_2 are being stored in similar containers with similar safety philosophy and similar challenges.

3.1 A road tunnel and ro-ro perspective

Tunnels are enclosed spaces with characteristic challenges for AFVs, similar to closed ro-ro spaces. Much research has been conducted within the tunnel field, not least with regards to hydrogen safety. The conducted research within the tunnel field is explored which also can benefit the ro-ro ships.

Several earlier tunnel studies are summarised in previous work undertaken by RISE, such as [8, 14] or others such as [15]. Compared with the open, tunnels produce higher blast wave pressures for the same event, e.g., a pressure vessel explosion. Secondly the release of combustible gases may accumulate inside the tunnel enclosure. Concerning the second issue there is a great difference between studies that investigate potential worst-case scenarios and actual release experiments or simulations in tunnel environment. Due to ventilation and entrainment of air into the gas plume, the size of ignitable gas clouds is drastically reduced. It may seem unfair if, for example, the greatest safety benefit of hydrogen being its high buoyancy was not included in hazard studies. For example, LeFleur & Glover [15] report of a study of the theoretically worst scenario (a tunnel filled with a stochiometric gas cloud), followed by a dispersion study from a real gas release, which showed a reduction in the overpressure by two orders of magnitude. Moreover, a probabilistic study reduces the expected risk of a gas explosion even more. Naturally, the most likely event is a hydrogen jet flame due to a fire that is not believed to compromise the strength of concrete tunnels, nor steel structures [15].

Molkov and Dery [16] have investigated the blast wave decay correlation for a hydrogen tank rupture in a tunnel fire. Compared to high explosive, a compressed gas tank rupture has lower initial pressure, slower decay with distance, longer positive pressure phase duration, larger negative phase amplitude and stronger secondary shocks. In the far-field, the blast wave from a stand-alone or under-vehicle tank rupture in a fire have a similar strength. The loss of mechanical energy to demolish and move the car is compensated by an increase in chemical energy due to higher rate of turbulent combustion under the vehicle. However, in the near field the presence of a vehicle above the tank decreases the blast wave essentially. For tunnel explosions two zones can be defined: Zone 1, near the explosion, is dominated by reflections from the tunnel walls; Zone 2 is dominated by a one-dimensional planar blast-wave propagation where the overpressure is mostly dependant on the tunnel height. As an example, a 700 bar, 62 l tank rupture in a long tunnel with a cross section area 56.4 m^2 result in fatality (>100 kPa) within 15 m, serious injury (16.5 - 100 kPa) within 190 m, and slight injury (1.35 - 16.5 kPa) within 7 km from the tank rupture. In other words, this is a serious and problematic event. Following a fire there is some time for tunnel users to evacuate but dealing with the risk of tank rupture is very problematic for the rescue service.

RISE have in the project Safe and Suitable Firefighting (SSF) [5] performed simulations of a pressure vessel explosion in a typical ro-ro space. The ro-ro space has a dimension of 91.4 m × 22.3 m × 5 m, and the tank was placed 0.3 m above the floor, 10 m to one end of the ro-ro space. A summary of parameters of gas tanks used in the simulations is shown in Table 1. Parameters of spherical gas tanks used in the simulations [5]..

Table 1. Parameters of spherical gas tanks used in the simulations [5].

Fuel type	Vehicle type	Tank radius [m]	Simulated volume (ideal gas) [L]	Real volume (real gas) [L]	Mass [kg]	Tank pressure [bar]
CNG	Light-duty	0.22	42	89	6.2	230
CNG	Heavy-duty	0.35	176	375	26.2	230
H_2	Light-duty	0.25	62	86	3.5	700
H_2	Heavy-duty	0.31	122	176	6.9	700

Figure 4 summarizes calculated overpressure versus distance for four different tank ruptures along the length of the space. The safety distances for avoiding injury and fatality for the small and low-pressure tank (42 L and 230 bar) are 25 m and 4 m, respectively. For the large and high-pressure tank (122 L and 700 bar), it is not recommended to let the firefighters (or other people) standing on the same ro-ro space due to risk of injury. The safety distance for avoiding fatality is 7 m for the large tank of 122 L and 700 bar, as shown in Figure 4 (black broken line).

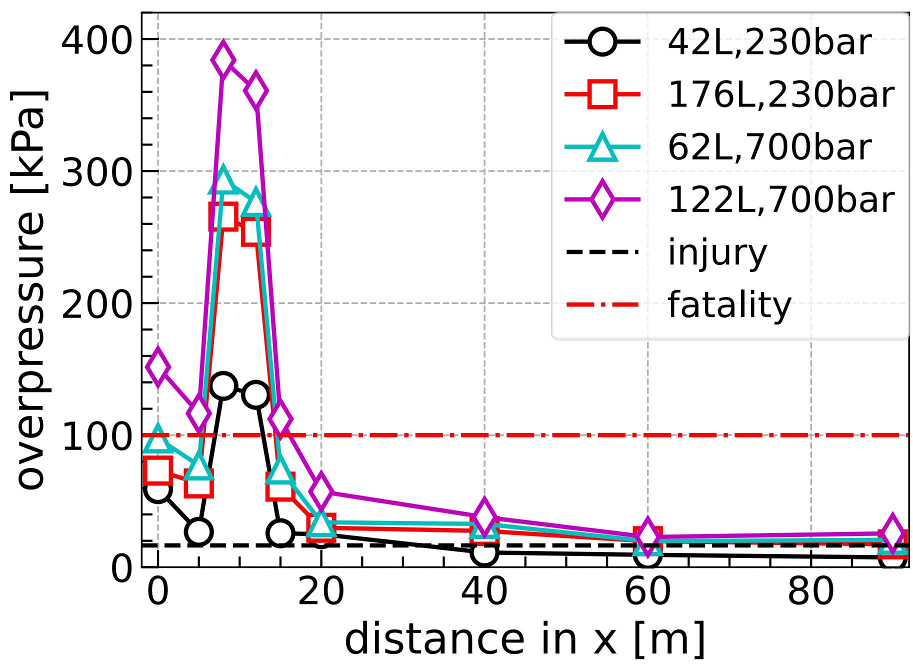

Figure 4 Calculated overpressure versus distance along the length of the ro-ro space for four different tank ruptures. Note that the tank is located at a distance of 10 m [5].

3.2 Fire tests carried out in 2019

The safety of vehicle compressed gas containers exposed to a local fire were evaluated in a previous project and report [2]. Eight fire tests were performed in 2019 on eight CNG containers (one in each test) with two different tank types (steel and composite). CNG vehicles are designed according to safety standards of UNECE Regulation 110. To reduce the risk of explosion, CNG cylinders should be equipped with a TPRD that should activate at 110 °C ± 10 °C. CNG tanks are tested against a 1.65 m long fire source. The purpose of the tests in 2019 were to evaluate whether a local fire could result in a pressure vessel explosion. The four tests with steel containers resulted in a jet flame in accordance with the prescribed outcome in the UNECE regulation, despite that the regulation does not include a local fire exposure. The local fire exposure on the composite containers, however, resulted in a pressure vessel explosion in one (a local fire, not prescribed in the UNECE regulation) out of four tests. The report argued that the container failed because composite does not conduct heat very well, which means that it takes long time for the TPRD to activate, and because the composite material is degraded by the fire.

3.3 Fire test carried out 2021 in BREND 2.0

It has been uncertain whether extinguishing media may prevent the TPRD from releasing and thus cause a pressure vessel explosion. [17-20]. Therefore, fire tests were performed in BREND 2.0 to investigate the possible risks with water application unto compressed gas containers. These tests will be presented in a separate scientific paper. Below a summary of the tests and its results is presented.

Three different designs of compressed gas containers for passenger car usage were used in the fire tests. Two CNG steel tanks, three CNG composite tanks, and two H_2 composite tanks. All gas tanks were fitted with valves and a TPRD at one end. A heptane pan was placed below the tank. Water was applied unto the tanks with a metal pipe. In the pipe, holes were drilled to discharge the water evenly along the container surface. The rod was placed such that the TPRD was wetted. In some tests a hood was placed to cover half of the tank, see Figure 5.

Figure 5 Test set-up with container mounted above the fire pan. Water application without (left), and with hood (right). Photo: RISE

The water set-up applied roughly 10-15 mm/min water unto the tank and the TPRD, which was enough to cool the TPRD and thus avoid it to activate for at least 20 min for the composite tanks and steel tanks exposed to smaller fires, and 13 min for a steel tank exposed to a widespread fire. For a manual fire extinguishment, a larger water flow rate is used (than the ones applied in the tests) that will result in a more significant cooling effect. At the same time, the fixed extinguishing system installed in a ro-ro space or manual extinguishment cases might not hit the TPRD directly (or continuously) which will reduce the TPRD cooling significantly. Nevertheless, for the three different gas containers used in these 7 fire tests, none resulted in the most dangerous failure mode: pressure vessel explosion. Thus, it can be concluded that a fast intervention can be the safest option when the risk of life or fire spread is significant, e.g., on ro-ro ships.

Based on these tests, an offensive tactic such as the CTIF (The International Association of Fire & Rescue Services) method that was reported in the BREND report [1] can be recommended to deal with fires in gas vehicles, or indeed any vehicle fire. If the fire is extinguished with a limited fire exposure of the gas tanks below 15 – 20 min before the extinguishment starts, and energy storage is being cooled, many risks, including the risk of pressure vessel explosion, are reduced. The risky window where a pressure vessel explosion can occur is limited as soon as cooling of the tanks would begin. Note that there can be risks associated with a defensive tactic as well, e.g., fire spreading to other vehicles. In any case, an overall risk assessment is required to decide the optimal tactic as events evolves. Another important parameter is whether a fixed firefighting system (FFFS) is available or not, and whether it manages to control the fire. Also, note that a risk with jet flames is that the TPRD of nearby gas vehicles is activated which can result in a very fast fire spread [21]. For ro-ro spaces with a large portion of gas vehicles, Tamura therefore argue that the fire must be detected early and extinguished before the first TPRD activates, which could happen after a few minutes fire exposure of the TPRD. However, a fast response, e.g. within 10-20 min from fire ignition, is identified by North [22] as an important factor for combating any vehicle ro-ro fire.

3.4 Jet flames

In the tests performed by RISE in 2019 and in 2021 on fire exposed CNG and hydrogen tanks, several jet flames of various lengths, directions and durations occurred. The longest jet flame was 10 m, see Figure 6.

Figure 6 A 10 m long CNG jet flame during the 2019 test series [2]. Photo: RISE.

Many jet TPRDs released in four directions or more, resulting in several smaller jet flames, see the CNG jet flame in Figure 7 that occurred after the pan fire had extinguished is an example.

Figure 7 A CNG jet flame after the pan fire had extinguished; the pressure was above 350 bars when the TPRD released. All flames are from the jet flame. Photo: RISE.

Incident heat flux levels between 2 kW/m² and 8 kW/m² were recorded at the point (X=5 m, Y=5 m) with the TPRD in origo (X=0 m, Y=0 m). At 12 m or above, incident radiation levels were low, 2 kW/m² or lower. The jet flames are fairly thin from a heat flux perspective which means that the resulting incident heat flux is fairly low compared to many other fire situations, e.g., fully developed fires with thick black smoke under the ceiling inside enclosures. Another important factor for injuries from heat or incident heat flux is the time duration; jet flames from compressed gas tanks last for a short period of time in this respect, often about 1 min duration with declining power as the pressure inside the container drops.

3.5 Post extinguishment

Tamura [23] has shown that composite containers regain its strength when they are cooled, e.g. 30 min after the fire has been extinguished. In the fire tests carried out 2019 and 2021, gas often started to leak through the composite container after 5 – 10 min fire exposure. That the container slowly starts to leak through the material did not result in any hazardous events but resulted in a slow and controlled fire. This also means that fire exposed composite containers where the TPRD has not activated may be leaking after the fire is extinguished. Since methane and hydrogen are light gases and quickly is dispersed below ignition levels, this will most likely not result in any hazardous situations in larger spaces such as tunnels or ro-ro spaces. In the tests performed in 2019 and 2021 steel containers were pressure tested with water before and after fire exposure. The three steel tanks that were pressurized after fire exposure had regained its strength afterwards and even handled a higher pressure than when the same type of tank was pressurized without any fire exposure. According to Tamura [23] a double margin of safety is achieved from 1) The pressure in tank increase during fire but is reduced again when the tank has cooled down 2) The material regains its strength when it is cooled down (but may be leaking according to tests carried out by RISE 2019 and 2021).

4 Risks with toxic gases from EV fires

Unlike vehicles fuelled by compressed gases, the primary risks associated with EVs is not related to explosions but the release of toxic gases. These gases are found in combustion products for all type of fires, for vehicle fires with the primary gases released being CO_2 and CO which are in significant excess compared to other gases [3]. Other gases typically found are SO_2, NO, NO_2, HCl and HCN, all of which are asphyxiant (cause suffocation) or irritant (can cause chemical burns or similar) gases [24]. For EVs, the significant presence of hydrogen fluoride (HF) in combustion gases has sparked a major concern due to the toxicity and possible skin uptake of HF. According to E-TOX project [3], where full-scale tests on two EVs and one ICEV was conducted, it is the levels of HF that represent the largest difference in the released combustion gases between the types of vehicles, although there are several toxic gases present irrespective of the type of vehicle burning. The concentration of HF in combustion gases varies and depends on the cell chemistry, it is reported to be in the range of 15 to 170 mg Wh^{-1} [3].

4.1 EV fire in ro-ro space

Discussions during the project's first reference group workshop (February 2021) it was clear that the focus of EV fires should be on the toxic gases, and not on flammable gases (which may also be produced from a compromised battery before or during a fire). Two of the uncertainties expressed with EV fires in ro-ro space is whether the protective clothing can withstand the toxic gases and if water application can "wash away" and reduce the toxicity. There is currently no good data available on how for example irritant gases will stick to water droplets and dissolve in the water in such a case. Probably the HF concentrations will decay but applying water to the fire source might as well increase HF production as shown in fire tests [25-28]. However, these results are based on battery cell level tests and in a ro-ro space, without direct access to the batteries in the vehicles, the effect of washing off the smoke content is probably predominant. RISE has at the moment an ongoing research project with the goal to perform full-scale EV tests including sprinkler together with gas analysis, such that better data might be available in the future, it is called E-TOX 2[3]. Simulation of drencher and its possibilities were not in the scope of BREND 2.0, but a simplified model was decided to simulate. The protective equipment was the main part of Safe and Suitable Firefighting project and the research on the possible consequences of fires in electric and gas vehicles indicate that fire suits, approved according to EN 469 level 2 (together with gloves, boots, flash hood, long-sleeved undergarments, and BA), provide a good protection against heat flux, temperature, and fire gases [5].

As of today, charging of EV are not allowed by the operators' part in this study. But the operators are working towards getting the safety, the routines, and systems ready for making it soon be available. European Maritime Safety Agency (EMSA) is also developing guidelines for EV charging on ro-ro ships.

For electric vehicles, one of the conclusions from BREND [1] was for any personnel, e.g. taking part in firefighting activities, to avoid the fire gases as much as possible due to

[3] ETOX 2 - Analys av släckvatten från bränder i elfordon | RISE

the uncertainty about how toxic they are. This conclusion can lead to a delay in firefighting operations, which can have major consequences for the ship, its passengers, and the crew. For the land-based rescue service it might be a possibility to let a vehicle fire burn out, if risk of fire spread is not present, on a ro-ro ship, this is normally not an option. There is a need for more research in this area to be able to improve the risk assessment in manual firefighting and reduce the risk of harmful exposure to personnel in a rescue operation. Therefore, fire simulations were conducted as part of this project, BREND 2.0, to investigate how gases from EV fire and ICEV fire are spread in a ro-ro space. The computer simulations were conducted using Fire Dynamics Simulator (FDS), a program for low-speed flows, with a focus on smoke and heat transport from fires[4], see section 4.2.

Ro-ro space conditions can vary significantly, it can be fully closed, with mechanical fans ventilating the space (under normal conditions), it can also be partly open in one or two ends and/or in the side plating. This variation in ventilation conditions is one aspect that was reviewed via the scenarios for the computer simulations; to see how the ventilation available affected the gas concentrations in the space. However, it should be noted that in the case of fire, the strategy onboard is to shut off mechanical ventilation and close fire dampers, so no mechanical ventilation was considered during the fire. Studies on the use of mechanical ventilation during fire in ro-ro spaces are ongoing, for example in LASH FIRE[5].

Regarding the protection against gases by firefighting protective clothing, a study by the Swedish Defence Research Agency (FOI) [29], was studying the possible health risks of HF upon smoke diving exercises and the skin up-take of HF. Firefighters that were fully dressed (underwear trousers/sweater, thick socks, fire suit trousers, fire suit jacket, boots, balaclava/flash hood, helmet, gloves) and equipped with breathing apparatus (BA) and face mask, performed different exercises in a HF contaminated enclosure and the penetration of HF through the fabric of their clothes was measured. The study found that the concentration of HF on the inside of the fire suit was 10 to 260 times lower than on the outside of the fabric, resulting in an average protection factor of 120. According to the authors, a person only wearing BA (i.e., no clothes) would need to smoke dive for 14 h in 100 ppm of HF to achieve a lethal dose of HF via skin uptake. Using full protection the concentration in the smoke would have to be increased to 12 000 ppm for 14 h of smoke diving, on average [29], to provide a lethal dose.

When it comes to inhalation (i.e., without BA) of fire combustion gases, several compounds in gaseous phase are highly toxic, as noted in the introduction to this section. The combined threat, as measured by the fractional effective dose (FED) of asphyxiants and fractional effective concentration (FEC) of irritants found in smoke is consider the main threat and, in such cases, there is no practical difference between EVs and ICEVs. As a design value, 0.3 (equivalent to 11 % of the general population being incapacitated by exposure [30]) can be used.

[4] https://pages.nist.gov/fds-smv/
[5] www.lashfire.eu

4.2 FDS Simulations

Full scale fire experiments, particularly at the size of a ro-ro deck, can be prohibitively expensive and impractical to carry out. Computer modelling and simulations can provide a more cost effective means to investigate the movement of smoke and toxic gases around a ro-ro space and the associated risks. Simulations also have much lower additional costs for running sensitivity studies, e.g., how the ventilation conditions or fire size affect the outcome and are therefore well suited to wider studies. As part of BREND 2.0 a series of simulations in FDS has therefore been undertaken to investigate the movement of smoke and toxic gases as well as the temperature and radiation exposure in a ro-ro space subjected to an EV fire. Full details of the simulations can be found in the technical report *BREND 2.0: Fire simulation technical report* [31]. Below a summary of the simulations and its results is presented.

The simulations used data from full scale experiments undertaken as part of the E-TOX project [9] conducted in 2020, to define the fire inputs for simulations.

The simulation series in BREND 2.0 can be split into 3 scenarios:

- Scenario 0: Study of the sensitivity of toxicity levels in the smoke to the design fire chosen. The geometry utilised for this scenario was a small space open ended, representing a section of an open ro-ro deck.
- Scenario 1: Study of a large fire on a ro-ro deck involving 3 vehicles ignited by an external source (such as leaking oil). This scenario has been modelled as several "sub-scenarios" to study variations and sensitivity cases including multiple ventilation conditions and a scenario with combustion engine vehicles (ICEV) in place of EVs.
- Scenario 2: Study of the initial stages of a single EV fire on a ro-ro deck ignited from thermal runaway. This was modelled as two sub-scenarios with different ventilation conditions.

For scenario 1 three different ventilation conditions (A, B and C) were modelled:

A. A fully enclosed ro-ro deck with mechanical requirement for normal ventilation which turns off upon detection of the fire.
B. An enclosed ro-ro deck with an open stern (natural ventilation).
C. An open ro-ro deck; has an open stern and openings accounting for 10% of the area of each long side (natural ventilation). A visualisation of this can be seen in Figure 8.

Scenario 2's sub-scenarios used geometries A and C from above.

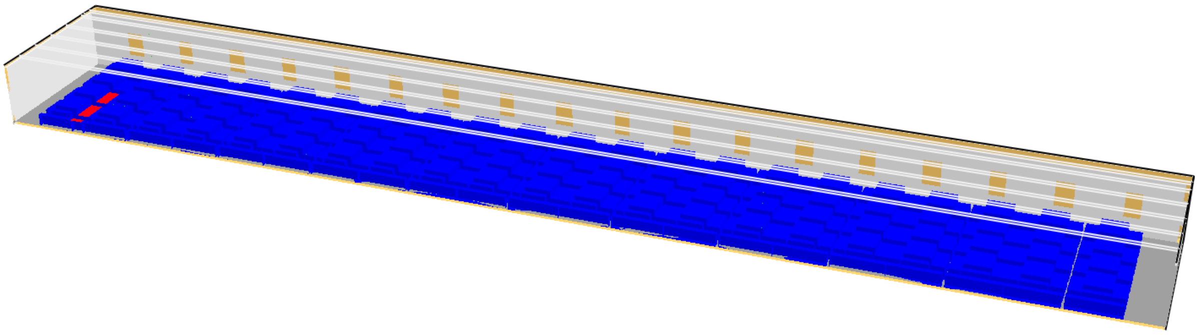

Figure 8 Visualisation, with hidden ceiling and cut through the middle, of the Scenario 1 sub-scenario with an an open ro-ro deck geometry.

The geometry utilised in scenarios 1 and 2 is representative of a ro-ro deck 91.4 m long by 22.3 m wide and 5 m high and can be seen in plan, along with the fire location for scenario 1, in Figure 9.

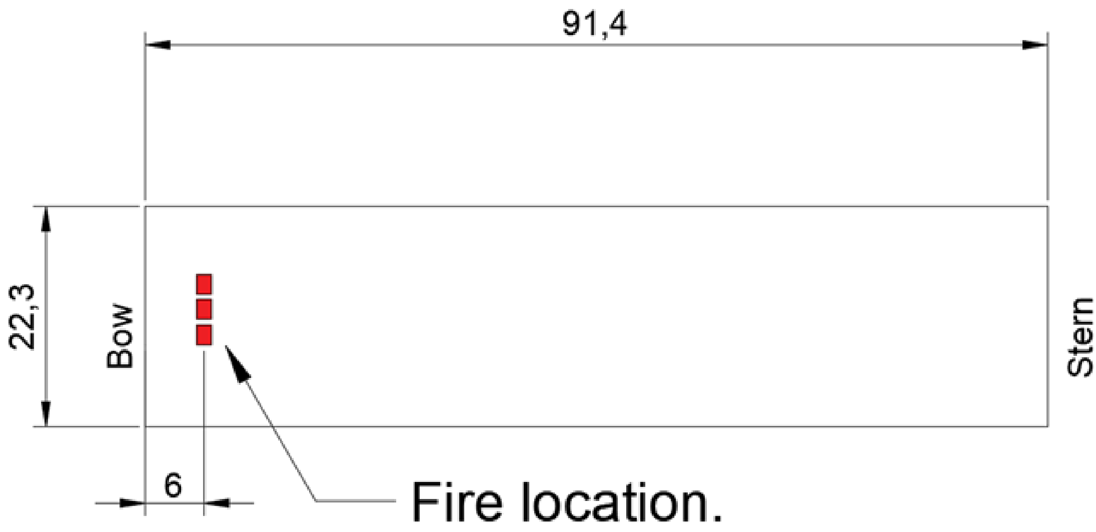

Figure 9 Plan of full ro-ro deck geometry utilised in scenarios 1 and 2.

The inputs for the fires used in the Scenario 1 sub-scenarios, both in terms of Heat Release Rate (HRR) and the release rate of the toxic gases, can be seen in Figure 10 and Figure 11 respectively.

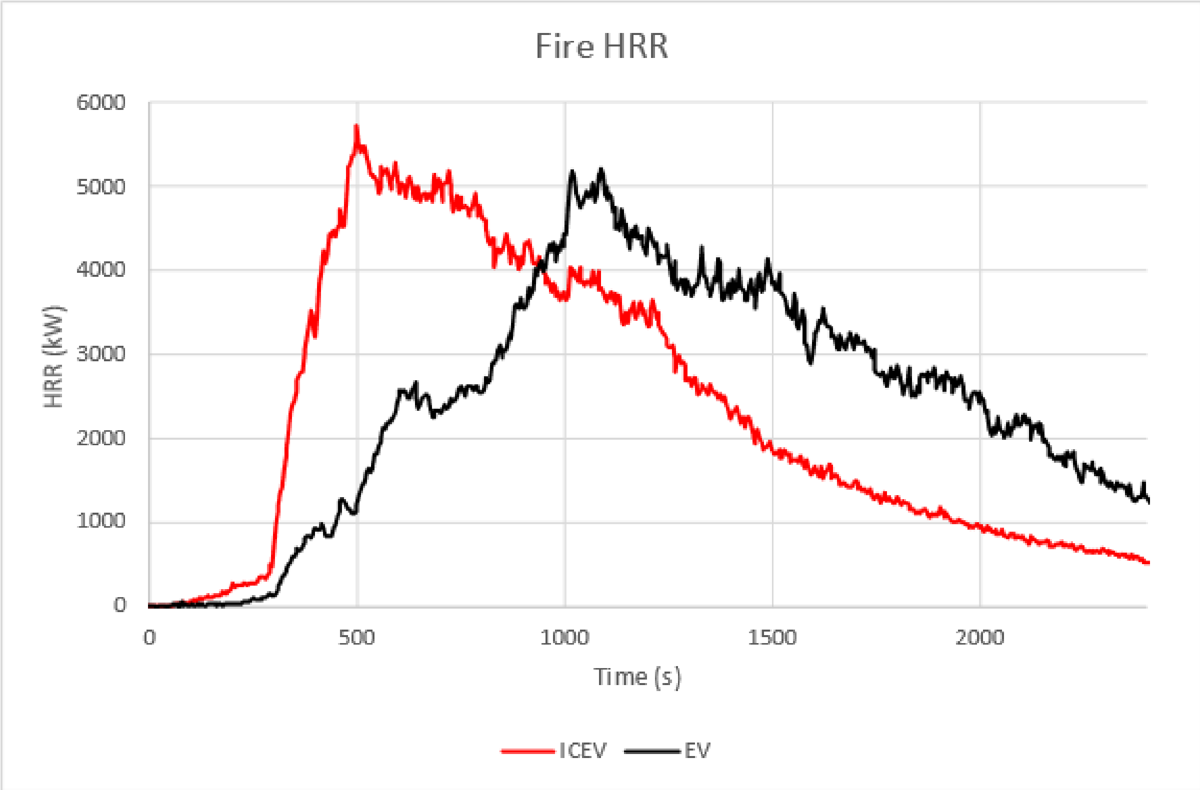

Figure 10 Heat release rate histories from E-TOX experiments utilised as inputs to the simulations.

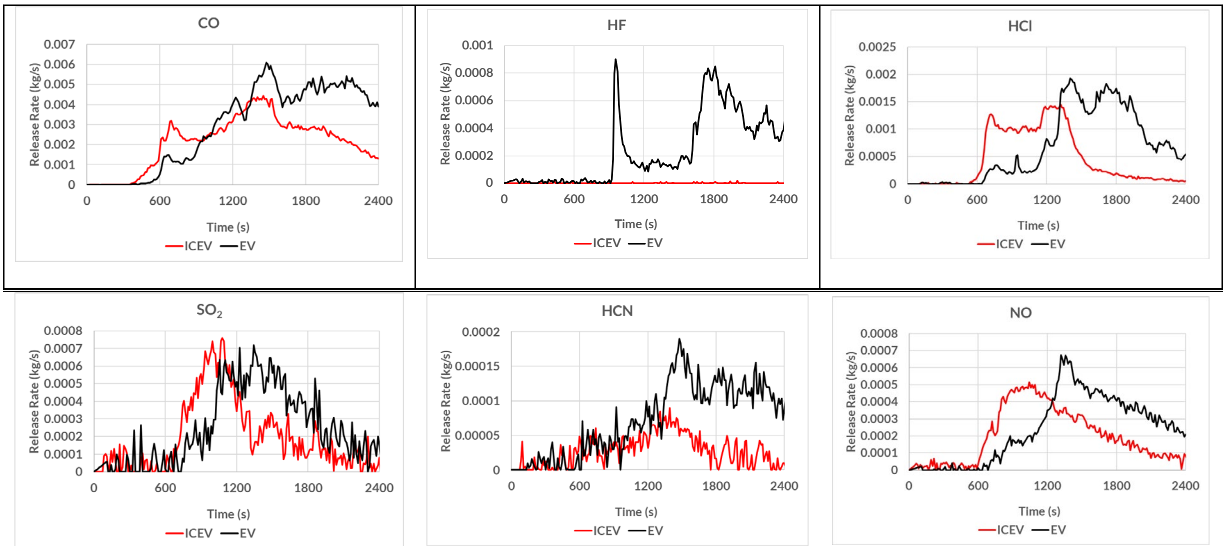

Figure 11 Toxic species release rate histories from E-TOX experiments utilised as input to the simulations.

There were no experiments undertaken in the E-TOX project that directly correlate to the fire development investigated in Scenario 2. However, E-TOX [9] did include experiments of smaller battery components from single cells up to a full pack, and the design fire for scenario 2 was developed by overlaying the HRR curves from these individual elements and creating a combined HRR-curve. This was done so the design fire starts by following the build-up of the single battery cell fire and then transfers to following the 2-cell curve after the peak of the single cell and so on up to the whole car. The design fire curve and the various individual curves used to make it can be seen in Figure 12. As scenario 2 is primarily interested in the early stages of the fire, and to keep the run times reasonable, only the first 20 minutes of the fire were simulated. The fire therefore does not reach the full peak HRR of a car fire, and so the peak is lower than that in Scenario 1.

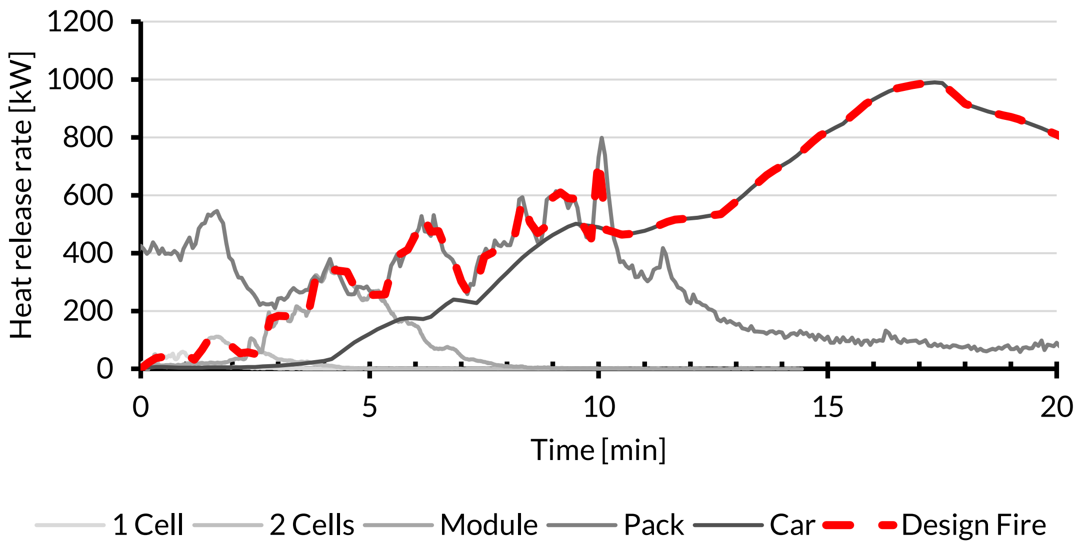

Figure 12 Demonstration of the construction of the HRR curve for Scenario 2 using the build-up of battery components

In simulation models for both Scenario 1 and Scenario 2 measurements of gas concentrations and temperatures are recorded both at a series of point locations. Figure 13 shows the locations for Scenario 1, point locations, and as 2D slices on all 3 axes. For Scenario 0 only point locations were used.

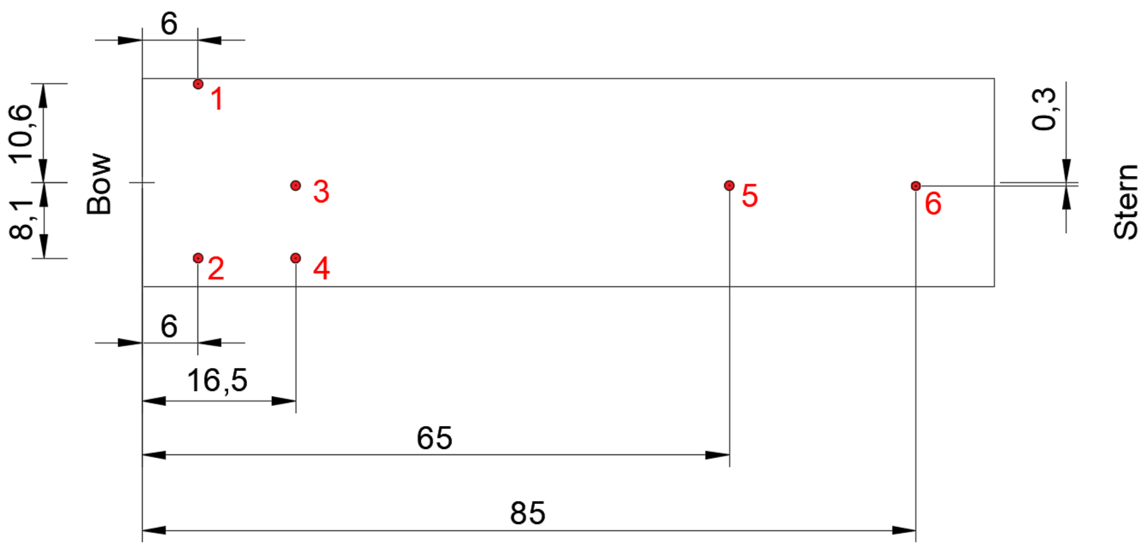

Figure 13 Location of point measurements for Scenario 1, measurements taken at multiple hights at each location.

4.3 Simulation Results

Full results and discussion of computational sensitivity analysis undertaken can be found in the modelling technical report [31]. This section provides an overview of the results highlighting the main conclusions from the modelling.

In Scenario 1's low ventilation sub-scenarios, closed ro-ro deck, it was observed that the smoke layer quickly descends from the ceiling to fill the whole space, see Figure 14. For both other geometries considered a distinct boundary was formed between a smoke layer and a clear layer below, see Figure 15. In both the closed ro-ro deck with open stern and the open ro-ro deck the location of the boundary was over 2 m above the deck level.

Figure 14 Sideview from Smokeview capture showing the filling of the closed ro-ro space with smoke after 1000s under the Scenario 1 fire.

Figure 15 Smokeview capture showing the development of a defined smoke layer in an enclosed ro-ro space with an open stern under the Scenario 1 fire. Capture taken at 1000s.

To compare the relative toxicity of the smoke from EV and ICEV fires the fractional effective concentration (FEC), and fractional effective dose (FED) were calculated at the point measurement locations across shown in Figure 13. FEC and FED are means of calculating the levels of toxicity based on the percentage of the general population who would be incapacitated by exposure to the gases, for irritant and asphyxiant gases respectively. They are calculated in accordance with ISO 13571:2012 [30] and further details can be found in the technical report of BREND 2.0 [31].

Calculated values for Scenario 1 EV and ICEV fires in the enclosed ro-ro deck geometry and the EV fire in the open ro-ro deck configuration can be seen in Table 2.

Table 2 Comparison of calculated FEC and FED values for ICEV and EV fires at point locations in Scenario 1.

Height above deck (m)	Location	EV Fire (Enclosed deck)		ICEV Fire (Enclosed Deck)		EV Fire (Open Deck)	
		FEC	FED	FEC	FED	FEC	FED
1	1	3.91	4.95	0.82	1.05	0.01	0.01
	2	4.08	4.83	0.80	1.00	0.01	0.00
	3	3.03	3.30	0.80	0.95	0.01	0.00
	4	3.32	4.77	0.80	1.01	0.00	0.00
	5	2.13	2.83	0.76	0.96	0.00	0.00
	6	1.69	2.84	0.75	1.02	0.00	0.00
2	1	5.58	5.63	0.82	1.10	0.01	0.01
	2	4.58	5.29	0.80	1.07	0.01	0.00
	3	2.92	3.63	0.81	1.02	0.01	0.00
	4	3.90	5.55	0.80	1.10	0.00	0.00
	5	2.35	3.00	0.76	1.05	0.00	0.00

Height above	Location	EV Fire (Enclosed deck)		ICEV Fire (Enclosed Deck)		EV Fire (Open Deck)	
	6	1.70	2.87	0.77	1.09	0.00	0.00
3	1	5.45	5.52	0.86	1.19	0.16	0.06
	2	4.57	5.17	0.80	1.15	0.08	0.03
	3	2.79	3.72	0.81	1.12	0.04	0.02
	4	3.50	5.10	0.80	1.17	0.04	0.02
	5	2.35	3.10	0.79	1.13	0.04	0.01
	6	1.70	2.88	0.80	1.15	0.06	0.00
4.9	1	4.67	8.60	2.58	1.56	0.64	0.55
	2	4.12	6.90	0.88	1.44	0.54	0.43
	3	4.02	5.91	0.83	1.41	0.60	0.48
	4	3.87	5.91	0.83	1.42	0.57	0.46
	5	2.06	3.10	0.81	1.20	0.37	0.28
	6	1.69	2.91	0.80	1.17	0.34	0.26

In the closed ro-ro deck, the maximum values for the EV fire are significantly higher than for those for the ICEV fire, however in both cases they are well above the normal allowable design value of 0.3 (equivalent to 11 % of the general population being incapacitated by exposure [30]). In comparison the maximum levels for the EV fire in an open deck only get above this limit very close to the ceiling, and therefore well above head height, with low level values not exceeding 0.01.

The results demonstrates that ventilation is more important in maintaining tenable conditions within a space than the source of the fire. But being clear, this project has not studied the impact of maintaining mechanical ventilation on for the duration of the fire. The ventilation conditions studied and discussed in this report relate to the differences in natural ventilation as defined by the type of ro-ro space, i.e. open ro-ro space with open end and openings in the side plating, and closed ro-ro space with an open end or a closed ro-ro space with no openings.

The sub-scenarios for Scenario 1 also demonstrated that the presence of HGVs will have limited impact on the smoke movement around a ro-ro deck but can provide a shield against high levels of radiation exposure. Modelling of a simplified drencher system was also studied but the results suggest that the level of simplification assumed is too high to allow detailed assessment of their impact on the tenability conditions within a ro-ro deck.

The results from the Scenario 2 sub-scenarios confirmed the importance of ventilation with the maximum FEC and FED values calculated exceeding 0.3 at all heights in the enclosed deck model while only exceeding 0.3 at the ceiling in the open deck model, see Table 3.

Table 3 Maximum calculated values of FED and FEC for the Scenario 2 models.

Height	Location	Enclosed deck		Open deck	
		FEC	FED	FEC	FED
1	1	1.19	0.42	0	0
	2	1.43	0.6	0	0
	3	1.28	0.5	0	0
	4	1.38	0.56	0	0
	5	1.32	0.56	0	0
	6	1.29	0.46	0	0

2	1	1.32	0.52	0	0
	2	1.42	0.64	0	0
	3	1.36	0.59	0	0
	4	1.41	0.63	0	0
	5	1.36	0.59	0	0
	6	1.43	0.64	0	0
3	1	1.37	0.6	0.01	0
	2	1.49	0.71	0.01	0
	3	1.45	0.68	0	0
	4	1.51	0.74	0	0
	5	1.43	0.67	0	0
	6	1.42	0.66	0.01	0
4.9	1	1.76	1.12	0.67	0.43
	2	1.78	1.1	0.56	0.34
	3	1.66	0.93	0.36	0.17
	4	1.75	1.08	0.49	0.29
	5	1.72	1.05	0.49	0.22
	6	2	1.37	0.83	0.58

Scenario 2 was focused on the early stages of a fire and also investigated how quickly conditions may become untenable should a fire start in an EV on a ro-ro deck. To this aim a review of the radiation levels with distance from the fire, and how long it takes to reach certain radiation thresholds was conducted. The times to reach 2.5 kW/m^2 (can be tolerated by bare skin for a prolonged period before experiencing burns), 5 kW/m^2 and 20 kW/m^2 (common limit of performance for firefighter protective equipment) can be seen in Figure 16 for the open deck model. The time taken to reach each threshold was slightly longer for the enclosed deck and 2.5 kW/m^2 threshold was not reached beyond 7.5 m and 6.1 m from the fire for the open and enclosed deck models respectively.

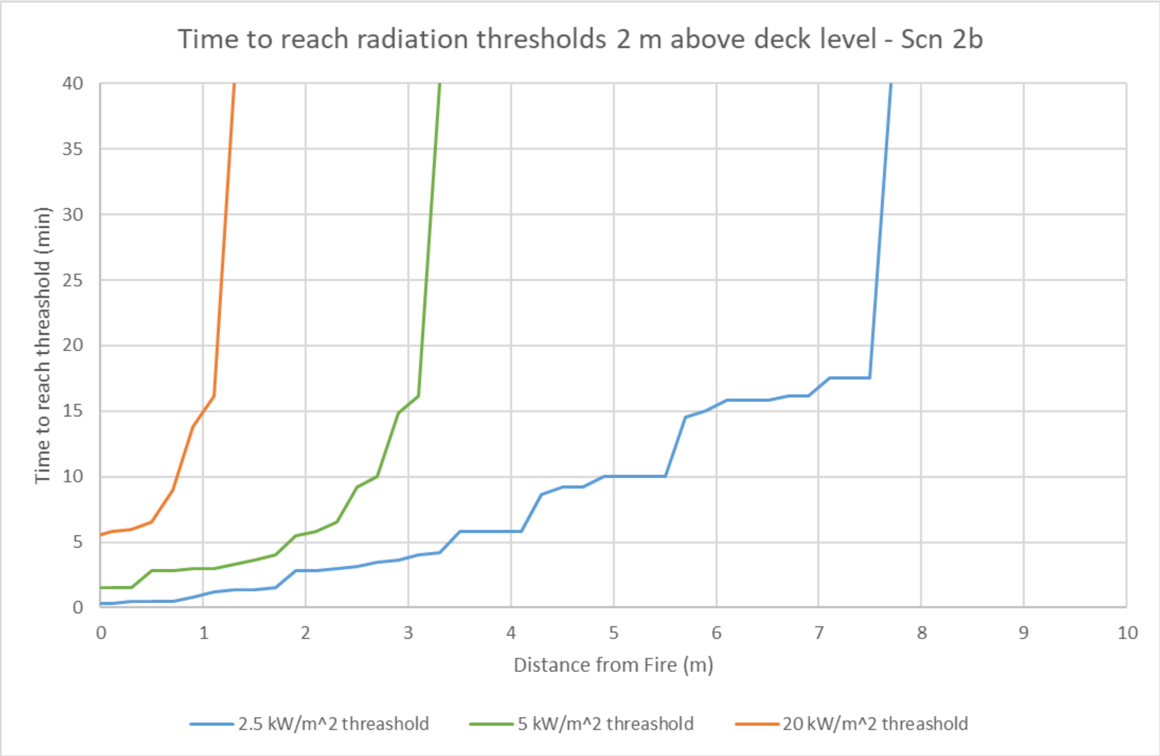

Figure 16 time to reach radiation thresholds for scenario 2b (open deck) model. *Note the simulation ended after 40 minutes, so distances with a 40-minute time did not reach the threshold in the simulation.*

Despite smoke filling the enclosed space, the temperature and radiation distribution within the enclosed ro-ro deck is highly non-uniform with significantly worse conditions in close proximity to fire and relatively cold temperatures at low level and remote from the fire, see Figure 17. This uneven distribution is even more visible in the higher ventilation scenarios.

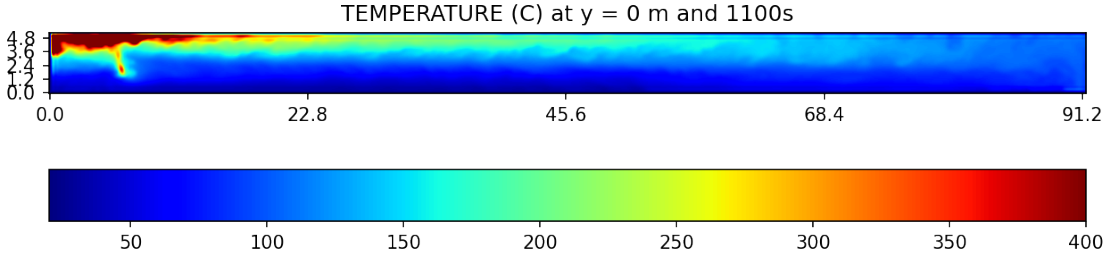

Figure 17 Slice through the centre of the ro-ro deck for a 3 EV fire in an enclosed ro-ro space showing the temperature distribution after 1100s from ignition.

5 Different pre-conditions for firefighting at sea

This chapter is mainly intended to make the end-user, the operators and the ship crew, aware of the pre-conditions that have been highlighted during this study to play a role in the risk assessment in the event of a fire. The end-user will be able to adapt the following recommendations for their ships with its respective pre-conditions.

In a ro-ro space environment, the drencher system (a water based fixed firefighting system) is an important safety measure to consider. All ships applying SOLAS Convention has a requirement of a fixed firefighting system in open and closed ro-ro spaces, on weather decks there are no requirement of fixed firefighting system to activate.

From the user-centred study by Bram, Millgård and Degerman [32] it is stated that the means for activation of the drencher system can be different on different ships, i.e., remote controlled activation or manual activation from the drencher station. Activation of the drencher system is normally needed to be a functional teamwork between the crew present at the fire, officers on the bridge and in the drencher room. From the interviews made in the study, it is shown that the crew can feel unsecure to activate the drencher system, due to design issues, unclear mandate to activate the system or lack of training. This is confirmed in the FIRESAFE study [33] which concluded *efficient activation routines* as the highest life risk reduction safety measure for ro-ro ship fires. This safety measure could be achieved with "*realistic training on the use of the fixed fire extinguishing system in order to achieve company defined goals for release times (e.g., 3 minutes from alarm to water on deck). Drills should be performed frequently in a realistic manner, preferably simulating failure of key components*".

From this BREND 2.0 study it was clear that the strategy for the operators was to use the drencher system as much and as early as possible, this is in mainly to prevent fire spread. In general, no persons are allowed to be in their vehicle during voyage, however, in traffic vessels all passengers are in their vehicle during the voyage. A general fire response strategy was defined in the beginning of the project together with the reference group. The fire response sequences were stated as follows:

1. First intervention by runner, without protective clothing.
    a) The runner is a staff that carry out fire patrol and detects the fire or is sent to verify a fire alarm.
    b) The runner is dressed in ordinary outfit depending on duty. The runner is not equipped with firefighting PPE such as fire suit and BA.
    c) The runner will make an initial firefighting attempt to extinguish the fire while it is small using e.g., hand-held fire extinguishers.
2. Activation of FFFS alternatively manual operation for spaces without FFFS, for example, weather deck.

3. Check the situation. The fire team is sent into the space to investigate the fire from a distance and if needed to do a manual intervention.

4. Post extinguishment. Fire team performs post-extinguishing at close range to the fire seat.

In the Safe and Suitable Firefighting project [5], two focus groups were held with safety coordinators, onboard crew and land-based firefighter. The aim was to gather input from the users on PPE used onboard, gather experience from fire incidents and discuss different fire scenarios. For instance it was confirmed that real fires are rare events on ships which means that training often is the only 'real' experience that the crew has. At the same time, those who have experience of real incidents, talks about how this expands beyond the standard training events. Thus, training is an important part when preparing the crew for firefighting interventions. It was expressed by a fire commander that in one unannounced drill it took the fire team around 25 minutes to get ready, while during a scheduled training it could take them 5-10 minutes. Another fire commander about to arrange such an unannounced drill chose to inform the crew about the day of the drill but not the starting time, to avoid shocking the crew.

From the user study in SSF [5] it is also clear that the land-based rescue services have more refined methods and resources for fighting different types of fires. For vehicle fires, they have a specific method, and some methods have even been developed for AFVs, e.g. a method for BEVs [34] or risk zones for gas vehicles [35].

Besides the various technical aspects that was brought up in this study so far: the ventilation conditions, the type of ship and type of ro-ro space and requirement of extinguishing system or not, the type of ship (passengers or not) the crew will also vary. The crew can vary from well-manned fire teams to smaller ferries with only two crewmembers. The firefighting outfit can also vary from ships where all member of the fire team has their own fire suit to crew that share suits (and thus have the "one-size-fits-all" size available at the fire station) and also various tools (e.g. thermal imagine camera, crowbar) can be used onboard. The response strategy for firefighting in ro-ro space will thus, among other things, depend on:

- Whether a fixed firefighting system (FFFS) is available or not;
- Whether there is a designated fire team and their:
  - training & experience,
  - physical fitness,
  - confidence & motivation.
- The number of smoke divers; and
- The personal protective equipment (PPE) for firefighting.

A set of general recommendations were developed and elaborated together with the reference group of the project; the recommendations are presented in section 7. The recommendations should work for any type of fire in a vehicle, regardless of fuel. Particular risks with AFVs are identified with a beware statement in red colour. In addition, training is highlighted since it is judged to be paramount to an efficient fire response in practice.

6 Conclusions

This chapter collects the conclusions from the previous chapter in this report. The conclusions are then used to form the recommendations presented in chapter 7.

Firstly, the relative number of fires for AFVs compared to conventional vehicle fire are currently lower (normalised for the total number of vehicles), although consequences can be more severe and can pose different problems. For EVs, the batteries rarely initiate vehicle fires and are difficult to ignite. For gas vehicles, it is argued that the likelihood of fire remains similar to conventional vehicles, although the fuel is less likely to initiate fires since it is stored more safely.

When li-ion batteries burn in EV fires, there are higher emissions of HF in the combustion gases, compared to fires in internal combustion engine vehicles (ICEV) on fire. However, while HF is very dangerous to inhale, studies outside this project have shown that the risk for a potential skin uptake of HF is low. It is unlikely that adverse health effects are caused during smoke diving from HF for firefighters wearing standard personal protective equipment. When it comes to inhalation of fire combustion gases (i.e., without BA), several compounds in combustion gases, from both EV and ICEV fires, are highly toxic in addition to HF, and the risk of exposure should be related to the combined impact of these gases rather than the isolated levels of individual species. These combined effects can be assessed using the fractional effective dose (FED) and fractional effective concentration (FEC) measurements for asphyxiants and irritants, respectively.

Simulations performed in this project show that the maximum FED and FEC values for an EV fire are significantly higher than for those for an ICEV fire. However, in the case of a closed ro-ro deck, the values are well above the allowable design value of 0.3 for both vehicle types, while in the case of an open ro-ro deck, the values are only exceeding 0.3 close to the ceiling. From the FDS simulations it can therefore be concluded that the differences in natural ventilation as defined by the type of ro-ro space is more important in maintaining tenable conditions for toxicity within a space than if the source of the fire is an EV or an ICEV.

For gas vehicles, the risks are primarily related to the probability of jet flames and explosions. It was found that application of water (roughly 10-15 mm/min) was enough to cool the TPRD. The application of water can thus avoid TPRD activation for at least 13 min for a steel tank exposed to a widespread fire, and up to 20 min for composite tanks and steel tanks exposed to smaller fires. Furthermore, experiments conducted (2019 and 2021) show that even where harsh conditions for the pressure vessels are created and maintained, for a considerable time, only one out of in total 15 tests resulted in the most vulnerable release, a pressure vessel explosion.

Jet flames occurred in many of the conducted experiments and a jet flame can reach 10 m and be directed in any of several directions. The radiation exposure from the jet flame is rather low. Recorded values were between 2 kW/m^2 and 8 kW/m^2 at the point (X=5 m, Y=5 m) with the TPRD in origo (X=0 m, Y=0 m). At 12 m or above, incident radiation levels were 2 kW/m^2 or lower. 2.5 kW/m^2 is a typical tenability limit for unprotected skin and for an EV fire, a radiation of 2.5 kW/m^2 was not reached beyond 7.5 m and 6.1 m from the fire for the open and closed deck models, respectively.

7 BREND 2.0 recommendations

These recommendations are based on the conducted work in the BREND 2.0 project, together with the previous BREND project [1], other RISE projects such as E-TOX [3] and Safe and Suitable Firefighting [5], and other recent studies, e.g. about HF exposure and health impacts [29] briefly summarised in the previous chapters of this report.

The recommendations were elaborated with the reference group established for the project and are also published separately in a Quick Guide to be find in the Appendix of this report.

7.1 Initial firefighting

It is recommended that the runner, as a rule of thumb, takes an offensive tactic to have a chance to extinguish the fire before it become too large to handle. If the fire is extinguished with a limited fire exposure of the gas tanks less than 15 – 20 min before the extinguishment starts, and energy storage is being cooled, many risks, including the risk of pressure vessel explosion, are reduced.

The initial firefighting should aim to extinguish any minor fires that are detected, e.g., with a suitable hand-held fire extinguisher. The runner should stay out of the smoke plume while trying to extinguish the initial fire while it is small. The reason staying out of the smoke plume is mainly because the runner is not wearing any special protection, rather arriving to the fire in what they wear at the moment of the alarm, and that fire combustion gases, several compounds in gaseous phase are highly toxic for inhalation. Most likely there will be no battery fire and no pressure vessel explosion at the initial stage of the fire development but beware of jet flame or flash fire from energy storage.

While the runner tries to extinguish the fire, preparations should be made to activate FFFS and to get the fire team ready in case the runner does not manage to extinguish the fire. Even if the runner is successful in extinguishing the fire, the fire team should be ready to cool down heated parts and handle a possible re-ignition or to deal with hidden fires.

7.2 Activation of FFFS (if available)

If the runner cannot extinguish the fire, the extinguishing system (if available) should be activated to control the fire as soon as possible. This is communicated by the runner to the commander on the bridge via a communication device which crew is carrying. A defensive tactic can then be to stay out of the smoke and the deck on fire until the fire burns out and any potential gas tanks have time to cool down. The temperature evolvement should be monitored (e.g., at deck above the fire or with fixed temperature sensors).

7.3 Fire team intervention

If no FFFS is available or if the FFFS is not working as intended, the fire team can make a manual intervention. An offensive tactic that aims to extinguish the fire using hydrants is supported by this report since cooling of energy storage and quick extinguishment of fire lowers the risk of pressure vessel explosion, jet flames, and thermal runaway.

Based on a risk assessment, a defensive or offensive tactic should be taken.

If there is a need for lifesaving or to protect the ship from an escalating fire, fire extinguishing through an offensive attack may be preferable, taking into account whether there is a designated fire team and their training, PPE, physical fitness, confidence, ambition, and preparedness.

For fire extinguishing using an offensive approach, the CTIF method (introduced in the BREND project) advocates a strategy with at least four (five including a team leader) fully equipped firefighters divided into two teams using one hose in each team with a water supply of at least 250 l/min. One team cool the energy storage and one team extinguish the fire. Small hose sizes, e.g., 28 mm, is faster and easier to use. The performed fire tests support such an offensive approach since cooling of the gas tanks and extinguishing the fire will protect against a pressure vessel explosion (and an escalating fire disaster), also that no battery is likely to be involved in the early stage of a fire.

One alternative to the CTIF method is that the FFFS replaces one of the teams so that a manual intervention is made with only one team. The same tactic could be used for all vehicles regardless fuel since many vehicle fires will have a similar initial development. The traction battery will take long time to become involved in any fire and gas tanks are designed to handle a certain fire with a margin of safety. Beware, even if a fire is relatively small, a local fire that is not extinguished and affects a gas tank for a certain time (ca 15-20 min) can lead to a pressure vessel explosion. Hence, a low-risk window of opportunity exists to make a fast intervention. The CTIF method further reduces the risks by applying water from a distance. As soon as the energy storage is being cooled or not affected by any fire, it will, regain a margin of safety against a pressure vessel explosion (see more in section 3.5).

If there are jet flames from the traction battery (below vehicle) or jet flames from gas tank´s TPRDs, the focus should be to cool the surrounding, prevent fire spread and try to extinguish seat of the fire. If possible and safe to do so, let the jet flame burn out.

7.4 Post extinguishment

Allow fire exposed gas tanks to cool down before the vehicle is approached. Gas tanks will regain their strength, but composite material may leak, this was shown in conducted experiments. Use smell, listen, or use a gas detector to verify gas leakages. Monitor cryogenic gas storages (LNG, LH_2) in case insulation is lost (boil-off risk), see chapter 2. Minor leakages are not an issue at open deck or weather deck. Nor should minor leakages be an issue in large, closed ro-ro spaces, but to be safe, turn on full ventilation (provided that the fire is extinguished so it does not re-ignite).

Monitor temperature and possible gas development for EVs that have been exposed to fire. This might require some kind of water-based tool developed for cooling or preventing fire spread, see BREND report [1].

7.5 Training

For a fast and efficient response, ambitious training routines are necessary. This was confirmed in performed focus groups as well as other studies, see section 5. Not only the manual intervention needs to be trained, also the activation of FFFS can be an issue causing concern by the crew.

It is recommended to have both announced and unannounced drills (or drills with unannounced starting times), this was for example mentioned in the user study in Safe and Suitable Firefighting [5].

Further, it is also recommended to include how to remove contaminated PPE safely in the drills. Contaminated PPE and equipment should be stored in airtight bags until washing and while handled, the skin should be protected, and inhalation avoided [36].

8 Closing remarks

BREND 2.0 has been successfully carried out with great input and in dialogue with the reference group and support from the steering group. The final seminar was held online on February 9, 2022, together with the RISE project Safe and Suitable Firefighting, and had around 50 external attendees from different organizations and different countries.

The importance and interest for the risk of fire related to new energy carriers has been obvious throughout the project. And the project group has given input to the European Maritime Safety Agency (EMSA) guideline on carriage of AFVs on ro-ro ships that is being prepared at the moment and will soon be released.

Finally, BREND 2.0 have prepared a quick guide on the formulated recommendations. The quick guide is intended to be used by e.g., crew, fire chief or organisations involved in training of crew. In Appendix A you find the Quick Guide.

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Appendix A - Quick Guide

Quick guide: Fire in new energy carriers on deck

To improve the possibility of a safe firefighting operation in ro-ro spaces, it is important to know how to assess the risks with alternative fuel vehicles.

This quick guide is intended to increase the knowledge of risks related to fires in alternative fuel vehicles (AFVs) on board ro-ro ships. AFVs include gas vehicles such as biogas/CNG, LNG, H_2 or LH_2 and electric vehicles (EVs). The information is based on the results from the research project BREND 2.0, which focused on risks with gas vehicles and EVs in relation to firefighting operations.

Alternative fuel vehicles

Available statistics today suggests that the likelihood of fires in AFVs is lower than for conventional vehicles. Both battery and gas vehicles are equipped with a range of safety systems, intended to protect them from fires.

Toxic gases are found in combustion products for all type of vehicle fires. EV fires result in higher emission of hydrogen fluoride (HF), compared to internal combustion engine vehicles on fire. HF is very dangerous to inhale, but studies outside BREND 2.0 have shown that the risk for a potential skin uptake of HF is low. It is unlikely that adverse health effects are caused during smoke diving from HF for firefighters wearing standard personal protection equipment.

Gas tanks containing compressed biogas or hydrogen are equipped with a temperature-activated pressure relief device (TPRD) that should release the gas in case of fire. Based on experiments it is concluded that a local fire exposure for more than 15 min, on the gas tank, can result in a pressure vessel explosion. But such situations are rare since a vehicle fire normally develops in a way that activates the TPRD. It is also found that application with water further lowers the risk of a pressure vessel explosion since the tank then is cooled, and thus protected.

Protective equipment and training

Research on the possible consequences of fires in electric and gas vehicles indicate that fire suits, approved according to EN 469 level 2 (together with gloves, boots, flash hood, long-sleeved undergarments, and BA), provide a good protection against heat flux, temperature, and fire gases.

For a fast and efficient response, ambitious training routines are necessary. Not only the manual intervention needs to be trained, also the activation of fixed firefighting systems (FFFS) can be an issue causing concern by the crew. A combination of both announced and unannounced drills are useful. If the crew is often waiting by their assigned mustering location when the fire drill start, occasionally unannounced drills can be a useful addition to the training routines. Consider the crew's maturity when deciding if and how to carry out this type of drill.

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Latest version available at: www.ri.se/en/brend2

FIRES IN AFVs – TACTICAL RECOMMENDATIONS

Cooling of energy storage and quick extinguishment of vehicle fires lowers the risk of pressure vessel explosion, jet flames, and thermal runaway. However, different ships mean different preconditions: Is there a fixed firefighting system available? What is the size of the fire team? What personal protection equipment (PPE) is available? How well-trained and confident is the crew? These are questions to consider when training and structuring the fire intervention. Depending on the preconditions for manual intervention and continuous risk assessment of the situation a defensive or offensive tactic can be taken.

1. INITIAL FIRE STAGE

Stay out of the smoke plume and, if possible to do so safely, try to extinguish the fire while it is small, for example with hand-held fire extinguishers. Most likely there is no battery fire and no risk for pressure vessel explosion at this stage.

> Beware of jet flame from the energy storage.
>
> For EVs: Stop the charging and break the power.

2. ACTIVATE FIREFIGHTING SYSTEM

If the initial fire cannot be extinguished, a deluge system should be activated (if available). This could be part of a defensive tactic where the fire is controlled using the deluge system. Then the crew can stay out of the ro-ro space until the fire burns out and any high-pressure compressed gas tanks have time to cool down. Monitor temperature evolvement (e.g., at deck above fire or with temperature sensors) to verify that the fire is being controlled or extinguished.

3. FIRE TEAM INTERVENTION

With an offensive tactic, initially, the AFV fire can be extinguished as a standard vehicle fire. Traction battery will take long time to become involved and gas tanks are designed with a margin of safety in case of a fire. If possible, cool the energy storage (including traction battery and gas tanks).

As soon as compressed gas tanks are being cooled or not affected by any fire, they regain a margin of safety against a pressure vessel explosion.

If there are jet flames from the traction battery (below vehicle) or jet flames from gas tank´s TPRDs the focus should be to cool the surrounding, prevent fire spread and try to extinguish seat of the fire. If possible and safe to do so, let the jet flame burn out.

> Beware that a local fire exposure of 15-20 min or more of CNG/H_2 gas tanks increase the likelihood of pressure vessel explosion. Hence, a low-risk window of opportunity exists to make a fast intervention.
>
> Also, watch out for jet flames from the traction battery (commonly seen below the vehicle) or from gas tank pressure relief devices (TPRDs).

4. POST EXTINGUISHMENT

EVs: Monitor the temperature and possible gas development for traction batteries that have been exposed to fire. Preventive suppression equipment should be ready to swiftly control a re-ignition.

Gas: Allow fire exposed gas tanks to cool down before the vehicle is approached. Gas tanks will regain their strength, but composite material may leak – smell, listen or use a gas detector to verify. Monitor cryogenic gas storages (LNG, LH_2) in case insulation is lost (boil-off risk). However minor gas leakage should not be an issue in large or well-ventilated ro-ro spaces.

USEFUL LINKS

- BREND 2.0 report
- Safe and Suitable Firefighting report & quick guide
- International Association of Fire and Rescue Services
- MSB: Healthy firefighers: the Skellefteå Model
- MSB: Literature about Lithium batteries (Swedish)

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