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ABSTRACT

This report includes the Proceedings of the 3rd International Conference on Fires in Vehicles – FIVE 2014, held in Berlin October 1-2, 2014. The Proceedings includes 21 papers given by speakers in six sessions; The fire problem, Materials, Ignition source characteristics, Fire development, Mitigation means, and Electric vehicles. A poster exhibition with 15 posters accompanied the sessions. The extended abstracts on the posters are included in the proceedings.

Each day was opened by two invited Keynote Speakers addressing broad topics of interest. The Keynote Speakers, Serge Métral, SNCF France, Steve Hodges Alion Science and Technology USA, Horst Schauerte, BVG Germany and Michael Försth, SP Sweden, were all invited as leaders in their field.

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PREFACE

These proceedings include papers and extended abstracts from the 3rd International Conference on Fires in Vehicles – FIVE 2014, held in Berlin October 1-2, 2014. The proceedings include an overview of research and regulatory actions coupled to state-of-the-art knowledge on fire related issues in passenger cars, buses, coaches, and trains.

Fires in transport systems are a challenge for fire experts. New fuels that are efficient and environmentally friendly are rapidly being introduced together with sophisticated new technology such as e.g. fuel cells. This rapid development, however, introduces new fire risks not considered previously and we risk a situation where we do not have sufficient 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 high attendance of experts, researchers, operators, manufacturers, regulators 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 vehicles. It is not confined to bus fires or train fires but includes them both, naturally since fire problems are often similar regardless of type of vehicle. This means that for example solutions for trains are useful for fire problems in buses and vice versa.

In the proceedings you will find papers on the fire problem, materials, ignition source characteristics, fire development, mitigation means and finally electric vehicles. We are grateful to the renowned researchers and engineers presenting their work and to the keynote speakers setting the scene. I sincerely thank the scientific committee for their expert work in selecting papers for the conference.

I would also like to take this opportunity to thank our event partner BAM for the co-operation and invaluable help to realize FIVE 2014 in the wonderful city of Berlin.

Björn Sundström
Chair of FIVE 2014

Note: the views expressed in the papers are those of the authors and not necessarily those of SP Technical Research Institute of Sweden, Department of Fire Research.
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Benefits of Standardisation in Fire Protection in Rolling Stock
FIVE 2014

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INTRODUCTION

Before 1970, passenger coaches were built with steel, wood, seats with wool, leather or leatherette with few electrical components reachable by passengers. These materials have poor fire behaviour characteristics.
Then, plastics became more and more often used: polyester, polyvinyl chloride … and more electrical components for the comfort of passengers.

When a fire occurred, the flash over was very quick and the vehicle was almost completely destroyed, hopefully, without injuries in SNCF coaches.

To decrease the risk of fire, SNCF and RATP worked together to set national rules to be applied on all new vehicles and for existing vehicles, on all refurbished parts. This work, started in 1973, was ended by the publication of the three French Standards from 1988 to 1992.

Then, work on European standards began in 1991 with the best practices of each European country. The result is the EN 45545 series published in 2013.
The main principle of these documents is to set requirements on the four successive layers of safety combined to produce a low level of residual risk:

![Diagram with layers of safety: Prevention, Mitigation, Evacuation, Rescue team leading to Residual risk]

**Prevent the fire:**
Use all practical means to prevent ignition in the train or limit the ability of materials to be ignited, for example:
- Material testing: flammability
- Control of the location and size of equipment producing heat (heating systems, high voltage equipment …)
- Flashover devices (arc barriers, shielding)
- Defining hazard levels for rolling stock
- Defining potential sources of ignition
- Control/confine flammable liquids on board (diesel, transformer oil, gas …)

**Mitigate the fire:**
Use all practical means in the event of a rolling stock fire starting, to limit its effect (heat, smoke, …) on passengers and staff, for example by:
- Material properties: flame propagation, heat, smoke (visibility), toxicity
- Fire barriers: partitions, floors, enclosures
- Detection / Shut down systems (energy) / Extinguishing
- Staff training in the event of fire
Facilitate the evacuation:
Use all practical means in the event of a developed rolling stock fire, to ease at best the evacuation of passengers and staff, for example:
- Staff training in the event of fire
- Emergency doors and evacuation devices (internal)
- Public information systems
- Continued train operation to reach a safe area

For rescue team
Use all practical means in the event of a developed rolling stock fire, to allow the rescuers to assist passenger and staff evacuation, for example:
- Staff training in the event of fire
- Emergency doors and evacuation devices (external)
- Public information system
- Procedures for rescuers use

These requirements depend on the hazard level as defined in EN45545-2. This hazard level depends of the operation category and the design classification of the vehicle as defined in EN45545-1.

Relation between Fire Safety and EN 45545 series

Summary of EN 45545 series
EN 45545-1 gives definitions, operating categories, fire scenarios
EN 45545-2 defines hazard levels and set requirements for fire behaviour for all materials used in rolling stocks in relation to their use, their location, their area and their mass.
EN 45545-3 set requirements for fire barriers and partitions
EN 45545-4, EN 45545-5 and EN 45545-7 set requirements for the rolling stock design
EN45545-6 set requirements for fire detection and fire suppression.

Requirements for the four successive layers of safety combine to produce a low level of residual risk are split into EN 45545 series.
- EN 45545-1, 2, 4, 5, 7 have requirements for the prevention;
- EN45545-2, 3, 6 have requirements for the mitigation
- EN 45545-4, 6 have requirements for the evacuation and rescue team
BENEFITS OF THIS STANDARDISATION

On the number of fire
With the implementation of these standards (French standards then EN standard), the number of fires occurring in passenger coaches where fire service involved has decreased dramatically.

![Number of fires vs. Year graph]

After 1980, most of burnt coaches have been repaired. Before 1980, most of burnt coaches were completely destroyed.

Since 2007, most of ignition of fire are on electrical parts, and the fire stops itself without need for firemen.

Use of EN45545 in refurbishing and upgrading projects:
TSI LOC&PAS (to be published in January 2014) refers to EN45545 and EN 50553, and for materials and component, their fire behaviour shall comply with EN45545-2.
TSI allows transitional periods for EN45545-2 with a specific clause for Fire safety: during 3 years after publication of the TSI LOC&PAS, it is permitted to use one of the five national standards BS 6853, NFF 16-101 and NFF 16-102, DIN5510-2, PN-K-02511 and PN-K-02502, DT-PCI/5A.

In each part of EN45545, the following statement is written: This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by September 2013, and conflicting national standards shall be withdrawn at the latest by March 2016. It means that the five national standards above have to be withdrawn before the end of the allowed transitional period given in TSI LOC&PAS.

In SNCF, we prefer to choose each time as possible materials and components according EN45545-2, in order to ease the maintainability after this transitional period.
AND TOMORROW?

EN 45545 series have to be revised to improve Fire Protection in Rolling Stock. Prior to this revision, feedback from the implementation of EN 45545 is needed to have a better idea of its related costs.

CEN TC256 WG1 is mandated to revise these EN45545 series and to write three new standards:
- EN for fire test on seats derived from Annexes A, B and D of EN45545-2;
- EN for toxicity test on materials for rolling stocks derived from Annex C of EN45545-2;
- EN for assessing the efficiency of Fire Containment and Control System (FCCS); as requested by European Railway Agency to close an open point in the Technical Specification of Interoperability LOC&PAS.

The kick-off meeting of CEN TC256 WG1 was held the 1st and 2nd April 2014. During this meeting, two drafts of amendments for EN45545-2 (Requirements for fire behaviour of material) and EN45545-5 (Electrical design) have been written. The goal of these amendments is to avoid difficulties with Notified Bodies and National Safety Authorities.

About 50 experts are members of CEN TC256 WG1, four task forces are decided:
1. Task Force "seats"
   The new EN for fire test on seat is mainly to take into account the British concern about the seat classification. One way is to have a modified burner – run at 28 kW for the first minute then at 7 kW for two minutes.
2. Task Force "Toxicity test"
   Pending the result of the work on ISO level by ISO TC92 SC1, this group has to revise Annex C of EN45545-2:2013 describing the test. The main goal is to improve reproducibility and repeatability of the results.
3. Task Force "FCCS"
   After conclusions of analysis done by a Survey Group with UNIFE and CEN TC256 WG1 expected before end of this year, a draft of EN for assessing the efficiency of these devices has to be written. Perhaps, the research project should be done to determine the fire source and the fire scenario to be tested.
4. Task Force "revision EN45545 series"
   All remaining comments coming from TS to prEN Enquiry or by the feedback of the use of these documents should be analysed to improve this EN.

Reasons to split EN 45545-2 in three documents are:
- simplify the revision process topic per topic;
- avoid losing time for expert involved for one topic during the discussion of another topic;
- allow to improvement of this set of documents step by step

EN45545-2:2013 Next EN45545-2

CONCLUSION

With common European rules, we hope that good levels of safety are achieved everywhere and costs will decrease.
Vehicle Fire Research – a Review

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ABSTRACT

When combustible fluids and flammable materials are stored in close proximity to potential ignition sources, as they inevitably are in self-propelled vehicles, fires are a real and present danger. Fortunately there are often means to mitigate the risks and damage caused by fire on a vehicle, but the approach varies with application. Vehicle fire research involving statistics, cause and origin, materials, and fire protection systems is almost as old a pursuit as the automobile itself, and such work continues. This paper presents an overview of vehicle fire research focused on highway and military vehicles.

KEYWORDS: vehicle fires, fire research, fire protection

INTRODUCTION

Fire safety is an important issue on any vehicle. As long as vehicles carry flammable materials such as fuel, lubricants, plastics, and ammunition in the case of military vehicles, fires are possible. Generally vehicle occupants, flammable materials and ignition sources are in close proximity and it is not always easy or practical for the occupants to safely evacuate in the event of a fire. Fortunately, vehicle design features can reduce the risks of fire, and, in some cases, fire suppression systems can limit the damage caused by fires. Many of the most effective design features are the product of experience and extensive research and development.

Some of the first automobiles had fiery endings. As early as 1891, a prototype three-wheeled, single-cylinder automobile was reported to be lost to fire [1]. The first patents describing means of (air and ground) vehicle fire protection date to the early 20th century, and at least one described precursors to modern methods, including automatic actuation where an orientation insensitive extinguisher (based on a flexible dip tube) was released by heat, radiation and mechanical shock sensors; see Figure 1 [2]. Despite such efforts, vehicle fire risks, real and perceived, persist – notable examples include the Ford Pinto recall in 1975 [3] and General Motor’s (GM) third generation C/K pickup truck controversy which ended in a settlement with the US’ National Highway Transportation Safety Administration (NHTSA) in 1994 [4]. Recalls of popular automobiles due to fire risks are a continuing issue [5].

Similarly, fires on heavy-duty vehicles, from passenger buses to tanks, have driven application specific research and development [6, 7]. While there are many similarities between fire protection methods, the differences between vehicle platforms, e.g., automobile, truck, bus or military, result in significant variations in approaches [8].
Significant vehicle fire research has been conducted over the last few decades. The goal of this research has been to further fire science as it relates to our understanding of vehicle fires, with the aim of reducing injuries and fatalities associated with motor vehicle fires. Notably, this growing body of important work, motivated in part by GM’s 1994 settlement with NHTSA, led to the organization of the SAE International (formerly Society of Automotive Engineers) Fire Safety Committee in 2005. Since the inception of the Fire Safety Committee, 129 peer-reviewed papers have been presented at the SAE World Congress and subsequently published [9]. The fire safety sessions have also included interactive panel discussions that featured experts in vehicle fire protection [10]. In 2013 an overview of vehicle fire statistics in the US was presented as a keynote [11] and in 2012 and 2014, keynotes were presented that described the unique challenges in the fire protection of electric vehicles [12, 13]. Session topics have ranged from laboratory science, including flammability properties of materials and analytical tools, such as computational fluid dynamic modeling, to the methodologies of field investigation, such as the correlation of burn patterns and fire origin. Other studies have addressed the prospective means of fire risk reduction in future technologies – for example, the flammability of next generation refrigerants – to retrospective studies of risk characteristics of designs currently on the road.

Advancements in vehicle development, especially those associated with the power train and fuel, may involve relatively new fire hazards that often require somewhat unique mitigation means. Recent collaborative efforts to understand emerging electric vehicle fire hazards (e.g., those associated with certain battery technologies) and develop applicable safety standards are notable examples [14, 15]. Clearly the need for vehicle fire research, in all applications, continues.

Highway Vehicles

Among the most dramatic fires are those that occur along with an automobile crash – at least in the movies. In reality post-collision fires are rare, usually relatively small and slow growing, and may start minutes after the crash. However, if an occupant is trapped inside a crashed vehicle, even a small, slowly growing fire can be dangerous. And in fact, post-collision fires are associated with a large fraction of vehicle accident fatalities due to fire. Overall, in the US, vehicle fire-related deaths account for approximately 10% of all deaths attributed to fire [11, 16].
Many significant aspects of vehicle fire protection have been described in the SAE Fire Safety papers and presentations. While mainly focused on automobiles, the papers have also addressed fire research aimed at the significant problems faced in many heavy-duty vehicular applications such as buses and trucks. Topics covered include (selected references given):

- Statistical overviews of the highway vehicle problem. The National Fire Protection Association (NFPA) and others have reported detailed statistics on vehicle fire causes, origins, and damage, as well as given guidance on the fire investigation methods that underlie the data [11, 16-19].
- In 2003 the first post-collision fire created in laboratory conditions was reported to the National Highway Transportation Safety Administration (NHTSA) [20]. The results, including the difficulty of pre-engineered fire protection systems to cope with post-collision vehicle distortions, were summarized and discussed in a 2005 SAE Fire Safety paper [21].
- In 2005, the first production automotive active fire protection system, developed by Ford and their suppliers for the Crown Victoria Police Interceptor, was described [22].
- The work of the SAE Technical Working Group (and others) studying hydrogen and fuel-cell vehicle safety standards and test protocols was reported annually from 2005 through 2011 [23-26].
- Other groups have expanded ideas developed in SAE Committees and Working Groups into prototype test protocols [27, 28].
- Several papers reported studies of hot surface ignition of underhood fluids. These were summarized in a 2010 paper [29].
- The flammability of plastics and the combustion byproducts of materials have been evaluated [30-32].
- The flammability of new and existing refrigerants have been studied [33, 34]
- Everything in a vehicle has a trade-off, and safety systems are no exception. The design trade-offs and cost-benefit analysis of fire protection methodologies have been the object of several studies [35-38].
- Evaluations of vehicle maintenance, design changes and/or features with respect to their effect on fire safety have been described [39-42].
- Full scale vehicle burn tests indicate that oxidation patterns and melted aluminum do not necessarily correlate with fire origin as is often assumed [43].
- Active fire protection systems have been discussed and evaluated [8, 10, 20-22, 44-46].

Passenger bus fires are relatively rare but do occur, mainly in machinery spaces, e.g., the engine compartment [47, 48]. Related to this is the trend toward not only better bus design and maintenance but also to the increased application of active fire protection systems for the engine compartment [48]. While fire protection of the engine compartment arguably increases the level of safety, the main benefit is asset protection. This is indicated by the fact that recent bus fires that resulted in a large number of injuries and fatalities, started on the bus exterior (e.g., in a wheel well, or at a fuel tank), not in the engine compartment, so active protection systems as currently designed and deployed would have had no effect on the outcome [49]. Strategic use of fire resistant materials, better means of egress and more thorough maintenance have been suggested as improvements that would be most effective, in addition to evaluating possible fire protection technologies for the wheel wells and other currently unprotected areas [50, 51].

**Military Ground Vehicles**

Militaries around the world operate many thousands of tactical and combat ground vehicles in hostile environments. Fire protection for these vehicles has been, and is, a significant design and development area [7]. Fires on military ground vehicles fall into two broad categories: peacetime and combat.
Peacetime fires in military ground vehicles are similar to vehicle fire experiences in the commercial sector:

- Fuel, hydraulic fluid, or lubricating oil component failures can lead to leakage of flammable liquids that are ignited by contact with hot surfaces and/or sparks;
- Electrical component failures or corrosion can lead to overheated circuits that ignite wire insulation or oily contaminants and other combustible materials; and
- Overheated brake components and trapped road debris can cause fires in the wheel well. Wheel well fires can also occur if a wheeled vehicle operates too long on ‘run-flats’ designed to offer temporary support when the main tires are deflated.

Many military vehicles have fire protection systems that protect the engine, wheel well and other machinery spaces against peacetime-type fires.

Combat fires, especially ones that involve the crew area, are unique in that they may demand essentially explosion protection of occupied areas. They are caused by threats that defeat other survivability layers, for example, armor, generally start and grow much faster than a human can respond, and can be lethal within a fraction of a second. However, vehicle design can do much to mitigate fire risks. Features such as compartmentalization, where flammable materials such as fuel and ammunition are isolated from occupied areas, and the use of fire resistant materials wherever practical, are particularly effective. The first lines of defense against catastrophic combat fires, after vehicle design, are for the vehicle to operate so as to not be seen, hit or penetrated. If all that fails then the ultimate layer of vehicle fire protection is an automatic fire protection system.

The first modern automatic fire protection system designed to protect vehicle crews from combat fires was deployed on several main battle tanks in the early 1980s. These systems effectively protected the crew and engine compartments using extinguishers charged with Halon 1301. Automatic extinguishing systems are designed to detect and extinguish fast-growth fires in a fraction of a second – much faster than any human can react. Since the Montreal Protocol was signed in 1994, many countries, including the US, agreed to phase out production of ozone-depleting substances (such as Halon 1301) as much as practical. Subsequently, for example, the fire protection materials used to protect the engine compartment in most military ground vehicles were switched from ozone-depleting ones to dry chemical and other agents with relatively benign environmental effects. Similarly, the automatic systems protecting the crew compartments of many vehicles adopted more environmentally friendly agents. Much of the international research in this area was presented in Halon Options Technical Working Committee sessions hosted by the US’ National Institute of Technology (NIST) [52]. Research efforts focused on more effective and environmentally friendly fire fighting systems continue [53].

**Different Approaches to Vehicle Fire Protection**

The military applies a useful categorization method to systems installed on their vehicles that depends on how the system relates to the intended vehicle mission. Obviously crew and vehicle survivability are of paramount importance when evaluating a system and assigning a relative value to it.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Military Vehicle</th>
<th>Passenger Bus</th>
<th>Automobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fire power</td>
<td>Perform Maintenance</td>
<td>Collision Avoidance</td>
</tr>
<tr>
<td>2</td>
<td>Concealment</td>
<td>Avoid Road Debris</td>
<td>Minimize Impact Effects</td>
</tr>
<tr>
<td>3</td>
<td>Mobility</td>
<td>Emergency Egress</td>
<td>Restraints</td>
</tr>
<tr>
<td>4</td>
<td>Armor and PPE</td>
<td>Fire Protection</td>
<td>Fire Protection</td>
</tr>
<tr>
<td>5</td>
<td>Fire Protection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

_Table 1. Layers of survivability_
Clearly, vehicles have different “layers of survivability.” For example, fast suppression systems that are appropriate in combat vehicles may not be the best solution for protecting bus passengers. Since a bus fire, fast as it may be, is typically much slower than a combat fire in an armored vehicle, it is likely that simpler solutions will be as effective at preventing injuries due to fire. Survivability layers for military vehicles, passenger buses, and automobiles are compared in Table 1.

‘Fire protection’ takes many forms. For example, Table 2 lists fire protection approaches for the vehicle types listed in Table 1. The italicized text in Table 2 represents potential fire protection layers that have been suggested in the past but are not widely implemented:

- One of the early automobile fire protection studies concluded that, while effective on large vehicles, or in static situations, pre-engineered fire suppression systems are not practical on small, relatively deformable vehicles such as the automobile [20, 21]. This leaves the possibility of an overheat detection and/or suppression system that might offer effective protection against automobile fires where significant deformations, such as those caused by a collision, are not involved.
- After the deadly 2005 fire on a passenger bus in Wilmer, Texas, one of the recommendations made by the National Transportation Safety Board (NTSB), in addition to better use of fire resistant materials, and improved means of egress, was to develop overheat detection systems for the wheel wells [50].

The differences in fire protection approaches ultimately stem from differences in the purpose and intended use of each type of vehicle.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Military Vehicle</th>
<th>Passenger Bus</th>
<th>Automobile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Compartmentalization</td>
<td>Compartmentalization</td>
<td>Compartmentalization</td>
</tr>
<tr>
<td>2</td>
<td>Fire resistant materials</td>
<td>Fire resistant materials</td>
<td>Fire resistant materials</td>
</tr>
<tr>
<td>3</td>
<td>External fire protection</td>
<td>Automatic engine fire extinguishing system</td>
<td><em>Underhood fire/overheat detection &amp; suppression</em></td>
</tr>
<tr>
<td>4</td>
<td>High-speed, automatic fire extinguishing system</td>
<td><em>Wheel well overheat detection</em></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Fire resistant uniforms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Layers of fire protection

CONCLUSION

The close proximity of flammable materials and ignition sources make vehicle fires a significant risk and thus an important safety issue. Fortunately there are often means to mitigate the risks and damage caused by fire on a vehicle, but the optimum approaches vary by application. Many of the most effective design features that reduce the risk of fire on a vehicle, and/or mitigate the effects of a fire if it does occur, are the product of experience and extensive ongoing research and development. Advancements in vehicle development, which may inadvertently introduce new fire hazards, motivate continued vehicle fire research.

REFERENCES


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Experience with fire safety measures in public transport buses
FIVE 2014

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ABSTRACT

This paper deals with the fire incidents the BVG had to deal with between 2004 and 2010 and the measures which were taken as a consequence. Firstly, the initial situation is outlined by a chronology of events which depicts the number of fire incidents and total losses of buses between the years 2004 and 2010. From this results the realisation that it was mainly the 12 metre bus model Mercedes Citaro which burned out completely and thus resulted in total losses. Reasons for the development of fire were various but generally started in the engine compartment. This leads to the second part, the analysis of problem fields, in which reasons for fire development are presented and examined. As a reaction to the high number of fire incidents and in order to prevent further fires, the BVG took various measures i.e. the review of maintenance processes and the thorough inspection of the entire bus fleet including the installation of fire extinguishing systems into buses. Their set-up and functionality as well as their positive and negative aspects as experienced by the BVG are delineated in the following. As a result of the installation, the number of fire incidents and total losses decreased and fires can be detected early on. Still, the fire extinguishing systems can only protect a limited area and amount of components and thus should be considered a supplementary measure to on-board fire extinguishers and early warning systems.

KEYWORDS: fire safety measures, public transport, fire extinguishing systems

INTRODUCTION

In the past, the BVG had multiple problems with buses catching fire and burning out completely. Especially in the years between 2004 and 2010 fire incidents appeared more frequently. The bus model which was affected the most was the Mercedes Citaro bus with a length of 12 metres. In the first part, the initial situation that led to the implementation of fire safety measures into the BVG’s public transportation buses is analysed and a chronology of events outlines the course of fire incidents over the years as well as the reasons for the fires in the burned out buses. Moreover, the BVG’s activities in order to solve the problems are given. In the following, problem fields which were responsible for fires are analysed. These include causes of fires, engine construction as well as the analysis of processes and deal with the cause of fires in general as well as the causes of total losses. Furthermore, the reaction of the BVG and measures taken in order to improve the situation and prevent further fire incidents are outlined and analysed regarding their effectivity. Afterwards, the Fogmaker and Dafo fire extinguishing systems which were standardly installed in BVG public transportation buses up from 2010 are introduced. First, their set-up in the engine compartment is depicted and their mode of operation and extinguishing functionality is explained. Then, the BVG’s experience with the fire extinguishing systems is presented and advantages and disadvantages of both systems are contrasted. Positively, the number of fire incidents could be decreased due to the fire extinguishing systems and other measures taken and total losses could be prevented completely. Also, safety for passengers could be increased. Negatively though, the fire extinguishing system cannot prevent all fire incidents as they only protect a limited amount of components and thus have to be seen as an additional safety measure in the engine compartment of buses. Furthermore, their activation does not always work properly and is caused by i.e. overheating of engine components without actual fire development. Finally, the paper concludes with a summary of the results.
INITIAL SITUATION

Between the years 2004 and 2010, the BVG struggled to cope with an accumulation of fire incidents in its public transport buses. At more or less regular intervals, buses caught fire and were destroyed by flames. Nine buses burned out entirely over the years as they could not be extinguished by both the drivers of the buses with on-board fire extinguishers and the fire brigade. While no passengers were harmed in the fire cases, these incidents meant high financial losses for the BVG and led to image problems, especially due to the accumulation of fire incidents in the years 2009 and 2010. Figure 1 gives an overview over the incidents and shows the chronology of events.

Figure 1: Chronology of events 2004 until 2010

As can be taken from Figure 1 most buses which burned out completely were Mercedes Citaro 12 metre buses. First problems occurred in April 2004, when a 12 metre Mercedes Citaro bus caught fire which flashed over to the entire bus in short time. Post-fire examinations detected that the reason for the fire was a cyclone filter clogged with oil coal and oil sludge which hindered air supply to the pressure regulator. Thus pressure could not be regulated anymore and the filter system overheated. Ultimately, the oil coal and oil sludge which clogged the filter were ignited by glowing oil coal particles and thus caused the fire. Another bus of the same type caught fire two years later in April 2006. In this case, the cause of fire is unclear and the origin of flames could not be identified conclusively. Two years later in November 2008 the only other bus model, a Solaris Urbino articulated bus, burned out completely. The reason for the fire was a defective turbocharger. Oil from the turbocharger dripped into the exhaust pipe and was ignited by glowing exhaust particles. In 2009, three Mercedes Citaro 12 metre buses caught fire and burned out completely in May, June and December. In the May incident, a cyclone filter which was clogged with oil coal and oil sludge was causal for the fire. Due to the clogging the air compressor was hindered and could not work properly which led to overheating and thus to fire development. In addition, insulating material is situated close...
to the filter. This material easily absorbs dripping oil and particles and thus is extremely combustible. Accordingly, the fire spread quickly in the engine compartment and flashed over to the entire bus. The June bus caught fire due to a defective exhaust pipe which was affected by corrosion. This led to a leaking of exhaust gases which were blown into the engine. The gases mixed up with lubricants and other operating materials from parts which are situated above the exhaust pipe and diffused into the insulating material. Glowing particles from the exhaust pipe then ignited the insulating material and fire flashed over quickly to the entire bus. In the December incident, the cause of fire was another defective exhaust pipe. In 2010, three more Mercedes Citaro buses caught fire and burned out completely in July, August and December. In the July bus, the cause of fire could not be identified clearly as the level of destruction was too high and the engine compartment was destroyed entirely. The August incident was caused by a defective exhaust pipe in combination with the above lying air cooler. An oil leakage in the air compressor led to a dripping of oil on the hot exhaust pipe. Due to glowing particles from the exhaust pipe fire was ignited and synthetic fuel tubes which were situated closely to the exhaust pipes caught fire. The burning fuel then caused a flashover of the fire to the bus. In the December case the cause of fire could not be clarified. Remarkably though, this bus had just been at a car workshop at Mercedes’ and potentially risky parts and components, i.e. exhaust pipes, CRT filters, air compressor tubes, v-belts, fuel lines, cooling agent tubes or brake hoses had been exchanged. In addition, various parts had been cleaned in order to assure proper functionality. The above mentioned and further problem fields will be described and examined in the further course of this paper.

Figure 2 and Figure 3 show two examples of burned out Mercedes Citaro 12 metre buses with only the framework left.
Generally, it can be said that all fires started in the engine compartment and spread from there over all engine parts and over the rest of the bus. Exceptionally, mostly Citaro buses burned out completely while other fire incidents which did not lead to a total loss of the bus were more or less evenly distributed over all bus models. Moreover, most of the Mercedes Citaro’s had been procured in 2002 and thus originated from the same production series [3]. Accordingly, their average age was between four and eight years which is significantly below the average durability of public transportation buses which amounts to 12 years. Confronted with the assumption of misconstruction, Mercedes denied responsibility due to the great variations in the causes of fire and assumed liability and costs for one bus only [4].

After all, Berlin was not the only city with problems in public transport and with the Mercedes Citaro 12 metre bus model. Similar problems arose in other German cities and other countries. One Mercedes Citaro burned out entirely in Halle/Saale and in Hamburg respectively. Moreover, four buses of similar construction burned out completely between 2003 and 2004 in London. After an examination of the cases, the reason for the fires was detected as a lack of maintenance. As a result, London’s public transport company withdrew all buses of this model from circulation [3]. This was not the way the BVG went. But in order to increase safety and prevent further fires, the BVG took various measures. Parts and components which were especially prone to deficiencies were exchanged by the producer, e.g. fuel tubes which were originally made out of synthetic material were replaced by a more solid material. In October 2010, all 91 Mercedes Citaro buses were withdrawn from circulation in order to undergo thorough technical examinations and inspections [3]. They were only authorised to go back into public transportation after an expert assessment confirmed their safety for public transport purposes. Also, an independent expert was instructed to revise processes and reveal potential areas of improvement. Both examination intervals and maintenance intervals were increased in order to guarantee that problem fields and potential risks were detected as early as possible. Moreover, the number of motorcar-mechanics was increased by thirty to ensure timely
maintenance of defective buses and guarantee swift operational availability of the buses. Advanced training in fire preventing measures as well as brush-ups on a regular basis were implemented to ensure that maintenance personnel was up to date and could identify potential problem fields easily. The bus drivers also underwent training on correct behaviour in case of fire. Besides, special guidelines and standards on fire prevention and extinguishing measures were included in public tenders for new buses up from 2010. As a result, every bus which was procured after 2010 was standardly equipped with a fire extinguishing system in the engine compartment. Buses which were procured before were subsequently retrofitted with the Fogmaker or Dafo fire extinguishing system which will be introduced in the course of this paper.

ANALYSIS OF FIELDS OF PROBLEMS

Despite the fact that it was mostly the same bus model which burned out entirely, the cause of fire was different in most cases as can be taken from the chronology of events above. In the following, potential problem fields will be introduced and analysed in the following.

In every case of fire, ignition took place in the engine compartment which is situated in the back of the buses. The reason for this is the general heat development in this area caused by the running of the engine and the exhaust pipe. When the engine overheats or motor heat interferes with i.e. a faulty part, oil leakage or a leak in the exhaust pipe, ignition is encouraged.

One of the various problem fields was the charge air cooler which is situated above the exhaust pipe. When there is an oil leakage in the charge air cooler, oil is dripping on the heated exhaust pipes, heats up and as a result catches fire or is ignited by glowing particles which are blown through the exhaust pipe.

Another problem field are the air compressor and the cyclone filter. In some cases, the air compressor drew in oil and thus coked the cyclone filter with oil coal or oil sludge. Also, the air hose could become porous. Both aspects hinder proper air flow and lead to an overheating of the components. The hindered air flow is unable to cool down and thus heats up the oil coal and oil sludge. If not recognised early, this can result in fire development by glowing oil coal particles. The same problem might occur in the CRT filter system.

Also, the soot particle filters can pose a problem. Especially in big cities such as Berlin there is a high level of fine particle air pollution. Combined with the driving style of buses – driving only short ranges from bus station to bus station, low level of speed-ups and constant stopping at bus stations and traffic lights – this leads to heavy load of the engine and bus in general and clogging of the filter. When the soot particle filters are defective or clogged, the engine performance is affected negatively which leads to heat development and can ultimately result in fire development.

Moreover, exhaust pipes bear certain risks due to the hot exhaust gases which run through them. Due to corrosion, exhaust pipes develop defaults and exhaust gas leaks occur. When heat of exhaust gases and engine combine, temperature is risen and potential ignition is encouraged. Also, glowing exhaust particles are blown through the exhaust pipe which can easily ignite oil from oil leakages, lubricants or other easily inflammable liquids and gases.

Furthermore, the insulation material poses a potential problem. If covered by aluminium foil in order to prevent combustibility, the insulating effect is affected negatively. If constructed openly in order to ensure a high level of insulation, the material absorbs all oozing liquids and gases, i.e. oil or lubricants and thus becomes highly combustible.

In addition, a defective fuel return line can be the cause of fire in buses. When fuel is leaking out of the fuel return line and is dripping on heated components which are situated around it, ignition is encouraged due to the high combustibility of fuel. Also, vaporisation of fuel due to heat might lead to ignition of the gas by glowing particles or sparks in the engine compartment.
Sparks are also caused when the brakes get stuck. This might lead to ignition of surrounding parts, especially when they are covered with synthetic material or lubricated for functionality reasons. Apart from defective parts and leaks, construction plays an important role in fire prevention as well. As most of the burnt out buses came from the same production series of 2002, the manufacturer Mercedes was criticised in the press and it was suggested that faulty design or construction errors may be responsible for the fire development [4]. One reason for this was the construction of fuel tubes which were made out of synthetic material and which thus easily melt or catch fire. These were exchanged for fuel tubes made of a more solid material in the course of events.

Another potential problem field was the engine construction. The Mercedes Citaro 12 metre buses were standardly equipped with vertical engines which were presumably a probable cause for the exceptionally rapid ignition of the Mercedes Citaro buses and the flashover of flames on the entire bus. The vertical engine is characterised by a tower-like construction with components situated above each other in a compact way. Therefore, heat which is radiated off of the parts combines and heat development is encouraged which leads to the so-called stack effect. This effect was suspected to lead to a quick spread of flames and finally to the fact that the Mercedes Citaro buses, once they caught fire, could not be extinguished anymore and thus ended in a total loss of the bus. However, an expert examination could neither find a correlation between the vertical engine and the quick spreading of fire nor confirm the stack effect as the engine is generally cooled down by the airstream which is generated by driving. Accordingly, the reason for the quick flashover of flames in the Mercedes Citaro bus model is still not conclusively clarified.

Furthermore, the service and maintenance processes were under suspicion and criticised in the press. As in London’s cases of vehicle fires deficiencies in maintenance processes were the reason for fire development, this was the logical conclusion. The BVG reacted by increasing maintenance personnel by thirty mechanics. In addition, maintenance intervals and inspections were condensed and processes were reviewed by an external expert. In order to prevent further total losses, a warning system for temperatures was installed in the engine compartment.

Generally, it can be said that various problem fields were found which were potentially responsible for the cases of fire in BVG buses between 2004 and 2010. Positively though they were perceived and addressed by reviewing and changing processes and improving construction. Also, there was never one clear cause of fire but an interaction of various aspects and risks which ultimately led to fire development. From the great variety of problem fields which arise in the engine compartment it can be deduced that this area requires special precaution measures. One possible measure is the installation of fire extinguishing systems which are introduced in the following.

INTRODUCTION OF THE FOGMAKER AND THE DAFO FIRE EXTINGUISHING SYSTEM

Fogmaker International AB is a Swedish company which develops, manufactures and sells fire extinguishing systems based on water mist since 1995. It is market leader in fire extinguishing systems for buses in Europe, Australia and the Middle East. Furthermore, its fire extinguishing systems are used in racing cars, forestry machinery, mining vehicles and construction vehicles. Apart from water mist, the fire extinguishers contain foam which smothers flames and prevents rekindling of fire. [5]

Dafo is a Swedish company which deals with product development, assembly and sale of fire extinguishing systems and also offers services related to them. Apart from buses the extinguishing systems are among others installed in construction machines, forestry machines, mining vehicles, wind energy power plants and shredding facilities. The extinguisher contains Forrex, an extinguishing agent which has been specifically developed for the engine compartment and is thus adapted to its functionality and risks. [6, 7]
Set-up

In the following, the set-up of the fire extinguishing systems is described. Generally, it is positioned in the engine compartment of the buses or next to the engine-independent air heating system [8]. An alarm button, a test button and a siren which is activated in case of fire are installed in the dashboard of the bus [8]. The fire extinguishing system consists of two bottles connected by a detector tube as depicted in Figure 4. The detector tube is laid through the engine. In the Fogmaker model, the detector tube is put under pressure while the Dafo model has an electric tube. Connected to the detector tube, there are two bottles and three actuators. The first bottle, the extinguisher cylinder, contains the fire extinguishing material. From this bottle, another tube is laid through the engine which is connected to various nozzles which spread the fire extinguishing material in case of fire. The second bottle, the detector cylinder, serves as a pressure detector in the Fogmaker model and also contains a control mechanism to monitor the pressure in the tube. In the Dafo model, the second bottle is connected to the electric tube and serves as a monitoring device. In addition, there are a manual actuator, an electric actuator and a magnetical valve for delaying the actuation. These devices are optional. The general set-up of the two fire extinguishing systems is similar as can be taken from Figure 4.

![Figure 4: Set-up of the Fogmaker and Dafo fire extinguishing systems [9, 10]](image)

Mode of operation

Generally, the fire extinguishing systems serve two purposes: preventing fire development and initiating the extinguishing process. Fire prevention is accomplished by the detector cylinder and the detector tube. The control mechanism in the detector cylinder monitors pressure variations and differences in electric flux and conveys data to the driver of the bus. Thus danger of fire development can be recognised early on and prevention measures can be initiated.

The extinguishing process of both fire extinguishing systems is described in the following. In the Fogmaker system, normal pressure in the detector cylinder amounts to 20-24 bar [8]. When heat in the engine rises over a certain level and fire ignites, the detector tube melts or becomes porously. As a result, the pressure in the detector tube decreases which is monitored by the detector cylinder. As soon as pressure sinks below 10 bar, the detector cylinder sends a signal to the
extinguisher [8]. This activates the extinguisher cylinder which pumps the extinguishing material into the extinguisher tube. Various nozzles which are connected to the tube then allocate water mist and foam over the engine with high pressure. The extinguisher cylinder contains water and nitrogen. Due to the high pressure with which the tube spreads these over the engine and the heat of the engine, water is converted into water mist which has an immediate cooling effect on overheated components. In addition, the water mist increases humidity in the engine compartment and thus averts oxygen supply to the source of fire. By that the risk of a redevelopment of flames is prevented [11]. Furthermore, the fire extinguisher contains frost protection agent and foam extinguisher which creates a water film on the engine [11]. The foam smother the fire and averts redevelopment of flames, especially when oil is involved.

In the Dafo system the electric tube is covered with synthetic material which melts in case temperature rises over a heat level of 180°C or fire develops [7]. This is detected by the detector cylinder and is reported to the driver of the bus. When the synthetic cover has melted, a short circuit is caused in the tube which activates the extinguisher bottle and the extinguishing material Forrex is spread over all engine parts. Due to its special adaption to engine requirements, the extinguishing procedure can quickly smother flames and prevent a redevelopment of fire. Moreover, it has a cooling effect which prevents redevelopment of flames. Generally, the Dafo fire extinguishing system is constructed in a very solid way which makes it resistant to vibrations, heat, cold, chemical liquids and mechanic influences [7, 10] which is especially advantageous for use in public transport buses which are in relatively strong utilisation and for use under extreme conditions such as mining and construction.

As a ground rule it can be said that two litres of fire extinguishing agent are required per cubic metre of gross volume of the space which is to be protected and extinguishing time which means the time until the extinguishing cylinder is emptied shall not exceed 20 seconds [12, 13]. In order to guarantee a proper mode of operation of the fire extinguishing systems, these aspects should be taken into account when deciding on the number and size of nozzles which are installed in specific cases.

The Fogmaker fire extinguisher works fully automatic and is independent from electricity supply [11] which guarantees its constant availability and functionality. As the cylinders are under pressure, the system might be prone to vibrations and mechanical effects in the engine compartment. As a result, the Fogmaker fire extinguishing system underlies more frequent examination and maintenance intervals than the Dafo fire extinguishing system. In contrast to that, the Dafo fire extinguishing system works with a pressureless extinguishing cylinder which is subject to less frequent examinations. As the fire extinguishing system is equipped with an electric tube, its functionality is assured whenever the bus’s engine is running. In order to guarantee its constant functionality, the fire extinguisher is further equipped with a battery which provides electricity in standstill phases.

EVALUATION OF THE FIRE EXTINGUISHING SYSTEMS

In the following, the fire extinguishing systems will be evaluated on the basis of the experience the BVG has made since installation and advantages and disadvantages will be outlined. Generally, it can be said that compared to the years between 2004 and 2010, the number of fire incidents in buses could be decreased as can be taken from Figure 5 and Figure 6. Figure 5 shows the chronology of events from 2004 to today and gives an overview over the number of total losses and the affected bus models as well as the number of additional fire incidents per year.
Figure 5: Chronology of events 2004 until 2014

Figure 6 depicts the development of fire incidents and total losses over the years. As can be taken from the graph below no total loss of a bus had to be recorded after the installation of the fire extinguishing systems and the thorough examination of all Mercedes Citaro 12 metre buses in 2010.
In the following, positive and negative experiences of the BVG with the fire extinguishing systems are presented.

**Positive aspects**

Since the first installation of fire extinguishing systems in BVG buses there have been notably less fire incidents. The reasons for this development are various including the increase of maintenance and examination intervals. Notwithstanding, the fire extinguishing systems are to a large share responsible for this positive development and increased awareness of potentially hazardous areas or components in the engine. As can be taken from Figure 5 which depicts the development between 2004 and 2014 measures taken by the BVG have been successful.

Apart from the fire extinguishing function both Dafo and Fogmaker can be considered as an early warning system. Heat rises, general temperature variations and variations in pressure (Fogmaker detector tube) can be discovered early on and thus maintenance personnel is able to react and initiate repairing measures.

Also, fire development during utilisation of the bus is detected early on and a spread of flames can be avoided by initiating the extinguishing process. This gives the bus driver the possibility to guide passengers into safety and to take further measures in order to deter flames from flashing over the entire bus, i.e. by use of the on-board fire extinguisher.

Fire cannot only be detected during utilisation of the bus but also in the stationary phase on the depot. The Fogmaker fire extinguishing system works independently from electricity and thus constant functionality is assured. The Dafo fire extinguishing system is equipped with a battery in order to guarantee functionality in the stationary phase. This is of special significance as buses stand closely in the depot and accordingly in case of fire flames could spread easily over several buses which would result in the loss of a large number of vehicles.

Moreover, a positive influence on BVG’s reputation could be observed. The decrease in fire incidents which is to a large extent owed to the installation of fire extinguishing systems and the communication of their installation to the public has influenced the public’s opinion on the BVG and
its public transport buses. People feel safe in the buses again and a potential decrease in the number of passengers can be reversed.

Additionally to safety aspects, both fire extinguishing systems also have ecological advantages. Fogmaker International AB has put a focus on environmental friendliness and manufactured the fire extinguishing system accordingly. The use of water mist and ecologically decomposable compounds guarantees that both use and manufacturing process of the Fogmaker fire extinguishing system have as little effect on the environment as possible. Dafo’s fire extinguishing agents are composed similarly and are also ecologically decomposable and non-poisonous for the environment. Besides, the cleansing process of the engine after an activation of the fire extinguisher can be conducted with water only. No use of chemicals is necessary to remove the extinguishing agents from engine components and thus environmental pollution can be avoided.

Furthermore, the level of destruction can be kept at a relatively low level. Apart from the reduction of fire incidents in general, flashovers of flames to bus parts outside of the engine compartment are unusual which results in significant cost savings for the BVG. Repair time is reduced which also entails a reduction in the number of standstill buses as withdrawal from circulation for an uncertain period of time due to high maintenance expenditure can be kept at a low level. Also, the constant monitoring of the engine and other parts in the bus which are exposed to a high heat level by the detector tube allows maintenance personnel to react to unusual heat variations and conduct repairing measures at an early stage.

Most importantly, no total loss of a bus has been recorded after 2010. This does not just result in significant cost savings for the BVG but also involves image improvements. The main reason for this is the prevention of fire development which was achieved by the installation of fire extinguishing systems into the buses and the revision of processes.

**Negative aspects**

Despite all the merits the Fogmaker and Dafo fire extinguishing systems have, there are still some problem fields which could not yet be solved. Firstly, the fire extinguisher only reaches a limited range of components and parts. As a result, the engine and associated parts can be restrained from catching fire while the rest of the bus is still exposed to certain risks. Especially the system of wiring on board of the bus bears a high risk as fires may develop in the area of cable ducts. Usually, the wiring system is incorporated in the framework, dashboard and boot of the bus and accordingly is not easily reachable or controllable. Thus deficiencies may be missed in the regular maintenance process. Even though risks outside the engine compartment may be significantly lower as there are no sources of heat or heat levels are significantly lower, the Fogmaker and Dafo fire extinguishing systems do not substitute manual fire extinguishers on board of the bus. They should be seen as an addition and a protecting measure for specially imperilled parts and components. Supplementary, it is recommendable to install fire alarms in strategically important points in the bus interior. Depending on the construction and position of engine, exhaust pipes and engine-independent air heating system, it may be necessary to include more than one fire extinguishing system into the bus or adapt the Fogmaker or Dafo fire extinguishers to specific construction requirements. This may lead to higher costs for the installation which can be avoided by standardised construction processes of the bus manufacturers. Also, reachability of all parts inside the engine by fire extinguishing material cannot be guaranteed depending on the laying of detector tube, extinguisher tube and the associated nozzles.

Furthermore, permanent and long-term functionality of the fire extinguishing systems cannot be guaranteed. After a certain period of time without activation, the fire extinguishing system requires a refill of detection material, extinguishing material and recharging of the battery as well as thorough examination of its functionality. This leads to a withdrawal of the affected buses from circulation for the examination time. In addition, the fire extinguishing system is object to permanent monitoring by
the maintenance personnel and needs to be tested on a regular basis. Especially in public transport this means a lot of additional work time for mechanics due to size of the bus fleet.

Another problem that arose especially with buses which have been subsequently retrofitted with fire extinguishing systems is the activation of the fire extinguishers. When the outside temperature is very high or when heat which emanates from different sources like engine, exhaust pipes and supercharger combines together, the heat level inside the engine may rise to the activation temperature which melts Fogmaker’s detector tube or causes short circuit in Dafo’s detector tube and thus leads to activation of the extinguishing process even though there is no actual fire. Also, the loss of cooling agent might lead to the engine compartment reaching the activation temperature. This does not just lead to high costs for cleaning the engine from foam, water mist and extinguishing agent, a refill of the extinguisher and re-installation of the extinguishing system in the bus but also withdraws the bus in question from circulation in public transport for an indefinite period of time. Ever since the retrofitting of BVG buses with the Fogmaker or Dafo fire extinguishing system, activation by heat development only could be observed several times which makes this a severe problem.

CONCLUSION

In the years between 2004 and 2010, several BVG public transport buses caught fire and nine of them burned out completely. The bus model which has been affected in most cases of total loss and suffered from most deficiencies was the Mercedes Citaro 12 metre bus. Due to the accumulation of fire incidents various measures have been taken to prevent fires in general and reduce destruction of buses by fire. Maintenance intervals and personnel were increased, parts were exchanged and the entire bus series was thoroughly examined by experts. Also, processes were revised by external experts. In order to increase safety and as a preventive measure, the Fogmaker and Dafo fire extinguishing systems were installed in all buses. These systems extinguish fires with water mist, foam and special extinguishing agents and are situated in the engine of the bus. Ever since the introduction of these measures, the number of fire incidents could be decreased and no total loss had to be recorded. Also, safety for passengers could be increased and the level of destruction could be kept at a low level due to the early detection of fire development in the engine compartment. This shows the positive development the BVG underwent and underlines the role of the fire extinguishing systems in this development. Still, the fire extinguishing systems only protect a limited range of components and have to be seen as an additional safety measure to on-board fire extinguishers and early warning systems. They are a special precaution measure for the engine compartment as most fire incidents have their origin in this area.

REFERENCE LIST


Bus fire safety – state of the art and new challenges

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ABSTRACT

Several bus fires with many fatalities are reported in the world each year and in Sweden 1% of buses burn annually. At the same time the fire requirements for buses are lower than for trains, ships, and aircrafts. Stricter regulations have been implemented the last decade but there are still great potential for improvement of the fire safety of buses. This paper summarizes the most important fire regulations for buses in Europe and presents some selected recent activities for further improvement of fire safety. Finally areas are pointed out where more research and/or regulations are desirable.

KEYWORDS: Bus fire safety, UN ECE Regulation No. 107, UN ECE Regulation No. 118, Fire test methods, Fire suppression, Fire detection

INTRODUCTION

Buses have lower requirements on fire safety than other public transports such as rail vehicles, shipping, and aviation [1, 2] with e.g. no requirements on heat release, smoke density, or smoke toxicity for materials on buses, while there are for trains, ships, and aircrafts [3]. Buses also have a relatively high frequency of fires. In Sweden fires are reported for 1% of buses annually, and 10% of all buses are involved in a fire during their service life [4]. Similar statistics from Germany shows that 0.5-1% of buses burn annually [1]. Though losses of lives caused by bus fires are relatively uncommon there are examples of disastrous bus fires in recent years such as

- Veracruz, Mexico 2014 (36 fatalities)
- Nagari Tanjung Lolo, Indonesia 2014 (7 fatalities)
- Karnataka, India 2014 (6 fatalities)
- Fundacion, Colombia 2014 (32 fatalities)
- Northern California, USA 2014 (10 fatalities)
- Qum, Iran 2013 (44 fatalities)
- Kothokota, India 2013 (44 fatalities)
- Lwengo, Uganda 2012 (30 fatalities)
- Yobe, Nigeria 2011 (18 fatalities)
- Wuxi, China, 2010 (24 fatalities)
- Uttar Pradesh, India, 2008 (63 fatalities)
- Hannover, Germany, 2008 (20 fatalities)
- Wilmer, USA, 2005 (23 fatalities)

Statistics indicate that the frequency might have increased due to tighter standards on emission and noise, which make the thermal environment in the engine compartment more challenging from a fire safety point of view [5, 6]. Although incident reports and statistics are not always exhaustive, literature indicates that, very approximately, 60% of the fires start in the engine compartment, 20% in the wheel well, and 20% in other areas such as the passenger or luggage compartment for example [5, 6].

Whereas the fire frequency of buses has been high historically, the positive side is that actions to reduce the problem have shown significant results. For instance information from Swedish insurance
companies [7] shows that 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 the insurance companies requested all buses to be equipped with automatic fire suppression system in the engine compartment. During the following six years no complete burnout occurred as a consequence of such fires. More recent data from Germany [8] shows similar positive effects. The scope of this paper is to summarize the most important fire regulations for buses in Europe and to present some selected recent activities for further improvement of fire safety, as well as pointing out areas where more research and/or regulations are desirable. In this paper the word bus comprehend buses and coaches.

CURRENT REGULATIONS

The requirements on fire safety for buses are mainly defined in the UN ECE Regulations No. 107 and 118.

UN ECE Regulation No. 107

Regulation No. 107 [9] covers a wide range topics for buses, many of them related to fire safety. The regulation is based on the European bus directive 2001/85/EC which basically was a mix of the now obsolete Regulation No. 36 [10] and the British Disability Discrimination Act. The main fire related requirements are:

- No flammable or liquid-absorbing sound-proofing materials in engine compartment are allowed.
- Heat-resistant partitioning between engine compartment (or any heat source) and rest of the bus.
- Safe construction and installation of cables.
- Fusing.
- Isolating switch for circuits with a voltage exceeding 100 V.
- Safe and accessible installation of the battery.
- Space provided for fire extinguishers and first-aid kits.
- No flammable materials within 10 cm of any potential heat source, such as exhaust systems or high voltage equipment for example.

Two important amendments related to fire safety have been issued for Regulation No. 107 the last years.

As of 2012-12-31 it is prescribed that the engine compartment, and each compartment where a combustion heater is located, shall be equipped with an alarm system detecting excess temperatures. This requirement is only valid if the engine compartment is located rear of the driver’s compartment. The alarm system shall be operational whenever the engine start is operated.

The most recent addendum stipulates that as of July 2014 an alarm system detecting either smoke or excess temperature shall be installed in toilet compartments, driver’s sleeping compartments, and other separate compartments. The alarm system shall be operational whenever the engine start is operated.

UN ECE Regulation No. 118

This regulation [11] has replaced the European directive 95/28/EC and originally covered fire performance of materials in the interior compartments of buses, which is defined as any compartment intended for passengers, drivers and crew. The regulation is designed for coaches carrying more than 22 passengers, and not for buses designed for standing passengers and/or city buses. In 2010 an amendment was issued with a test method and performance requirement for assessment of the capability of insulation materials (e.g. sound-proofing materials) to repel fuels or lubricants. In the
same amendment a test method and performance requirement was prescribed for electric cables. This amendment was a step meant to develop the fire prescriptions in Regulation No. 107 more quantitative.

In 2012 an amendment was issued regarding the fire performance of interior materials. Until then three test methods were employed for interior materials:

- Test to determine the melting behaviour of materials
- Test to determine the horizontal burning rate of materials
- Test to determine the vertical burning rate of curtains and blinds

The test to determine melting behaviour of materials is now required for materials installed above 500 mm from the seat cushion, i.e. including the roof, and for materials installed in the engine compartment and any other separate heating compartment.

The test to determine the horizontal burning rate, see Figure 1, was mandatory until 2012 for combustible materials in the interior compartments, with some exceptions. The test is similar to the test standards ISO 3795 [12] or FMVSS 302 [13]. This method has received arduous critics [14-18] for being too lenient based on the fact that test specimens are oriented horizontally, whereas much fire spread in a real bus fire occurs on vertically oriented products, and also based on the fact that the test is a small scale method not suited for bus fires induced by for example fire in the engine compartment or fire in a tire. In the aftermath of the disastrous bus fire in Hanover in 2008 it was decided by the GRSG (Working Party on General Safety Provisions) of UN ECE that the test for horizontal burning rate should no longer be applicable to vertically oriented materials. Therefore, in the latest revision of Regulation No. 118, the horizontal burning rate test is only valid for horizontally oriented materials in the interior compartment and in the engine compartment and any other heating compartment.

Figure 1  Test to determine the horizontal burning rate according to Regulation No. 118.

The test to determine the vertical burning rate, see Figure 2, is similar to the standard test ISO 6941 [19] and was originally only applicable for curtains and blinds. However, since this method was already implemented in the regulation it was deemed reasonable to use this as a replacement for the horizontal burning rate test for materials that are oriented vertically. Some modifications of the test method were implemented in order to make it suitable for stiffer and thicker materials than curtains.
and blinds. This change of test method constitutes a significant sharpening of the fire requirements on interior materials since vertical burning rate typically is faster than horizontal burning rate (the performance limit, not more than 100 mm/minute burning rate, is the same for the horizontal and vertical burning rate tests).

![Test to determine the vertical burning rate according to Regulation No. 118.](image)

Materials that fulfil the requirements for the vertical burning rate test are considered to also fulfil the requirements for the horizontal burning rate test. This means that materials that are mounted both horizontally and vertically only have to pass the vertical burning rate test.

As a mean of approaching the bus requirements with the more elaborate prescriptions for trains and ships the latest revision of Regulation No. 118 allows the use of the test method ISO 5658-2, lateral spread on building and transport products in vertical configuration [20], see Figure 3. Materials that are approved by this test are considered to also fulfil the requirements for both the vertical burning rate test and the melting test, provided no burning drops are observed.
Figure 3  Test according to ISO 5658-2 which is implemented in the latest revision of Regulation No. 118. A successful test renders unnecessary both the melting test and the vertical burning rate test.

Other UN ECE Regulations

There are other regulations with requirements relevant for fire safety that are applicable to vehicles more generally, and not only to buses.

Regulation 34 specifies requirements with regard to liquid fuel tanks.

Regulation 43 contains requirement on horizontal burning rate for plastic safety glazing (measured with the same apparatus as specified in Regulation 118).

Regulation 44 contains flammability performance requirements for materials of child restraint systems. This regulation refers to Regulation 118.

Regulation 67 contains prescriptions for vehicles using LPG (liquefied petroleum gas) in their propulsion system.

Regulation 100 provides requirements concerning electric power train of vehicles, including fuel cells. Fire safety is not mentioned directly but results from e.g. limitations on hydrogen emission during battery charge operations.

Regulation 110 contains prescriptions for vehicles using CNG (compressed natural gas) and/or LNG (liquefied natural gas) in their propulsion system.

Regulation 122 contains prescriptions for vehicles regarding their heating systems, in particular combustion heaters.
ONGOING ACTIVITIES

This section presents a selection of recent or ongoing activities aimed at improving bus fire safety, but which has not so far been implemented in international regulations.

Engine compartments

As most of the fires in buses commence inside the engine compartment most efforts the last years have been focused on improving fire safety in the engine compartment.

Encouraged by the statistics from the Swedish insurance companies, that indicated a significant effect of fire suppression systems in the engine compartment, SP initiated a project in 2010 with the purpose to develop a test standard for evaluating automatic fire suppression systems meant for bus engine compartments [4]. This work led to the standard SP Method 4912, Method for testing the suppression performance of fire suppression systems installed in engine compartments of buses and coaches [21, 22]. The standard includes eleven different tests in a realistic test rig, see Figure 4. The test report rates the tested suppression system based on the number of passed (extinguished) tests and the ability to protect against re-ignition. This means that manufacturers can compete with each other by improving their systems to increase the number of passed tests. It also allows e.g. purchasers to set stricter requirements, e.g. passing all tests, for buses frequently utilized in special hazard areas, such as tunnels and underground car parks for example. This standardized test is now gaining grounds within authorities, bus manufacturers, and fire suppression manufacturers. There are ongoing efforts by the Swedish Transport Agency to include parts of SP Method 4912 into Regulation No. 107. Such an amendment would be a further step in order to make the fire prescriptions in Regulation No. 107 more quantitative.

![Figure 4](image_url)  Fire test according to SP Method 4912. A fan is seen to the left.

Clearly the suppression performance of an automatic fire suppression system is an important factor in assessing the total quality of the system. However, it is also important that the system can function in the harsh environment of an engine compartment. Therefore SP has developed an extended testing scheme including a set of component tests [23]. The focus is laid on environmental durability testing.
with respect to vibration, shocks, temperature variations and corrosion, in addition to extinguishing capacity. These tests allow demonstration of the overall quality of the tested fire suppression systems for engine compartment in buses.

The changes in the regulations and the new test methods can improve the fire safety significantly. Still there are some areas that could improve the situation further. Real scale testing of fire suppression systems in bus engine compartments performed by BAM, Federal Institute for Materials Research and Testing in Germany, showed that even if the suppression system temporarily extinguished the fire, it reigned some seconds later [3]. This was mainly due to the sound-proofing insulation materials. It remains to see if the new requirements for the capability of insulation materials to repel fuels or lubricants in UN ECE Regulation No. 118 will improve this situation. The test campaign at BAM also included several tests of fire detection systems. Detection systems were found to, in general, be effective, but problems with promptness of spot thermal detectors where identified. This has also been confirmed in numerical simulations [24]. Given the obvious importance of fire detection SP initiated a project in 2013 [25] with the main objective to develop a test standard for assessing the quality of fire detection systems for the engine compartment of buses. This standard will complement SP Method 4912 and is expected to be finalized in 2015. Also, Southwest Research Institute (SwRI) in USA has developed a test fixture and test procedures for bus engine compartments where both detection and suppression systems can be tested [26].

**Tire fires**

The motor coach fire during the evacuation from the hurricane Rita, with 23 fatalities, in 2005 [27] is an example of the potential devastating effects of tire fires in buses. Tire fires are notoriously hard to extinguish and therefore efforts for protection and detection, rather than suppression, have been most focused on.

NIST, the National Institute of Standards and Technology, in USA performed a study [28, 29] where it was found that the fastest penetration route into the passenger compartment was that the tire fire ignites the plastic fender and glass-reinforced plastic exterior side panel which subsequently broke the windows. This route was much faster than fire penetration through the flooring or lavatory. Fire hardening experiments were therefore performed and it was shown that replacing the plastics by steel, or covering it with intumescent coating, was effective and delayed the fire penetration into the passenger compartment with 20 minutes or more.

A test method to evaluate early warning systems for wheel wells has been developed by SwRI [26]. The method evaluates sensors and algorithms used to detect a hot wheel, before a fire breaks out. The failure scenario of the test is either a dragging brake or a failed bearing.

**Smoke and toxicity**

Some improvements of the requirements on fire performance of interior materials have been implemented in UN ECE Regulation No. 118. Still, no requirements on smoke and toxicity apply for buses. In a recent project performed by BAM it was found that most of tested bus interior materials fail the smoke production requirements of rail vehicles according to the European train standard EN 45545-2 [30]. Furthermore all materials generated hazardous to lethal concentrations of toxic gases within a few minutes. This is also supported by material tests [15] and a full scale test of a bus fire [31] at SP. In the full scale test the fire was ignited in the rear luggage compartment and dangerous concentrations of toxic effluents were measured in the passenger compartment only 4-5 minutes after ignition. A more recent test at SP indicated high CO concentrations after only 3 minutes [32]. In another full scale experiment by NIST [28] the time from penetration of a tire fire through the window to untenable conditions due to toxic gases in the passenger compartment was approximately 10 minutes.
**Fire detection in other compartments**

Although bus fires commonly start in the engine compartment there are other locations where an early warning system is also desirable. This is exemplified by the bus fire in Hanover 2008 where a catastrophic fire propagation occurred after a passenger had open the door to the toilet compartment, where a well-developed fire was located. UN ECE Regulation 107 now requires thermal or smoke detectors in the toilet compartments, driver’s sleeping compartments, and other separate compartments. Therefore SP performed a study [33] to provide guidelines for fire detection in these spaces. It was found that smoke detectors are significantly faster than thermal detectors and that great care must be taken to the forced air flows in these small compartments.

**GAP ANALYSIS**

Great progress has been made with the recent improvements in the regulations and the situation is expected to further improve as new buses according to the new regulations are set on the market. With some further effort the situation would improve even more. This section contains a non-exhaustive number of items where new international regulations or research is desirable.

**UN ECE Regulation No. 107**

The markedly positive statistical results from the Swedish insurance companies indicates that fire suppression systems should be mandatory in the engine compartment of buses, and their quality should be assessed using a test method such as e.g. SP Method 4912. The detection systems are an important part of the fire safety measures and therefore these should also be mandatory with clear performance criteria, once a test method for this purpose is available.

There are many well-intentioned paragraphs regarding fire safety in Regulation No. 107 but in many cases there is a lack of stringent performance criteria. For example there is a requirement on a heat-resistant partitioning between engine compartment and the rest of the bus, but there is no defined test method or performance requirement. This requirement could be put on a firm basis e.g. by using a furnace as shown in Figure 5 which is proposed in Section 9.4 of Hammarström et.al. [31].

![Figure 5](image-url)
Similarly it would be of interest to require fire hardening near the wheels as studied by NIST [28, 29] and to require early warning systems as proposed by SwRI [26].

As a curiosity it can be noticed that Regulation No. 107 requires that space is provided for fire extinguishers and first-aid kits. As an alternative the presence of such items could be required, instead of space for the items.

**UN ECE Regulation No. 118**

Although the fundamental fire test method was recently changed from horizontal burning rate testing to vertical burning rate testing for interior materials these are both small-scale methods that were originally conceived to mimic a small ignition source such as a cigarette or a match. That type of threat was most relevant some 40 years ago when the horizontal burning rate test was defined, but today other fire sources such as fires in the engine compartment or in tires are more relevant. The fact that the ignition source is small in the test methods means that many materials extinguish by themselves or do not ignite at all. This is indeed an attractive property when the ignition source is small, but it does not reflect the outcome from a fire where the heat attack is larger or when large amounts of hot gases enter the passenger compartment via the floor (e.g. fire in the engine compartment) or via the windows or side walls (fire in a tyre). Therefore a single requirement on interior materials using a more realistic test method such as ISO 5658-2, lateral spread on building and transport products in vertical configuration [20], would be desirable.

Toxicity is still unregulated. BAM and SP have performed research that show that toxicity requirements for interior materials should be enforced for materials for buses. In this context it is interesting to notice that BAM suggests limiting toxic concentrations of single smoke gas components instead of limiting CIT values (Conventional Index of Toxicity). Since fires rarely start in the passenger compartment but are transported from other locations, e.g. the engine compartment, to the passenger compartment it would also be realistic to put toxicity requirement on all materials that are found in potential penetration routes for the fire, and not only on materials in the engine compartment and passenger compartments themselves.

**Hazard levels**

As pointed out in reference [3] the operating conditions for trains defines the fire requirements in the train standard EN 45545-2. In contrast buses only have one type of requirement. The requirements on buses could be differentiated based on the intended use. For example buses that will travel, and be parked, extensively in tunnels and underground constructions could have stricter requirements than buses used only above ground.

**CFD**

CFD (Computational Fluid Dynamics) has been considerably developed the last decade. The use of CFD for bus fire safety should be elaborate and the results should be put into practice. As an example, two independent studies [3, 31] have shown that the presence of combustible materials in the ceiling can drastically enhance the fire spread inside the bus, and that automatic opening of the roof hatches effectively reduces smoke levels in the event of a fire, thereby facilitating a safe escape. It has also been shown that CFD can be used in the design phase of detector installations on buses [33].

**Statistics**

In order to quantify the effects of e.g. amendments of the UN ECE Regulations, and in order to perform cost-benefit analyses with some degree of accuracy, a central database for bus fires would be helpful. Such a database should cover at least the European road net.
NEW CHALLENGES

The major new challenges within the field of bus fire safety are probably the alternative fuels that are gaining in importance, supported mainly by environmental concerns. Examples of such fuels, or energy carriers, are CNG, LNG, LPG, ethanol, methanol, RME (rapeseed methyl ether), batteries, hydrogen, and fuel cells. A striking example of the new threats was revealed when a fire broke out in a CNG-powered bus in Wassenaar in 2012 in the Netherlands [34, 35]. The gas cylinders on the roof on the bus heated up and activated the safety valves, resulting in 15-20 meters long flames shooting out during four minutes. This demonstrates the radically different fire threats with fuels such as CNG, LNG, and LPG, as compared to traditional fuels such as diesel which are liquid at ambient temperature. The risk with a fire is no longer limited to the bus and its passengers and driver, but also to the nearby environment.

Although liquid fuels will not expand in such a way as CNG upon heating, new liquid alternatives also poses new challenges due to new requirements on fire extinguishing, for ethanol and methanol, and also due to increased ignitability, for ethanol, methanol, and RME [36].

The increased number of vehicles running on alternative fuels means that the frequency of such vehicles in tunnels and other underground spaces will also increase [37]. If the CNG fire in Wassenaar would have occurred in an underground facility the effect could have been disastrous. Some countries have restrictions on the use of alternative fuels in tunnels and underground garages [38]. As an example, gas buses are not allowed in the Helsinki bus terminal [39]. Clearly, more research is needed in this field in order to obtain appropriate regulations.

CONCLUSIONS

Although the regulations on fire performance on buses have been strengthened the last decade the requirements are still considerably lacking behind other public transport means such as trains, ships, and aircrafts. The frequency of bus fires is still high and several bus fires with many fatalities are reported each year. A bus also represents a high fire load which can cause damage to the surrounding environment like in a city or in a tunnel.

Most fires start in the engine compartment and it is therefore desirable that fire detection and suppression systems are prescribed for this compartment. Tire fires are also common. Since suppression of such fires is difficult an early detection system is recommended together with fire hardening of materials near the wheel well. The requirements on materials in buses are deficient and more realistic test methods, as well including the measurement of toxic gases and heat release rate, would be advantageous.

New fuels imply new challenges for bus fire safety. More research is required in order to understand the effect of fires on the nearby environment as well as to understand the effects on ignitability and fire extinguishing. Once such data is available new mitigation strategies and regulations can be implemented.
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Vehicle Fire Investigation Statistical Study

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ABSTRACT
This research focuses on the analysis of figures related to the vehicle fire investigations served by the “Laboratoire Central de la Préfecture de Police” (LCPP) between 2001 and 2013, to study their spatial and temporal dimensions and confirm or reverse the believes of fire investigators regarding particular conditions tending to favour the occurrence of investigations on burned vehicles such as the location, the season of the year, the day of the week, the hour of the day and even the phase of the moon. Fire investigators also felt that fire debris samples were useless in cases of completely burned vehicles, thus the relationship between the destruction level of burned vehicles and the results of fire debris analyses is also considered in this study. In the meantime, French official figures of different sources (fire departments, police services and insurance companies) regarding vehicle fires are compared with American and European statistics (Denmark, Finland, Norway, Sweden and United Kingdom).

KEYWORDS : fire investigation, vehicle, statistics

INTRODUCTION
This statistical study concerns vehicle fire investigations considered over a 13-year period, from 2001 to 2013. The “Laboratoire Central de la Préfecture de Police” (LCPP) of Paris, in France, provides a response unit available 7 days a week and 24 hours a day which primary tasks are the risk assessment (following spills of dangerous products, carbon monoxide poisonings or electrical incidents leading to an electrocution) and fire or explosion investigations (origin localization, cause determination, on-site detection and different types of sampling including fire debris sampling).

The LCPP acts on more than 200 vehicle fires each year and investigated more than 2600 vehicle fires between 2001 and 2013. This research presents the figures regarding dimensions in space and time of the cases served by this unit and the reports written by the engineers following their investigations are used to also explore the relationship between the destruction level of burned vehicles and the results of fire debris analyses. Data regarding burned vehicles from different sources (fire departments, police services, insurance companies) are also compared with similar statistics provided by foreign countries such as United States, Denmark, Finland, Norway, Sweden and United Kingdom.
GENERAL INFORMATION REGARDING VEHICLE FIRES

Statistics from the “Laboratoire Central de la Préfecture de Police”

The fire investigators of the LCPP were asked if particular conditions tended to favour the occurrence of vehicle fires. Based on their broad experience, the number of vehicle fires was, for them, higher in so-called sensitive neighbourhoods, on clear days, at night, during the week-ends, and by the light of a full moon. Thus, this statistical study considers the number of vehicle fire investigations conducted by the LCPP between 2001 and 2013, in Paris and its close suburbs, for each season of the year, each day of the week, each hour of the day and even each phase of the moon.

Figure 1  Map of Paris (75) and its close suburbs (92, 93 and 94), source : cartograf.fr

<table>
<thead>
<tr>
<th><em>75</em></th>
<th><em>92</em></th>
<th><em>93</em></th>
<th><em>94</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Paris</td>
<td>Hauts-de-Seine</td>
<td>Seine-Saint-Denis</td>
<td>Val-de-Marne</td>
</tr>
<tr>
<td>49.9</td>
<td>23.8</td>
<td>42.3</td>
<td>34.3</td>
</tr>
</tbody>
</table>

Table 1  Vehicle fire investigations in Paris (75) and its close suburbs (92, 93 and 94) per 100,000 inhabitants, source: LCPP

<table>
<thead>
<tr>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.6%</td>
<td>23.8%</td>
<td>25.1%</td>
<td>24.5%</td>
</tr>
</tbody>
</table>

Table 2  Vehicle fire investigations regarding the 4 seasons of the year (spring, summer, autumn and winter), source: LCPP

<table>
<thead>
<tr>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.8%</td>
<td>13.4%</td>
<td>14.1%</td>
<td>14.7%</td>
<td>13.4%</td>
<td>14.7%</td>
<td>15.9%</td>
</tr>
</tbody>
</table>

Table 3  Vehicle fire investigations regarding the 7 days of the week (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday and Sunday), source: LCPP

<table>
<thead>
<tr>
<th>1 am – 4 am</th>
<th>5 am – 8 am</th>
<th>9 am – 12 am</th>
<th>1 pm – 4 pm</th>
<th>5 pm – 8 pm</th>
<th>9 pm – 12 pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0%</td>
<td>16.3%</td>
<td>15.8%</td>
<td>9.7%</td>
<td>8.3%</td>
<td>19.9%</td>
</tr>
</tbody>
</table>

Table 4  Vehicle fire investigations regarding the 24 hours of the day divided in 6 ranges of 4 hours (1 to 4 am, 5 to 8 am, 9 to 12 am, 1 to 4 pm, 5 to 8 pm and 9 to 12 pm), source: LCPP

<table>
<thead>
<tr>
<th>New moon</th>
<th>First quarter</th>
<th>Full moon</th>
<th>Last quarter</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.3%</td>
<td>28.5%</td>
<td>26.6%</td>
<td>24.6%</td>
</tr>
</tbody>
</table>

Table 5  Vehicle fire investigations regarding the 4 main moon phases (new moon, first quarter, full moon and last quarter), source: LCPP
Table 1 indicates vehicle fire investigations per 100,000 inhabitants happen, after Paris itself, more often in Seine-Saint-Denis, which is one of Paris’ most sensitive suburb. Though, a statistical bias may exist: police services located outside Paris are less comfortable calling the LCPP knowing the travel time of its fire investigation unit, and during which police forces are blocked to preserve the damaged vehicle.

Table 2 reveals no particular season of the year tending to favour the prevalence of car fires. Nevertheless, only an advanced analysis of the number of investigations on vehicle fires regarding the weather (sunny, cloudy, windy, rainy, snowy, etc.) of each single day of the past 13 years could help to determine if these investigations are more common in favourable conditions.

Table 3 advocates vehicle fire investigations are not more frequent on Saturdays and Sundays, and it appears they are relatively stable throughout the week.

Table 4 shows vehicle fire investigations occur more often after sunset: they are twice as frequent at night (from 9 pm to 8 am) than during the day (from 8 am to 9 pm). However, this table considers the time at which the investigation unit of the LCPP received a call for a vehicle fire that occurred a few hours before. This discrepancy explains why there are still 15.8% of calls between 9 am and 12 am, corresponding to early morning fires.

Table 5 suggests no ground for the fear of fire investigators to be on call during full moon nights.

Graph 1 shows a fluctuating trend in the number of vehicle fire investigations from 2001 to 2013. An increase of requests for burned cars was observed in 2005 and 2007, in comparison to the surrounding years, mainly explained by the French riots of October and November 2005 [1], and the presidential election in May 2007: social or political events seem to have a significant impact on the number of investigations related to suspicious vehicle fires. After 2008, the increase might be explained by a stricter policy, applied by police services, to call for a fire investigation team in most cases of burned vehicles.

However, one investigation may involve more than one vehicle but will still be reported as one case investigated by the LCPP. Besides, not all applications for vehicle fire investigation are processed. Since 2011, the cases filed without further action are registered. On the last three last years, there are more than 20% additional cases, not included in the previous figures, and closed as a “non case” based on the information gathered from the applicant, in particular when the vehicle is completely destroyed and no useful evidence regarding the origin or the cause of the fire could be provided.
Graph 2 shows an increase of the number of vehicle fire investigations in May 2007: the number of interventions is more than doubled in comparison to the average of the other months of the year.

Graph 3 illustrates the increase of vehicle fire investigations carried out during the last round of the French presidential election hold on Sunday, 6 May 2007. According to the New York Times, 730 cars were set on fire that night on the French territory to protest against the result of the election [2].

The balance sheet of the “Direction Générale de la Police Nationale” (DGPN) of Sunday, 6 May 2007 (stopped on Monday, 7 May 2007 at 6 am), reported 35 vehicle fires in the French capital exclusively [3], although the LCPP conducted less than 15 vehicles fire investigations on the entire weekend and on a wider area than Paris itself: police officers do not necessarily call the LCPP for every suspicious car fire, in particular when it is part of a series of cases noticed in the same area and already explained by special circumstances such as social protestations, for example.

Statistics from French fire departments, police services and insurance companies

After focusing on the number of fire investigations conducted by the LCPP on vehicles, this part of the research considers figures related to vehicle fires reported periodically by fire departments, police services and even insurance companies. Moreover, the proposed figures concern not only the LCPP’s action area but the entire French national territory.
In all cases, these three indicators do not take account of the fire cause, intentional or not, but provide different figures – and with good reasons.

Firefighters generally respond when vehicles are still burning. Each year, the number of interventions on vehicle fires are supplied by the “Sécurité Civile”. The “Direction Générale de la Police Nationale” (DGPN) provides, each month, the number of police services interventions on vehicle fires. However, one intervention may involve more than one vehicle but will still be reported as one call to the police emergency number. Insurance companies are involved after the discovery of a vehicle damaged by a fire. Indeed, the “Groupement des Entreprises Mutuelles d’Assurances” (GEMA) supplies, each year, the number of burned vehicles for which a compensation was paid by an insurance company. Thus, its figures ignore vehicles that are not declared (such as stolen vehicles) or not covered by an insurance, and vehicles that are too old to be eligible for a compensation.

Graph 4 shows a fluctuating trend of the number of vehicle fires on the French territory from 2001 to 2013. Even on a national scale, an increase of car fires is noticed in 2005 and 2007, in comparison to the surrounding years. The statistics of French police services are only available since 2006 and the fire departments and insurance companies data for 2013 are not yet disclose.

Graph 5 shows the number of interventions of police services on vehicle fires in France in 2007.
Graph 5 evinces a nationwide increase of the number of interventions of French police services on the very particular month of May of the 2007 election year, as well as the LCPP noticed an increase of the number of vehicle fire investigations, highlighted in graph 2 and graph 3.

Statistics from foreign countries

Foreign media often describe the vehicle fires occurring in France as a French specificity. In this way, statistics could be gathered for the United States and 5 other European countries (Denmark, Finland, Norway, Sweden and United Kingdom) on a 8-year period, from 2005 to 2012. They are compared to the previous figures provided by French fire departments, adjusted to a rate per 100,000 inhabitants.

Graph 6 illustrates the French problem of vehicle fires. Indeed, in 2005 and 2006, even if France was the considered country with the highest rate, the United Kingdom and the United States were close second and third. However, since 2007, the United Kingdom and the United States observed a clear decrease while there are still 88.4 vehicle fires for 100,000 inhabitants in France.
Graph 7 tells Denmark, Finland and Sweden also exhibit little changes in 8 years, but their rate never exceeded 50 vehicle fires for 100,000 inhabitants. For its part, Norway remained the studied country with the less of vehicle fires each year.

DESTRUCTION LEVEL OF BURNED VEHICLES & FIRE DEBRIS ANALYSES

In the end, this statistical study looks into the relationship between the results of fire debris analyses and the destruction level of burned vehicles.

Thus, this part of the research uses the reports written by the engineers following their investigations between 2001 and 2010 to provide an emerging answer to the question of fire investigators regarding the usefulness of fire debris samples in completely burned vehicles.

It is to mention, the fire debris were analysed in-house: the LCPP has an accreditation, following the recognised international standard NF ISO/IEC 17025: 2005, demonstrating its technical competence in analytical research and characterisation of flammable liquids.

General statements

Graph 8 illustrates the trend of fire investigators to privilege the hypothesis of an arson fire (with or without the spill of an flammable liquid) regarding the damages caused to the vehicle, the contextual information and the results of fire debris analyses. In 2,6% of this unit’s cases, the hypothesis of an accidental cause (other than malicious) could still be priviledged by fire investigators. Besides, the cause of the fire remains categorised as “unknown” when investigators could not decide between an accidental or an arson fire.

The fire investigation unit of the LCPP is requested by police officers or firefighters, but not insurance companies. As a matter of fact, this unit is generally called when the burning of a car is suspicious, explaining why arson vehicle fires are over-represented.

A number of relevant background information may raise suspicions: the vehicle was parked several hours before the fire occured, a can of gasoline was found near the car, a surveillance camera recorded the whole scene, witnesses saw people running away from the burning vehicle, etc. Moreover, almost all vehicle fires concern stopped vehicles and involve no casualties.
Graph 9  Specific cause retained by fire investigators in accidental vehicle fires from 2001 to 2010, source : LCPP

Graph 10  Specific cause retained by fire investigators in arson vehicle fires from 2001 to 2010, source : LCPP

Graph 9 indicates the electric cause as the overriding cause of the 2,6% of accidental vehicle fires investigated by the LCPP. Though, fire investigators sometimes recognized a recklessness. It is worth mentioning, as examples, the spill of gasoline following the draining of a vehicle reservoir and its ignition as a result of a spark produced by the battery-powered pump used by the garage employee, the ignition of the clothings of a sleeping smoking driver, the projection of embers assigned to a homeless person barbecuing near a caravan, and even the flying sparks of workers using a grinder.

The “other” category considers the inflammation of gasoline, in contact with high temperature engine components as a consequence of road traffic accidents whereas the “unknown” category corresponds to the cases for which fire investigators privileged the hypothesis of an accidental vehicle fire, but its specific cause could not be identified.

Graph 10 bares the specific cause of arson vehicle fires stays unknown in most cases served by the LCPP, otherwise the use of an open flame (a lighter, an ignited cloth or even matches) is a hypothesis often privileged by fire investigators. But 24,0% of accelerant spill are counted and the incendiary devices such as molotov and incendiary...
are sometimes worth consideration especially when glass bottles are recovered. The “other” category here includes the fraudulent attempt to start a vehicle in a failed robbery, as well as the intentional degradation of engine compartment mechanical parts. Besides, the “unknown” category corresponds to cases for which fire investigators privileged the hypothesis of an arson vehicle fire, but its specific cause could not be identified.

**Fire debris sampling and analysis results**

<table>
<thead>
<tr>
<th></th>
<th>No sampling</th>
<th>Sampling</th>
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<tbody>
<tr>
<td>Arson vehicle fires</td>
<td>18,2%</td>
<td>81,8%</td>
</tr>
<tr>
<td>Accidental vehicle fires</td>
<td>59,2%</td>
<td>40,8%</td>
</tr>
</tbody>
</table>

*Table 6  Cases with or without sampling regarding the vehicle fire cause from 2001 to 2010, source: LCPP*

<table>
<thead>
<tr>
<th></th>
<th>Positive result</th>
<th>Negative result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arson vehicle fires</td>
<td>43,5%</td>
<td>56,5%</td>
</tr>
<tr>
<td>Accidental vehicle fires</td>
<td>25,0%</td>
<td>75,0%</td>
</tr>
</tbody>
</table>

*Table 7  Analysis results (positive or negative to the presence of a flammable liquid), in cases with sampling(s), regarding the vehicle fire cause from 2001 to 2010, source: LCPP*

**Graph 11  Accelerants recovered in arson cases with sampling and analysis results positive to the presence of a flammable liquid from 2001 to 2010, source: LCPP**

*Table 6* indicates samplings are more than common in arson vehicles fires with 81,8% of cases where carbonized residue are sampled for a further flammable liquid research. Though, this number falls to 40,8% for accidental vehicle fires.

This high rate of sampling in accidental cases can be explained by the lack of information sometimes available to the investigator at the time of the original investigation, or some investigators’ preference to sample fire debris anyway to exclude other hypotheses.

*Table 7* shows positive results occur more often in arson vehicle fires than in accidental vehicle fires. Past contaminations and fuel releases following the puncture of the tank during the fire are the main explanations to the presence of accelerants in sampled carbonized residue of accidental vehicle fires.

*Graph 11* illustrates the distribution of flammable liquids identified in arson vehicle fires: gasoline (aka. petrol) is first and diesel (aka. gazole), second. Then comes, in a decreasing order, mineral spirit (aka. white spirit), methylated spirit (aka. denatrated alcohol), ethanol (aka. ethyl alcohol), firelighter (aka. briquettes), acetone (aka. propanone) and mineral oil (including paraffinic oils, aromatic oils and
naphtenic oils). The “other” category includes, for example, oxygenated solvent, windscreen wiper fluid (with ethylene glycol) and rectified turpentine spirit. However, analysis results are sometimes positive to more than one accelerant. As mentioned above, the drilling of the vehicle tank, especially in violent fires, releases fuel and contaminates its nearest environment and the vehicle motorization type of fuel is often recovered in addition to the accelerant used by the arsonist to help setting fire, or alone if the arsonist did not spill any accelerant. Moreover, certain flammable liquids are found in fire debris samples as a result of a past contamination which can be explained by the use of vehicles as means of transport or storage of such liquids, for example.

**Destruction level and fire debris sampling**

<table>
<thead>
<tr>
<th>Level A</th>
<th>Level B</th>
<th>Level C</th>
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</thead>
<tbody>
<tr>
<td>14.9%</td>
<td>47.5%</td>
<td>34.6%</td>
</tr>
</tbody>
</table>

*Graph 12 Cases with or without sampling(s) regarding the vehicle destruction level from 2001 to 2010, source: LCPP*

**Table 8** presents the 3 different vehicle destruction levels considered in this research. Level A is the lowest destruction level: damages occurred only in one compartment of the vehicle (engine, passenger or trunk compartment) and are superficial. Level B involves generalized damages to the vehicle but combustible materials still remain. For its part, level C is the highest destruction level and refers to a completely destroyed vehicle.

This table indicates nearly half of the vehicle fire investigations served by the LCPP concern a B level of destruction and 34.6% of the interventions affect entirely destroyed vehicles.

In fact, there are even more vehicles with a C destruction level but some investigators close them as “non case” and, thereby do not appear in these figures.
Though, vehicles with a A level of destruction are less common: when the fire is set correctly, the vehicle ends with a B or C destruction level.

**Graph 12** indicates fire debris are sampled in 93,4% of the investigations of the LCPP on vehicles with an A destruction level. However, the rate of fire debris sampling falls to 76,3% on vehicles with a C destruction level.

Indeed, in the personal experience of some fire investigators, if accelerant was used to set fire, there is little hope of finding traces of it when there is nothing else left than the metal structure of the vehicle: residual traces are lost in the fire and samplings are no longer useful.

**Zoom on 153 particular cases with a known spill of accelerant**

Between 2001 and 2010, 153 arson vehicle fires involved for sure the use of an accelerant, based on the recovery of a bottle filled with flammable liquid, the recovery of a bottle of flammable liquid (and a lighter or matches), the discovery of a gasoline-soaked rag and even the use of surveillance camera records showing people setting the fire.

Thus, 137 vehicle fires followed the spill of an accelerant and 16, the throw of an incendiary device.

<table>
<thead>
<tr>
<th>Level A</th>
<th>Level B</th>
<th>Level C</th>
</tr>
</thead>
<tbody>
<tr>
<td>12,4%</td>
<td>59,5%</td>
<td>21,6%</td>
</tr>
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</table>

**Table 9** Vehicle destruction levels of the 153 considered arson fires on vehicles with a known use of accelerant from 2001 to 2010, *source: LCPP*

**Graph 13** Analysis results (positive or negative to the presence of a flammable liquid) regarding the vehicle destruction level of the 153 considered arson vehicle fires from 2001 to 2010, *source: LCPP*

**Table 9** shows 21,6% of completely destroyed vehicles, that is 33 arson vehicle fires over the 153 previously highlighted in this study. Facing solely the metal structure of the vehicle but knowing for sure an accelerant was used to set fire, charred debris have still been sampled of these 33 vehicles. The whole interest is here to determine whether or not fire investigators are right when suggesting any accelerant is recovered by analysis of fire debris from carcasses of burned vehicles.

**Graph 13** bares 39,4% of analysis results positive to the presence of an accelerant although the fire debris have been sampled from ruined vehicles, that is 12 arson vehicle fires over the 33 mentioned above: 9 with gasoline, 1 with diesel, 1 with white spirit and 1 with kerosene. For gasoline and diesel, the accelerant has been identified without being able to confirm the hydrocarbon exogenous origin. Positive analysis results are even higher for vehicles with a lower level of destruction : 76,8% for B
level and 89.7% for A level. However, there are still 10.3% of negative analysis results for fire debris sampled in vehicles with superficial damages caused by the fire: the accelerant has been spilled on a hostile operating area which has completely melted in the fire (a rear-view mirror or a car bumper).

CONCLUSION

This statistical research did not reveal any particular conditions tending to favour the occurrence of vehicle fires besides the location and the hour of the day: vehicle fire investigations conducted by the LCPP are twice as frequent at night, between 9 pm and 8 am, and they are more prevalent after Paris itself, in one of Paris’ most sensitive suburb.

Moreover, the fire investigation unit of the LCPP noticed, as well as French police services, a great increase of the number of interventions related to vehicle fires in May 2007, the hosting month of the French presidential election. Indeed, social or political events seem to have an impact on the number of suspicious vehicle fires.

For foreign media, vehicle fires are a French specificity and the comparison of French national figures with American and European statistics reinforce this view. Although, the United States and the United Kingdom presented an important decrease of vehicle fires in the last 8 years, France still have quite stable figures.

Furthermore, this study addressed the relationship between the analysis results of fire debris and the destruction level of burned vehicles, using the wide information provided by the reports written by the engineers following their vehicle fire investigations between 2001 and 2010. As a matter of fact, the usefulness of fire debris samples has been demonstrated: even when the metal structure of the vehicle is the only thing remaining, an accelerant used to set fire is likely to be recovered.

Besides this statistical research, full-scale experiments have been planned on undamaged vehicles and different amounts of gasoline were discharged on seats of passenger compartments before setting fire: even when the spill area of completely destroyed vehicles is precisely known, regardless the quantity of flammable liquid used, the latter is not always recovered by fire debris analysis.

REFERENCES


Investigation of a fire with two biogas buses in city traffic in Helsingborg, Sweden the 14\textsuperscript{th} of February 2012

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ABSTRACT
On the morning of 14\textsuperscript{th} of February 2012 a city bus collided with another parked bus at a slow speed and both buses overturned in flames. Due to the time of day and the fact that the place of the collision was at an end station there were only 5 passengers present. All passengers and the drivers were successfully evacuated.

The accident was investigated by The Swedish Accident Investigation Authority (SHK), who is an independent state authority with the task of investigating accidents and incidents when an investigation is important from the viewpoint of safety or it indicates other substantial shortcomings in safety arrangements. This paper presents the investigations and full scale tests carried out in order to determine what happened and how the accident could happen as well as provide a basis for decisions regarding appropriate measures to be taken so it will not happen again. It will present the correlation of a permanent suppression system in the engine room and the possibilities to evacuate a bus on fire safely without injuries on the passengers.

KEYWORDS:
Bus fire, biogas, evacuation, training, rescue service, fire suppression system, full scale test

INTRODUCTION
In Sweden there are annually incidents and accidents with about 138 buses or coaches that results in a fire. Statistically that is 1\% of the national fleet, which also means that every 10\textsuperscript{th} bus will have a fire during its period of active average traffic use off 10 years.

A fire in a bus can occur in many different ways and because a number of reasons. Even if all effort to prevent a fire should be taken it’s really not realistic to believe that a fire will not occur. In order for people not to be injured or killed in a bus fire it is necessary for the bus to be designed, equipped and maintained so that its fire safety design will prevent a fire in the engine room to transfer within the bus, and also to prevent smoke and toxic gases to spread into the passenger compartment.

If a fire happens and despite the taken measures against spreading of the fire or gases an evacuation of the bus is actualized, the objective must be that there are enough doors or windows that allows a safe passage for the passengers to evacuate even if some passages are blocked or otherwise not possible to use. Finally a driver must have proper education and knowledge so that in a stressful and dangerous situation the driver can act properly to protect and assist the passengers in an evacuation before the rescue services arrives.

METHOD AND RESULTS
The authority formed a commission to investigate the accident that happened. Interviews were made with people engaged in the accident and the national acts and ordinances were examined. A technical examination of the vehicles was performed together with a fire investigation. With input from that work a full scale test took place with the aim to find how fast a bus fire spreads and what time a bus can be evacuated.
INTERVIEWS
Interviews were made with the both drivers, the passenger and bystanders that witnessed the accident as well as maintenance personnel at the company of the buses. The result from these stated that it was very slippery on the roads at the time for the accident. The bus that ran into the one perked held a low speed and that the collision was very light and the fire started immediately. Both drivers had the mandatory education and the education contained fire knowledge, but no training of a bus on fire.

The company follows its own maintenance program that is customized to manufacturer's recommendations. Inspections and service are divided into different levels with their own protocol for service and inspection points that mechanic follow and document the checks carried out. Inspection of portable fire extinguishers and engine compartment fire suppression system is performed by the company's own service personnel every six weeks. Inspection was only visually and by hand and upon failure, the nozzles were replaced.

RULES AND LEGISLATION
There are several national laws and regulations in Sweden that regulate bus services. Along with these rules there is also an environmental objective of fossil fuels in public transports that will result in all Swedish motorized vehicles powered by renewable fuels at 2020.

Operating licenses are decided by the county board of the county in which the company is registered and may be granted with respect to skills, economic conditions, the law and willingness to meet its obligations to the public as well as other elements of the situation is deemed appropriate to run the business. In order to use vehicles for commercial passenger service it is required by the Vehicle Ordinance that the vehicle has been successfully suitability inspection. In each vehicle used in commercial carriage of passengers shall, in order to prove the suitability of approved inspection, carry a valid certificate.

The Work Environment Act controls including employer liability even with regard to road safety in such a way that illness and accidents on the job and a satisfying work environment. The Act of Occupation Operator will place demands on competence on the professional driving skills and basic education to ensure that all drivers have the skills necessary for the profession. Regulation say that buses put into circulation Feb. 13, 2004 or later must meet the requirements of Directive 2001/85/EC or equivalent ECE Regulations (Regulation 107). Older buses will meet senior national regulations. The purpose of the directive is to provide increased security and availability of buses. In connection with the incorporation of the directive into Swedish legislation there became an insurance requirement that new buses over 10 tons from 2005 would be equipped with a fixed fire extinguishing system. Specific routine schedules for checking buses security equipment should also be established.

Requirements for vehicle characteristics and equipment lies upon The Transport Agency and shall ensure inspection work to function well regarding road safety, the environment, price trends, technology and accessibility. In The Vehicle Act are also the basis for the technical inspection of the vehicle to control that vehicles meet the prescribed requirements for the protection of life and health. Buses shall be annually inspected by an accredited inspection body. They are, however, not to verify the operation of the automatic fire suppression systems since these systems are not mandatory.

TECHNICAL EXAMINATION AND FIRE INVESTIGATION
A technical examination showed that there were no defects in the brake system of the bus and the tires were according to the regulations. The engine and its details worked as intended. The collision happened due to the slippery road. The rear end of the parked bus was pressed forward about 0,1m and containers with servo oil and fuel filter broke and the oil leaked into the engine room. A part of the installed suppression system had loosened from its position and was found on the floor.

Heavy vehicles like buses commonly have a pneumatically controlled braking system, i.e. air brakes. These brakes require a compressor that supplies the bus's brake circuit tanks with compressed air. The compressor is driven by the bus's engine and all compressed air is consumed when the driver brakes
Compressed air is also used for the vehicle's door system. If the air circuit is damaged in the fire the doors can end up in a closed position. In a collision or fire can occur that cause a short circuit in the electrical system which may enable the driver to operate the doors. On all new buses, there are controls both outside and inside the bus where passengers or other outside persons can open the door. It can be difficult for passengers to know in advance how to expose the doors. On some buses, it is clear only that there is an emergency release and that will push up the doors. In other buses passengers should be able to force a seal or protecting glass in front of a handle open. In order to reach the handle on some busses it required a length of at least 170 cm.

The fire investigation determined that the fire started in the engine room on the parked bus due to a gas leakage arisen from the collision. The gas was ignited by the lamp in the engine room that was under power though the bus otherwise was shut down. With the hydraulic oil that was spilled the fire had grown rapidly with high intensity and spread fast. The fire investigation showed that a fire with that pattern would probably not be extinguished by a fire suppression system for engine rooms. The investigation also pointed out that the heat was so high that the aluminum spring in the brake cylinders had begun to melt. If the spring melts the vehicle will be in neutral with no brake power.

The investigation of the parts of the parked bus's fuel system indicates damage to the rear of the fuel filter housing arisen before the fire. The reconstruction shows that the upper front on the driven bus pressed the parked bus rear engine hatch into the engine compartment. The front met a crossbar in the parked bus engine cover, positioned in level with the lower half of the rear fuel filter which explains the damage on the filter canister. The possibility for the filter container to fold away at impact was made impossible by a steel bracket behind the filter. The damage to the fuel system could have been avoided if the parts have not been placed in the narrow space between the rear engine cover and the upper engine compartment wall forming impact zone for the rear-end collision.

**FULL SCALE FIRE TEST**

A full scale test was performed with two buses. The first test was to determine fire and smoke transportation to establish critical time for evacuation of the bus. The purpose of the first test was to investigate the fire and smoke transportation in the bus to get an idea of the conditions for evacuation, while the purpose of the second fire test was to investigate the degree to which a functioning detection and extinguishing system in the engine compartment would be able detect and extinguish, or delay the fire and thereby improve possibilities for a safe evacuation. The fire scenario was chosen so that it would mimic the accident in Helsingborg.

To achieve high repeatability in the fire experiments, two buses of the exact same model were used. In this way, the difference in fire development examined both with and without an installed fire suppression system would be minor. In both cases, the bus's engine was turned off so that the engine fan did not contribute to any air supply through the engine compartment. During the tests all bus doors were open. For security reasons, the gas tanks were emptied of gas. The fact that the tanks were empty did not affect the outcome because critical levels for passengers to evacuate were reached before the gas tanks were involved in the fire.

The first test with a bus not equipped with fire suppression system in the engine compartment was started with a fire that was allowed to grow into a fully developed fire involving the entire bus. A simulated leakage was created with a pipe with nozzle that was installed in the engine compartment. Methane gas was used as biogas consists of approximately 92% of methane. The gas flow was adjusted to as realistically as possible to mimic the circumstances of the accident. Shortly before the test started, five gallons of hydraulic oil was sprayed evenly in the engine compartment to deliver the approximated amount of oil that may have leaked out in the collision.
A pilot flame was lit and the gas ignited immediately. The bus was then allowed to burn freely until the whole bus was in flames and the fire eventually subsided. During the fire data from the temperature and the gas analyzer was recorded. The experiment was stopped when only minor scattered flames remained. Critical levels occurred after 3 min and 13 sec at the rear door of the bus.

The second test was to find out how an installed fire suppression system would affect a bus fire in the engine room. The engine compartment on the second bus was provided with detection and extinguishing systems. The aim was to get a picture of the extinguishing system extinguishing or reducing effect and any effect on the time available to perform a safe evacuation of the bus. Before the test the same type of fire suppression system as in Helsingborg was installed in the engine compartment by the manufacturer in order to extinguish the fire. The capacity of the system was representative of the fire suppression system installed in buses today and was increased in amount of nozzles and extinguishing liquid to meet current directives. The manufacturer had no knowledge of where the fire would start.

The experiment was prepared and started in the same manner as in the experiment without extinguishing system, but with the difference that a spark igniter is used to ignite the gas leaks instead of a pilot flame. The reason was to avoid the heat from the pilot flame affected the activation of the detection system. The gas ignited leakage of the ignition device and after 9 seconds detected fire by plastic tubing that was positioned just above fire burned off. The extinguishing system was activated with a few seconds delay. No mist became visible in the engine compartment. The extinguishing agent spurted out through a vent on the left side of the engine compartment. The test was aborted and the fire put out.

An examination of the extinguishing system showed that of a joint had become loose with the result that a large part of the extinguishing agent was sprayed out through the opening. According to the manufacturer and the installer of the system the reason for the loose thread was that the link was incorrectly applied. The connection could not withstand the high pressure of 105-110 bars in the system.

Before resuming the fire test the extinguishing system linkages in the engine compartment were controlled by the manufacturer to ensure that they were properly tightened. The manufacturer replaced the detection system and installed it at a different location than the previous attempt. The purpose was to delay the detection to use the heat of the fire for the water mist to evaporate more efficiently in the engine compartment, thus generating a better extinguishing effect.

New hydraulic oil was added into the engine compartment to compensate for the oil that had been burned during the first attempt. In the retrial the detection hose burned off after 3 minutes, much later than in the aborted test because the hose was moved and positioned further away from the initial flames from the gas leakage. When the extinguishing system was triggered all joints held together. There were no visible effect on the flames but the fire and its critical levels were delayed with approximately 10 minutes.

FULL SCALE EVACUATION TEST

Parallel to these tests another bus was used and an evacuation test was performed. 75 senior citizens evacuated the bus during simulation with different scenarios and evacuation possibilities and the role of the driver. The purpose of the selection of the passengers was not that it would be representative of the most frequently occurring group of occupants. It should rather be seen as representative of one of the evacuation point typically slower but still realistic group of passengers.

At the first evacuation test all three doors were opened and all were used as an escape route. In the second experiment only the front door was opened. The second evacuation test simulated a case where the bus driver does not get up in the middle or rear doors. This test can also represent a case where the middle and rear door blocked by strollers as well as people who require extra time and help to get them down the stair, or a fire.
The passengers were aware that the purpose of the tests and were asked to leave the bus quickly and safely, and that, moreover, behave as they would in a real situation. The bus was parked and the doors were closed when the tests began. In both tests, the driver participated actively and moved several times in and out of the bus and was also standing at one of the doors and helped the passengers down the stair. Every test ended with the driver walking along the bus aisle and looked into each seat to ensure that everyone was out.

The results showed that the passengers were all evacuated in 1 min 28 sec when all doors were available but made it on 2 min 47 sec when only one door were available for evacuation.

RESULTS OF THE FULL SCALE TESTS
At the first attempt the extinguishing system failed due to a poorly tightened coupling and on the second attempt there was no apparent effect on the flames at the time of activation. The system was not able to extinguish the fire even though the manufacturer had been commissioned to install the system to extinguish the resulting fire. The reason for this was probably that no nozzle was pointed directly at the place where the fire occurred. Two nozzles were placed around the simulated gas leak, but low down and facing forward in the engine compartment. Had the nozzles been placed at the engine compartment roof and facing down, it is not impossible that the fire had been extinguished. It is important to ensure that the areas of the engine compartment where fire can occur really are covered by nozzles.

Critical conditions in the passenger compartment were delayed about 10 minutes compared to the experiment without extinguishing systems. Although some of the time difference may be due to small variations in procedures, such as wind conditions, the difference is significant. The large amount of extinguishing agent as required by current guidelines wet engine compartment and thus delayed the spread of fire and time was won for passengers to evacuate the bus.

In Helsingborg, the buses had permission to have 65 respectively 121 passengers. The evacuation test with 75 people from the older generation is not representative of an average population of traveling in a bus, but not an impossible scenario at certain times and in certain neighborhoods. The scenario is also highly possible as the growing industry with sightseeing tours for senior citizens grows rapidly.

In the fire test critical levels was reached at the back door by 3 min 13 sec. The evacuation of the passengers took 1 min 28 sec when all the doors were used. In this case, therefore, the driver may be aware of the fire and decide on evacuation within 1 min 45 sec from ignition. Fire experiment without detection and extinguishing systems shows however that a driver doubtfully had detected the smoke during the first 2 minutes, and in the test with 75 passengers evacuating it would hardly have been possible without injuries. Even less so had they been able to evacuate without severe injuries if the bus had been crowded with 121 passengers, which was allowed.

CONCLUSIONS
The investigation found that there is no national law that regulates permanent fire suppression systems for engine rooms on buses or coaches. If no demand is stated in the agreement for running an operation with buses there is no adequate criteria for permanent fire suppression systems in engine rooms.

The full scale tests showed that it is of outmost importance for a successful evacuation with an early detection of the fire. The driver had doubtfully noticed the smoke during the early stage of the fire and the evacuation test shows that in a bus full with travelers an evacuation could not have been done without severe injuries on the travelers.

The Swedish Transport Agency was recommended to introduce a regulatory system with rules and demands on permanent fire extinguish systems for engine rooms on buses and to institute regulations about control of the extinguish systems together with the ordinary vehicle survey.
Together with the Swedish Civil Contingencies Agency the Swedish Transport Agency were recommended to increase the driver education with and adjusted for fire safety and evacuation scenarios and that the fire fighters are educated in, and will have sufficient materiel, to perform a efficient work when bus fires occur in general and buses on biofuel in particular.

REFERENCES

Fire in a CNG bus

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ABSTRACT

On 29 October 2012 a fire broke out in a natural gas (CNG)-powered regional bus in Wassenaar, The Netherlands. After the driver had brought the bus to a halt and the occupants had alighted, the fire spread from the engine compartment to the rest of the bus. The fire caused the natural gas cylinders on the roof of the bus to heat up, activating the safety valves that prevent the cylinders from exploding. Horizontal flames 15 to 20 metres in length shot up from the natural gas that had been released. The shooting flames continued for about four minutes in total. Since no people or buildings were located within reach of the shooting flames, the consequences of the fire were limited.

The incident with the bus in Wassenaar, combined with the increasing use of CNG as a fuel, prompted the Dutch Safety Board to investigate to what extent the risks associated with the use of CNG are controlled. Both local governments and the national government encourage the use of CNG for its environmental benefits. However, its safety risks for drivers, passengers and the environment are not incorporated in their assessment, nor do transport companies or bus manufacturers assess these risks.

The bus involved in the fire in Wassenaar complied with the technical regulations, as did its CNG system. The cylinders on the roof are fitted with a mandatory temperature-triggered safety valves in order to prevent the risk of explosion the cylinders. As the incident demonstrates, this safety measure introduces another safety risk, namely the occurrence of large shooting flames when the vented gas ignites. In this particular CNG system, the position of the blow-off valves caused the flames to shoot out in a horizontal and sideward direction. The occurrence of the large shooting flames in horizontal direction is due to a gap in the vehicle regulations.

Key words: compressed natural gas (CNG), vehicle regulations, risk assessment

Figure 1: Bus on fire (left) and shooting flame. (Source: Regio15.nl)
REASON FOR THE INVESTIGATION

Although there were no casualties in the bus fire, the shooting flames could have had considerably severer consequences had the location been different – a narrow shopping street or a tunnel, for instance. What is striking in this incident is that precisely the safety mechanism which is built in to prevent an explosion, in turn, posed another hazard, namely the long shooting flames. Partly in view of the fact that the use of CNG (compressed natural gas) has been enjoying rapid growth in recent years, the Dutch Safety Board felt that it was important to conduct an investigation.

The results of this investigation by the Dutch Safety Board were published in a full report [1]. The report is available on the website (www.safetyboard.nl). This paper describes the main lessons learned from the investigation and concludes with recommendations.

THE ACCIDENT

On 29 October 2012 a fire broke out in the engine compartment of a CNG-powered public transport bus. The bus, which was carrying one driver and five passengers, was operating in the Wassenaar urban area at that time. When the bus driver looked in his mirror and saw smoke developing, he continued driving to the next suitable location where he felt he could bring the bus to a halt. He had meanwhile alerted the transport company’s traffic control centre, which in turn alerted the emergency services. After he had allowed the passengers to alight, the driver walked around the back of the bus to the engine compartment with a fire extinguisher, but the fire had already reached such an advanced stage that he was unable to extinguish it. The fire then spread rapidly to the interior of the bus. For a chronological overview of the events and the development of the fire, see Figure 2.

The fire had already fully developed when the fire brigade arrived (11 to 14 minutes after the fire had first been reported by the driver to the transport company's alarm centre). In accordance with the deployment instructions, the fire brigade decided to allow the fire to burn out in a controlled manner.

In CNG-powered buses, gas is stored in roof-mounted high-pressure cylinders. When the cylinders heat up pressure builds up inside and the tensile strength of the cylinders weakens. To prevent the risk of explosion the cylinders are fitted with a mandatory temperature-triggered pressure relief device. If the temperature exceeds the threshold value of 110° Celsius, a valve opens venting the gas in the cylinder.
Several blow-off valves opened during the fire. The vented natural gas ignited, causing flames to shoot out. As a result of the high pressure in the cylinders and the type of blow-off valves, flames 15 to 20 metres in length shot out. The blow-off valves were located in a position which caused the flames to shoot out in a horizontal and sideward direction (see Figure 1 and 3).

Since no buildings were located directly alongside the road and there were no people in that particular area, the consequences of the shooting flames were limited to fire damage on the road surface, trees and shrubs. No personal injuries were sustained by the occupants, bystanders or emergency response personnel. However, the bus was completely destroyed, see Figure 5.

LESSONS LEARNED FROM THE INVESTIGATION

CNG as engine fuel

CNG is the abbreviation for compressed natural gas. It is produced by compressing natural gas to a pressure of around 200 bar using a compressor. CNG is mainly used as an alternative fuel for petrol and diesel in motor vehicles. CNG offers the following advantages over conventional fuels.

Currently, when CNG is used as engine fuel the exhaust fumes emitted usually contain fewer particulates, nitrogen oxides (NOx) and carbon dioxide (CO₂) than diesel or petrol. This difference is subject to change as a result of the development of new petrol and diesel engines. Apart from the potential emissions advantages, the use of CNG causes less engine noise.

If natural gas alone is used as a basis for CNG, it will still be an ‘unsustainable’ fossil fuel. However, natural gas can be mixed or replaced entirely by biogas (also known as ‘green gas’). Biogas is produced as a result of the fermentation or heating up of crop residue, animal dung, waste from wastewater purification plants, organic waste, etc. After reprocessing, biogas – like natural gas – consists primarily of methane (CH₄) and offers the same emissions advantages when used as engine fuel. Biogas is distributed (by admixing) through the regular natural gas network.

Aside from the above, for users at least, CNG is cheaper than petrol or diesel. This is mainly because energy tax on natural gas and biogas is considerably lower than the duty on diesel and petrol.
Compared with similar vehicles running on petrol or diesel, the disadvantage of current CNG-powered vehicles is that they require a larger volume of fuel for the same operating range. The capacity of the fuel cylinders on a CNG-powered public transport bus is more than 1,700 litres (for an operating range of 500km), whereas diesel versions of these vehicles suffice with a tank capacity of several hundred liters. For this reason the fuel cylinders in low-floor CNG-powered buses are mounted on the roof. To reduce weight, CNG cylinders are made of synthetic material rather than steel.

In the Netherlands over 5,200 vehicles currently run on CNG (Source: RDW), mainly passenger cars, light commercial vehicles (vans) and public transport buses. This is but a small portion of the total national vehicle fleet comprising around nine million vehicles.

The European Commission promotes the use of alternative engine fuels such as CNG in the interests of the European climate objectives and energy safety. Based on EU directives a national target was defined to increase the share of biofuels (a mere 2% in 2010) to 10% in 2020. Alongside biodiesel, biogas is expected to make a substantial contribution to the target figure.

A total of over 5,100 public transport buses operate in the Netherlands (Source: KPVV). At the end of 2012 some 12% (over 600 buses) ran on CNG, distributed across eight concession areas and seven transport operators [2]. The Netherlands have been divided into 46 concession areas. 13 transport operators carry out public transport by bus in the Netherlands [3].

In recent years a number of public transport authorities have explicitly stipulated in their call for tenders for public transport bus services that CNG be used as fuel. This also applies to the concession the Haaglanden Urban Region awarded to Veolia in 2009 for bus services in The Hague Region, which included the bus involved in the fire in Wassenaar.

The condition stipulating that CNG be used as fuel for buses stems from a political decision taken by the relevant municipalities based on their aim to achieve environmental objectives. During the decision-making process consideration was neither given to the safety risks, nor the consequences of matters such as parking, fuelling stations, etc.
Environmental risks posed by CNG-powered buses

The flames that shot up during the bus fire in Wassenaar pose a safety risk for the environment. If environmental risks are associated with road vehicles, these risks usually relate to the carriage of dangerous goods as cargo. Comprehensive laws and regulations apply to the carriage of dangerous goods, and set out regulations for the vehicle’s equipment and the packaging of the cargo as well as the roads that may and may not be used. The principle underlying these requirements and deployment restrictions is that the road traffic risks to which people located in the vicinity of roads are exposed may not exceed a certain level. As stated, these regulations only apply to vehicles carrying dangerous goods as cargo. Other vehicles usually also carry a dangerous cargo on board namely engine fuel, but these vehicles are not subject to the above regulations. This in itself is logical because engine fuel in a sense forms part of the vehicle itself, which means that vehicle regulations should provide for adequate control of the associated risks. In certain situations the vehicle regulations are not sufficient. In these situations, engine fuel could pose a risk for people and objects located in the vicinity. As the Wassenaar incident showed, this could, for instance, be the case if fire breaks out on a CNG-powered bus. The municipalities located in The Hague Region [regio Haaglanden], where CNG-powered buses operate, failed to recognise that in certain situations CNG-powered buses carry other or higher risks than the diesel-powered buses used in the past. Incidentally, these specific risks were not pointed out to the municipalities by the transport parties involved, who likewise failed to recognise these risks, as explained further on in this document. Consequently, the specific environmental risks posed by CNG-powered buses were not structurally assessed. Given the potentially severe consequences, in the Dutch Safety Board’s opinion a risk assessment should still be performed.

The decision to switch from diesel to CNG-powered buses in the above region was taken by the Haaglanden Urban Region [Stadsgewest Haaglanden]. The transport company (Veolia) was only involved in implementing the decision but had no role in the decision-making process itself (choice of fuel). It emerged from interviews with the Haaglanden Urban Region that the municipalities involved opted for CNG based on environmental objectives and failed to assess the possible consequences for safety during the process. In the Dutch Safety Board’s opinion, the safety consequences should have been assessed on account of the environmental risks described above. The Dutch Safety Board is furthermore of the opinion – due in part to the requisite knowledge – that it would be advisable to involve transport companies in the decision on the choice of fuel.

Vehicle regulations

The bus involved in the fire in Wassenaar complied with the technical regulations, including its CNG system. The CNG system operated as envisaged in these regulations. This means that the current requirements applicable to CNG systems allow for the occurrence of shooting flames, as was the case in Wassenaar. The above requirements are drawn up at international level. The RDW, which falls under the responsibility of the Ministry of Infrastructure and the Environment, represents the Netherlands in this context. In terms of safety, international vehicle requirements relate mainly to road safety and occupant protection. The requirements only partially acknowledge that environmental risks may also occur. A measure has, for instance, been taken to prevent gas cylinders from exploding by means of a valve which allows the cylinder contents to escape if the cylinder heats up. The rules, however, fail to recognise that this creates other risks, such as shooting flames or an explosive gas cloud. In the Dutch Safety Board’s opinion vehicle requirements must be tightened in this area.
Risk awareness and interpretation of duties by the parties involved

The Haaglanden Urban Region is the contracting party for public transport bus services in The Hague Region, which includes Wassenaar. The concession was awarded – in accordance with the rules – on the basis of a public tendering procedure. The schedule of requirements for the tender contained several criteria, such as the frequency of bus services, punctuality and self-evidently the price. No requirements on physical safety, however, were imposed by the Haaglanden Urban Region. Incidentally, this is not laid down by law. The Dutch Safety Board believes that a contracting party who engages another company to perform high-risk activities has a responsibility towards society to ensure that the contract is performed in the safest possible manner, even if no such legal requirement exists. The Dutch Safety Board fails to see why public passenger transport should form an exception in this respect. On the contrary, in this sector too contracting parties (in this case the public transport authorities) should feel jointly responsible for the safety of the operations performed under their contract. The Dutch Safety Board has established that the Haaglanden Urban Region’s limited interpretation of its duties is not an isolated case. In previous investigations into incidents involving public passenger transport (such as the metro fire and metro collision in Amsterdam and hydrofoil safety issues) the public transport authority involved held the view that it had no role in controlling the safety risks. In these instances too, the argument put forward was that joint responsibility cannot be assigned to the public transport authorities under the current laws and regulations. For this reason in the Dutch Safety Board’s view the relevant legislation should be amended such that it the requirement is still imposed on the public authorities to ensure that they pay due attention to controlling risks. Incidentally, during the procedure in which the parties involved were given an opportunity to respond to the draft version of this report, the Haaglanden Urban Region stated that it now in fact endorses the assignment of responsibility referred to above.

Veolia, a transport company, won the tender at that time and thus became the ‘concessionaire’. The company did not perform its own risk analysis concerning switching to CNG, but limited itself to the purchase of approved CNG-powered buses. Had Veolia included additional safety measures, it could possibly have priced itself out of the market as the contracting party had not requested any such measures in its schedule of requirements. Apart from this issue in the tendering procedure, the Dutch Safety Board deems that a transport company is primarily responsible for the safe operation of transport services. In this context the Dutch Safety Board finds it striking that companies operating public bus services are not required by law to ensure they have a safety management system (SMS) in place. This contrasts with other modes of public transport, where – based in part on European regulations – this either already is mandatory (train transport) or is due to become mandatory in the near future (tram and metro transport). In the Dutch Safety Board’s view this should also be mandatory for public transport bus services.

The bus operating in Wassenaar was built by MAN, a German manufacturer. MAN had purchased the CNG system for this particular type of bus from a supplier. While MAN indeed complied with the regulations, the company itself had taken no additional safety measures. The manufacturer pointed out that its customers do not even ask for such measures. This means that there is no incentive in the bus market to exceed the stipulated regulations. Bus manufacturers apparently compete on price, and to a lesser extent on safety, unlike the passenger car sector where safety is a key selling point. In view of the manufacturers’ attitude, which the Dutch Safety Board similarly observed in a previous investigation, improvements can only be expected if customers (in this case the transport companies) request that improvements be made, or if vehicle requirements are tightened. In the Dutch Safety Board's opinion – and as stated earlier – the latter should be carried out.
Fire brigade deployment procedure

When the CNG-powered buses were launched in The Hague Region the fire brigades in this area were not notified by the organisations concerned. The fire brigades therefore only began to make preparations for fire prevention in CNG-powered buses after the buses had already been operating for some time. In addition, there was no joint or coordinated approach and the fire brigades did not hold the requisite expertise. This gave rise to different and partly incorrect deployment protocols among the various fire brigades. The Dutch Safety Board deems it advisable to centralise the development of deployment protocols.

Figure 5: The burnt-out bus (Source: Rene Hendriks, Regio15.nl).

Learning from accidents

The Dutch Safety Board established that none of the parties systematically learns lessons from incidents and accidents. This occurs at different levels. In terms of vehicle regulations, the authorities concerned – the RDW in the Netherlands – do not systematically collect information about relevant accidents to determine whether there is a need to tighten the technical requirements with which vehicles must comply. In respect of the implementing parties, neither the public transport authorities nor the transport companies have put procedures in place to collect and analyse accident information for the purpose of learning lessons. The Dutch Safety Board deems it vital to learn lessons on a structural basis on both fronts.
WIDER PERSPECTIVE

The safety problems identified are not unique to CNG-powered buses in The Hague Region. In the first place CNG-powered buses similar to the buses operating in The Hague Region are also used in other areas. The number of CNG-powered buses in the Netherlands currently totals over 600. The total number of CNG-powered buses in Europe is around 156,800 [4]. The vast majority of these buses are located in Eastern European countries (such as Russia, Ukraine, Georgia, Armenia and Turkey). The number of CNG-powered buses in Italy, France, Germany, Spain, Sweden, Greece, Portugal and the Netherlands (Mainly in the urban regions) totals at least 9,000.

Besides the increase of CNG as engine fuel for buses, CNG is increasingly being used as engine fuel for other types of vehicles. In the Netherlands over 3,000 passenger cars and around 2,500 vans currently run on CNG. The CNG cylinders in these vehicles are also fitted with temperature-triggered pressure relief devices (PRDs) and in the event of heating up may vent the supply of natural gas. It should be noted that the capacity of CNG cylinders in passenger cars and vans is generally five to ten times lower than those of CNG-powered buses. However, CNG-powered trucks carrying a supply of CNG similar to that of CNG-powered buses are now available on the market. It is striking that CNG-powered trucks too are mainly deployed in urban areas (such as a refuse trucks). The explanation lies in the specific advantages and disadvantages of CNG (low exhaust emissions and less engine noise or a relatively narrow operating range). Regrettably, however, it is precisely in the urban environment where the specific safety risks inherent in CNG are the most prevalent.

At the administrative level, the Dutch Safety Board largely sees the same pattern for other CNG-powered vehicles as described earlier for CNG-powered buses; in other words the government authority (primarily the municipal and the provincial authorities) promotes the use of CNG as engine fuel yet fails to take account of the specific safety aspects.

The Dutch Safety Board is aware that alternative engine fuels, such as CNG and hydrogen, can have significant advantages. When introducing alternative fuels, however, a proper assessment should be made of the extent to which they carry specific safety risks, not only for the occupants and other road users but equally for the environment. The environmental risks may, for example, relate to large shooting flames in the event of a bus fire, which moreover are invisible in the case of hydrogen. It is key to prescribe as mandatory that these risks be controlled in adequate vehicle regulations. Furthermore both the manufacturers and the operators of these types of vehicles should be aware of the fact - now more than has been the case to date - that an innovation carries inherent risks. These parties should not automatically rely on vehicle regulations but should, where necessary, take additional measures based on their own critical assessment. In addition, the authorities involved should critically assess in what situations or on what conditions new technology can be deployed responsibly in the light of the residual environmental risks.
RECOMMENDATIONS

The Safety Board has formulated the following recommendations:

1. **Identification and analysis of the environmental risks associated with current CNG-powered buses**

   To the public transport authorities and transport companies operating CNG-powered buses:

   Identify the risks for the environment associated with the use, maintenance and parking of CNG-powered buses and take measures to reduce these risks.

2. **Formulate and tighten vehicle regulations**

   To the Minister of Infrastructure and the Environment:

   a. Ensure that the international vehicle regulations applicable to CNG systems (UN/ECE Regulation 110) are tightened to ensure that the risks for the environment are controlled in the event of vented gas.

   b. Ensure that the RDW systematically collects the relevant accident information and applies that knowledge when international vehicle regulations are established or amended.

3. **Duty to ensure safety on the part of the public transport authorities and transport companies**

   To the Minister of Infrastructure and the Environment:

   Incorporate in the Passenger Transport Act 2000 [Wet personenvervoer 2000] the following requirements:

   - that bus companies systematically control the risks associated with their operations by means of a safety management system;
   - that the authorities contracting public transport bus services impose requirements on the transport company for controlling safety risks.

4. **Development of the fire brigade deployment procedure in the event of vehicle fires**

   To the Security Council [Veiligheidsberaad]:

   (The Security Council is comprised of the 25 chairmen of the safety regions and functions as a national platform for the security regions.)

   Ensure that the deployment procedure for fighting fires in vehicles powered by non-conventional fuels (such as CNG and hydrogen) is centrally developed.

REFERENCES

The full report “Fire in a CNG bus” contains an overview of the sources refered to in Appendix F.


MEANS OF ESCAPE IN THE EVENT OF BUS/COACH FIRES

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ABSTRACT – Means of Escape in the Event of Bus/Coach Fires

Fires in buses/coaches are a risk to passengers and a risk to an industry that wants to promote safety for their passengers. Reports from tragic incidents that have resulted in fatalities indicate delays in evacuation and/or inadequate means for passengers to escape.

This presentation would explore the fundamental principles of means of escape as applied to bus/coach travel. It will look at exit design and position and the challenges faced by manufacturers and operators as they look to combine functionality with escape principles. It will concentrate on transport used in longer journeys where access/egress are not a frequent feature but comfort and luggage capacity are.

The presentation will consider the factors that impact on fire development and, therefore, the time available for escape. It will consider passenger behaviour and will look at the need to take into account the nature of the vehicle occupancy. In particular, it will look at evacuation involving passengers with limited mobility or other factors that may lengthen evacuation times. Safety critical information for passengers will be examined and how that information may be shared.

Finally it will examine the role of the ‘responsible person’, usually the driver, in initiating and guiding evacuation. This will emphasise the importance of driver training.

Keywords: means of escape, fire development, evacuation, vehicle occupancy
MEANS OF ESCAPE IN THE EVENT OF BUS/COACH FIRES

INTRODUCTION

Fires in buses/coaches are a risk to passengers and a risk to an industry that wants to promote safety for their passengers. Reports from tragic incidents that have resulted in fatalities indicate delays in evacuation and/or inadequate means for passengers to escape.

BACKGROUND

To the credit of the bus/coach industry, this form of travel is widely known to be relatively safe\[1\] Yet a fire in a bus attracts attention that can be damaging to the reputation of the industry and is regarded differently by the public. For instance, a car accident involving a family on the way to school is reported as a car accident; a bus carrying children to school would be reported as a ‘school bus’ accident and viewed from the viewpoint that the care of children had been handed to a bus company and somehow they had failed.

An additional factor that sets apart fires in bus/coaches is that it can often involve a larger number of people/victims and inevitable attracts more attention. A fire occurring in a ‘sleeping bus’ near Hanover, northern Germany that killed 20 elderly people received widespread coverage and still features high in internet search engines.
Similarly, a bus fire in southern India that killed 42 people received international coverage including from the BBC[1].

A worrying feature of the accidents referred to above and many others reported around the world is the reference to difficulties experienced by passengers in escaping the blaze and the speed with which a fire developed. For instance, one quote in a news feed[2] ‘Some of the victims had difficulty walking and were unable to escape in time, the tour company said’; in another fire[3] it was reported that ‘A group of schoolchildren had a miraculous escape when they were evacuated from a bus minutes before it burst into a raging fireball’. There is a recurring message of rapid fire spread and difficulty escaping. It is timely, therefore, to consider the principles of Means of Escape and how they can be applied to bus/coach transport.
MEANS OF ESCAPE PRINCIPLES

An old established principle of escape is that people should be able to escape from fire by their own unaided efforts and without being placed at hazard whilst doing so[4]. A similar definition can be given as occupants should be able to reach a place of safety, unharmed, in the event of a fire occurring[5]. The emphasis in these and other definitions is being able to travel away from a fire and reach a place of safety - in terms of bus/coach you would expect this to be away from the vehicle - usually by their own means. To achieve this outcome, needs a number of components.

Exit provision

In considering the position of exits, other than in a small vehicle, it is reasonable to expect that a fire or other emergency may render an exit unavailable. Exits must be true ‘alternatives’ and not capable of being rendered unusable by the same event. They should also be accessible without undue difficulty, easy to operate and negotiate and well marked. The remaining exit(s), therefore, must be sufficient to allow all the passengers to leave before the environment within the passenger compartment becomes untenable. Such provision must also be mindful of the varied nature of passengers whether it be the very young (school bus for instance) or the elderly and infirm.

Access v egress

This is an area where there can be differences between buses designed to be used for urban routes where there expected to be multiple stops for passengers to board or leave. By design, these buses are more likely to have ample exits designed to maximise the flow of passengers on and off the bus including features such as ramps and lowered suspension. Intrinsically these designs will offer more effective exit provision in the event of fire. One qualification, however, is that in some emerging economies they do not have the luxury of different buses for different purposes/locations so some of these design benefits may not be realised.
With regard to buses designed for inter-city type travel or touring, the design emphasis is on passenger comfort, passenger numbers and luggage capacity. We see, therefore, designs that have limited entrance/exits in ‘normal’ use and rely on emergency exits in the event of an emergency. We also see luggage stored at a low level on a bus with the passenger compartment situated above the luggage. This often means emergency exits are at window level up to 2m above ground level creating a potential hazard to escaping passengers and a daunting ‘leap of faith’.

In some cases vehicles are designed for overnight travel and known as sleeping coaches. This produces another challenge for designers as passengers are provided with reclining chairs or beds where space is at a premium. Provision should still be made for evacuation in an emergency with sufficient exits that are easily available. There is likely to be a need to factor in more time for escape if it is expected the reaction time of passengers will be delayed.
ESCAPE TIME

A simple concept exists to base the time needed for escape[6]. This is based on a relationship between Critical Time and Reaction Time. Critical Time is the time available before a compartment becomes intolerable due to the effects of fire and smoke and Reaction Time is the time taken for passengers to react to the fire and reach a place of safety. Means of Escape should be designed so that the Reaction Time is less than the Critical Time. Designers and operators can look at both elements of this ‘Time equation’ to increase the safety of passengers. For instance, whilst measures to mitigate a fire and reduce fire development can increase the Critical Time improving the size, position and accessibility of exits can reduce Reaction Time.

Fire Development

A primary means of reducing fire risk is to have quality design and manufacture to minimise the likelihood of fire. Similarly, modern engine fire suppression systems can minimise the impact of fires in these areas. In terms of means of escape, however, reducing fire development is an important consideration as it increases escape times. Images of bus fires are very revealing. There are many examples of bus fires that are attributed to such things as electrical causes yet show a bus totally consumed in fire. On examination, it can be seen that the area responsible for fire development is the passenger compartment and the item on fire is the soft furnishings such as seat upholstery. In aircraft, for instance, this would be unacceptable as seats have to be able to pass simple functional fire tests that reduce their ignitability and their ability to develop a fire.

Passenger Behaviour

It is known that there is a tendency for people escaping from a fire to instinctively head for the exit by which they entered – the familiar route. For people to consider alternative exits requires knowledge and understanding on their part and can be encouraged by the action of a ‘responsible person’.

A useful comparison is to think of the standard information given to passengers before every air flight which gives a thorough overview of evacuation procedures and identifies alternative exits. An alternative means of providing such information in other forms of transport is beginning to emerge through the use of technology on TV screens that, with the use of standard symbols, can be an effective way of giving information. Emergency evacuation information should be given a higher priority.
Passenger Mobility

Passengers come with varying degrees of mobility and ability to evacuate quickly. Anecdotally, this author expected the age profile of coach users to be older but this would be too sweeping a generalisation. For instance, a report commissioned by the EU[7] said ‘The results show a significant difference between the Member States: users in Greece and Spain tend to be young, whereas in the UK and Sweden users tend to be older. In the UK, users of occasional coach services tend to be much older than users of regular services, whereas the reverse is true in Sweden. This may indicate that school tours account for a significant proportion of occasional trips in Sweden’. This shows the challenges faced by coach operators who have to plan for passengers of all ages, sizes and mobility levels.

Bus/coach designers must plan for likely occupancy and their ability to negotiate exits. It is perhaps only on bus/coaches where it is common to see emergency exits reached via breaking/removing windows having first negotiated seating before facing a significant drop to the ground!

THE ‘RESPONSIBLE PERSON’

Mentioned above has been the role of what could be called the ‘Responsible Person’ – normally the driver. If a parallel is drawn with aircraft safety, one provider[8] says ‘The primary responsibility of the cabin crew during an evacuation is to direct passengers to evacuate the aircraft using all of the usable exits’ and recognises that ‘An assertive cabin crew that uses short, clear commands will have an immediate impact on the rapidity of the cabin evacuation’. These principles can be applied to drivers.

A driver should be trained and regularly assessed as to their competency in emergency evacuation. It should be recognised that their action in the early stages of an emergency can have a significant bearing on the outcome. Recognising early on that an evacuation should be initiated will save valuable time. Similarly, a driver can give guidance, direction and confidence to passengers enabling a swift evacuation.

CONCLUSION

The risk from fire in buses/coaches can be reduced by design and active fire suppression systems. Adequate provision needs to be made for escape that takes account of passenger characteristics and behaviour enhanced by proper driver training.

Mike Hagen CEng, BEng, CFIFireE
Reference List

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Lithium-ion (Li-ion) battery technology is rapidly becoming a preferred choice for battery power across all segments of society. This relatively new technology offers significant improvements in energy and power density over conventional battery technologies, such as lead acid, nickel cadmium (NiCd), and nickel metal hydride (NiMH). In transportation vehicle applications, Li-ion batteries deliver more energy and power with less weight and maintenance than conventional batteries, making them a desirable choice of manufacturers.

The Boeing 787 Dreamliner uses several types of Li-ion batteries to power different systems on board the aircraft. The largest type of these batteries is used in two systems on board the aircraft. One provides power to start the Dreamliner’s auxiliary power unit (APU) and another (the main battery) provides power to selected electrical/electronic equipment during ground and flight operations.

Here, we describe the NTSB’s laboratory examination procedures used to analyze the fire-damaged Li-ion battery from the 2013 Logan International Airport incident involving a Japan Airlines Boeing 787 airplane. The objectives of the examinations were to (1) document the condition of, and damage to, the battery; (2) determine the origin of the failure; and (3) determine the cause of the failure.

INCIDENT SUMMARY

On January 7, 2013, about 10:21 Eastern Standard Time, cleaning personnel discovered smoke in the aft cabin of a Japan Airlines (JAL) Boeing 787, JA829J airplane, which was parked at a gate at Logan International Airport. About the same time, a maintenance manager in the cockpit observed that the APU—the sole source of airplane power at the time—had automatically shut down. Shortly afterward, a mechanic opened the aft electronic equipment (E/E) bay and found heavy smoke and fire coming from the front of the APU battery case. No passengers or crewmembers were aboard the airplane at the time, and none of the maintenance or cleaning personnel aboard were injured. Aircraft rescue and firefighting personnel responded, and one firefighter received minor injuries. The airplane had arrived from Narita International Airport, Narita, Japan, as a regularly scheduled passenger flight operated as JAL Flight 008.

BATTERY DESIGN

Both the main and APU batteries consist of eight Li-ion cells that are connected in series and assembled in two rows of four cells (see Figure 1). Table 1 shows the specifications for the APU battery and cells. Insulation sheets provide electrical insulation and physical separation between each cell and between the cells and the aluminum battery case, which is electrically grounded. Upper and lower fixation trays secure the position and orientation of the cells in the battery case.
Figure 1. Exemplar for the 787 main and APU batteries.

Table 1. Battery and Cell Specifications

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<thead>
<tr>
<th>Specification</th>
<th>Battery</th>
<th>Cell</th>
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<tbody>
<tr>
<td>Nominal capacity (ampere-hour)</td>
<td>75</td>
<td>75</td>
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<tr>
<td>Nominal voltage (volts)</td>
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<td>3.7</td>
</tr>
<tr>
<td>Operational voltage range (volts)</td>
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<td>2.5 to 4.025</td>
</tr>
<tr>
<td>Weight (kilograms)</td>
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<td>2.7</td>
</tr>
<tr>
<td>Dimensions (centimeters)</td>
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<td></td>
</tr>
<tr>
<td>Width</td>
<td>27.7</td>
<td>13.2</td>
</tr>
<tr>
<td>Depth</td>
<td>36.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Height</td>
<td>21.6</td>
<td>19.6</td>
</tr>
</tbody>
</table>

*Battery specification information was based on information from a Thales Avionics Electrical Systems document. Cell specification information was provided by GS Yuasa.

In addition to the eight individual battery cells, the battery case contains two circuit boards that comprise the battery monitoring unit (BMU); a Hall effect current sensor for current monitoring; a contactor; bus bars for the main current pathways between the cells and to the J3 connector, which leads outside the battery case; and sense wires leading to the BMU. By and large, these components are noncombustible, with the exceptions of the polymeric insulation and spacer materials. Figure 2 shows the battery components.
Figure 2. Components of the main or APU battery.

BATTERY CELL DESIGN

Each cell has three internal electrode winding assemblies, as shown in Figure 3. Each winding assembly is about 10 meters long and is configured as a multilayer continuous sheet of an electrode, followed by a separator, followed by another electrode, and then another separator. These windings are welded to current collectors, which are affixed to the cell’s electric terminals.

The electrochemistry is similar to that of other cobalt oxide Li-ion batteries. One electrode (the anode) is a copper foil coated in carbon; the other electrode (the cathode) is an aluminum foil coated in a lithium cobalt compound. The electrolyte is composed of lithium salt in an organic solvent. This cell has primarily nonflammable components, but the electrolyte is flammable.
EXAMINATION METHODS AND PROCEDURES

The fire-damaged APU battery was removed from the aircraft by firefighters on scene. It was subsequently shipped to the NTSB materials laboratory in Washington, DC, for examination. An investigative group was formed, consisting of NTSB materials laboratory staff and supported by technical expertise from the parties to the investigation. In this instance, additional expertise was sought to augment the examination and analysis procedures. Technical consultants from other federal agencies and private laboratories with specific experience in Li-ion technology research and failure analysis were added to the investigative group.

A variety of destructive and nondestructive examination methods were employed at the NTSB’s laboratories and other laboratory and testing facilities. These examinations included optical and scanning electron microscope (SEM) analysis with energy dispersive spectroscopy (EDS), radiographic analysis (digital radiographs and computed tomography [CT] scans), and microhardness testing.

INITIAL EXAMINATION OF BATTERY ASSEMBLY

Initial visual examination indicated thermal and mechanical damage, including localized hot spots, on the external surface of the battery case. The mechanical damage was correlated to the firefighting activities and removal of the battery from the aircraft. SEM/EDS analysis was conducted on the hot spots and determined that they originated in the inside of the battery case, therefore ruling out external sources such as electrical short circuiting and mechanical damage as an initiating event. The aluminum top (lid) of the case was bulged upward, exposing the internal components. The top was removed to reveal the upper surface of the battery assembly, which exhibited severe thermal damage to the entirety of its internal components. Voltage measurements taken of each cell indicated that the battery was completely discharged, and electrical continuity measurements indicated that all cells except for cell 8 had shorted “closed.”
The thermal damage to the battery components, such as charring of materials and distortions of the cells, indicated areas of higher interest and probability of identifying an origin of the thermal event. However, the level of damage obscured clear distinction of the components and prevented immediate disassembly of the battery. A more deliberate disassembly process was necessary to avoid destroying any potential evidence that might indicate the root cause of the failure. Figure 4 shows the condition of the battery as received in the laboratory (with the top of the case removed).

Disassembly of the damaged battery was guided by the use of radiographic imaging of the intact assembly. This imaging method rendered a nondestructive view of the entire volume of the battery assembly. Once analyzed, the fire-damaged battery components could be carefully extracted from the case, with the prior knowledge of the internal structure that helped to identify and avoid destruction of any possible mechanical deformation or foreign debris that might be present.

Because of the physical size of the battery, the imaging equipment must have sufficient energy to penetrate the battery and sufficient volumetric and weight capacity to support and rotate the battery for imaging. In this instance, a Nikon Metrology 450 kV Microfocus scanner was used. The X-ray source in this equipment has an X-ray focal spot size of 80 μm.

To produce digital radiograph images, the battery was subjected to a process similar to a conventional X-ray. As such, the images contain elements throughout their volume superimposed on each other. The whole battery was imaged at least twice, and the separate images were obtained at positions rotated by up to 90 degrees.
For the CT scans, the battery was loaded into the imaging unit and placed on a turntable. The battery was then rotated in front of the X-ray source, and the X-rays were captured by a detector after they went through the battery. The X-ray source produced a cone of X-rays, and the portion of the battery imaged was adjusted slightly after each scan volume was completed until the entire assembly (or region of interest of the assembly) was scanned.

The scan volume created in the scanning process was approximately 1,600 pixels by 1,700 pixels by 2,000 pixels in volume for a whole battery scan and had resulting file sizes ranging between 5.8 gigabytes and 24 gigabytes.

Each CT volume was evaluated using the VGStudio Max software package. Post-processing using this software permits viewing individual two-dimensional planes or “slices” cut across the image in detail or can be used to create a three-dimensional reconstructed image of the component. During the CT scan evaluation, some sections of the components were digitally removed to allow closer observation of interior parts. This procedure was beneficial when searching the images for signs of foreign materials within the battery case, external to the cells.

The results of the radiographic imaging work indicated that although several of the battery cells had permanently deformed (bulged), they remained mostly intact. In the radiographic image (see Figure 5), one can clearly see the bulging of the cells and the electrode windings that remained within each cell. Also evident was both cell-to-cell and cell-to-battery-case contact. The imaging revealed an absence of foreign materials within the battery and external to the cells.

Following a complete review of the radiographic images, the battery was prepared for disassembly at the NTSB materials laboratory. The radiographic images provided critical benefits to this procedure. Investigators could view the internal volume of the battery to aid in disassembly and reduce damage during disassembly. They could also document the precise orientation of components that would be disturbed upon disassembly.

Figure 5. Radiographic image of JAL APU battery indicating cell locations.
From this image (see Figure 5), it is apparent that the cells on the right side of the figure (cells 5-8) experienced greater mechanical damage, in the form of bulging, than those on the left side. This pattern also corresponded to more severe thermal damage to the polymeric materials on the right side of the battery.

Disassembly began by removing the rivets along the seams of the aluminum battery case and folding down the sides. Figure 6 shows the side of the battery that experienced the greatest thermal and mechanical damage. When the sides of the cells were exposed, it was apparent that cells 5-8 had relieved pressure through their vent discs. Cells 1-3 also vented but with less deformation of their vent discs.

**BUS BAR EXAMINATIONS**

Next, the bus bars and wiring harness were removed, and then each of the eight cells was removed. Each bus bar was removed from each cell and examined.

For each bolted connection, the condition of the faying contact surfaces was visually evaluated using a 5X to 50X zoom stereo microscope. No dark oxides or interference colors associated with high-temperature resistive heating were observed on the surfaces of the bus bars.

Metallurgical cross-sections of some of the bus bars were prepared to facilitate microhardness testing and microstructural evaluation. Figure 7 shows the section of the bus bar connecting cells 4 and 5.
The cross-sections were mounted and polished, and their microhardness was tested in accordance with ASTM E384-11e1. The locations of the microhardness indentations are displayed in Figure 8. The mounted samples were then microetched in accordance with ASTM E407-07e1. No microstructural changes, such as grain growth or hardness changes associated with localized heating, were observed.

**WIRING HARNESS EXAMINATIONS**

When enough of the charred debris had been removed from the top portion of the battery to permit evaluation, the physical condition of the BMU’s cell voltage-sensing wiring harness was evaluated.

The overall appearance of the wiring harness was consistent with exposure to a high-temperature environment with areas of varying severity. The insulation on the wires was mostly intact, but it exhibited varying degrees of thermal discoloration and staining from the expelled battery cell contents (carbonaceous, electrolyte, and cathode material). Evaluation of the thermal damage to the wiring harness suggested an area of higher temperatures or an area of longer exposure to elevated temperatures during the event. This also corresponded to areas of higher thermal damage to items such as the upper and lower fixation trays. The concentrated thermal damage suggested an area of higher interest for establishing an origin.

**DETAILED CELL LEVEL EXAMINATIONS**

Following the disassembly of the battery, each cell was subjected to additional radiographic imaging. The resulting CT scans had a scan volume of approximately 1,300 pixels by 650 pixels by 1,850 pixels for each battery cell. As an example of the detail that can be obtained, the CT scan shown in Figure 9 clearly shows a breach in the case of cell 5 less than 2.54 millimeter long.
Prior to the extraction of the electrode windings from the cells, these scans were examined for any signs of damage, contamination, or other anomalies. Once these scans were reviewed, they were used to guide the disassembly process of the electrode windings from the cell case.

The disassembly procedure used a Dremel® abrasive disc cutoff tool to circumnavigate the top of each cell case at the location of its weld seam. Cuts were also made down the longitudinal sides of one of the cell’s faces to excise a panel of the cell case. This then allowed the header and windings to be removed from the remainder of the cell case. The current collectors attaching the windings to the cell header and terminals were then cut to liberate the individual electrode windings. Each of the three electrode windings was then carefully unwound on an examination table. Figure 10 shows one 10-meter-long length of the thermally damaged electrode from cell 6, unrolled on an examination table for visual inspection.

The entire surface of both sides of each electrode was then examined by the unaided eye and digitally photographed. Any anomalous areas of interest were carefully sectioned and examined further with digital microscope and SEM. Areas of special interest included those showing unique thermal damage, such as burn-through spots and regions of discoloration. Figure 11 shows such anomalous areas on the electrode from cell 6. They are characterized by localized hot spots identified by purple
hues in the copper foil. Additionally, these hot spots exhibit radiating patterns and repeat in the same relative position along the wraps of the winding. Small holes along the top edge of the copper foil indicate short circuiting between the electrodes of the winding.

Figure 11. Cell 6 electrode with anomalous areas of interest.

In these areas, SEM imaging was performed at magnifications of 100–1,000X, and EDS was employed on anomalous features to examine their elemental constituents. The SEM/EDS examinations were conducted to identify any evidence of dendritic growth of lithium, copper plating, or foreign materials. These features are known to cause field failures of Li-ion batteries, and are therefore of high interest to the investigation. Examples of SEM images in the areas contained in the previous photograph are shown in Figure 12. SEM/EDS proved very capable of characterizing these anomalies, but can be extremely time consuming. This is largely due to the limited field of view afforded by the SEM. This resulted in several hours of SEM analysis per anomalous region of interest.

Figure 12. Cell 6. Aluminum protrusion projecting through the bottom of a copper foil wrap, (left). Hole in the bottom of the copper foil adjacent to the aluminum protrusion (right).
LABORATORY TESTING

In addition to the examinations of the incident battery discussed above, additional testing on exemplar cells and electrodes was conducted to examine certain electrode, cell, and battery level characteristics. This information will be used to analyze potential causes of the battery failure.

SOFT SHORT TESTING

A population of 40 exemplar cells, collected from 5 exemplar batteries, was evaluated for high impedance short circuits referred to as “soft shorts.” Soft shorts have the potential, in some cases, of developing into low impedance shorts often referred to as “hard shorts,” which can then lead to a thermal runaway. Two methodologies were used, one referred to as the Darcy method [1] and the other a proprietary method patented by TIAX [2]. The general idea behind the Darcy method is to discharge the cells being examined and then monitor the cells voltage recovery over a long period of time (i.e., weeks). If a cell’s voltage recovers and then begins to drop over time, that is an indication of the existence of a soft short. The TIAX method monitors the balance of current flow among cells that are assembled in a battery pack and looks for a cell that becomes a current sink, indicating the existence of a soft short.

DESTRUCTIVE PHYSICAL ANALYSIS (DPA)

Two of the exemplar cells were selected for destructive physical analysis (DPA) with the goal of disassembling a cell and unwrapping the electrodes at a full state of charge (100% SOC). At a full state of charge, the cathode material will have a gold color appearance, which can help highlight anomalies such as foreign object debris, lithium plate out, and differences in electrode lithiation. Full state of charge destructive physical analysis of large lithium-ion cells is not commonly practiced in the industry and can be dangerous. One cell was used as a test case to experiment with the disassembly process. The other cell, which was taken from the exemplar main battery of the accident aircraft, was disassembled at a full state of charge. The DPAs of the cells allowed for careful examination of the electrodes for uniformity of construction, artifacts of construction, or other features not available for examination by other means or from the incident cells themselves.

COIN CELL TESTING

The first exemplar cell to undergo DPA was also used to collect intact electrode material for the creation of coin cells. Coin cells are an industry standard method for evaluating the chemical stability and performance of electrode material and electrolyte combinations. Coin cell tests do not simulate or replicate all the characteristics of a full cell assembly. The coin cells were used to evaluate the chemistry of the cells and, in particular, their propensity for lithium plating when charged at the extremes of the operating envelope of the battery.

SUMMARY

The in-service failure of the Li-ion APU battery on board the Boeing 787 Dreamliner required a unique mix of technical expertise and analytic techniques to document the damage and condition of the battery, and determine the cause and origin of the failure. Investigators from the NTSB materials laboratory were supported by experts from the parties to the investigation, and by additional expertise from other federal agencies and private consultants.

A combination of destructive and nondestructive analytic techniques was used to disassemble the battery into its components and examine each individually. Radiographic imaging successfully guided the disassembly and eliminated unnecessary destruction of evidence. Visual and microscopic examinations aided the radiographic imaging by identifying overall damage patterns and localized damage. Other methods (including microhardness testing and EDS) helped to rule out external short circuits and mechanical damage as factors in cause of the battery failure. Further laboratory testing,
such as soft short testing, destructive physical analysis at 100% state of charge, and coin cell testing, were employed, but did not result in any significant findings that could be attributed to the cause of the battery failure.

At the time of this writing, the NTSB’s investigation is still ongoing, and its results have not been made public. Therefore, we refer the reader to the NTSB’s website, http://www.ntsb.gov, for conclusions regarding the origins and causes of the battery failure once they become available.

REFERENCE LIST


2. The basis for the TIAX soft short test method is contained in US patents 7245108 and 7193392.
Evaluation of the thermal decomposition of solid materials in tunnel related conditions with a Controlled Atmosphere Cone Calorimeter

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ABSTRACT

Tunnels fires may lead in most of the cases to dramatically consequences, both human and infrastructural. In order to manage the fire safety design in these particular infrastructures, design fires curves are usually used. However, their construction is based on empirical observations and many assumptions are done. Increasing the knowledge on the fire phenomenon, especially in the early stage of the fire scenario appears then very important, but asks for a precise evaluation of the thermal decomposition process of solids materials. The main objective of the present work is thus to describe the conditions in which several road transport external materials can be involved in a tunnel fire and the way they could contribute to its growth. An experimental campaign at material scale using the controlled atmosphere cone calorimeter on different materials (Polyisocyanurate foam, Acrylonitrile Butadiene Styrene and Ethylene Propylene Diene Monomer) is currently leaded to evaluate their contribution to fire. The experiments are conducted at different irradiance levels and local oxygen concentrations in order to be representative of real fire conditions in tunnels. Besides, the construction of a predictive numerical model is performed in order to evaluate, from the experimental data obtained, the response of different parameters that are responsible in the development and growth of a tunnel fire (as the time to ignition, the mass loss rate, the gaseous emissions, etc.). The methodology used to perform the experiments, the first results obtained and the numerical approach, are presented in this paper.

KEYWORDS: Thermal degradation, tunnel fire, controlled atmosphere cone calorimeter, pyrolysis, mass loss rate.

INTRODUCTION AND CONTEXT

Fire can probably be considered as one of the worst phenomenon that can occur in a tunnel. Indeed, the specific enclosure of these infrastructures potentiates the fire growth. Moreover, tenability conditions for users are worsened, due to the confined conditions in which a fire can occur: high temperature, important smoke production, high toxic gases concentrations, limited escape ways, etc. In order to prevent disasters that tunnel fires can generate, it is necessary to increase knowledge on fire dynamics in these particular infrastructures. Nowadays, the main issue is the fire growth prediction which is quite complex to evaluate. It is strongly related with (1) the tunnel ventilation conditions and their evolution, (2) the involved materials in fire, (3) the infrastructure geometry. Because of the cost and technical limitations, it is rarely possible to perform some full-scale experimental tests in order to design the fire safety in a tunnel (ventilation devices, emergency egress routes, mark-up, etc.). In order to respond this problematic, fire safety engineering using Computational Fluid Dynamics (CFD) have brought some responses even if the models must be used with caution and exclusively by experts. Moreover, in order to model some fire scenarios that have also to be chosen with caution, there is an important need in empirical input data. Nowadays, input data used to model tunnel fires are Heat Release Rate (HRR) curves, which describe three steps as
illustrated in Figure 1: a growth period (1), a fully developed state (2) and a decay period (3). These curves are prescribed by regulatory instances as a basis to design the fire safety devices such as ventilation in a tunnel. They are based on different laws and equations [1]-[4], which have been constructed from full scale tests results observations with different fire scenarios and combustible involved [5], [6], [7]. Since several years, numerous research projects including full scale tests have been leaded all around the world. Only a few are referenced in this paper, but the reader can find complementary information in searching for the following projects: UPTUN, FIT, DARTS, SafeT, SIRTAKI, Virtual Fires, Safe Tunnel, EuroTAP, SOLIT, L-surF, EGSISTES. However, the fire conditions reached in a tunnel, in terms of smoke temperature, radiative, convective effect energy amount implies complexities in measuring the different parameters which are needed to determine the evolution of a fire and especially the HRR [8]. These curves are used as a basis for regulation and guidance for tunnel safety design conception [9]. There are numerous regulation and guidance documents on design tunnels fires. The cited document summarizes quite well the different sources where these documents can be found.

Even if these simplified models exist and are widely used, they can be really inaccurate to represent the real fire phenomenon evolution. Indeed, most of the parameters used to their construction are approximated due to a lack of knowledge. These curves are, for example, really limited when dealing with multiple vehicles involved fires (see [10]). Even if there are widely used, they do not yet consider the exact mechanisms of propagation, growth and the parameters which can severely affect the fire development.

The evolution of the first stage (i.e. the growing phase) during a tunnel fire, depends on many factors, but especially of the reaction to fire of materials involved in the phenomenon. Nevertheless, as a global HRR is considered to model the fire growth, there is no consideration of the involved combustibles in the fire phenomenon, even if a specific scenario is considered. Regardless the fire scenarios, which can be very numerous (collisions between vehicles, collision of a vehicle with a sidewalk, overheating of a mechanical part of car or truck, short-circuit or overcurrent of a vehicle electrical or electronical device, etc.), and the propagation modes of the fire source (convection, radiation, direct attack from the flame, etc.), the transmitted energy will always have a significant impact on the external parts of involved or proximity located vehicles. Thus, it is particularly important to focus on the thermal behaviour of the specific materials, which constitutes the outer shell of light or heavy vehicles to determine the way they could contribute to the fire growth and to its propagation.

In order to determine both the contribution and the capacity to propagate fire of a specific material, it is important to focus on describing its thermal decomposition and the parameters that are associated with: the Mass Loss Rate (MLR), the ignition time, the gaseous emissions and the HRR. Moreover, the determination of the aforesaid parameter has to be done considering realistic conditions of an early stage fire in a tunnel. In this early stage, the irradiance level reached at the material surface is limited [11]. Besides, the local oxygen availability can be lowered comparing to ambient conditions due to the combustion phenomenon which locally consumes much of it. Even if there are other parameters to consider, in order to describe accurately the thermal degradation of polymeric materials used as outer shell of vehicles, these two factors effects are preponderant considering the thermal degradation.
To determine precisely the effect of these parameters, it is necessary to perform some experiments varying both the irradiance level received at the surface material and the degradation environment local oxygen concentration. Tunnel full scale tests are really onerous and are besides both difficult to perform and associated with important errors on the results. Considering all those points, it is obvious that such parameters determination have to be realised at small scale and on non-complex materials in order to obtain some reliable and accurate results.

Thus, the work presented in this paper focuses on the determination of the usual studied thermal degradation parameters at material scale using a Controlled Atmosphere Cone Calorimeter (CACC) apparatus, to describe the reaction to fire of three polymeric materials in tunnel fire related conditions, classically involved in early phase of a tunnel fire. The present study thus focuses on the thermal decomposition of a Polyisocyanurate (PIR) foam, used as a thermal insulation material for many trucks, an Acrylonitrile Butadiene Styrene (ABS) similar to those used for mudguard and certain bumpers, and of an Ethylene Propylene Diene Monomer (EPDM) as those included in vehicle door seals. These materials have been chosen because they are the ones that can be involved very early in the fire phenomenon, as they are all external materials for lights or heavy vehicles.

The following sections provide information firstly on (1) the testing protocol that has been used to assess the burning behaviour of different materials (2) the results obtained on the measured parameters depending on the tests conditions. In a second part, a predictive methodology to determine on a large domain the burning behaviour of polymeric materials will be presented as well as the first results obtained using this methodology.

**EXPERIMENTAL METHODOLOGY**

**Controlled Atmosphere Cone Calorimeter**

As explained before, in order to describe the thermal decomposition of road transport polymers components, it is important to focus on their reaction to fire at small scale. Tests have been performed using the specific apparatus of the CACC [12]-[13], presented in Figure 2. It has been developed to determine the thermal decomposition and the burning behaviour of materials at small scale, in an oxygen controlled enclosure which design has been defined in [14]. These enclosure conditions are the main improvement comparing to the classical cone calorimeter described in ISO 5660-1 standard [15].

![Figure 2 Schematic representation of the Controlled Atmosphere Cone Calorimeter](image)

It consists in a box placed beneath the cone heater which can be closed by a door, equipped itself with a window, allowing to visually check the reaction to fire of a sample during the test. The CACC is equipped with two inlet ports at the bottom, from which emerges the oxygen-nitrogen gaseous mixture. The flow rates of the two gases are respectively controlled thanks to two rotameters to
achieve the required oxygen concentration inside the box, which accuracy is checked permanently with an oxygen analyser. Global flow rate within the enclosure is one of the most important parameters to control during this kind of tests. Indeed, Marquis et al. have proven that it must be chosen high enough to prevent the vitiation of the atmosphere, but low enough not to disturb the degradation phenomenon \( \text{(i.e. flame blow)} \) [13]. For the present experimental campaign, the global flow rate inside the enclosure has been fixed to \( 160 \pm 5 \text{ L.min}^{-1} \), according with [13].

Above the cone heater, a 60 cm stainless steel chimney has been fixed to the cone as described by Marquis et al. [13]. Among others advantages, it prevents the diffusion of the ambient air in the enclosure, which can severely affect the oxygen concentration at the surface of the sample. Thanks to the adaptation of the ISO standard cone calorimeter, the controlled atmosphere one allows to control the oxygen concentration in the enclosure in a range from 0 \%vol to ambient conditions (21 \%vol). This apparatus is thus perfectly adapted to simulate the vitiation of the atmosphere and to approach experimentally the burning conditions that can be found locally in an early stage of a tunnel fire at the surface of solid materials.

It is also possible varying the irradiance levels imposed to the material, as using the classical cone calorimeter. The studied domain during the experimental campaign, illustrated in Figure 3, extends for the irradiance level from 20 to 50 kW.m\(^{-2}\) and for oxygen concentrations from 0 to 21 \%vol. The ranges of the two parameters have been chosen to be representative of an early stage during a tunnel fire (see [11] for irradiance level reached in the early stage).

![Figure 3](image)

**Figure 3** Limit of the studied domain in Controlled Atmosphere Cone Calorimeter for the PIR foam

**Gas analysis**

In order to quantify and to qualify the gaseous emissions associated with the thermal decomposition of the different tested materials, a Fourier Transform Infrared (FTIR) has been coupled with the CACC. The FTIR is one of the methodologies available for a continuous analysis of the fire effluents, as presented in the following [16]-[17]-[18]-[19]. This apparatus is calibrated for fifteen gaseous compounds in different concentrations ranges.

Table 1 presents the quantification limits for three of those gaseous species, CO and CO\(_2\) which are the privileged ones to assess the ventilation regime of the fire (i.e. well ventilated, under ventilated) and the CH\(_4\) which is useful to determine the conditions in which the material decomposition is associated with a combustion phenomenon. Gaseous concentrations of other quantified gases are also interesting to study but they won’t be presented here because of the paper size restriction.

<table>
<thead>
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<th>Component</th>
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<td></td>
<td>High: 8802</td>
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<tr>
<td>Carbon dioxide</td>
<td>CO(_2)</td>
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<tr>
<td></td>
<td></td>
<td>High: 50140</td>
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<tr>
<td>Methane</td>
<td>CH(_4)</td>
<td>Low: 0,3</td>
</tr>
<tr>
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</table>

During the experiments, the sample lines (from the ring probe to the gas cell of FTIR) were heated up to 180\(^\circ\)C to avoid gaseous compounds condensation. The sampling line was connected to a filtration box composed of two stainless steel heated filters of different dimensions (2\(\mu\)m and 10\(\mu\)m). After having been filtered, gases were transported to a 2 L gas measurement cell with a 10 m optical path.
length. The spectrometer used for the analysis was a FTIR Thermo-Nicolet Magna IR 550 Series II equipped with MCT-A detector. During the experiments, the data acquisition resolution was set to 0.5 cm⁻¹. The pressure inside the gas cell was regulated all along the test to be constant at 650 ± 10 torr as prescribed in [20].

**Materials**

The experiments in CACC have been conducted on three different materials but, due to the important amount of results, the ones that are presented in the following sections focuses on a free rigid polyurethane-isocyanurate) foam (PIR). This material is a commercial foam including flame retardant with a density of 80 kg.m⁻³. Tested samples were conditioned at (23 ± 2) °C and at a relative humidity of (50 ± 5) % for more than 88 hours in accordance with the specifications of the ISO 291 standard [21]. The tested samples were (100 ± 2) mm long, (100 ± 2) mm wide and (30 ± 1) mm thick, with a mass of (23.3 ± 1.1) g. This type of foam has a high mechanical strength, a low weight and is usually used as an insulation material. It is notably used as a road transport material to ensure the insulation of frigorific trucks and isothermic vehicles.

Although the experimental campaign is currently in progress and concerns also two other materials: an EPDM and an ABS. Both are used as external materials of vehicles respectively for the vehicle door seals and mudguard / bumpers. These materials have been chosen because they are the one that are directly exposed to a fire which develops inside a tunnel from the outside of a vehicle. Previous research leaded by CETU (French organism for tunnel regulation and guidance) demonstrated the importance of these materials in fire propagation on vehicles. Results for at least one of these particular materials will be presented, during the Fire in VEhicles (FIVE) conference.

**EXPERIMENTAL RESULTS**

Different parameters have been focused on to determine the reaction to fire of different road transport polymeric materials. The results presented here will only concerns the MLR and three gaseous compounds: carbon dioxide, carbon monoxide and methane.

Regarding the MLR, it is interesting to focus on the trends that can be identified thanks to the tests results. Figure 4 presents the results obtained for this parameter under the degradation conditions.

![Figure 4](image)

It is obvious that both the irradiance level and the oxygen concentration affect the MLR of the PIR foam. It can be seen on Figure 4 that the effect of the irradiance level is preponderant. Although, the oxygen concentration is also important because it determines the possibility for the gaseous
combustibles emitted during the decomposition to ignite and to lead to a combustion phenomenon. As the combustion is possible, it affects considerably the MLR of the material because of the thermal feedback that the flame imposes at the surface of the material. It is otherwise important to note that the tested PIR foam is an excellent material in terms of reaction to fire. Indeed, its Critical Heat Flux (CHF), which was determined to be 47 kW.m\(^{-2}\), is very high and thus, on the different tested conditions, there is only one case where a combustion phenomenon over the surface of the material can be observed (21 %vol O\(_2\) / 50 kW.m\(^{-2}\)). There are two other conditions where combustion can be observed, but the flame is not directly at the surface material because the stoichiometric conditions for combustion are achieved at the outlet of the chimney (15 %vol O\(_2\) / 50 kW.m\(^{-2}\) and 21 %vol O\(_2\) / 35 kW.m\(^{-2}\)).

Regarding the emissions of gaseous compounds, it can be seen on Figure 5 that the emissions of CO and CO\(_2\) are strongly affected by the local oxygen concentration.

The lack of oxygen available in conditions where its concentration is decreased, does not allow the oxidation of the char formed at the surface material and thus the measured concentrations of CO and CO\(_2\) are very low comparing to the ones quantified in ambient conditions (see Figure 5 a). One of the most important things to note is that regardless the tests conditions, an important quantity of char is formed at the surface of the material. As the oxygen concentration in the enclosure is not always high enough to allow the degradation of the formed char, the carbon residue formed at the surface material cannot be oxidized in numerous conditions. Thus, important variations can be observed in the measurement of CO and CO\(_2\) between well and under oxygenated conditions.

**Surface representation**

Considering the number of parameters that can be taken into account in studying the thermal degradation of a polymeric material on a large domain as it is done in this study, it is quite difficult to determine some precise trends due to the quantity of results to focus on. In order to have a global overview of the response of a specific parameter depending on the oxygen concentration and the irradiance level, it is possible to use a surface representation of the averaged considered parameter on the whole studied domain. Thus, each parameter can be represented on a tridimensional domain where x and y axes are respectively the irradiance level and the oxygen concentration and z axis represents the response of the parameter studied as shown in Figure 6. This figure presents respectively the Specific MLR (MLR integrated on the exposed surface of the sample in CACC) and the CO and CO\(_2\) concentrations averaged on the whole duration of the tests (1800s).
Figure 6  Surface representation for the PIR foam of the Specific Mass Loss Rate (a) and of the concentration of CO (b) and CO$_2$ (c) averaged on tests duration under different conditions. Each point plotted represents an averaged value for specific condition of oxygen concentration and irradiance level.

Figure 6 shows that the emission of the two considered gases is strongly related with the degradation kinetic of the foam, itself strongly dependant of both the amount of energy received and the oxygen concentration in the degradation environment. This kind of representation allows having a better understanding of the degradation phenomenon and especially the conditions that can lead to the emission of specific gases. The results are presented here considering the mean values for SMLR or emitted gases. It allows comparing the different conditions on the same time basis. Although, results could also be presented as maximum instantaneous emitted values, global sum of values on a period duration, etc. On Figure 6, there are fifteen points plotted, representing a surface, where each point corresponds to one test performed experimentally. These points are all associated to an irradiance level and an oxygen concentration couple. The surface representation illustrates the importance of the two considered parameters on the burning behaviour of the material. Thus, it can be observed that decreasing the oxygen concentration or the irradiance level imposed to the sample leads to a global decrease of the degradation kinetics. Moreover, plotting all the parameter as surfaces (especially combustibles gases) allows to predict the areas of the domain where the degradation of the material is combined to a combustion process. As an example, the surface representation for methane (CH$_4$) as shown in Figure 7 allows to better understand the combustion limits. When this specific gas is quantified with the FTIR apparatus in high concentrations, it shows that a combustion process does not occur. Indeed, in the case of a combustion process the methane is oxidized into the flame and its concentration is then lowered.

Figure 7  Surface representation for the PIR foam of the total CH$_4$ concentration under different conditions. Each point plotted represents a total emitted value for each condition.

As it can be seen on Figure 7, there is an increase in the quantity of quantified CH$_4$ when increasing both the oxygen concentration and the irradiance level. Although, the measured concentrations for the following conditions (21 %vol O$_2$ / 50 kW.m$^{-2}$, 15 %vol O$_2$ / 50 kW.m$^{-2}$ and 21 %vol O$_2$ / 35 kW.m$^{-2}$) are lowered comparing to what should be obtain if we consider the methane concentration increasing
trend. This indicates that the methane, for these three conditions, is consumed by the chemicals reactions that occurs in gaseous phase, in other words by the combustion process.

It is important to note that the study of the gaseous emissions allows determining some useful information about the burning behaviour of materials, although these results have to be considered with caution. Indeed, the CACC design as it was used in this study and because of the position of the FTIR sample line does not allow to have an accurate value of the emitted gases. Once the gases are emitted, they transit by the chimney and are then mixed with ambient air in the exhaust duct. Some post oxidation phenomenon can occur and it’s nearly impossible to determine how accurate the gaseous quantification is. As an example, from the total quantity of measured CO$_2$, one part is associated with the degradation process one other part is due to post oxidation process.

**NUMERICAL MODEL**

The surface representation allows defining some trends on the thermal behaviour of a specific material and on the gaseous emissions associated. From this surface representation, a numerical model has been elaborated in order to predict the response of selected parameters in conditions that haven’t been tested experimentally. This numerical approach is based on the use of polynomial models of multiple linear regressions and can be expressed by Eq. (1).

\[
    y = a_0 + \sum_{i=1}^{N} a_i x_i + \sum_{i=1}^{N} a_{ij} x_i^2 + \sum_{i=1}^{N} a_{ij} x_i x_j + \cdots + \sum_{i=1}^{N} a_{ijk} x_i x_j x_k + a_{i..N} x_i \cdots x_N
\]  

Where:

- \( y \): Response of the selected parameter
- \( a_i \): Polynomial coefficients
- \( x_i \): Polynomial factors

The polynomial model used in the study uses two variables \( x_1 \) and \( x_2 \) which represents respectively the irradiance level and the oxygen concentration. Other variables can be introduced in the model, but they have to be quantified and taken into account previously as input data of the experimental conditions. Besides, different polynomial orders can be considered for the model, but it is important to choose the order considering the number of reference points available to avoid numerical errors [22].

**NUMERICAL RESULTS**

The objective in using the model is to determine the coefficients of the polynomial from the experimental data collected, thanks to the CACC, for the different tested conditions. Thus, using the coefficients, it is possible to calculate numerically the response of a chosen parameter for selected conditions of irradiance level and oxygen concentration on the whole domain. A complete numerical surface (black grid) can thus be plotted as shown in Figure 8 for the whole domain.

![Figure 8](image_url)

*Figure 8  Numerical surface calculated using polynomial models for different parameters for the PIR foam a) SMLR; b) CO yield; c) CO$_2$ yield*
This figure illustrates that the model is pretty accurate to represent numerically the response of the parameters experimentally determined. Indeed, the black grid on this figure is in perfect accordance with the plotted points which illustrates the experimental responses.

As the model created represents a whole surface, it also allows predicting the response when it is unknown (i.e. where no experimental data are available). When the polynomial model has been calculated and the polynomial coefficients determined, it is possible to predict the response of a parameter for each couple of irradiance level and oxygen concentration for any point of the domain.

Figure 8 represents the response for different parameters averaged on the whole duration of the tests, but it is also possible to create a surface at a chosen time during the test. In this case, each surface is constructed using the same model but the coefficients of the polynomial needs to be calculated for each one. Calculation for all time steps of the tests of the different surfaces creates thus a metamodel where one model is available for each time step with its proper coefficients. Taking as an example the SMLR, the tests durations were 1800s with a 5 s step to collect data. Thus a total of 360 surfaces can be plotted which altogether form the metamodel which describes the degradation kinetic of the PIR foam on a domain from 20 to 50 kW.m\(^{-2}\) and from 0 to 21 %vol O\(_2\). An example of this extension of the methodology is presented in Figure 9.

![Figure 9 Example for PIR foam of a metamodel describing the SMLR over different conditions of irradiance level and oxygen concentration. Surfaces for a) 0s, b) 300s, c) 600s, d) 900s, e) 1200 and f) 1800s have been extracted from the metamodel.](image)

As it is possible using the created model to determine the response of a parameter numerically where no experimental data are available for an averaged parameter response, it is possible using the metamodel to do it the same way, but in integrating the evolution of the response over time. This metamodel allows then to plot the parameter curves over time, for a considered irradiance level – oxygen concentration couple, whether or not experimental data are available. Figure 10 presents the results for this particular point for the SMLR of the PIR foam using a 2\(^{nd}\) and 3\(^{rd}\) order model.
As it can be seen on Figure 10, interpolation of data using the metamodel allows describing numerically the evolution of a parameter for a specific condition. Moreover, regardless the condition considered, the modelled curves are in perfect accordance with the experimental curves (see Figure 10 a, b and c). It illustrates that the model, which is constructed from the experimental data is firstly perfectly able to reproduce these experimental data. Secondly, regarding the predictive curve on Figure 10 d), it can be seen that the shape and form of this curve, as well as the SMLR reached values are in accordance with the other curves. It means that the model seems to also be able to determine the response value for unknown conditions. The best way to ensure that the predictive curve is in accordance with the real physical values, should be to perform the test. However as the objective using this methodology is to predict responses of parameters for untested conditions, it is important to find a way to demonstrate that the results obtained with the metamodel are accurate without leading tests. There is still a lack of mathematical and statistical validation for this metamodel and further work is needed in order to check the accuracy of the obtained results and the robustness of the method. Notwithstanding, it is possible to prove that the values calculated for the Figure 10 d) curve is in accordance with the experimental values obtained for the nearest tested conditions. Such an analysis is shown in Table 2.

Table 2: MLR mean and max values obtained experimentally for different experimental conditions that surrounds the condition where the values where calculated thanks to the metamodel

<table>
<thead>
<tr>
<th>Oxygen concentration</th>
<th>15 %volO2</th>
<th>21 %volO2</th>
<th>18 %volO2</th>
<th>15 %volO2</th>
<th>21 %volO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance level</td>
<td>35 kW.m⁻²</td>
<td>35 kW.m⁻²</td>
<td>40 kW.m⁻²</td>
<td>50 kW.m⁻²</td>
<td>50 kW.m⁻²</td>
</tr>
<tr>
<td>Mean MLR value</td>
<td>0.019</td>
<td>0.022</td>
<td>0.023</td>
<td>0.024</td>
<td>0.027</td>
</tr>
<tr>
<td>Total MLR value</td>
<td>6,715</td>
<td>8,088</td>
<td>8,183</td>
<td>8,751</td>
<td>9,714</td>
</tr>
</tbody>
</table>
CONCLUSIONS AND PERSPECTIVES

The results presented in this paper show that it is possible to describe with a great accuracy the thermal behaviour of a material considering both the solid and the gaseous phases. It has been shown that the cross-linked exploitation of different parameters such as MLR and gaseous emissions can bring important information on the reaction to fire of a polymeric material. The tests performed have allowed to describe the thermal degradation of road transport materials considering different degradation conditions, varying oxygen concentration and irradiance level received at the material surface in ranges that can be the ones representatives of the early stage of a tunnel fire. Moreover, the surface representation is perfectly adapted to present the results of this type of study, which analyses concerns many parameters in many different conditions. It offers the possibility to cross the different results on chosen parameters in order to determine with a great accuracy the thermal behaviour of a polymeric material (i.e. parameters that affects the combustion regime, the thermal degradation, etc.)

Besides, the presented predictive methodology allows determining with a few experiments, the response of a chosen parameter on a large domain, regardless the selected conditions. It is an interesting mathematical tool which offers a good alternative to the development of pyrolysis model to determine the thermal behaviour of a material. The results presented in this paper focuses on the material scale and further work would have to bring the proof that the results obtained could be up-scaled to approach the reaction to fire of complex fire scenarios at full scale.

Otherwise, it is now necessary to lead a complete analysis to prove the accuracy of the methodology and its capacity to predict the burning behaviour of solid materials varying the degradation conditions (irradiance level and the local oxygen concentration). Application of the methodology to the results obtained for the other materials during the experimental campaign will allow validating its robustness. Finally, if the method proves its capacity to predict the thermal behaviour of solid material in varying ventilated environment such as tunnel fires, it could be used in the field of fire safety engineering to better describe the models used to design the safety equipment and devices that can be found in a tunnel.

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Fire Safety of Rail Vehicles – The Significance of Luggage

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ABSTRACT

This study deals with the fire behaviour of luggage focusing on heat and smoke release characteristics. The impact of a representative burning piece of luggage as ignition source inside a railway vehicle is analysed by means of numerical fire simulations and assessed with respect to fire spread as well as toxic and visibility impairing effects on passengers.

KEYWORDS: rail vehicles, luggage, experimental investigation, CFD fire simulation, design fire

INTRODUCTION

In Europe, rail vehicles feature a high standard of safety and, therefore, rank among the safest means of conveyance. However, if it comes to a rail accident, the probability for this to be a fire incident ranges (only) in a single-digit percentage [1]. Nevertheless, concentrating on fires occurring in passenger trains, there are casualties with a large number of victims to be faced [2]. One explanation is that railway vehicles form a closed system [3] where simultaneously several 100 passengers are potentially present. Thus, depending on the rail infrastructure, passengers may be forced to stay on board in case of fire up to 15 minutes until a safe place is reached and an evacuation becomes feasible [4]. Regarding fire safety in rail transportation, normative requirements as well as the options for performance-based analyses with numerical methods are currently changing [5]. Whereas the fire behaviour of the constructional materials and products (linings, seats, electrotechnical equipment) can be reliably appraised, the luggage brought onto a train by passengers is quantitatively unknown, in particular when focusing on the fire characteristics [6]. Current research results show that luggage represents up to 50% of the total fire load inside a train vehicle and therefore, can be the crucial factor for a fire spread which may result in a flashover [2][6]. Investigations in the rail fire incidents in Baku in 1995 with more than 500 persons killed or injured as well as in Kaprun in 2000 with 155 casualties show the significant influence of fire load carried by passengers [2][6][7]. Nevertheless, in the majority of the research projects conducted in the past, the influence of luggage to the fire safety of rail vehicles was either not taken into account or only in a generic way. An essential cause for this is that specific research results regarding the fire behaviour of luggage are rarely available [6][8].

The European harmonised standard EN 45545 defines fire safety requirements for rail vehicles. It considers larger (secondary) ignition sources, for example luggage fires, via an ignition model that is characterised by a heat release rate of 75 kW for two minutes followed by 150 kW for a period of eight minutes [4][9]. This linearized heat release rate vs. time relationship was derived from fire tests on single upholstered seats used in train vehicles within the FIRESTARR research project [10]. Further heat release rate curves that should represent a burning piece of luggage as ignition source for a vehicle design fire can be found in several regulations on national level in Germany as well [11][12][13]. However, the fire effluents from a burning piece of luggage that may cause toxic effects and impairment of visibility are neither taken into account in the EN 45545 ignition model nor in any regulations.

Thus, the core issues necessary to investigate in this study are to:

- characterise the burning behaviour of representative pieces of luggage with respect to heat release rate and the emission of toxic and visibility impairing substances,
- evaluate the impact of such an ignition model on fire spread and safety of occupants inside a railway vehicle.
FIRE BEHAVIOUR OF LUGGAGE

Ignition Sources
To investigate the fire behaviour of baggage with its energetic and especially effluent emissions, an analysis of ignition sources that may be present in rail vehicles is conducted. To protect passengers and staff locations containing combustion engines, fuel tanks and pipes or high power electrical equipment have to be separated via fire barriers for at least 15 min according to EN 45545 [4]. Hence, with respect to this study, only ignition sources being possibly present in the passenger and staff area have to be considered. These can be subdivided into ignition sources originating from the vehicle system itself (e.g. electrical faults, hot surfaces) and ignition sources externally brought in (matches, lighters, etc.). The majority of ignition sources being typically present in rail vehicles can be found in standardised test methods. Here, the assortment ranges from a smouldering cigarette (< 1 W) to a square burner (7 kW), assumed realistic for a piece of baggage to be exposed to.

Preliminary Tests
Thereupon, the effect of selected ignition sources is assessed based on a test series with identical pieces of baggage (preliminary tests) to determine an adequate ignition source for the subsequent experimental investigations (main tests). The following normative ignition sources are applied:

- »Match-flame equivalent« as required in EN 45545 part 2, specified in EN ISO 12952 part 2,
- »T-burner« representing a burning crumpled newspaper, specified in ISO 11925 part 3,
- »Square burner« as required and specified in EN 45545 part 2,
- »Paper cushion« as required in DIN 5510 part 2, specified in DIN 54341 and UIC 564 part 2.

Figure 1 shows the measured heat release rates (HRR) for the preliminary tests. The HRR curves of the baggage pieces ignited by the T-burner, the square burner and the paper cushion increase similarly within the first minutes. Solely the curve with the match-flame equivalent ignition source behaves significantly decelerated. Since the T-burner features a number of advantages relative to the square burner and the paper cushion it is selected to be an appropriate ignition source for the subsequent main tests. In addition, the T-burner fire test is repeated on a further identical piece of baggage in order to assess the reproducibility.

Figure 1: Heat release rates measured in the preliminary tests with identical pieces of baggage
Luggage Pieces for the Main Tests
Pieces of luggage typically existent in rail vehicles are identified and typified with respect to their nature and composition in order to analyse their fire performance. In sum, eight pieces of luggage containing usual travel articles are prepared for experimental analysis. The following two figures illustrate an exemplary visualisation of the assemblies for the main tests: number 1 “beach holiday” and 3 “business trip”.

Test Configuration
Since an appropriate test configuration to characterise experimentally the fire behaviour of luggage does not exist so far, it has to be developed within this research. To provide as realistic conditions as possible and a practicable acquisition of the required fire parameters is a focus of the approach. The experimental investigations are carried out under an ISO 9705 hood utilising the sensor instrumentation existent inside the exhaust duct. The heat release rate is calculated based on oxygen consumption, where the fraction of oxygen is quantified via a paramagnetic analyser and carbon monoxide (CO) and carbon dioxide (CO₂) via a non-dispersive infrared spectrometer. Light obscuration is recorded inside the exhaust duct to determine the optical smoke density. Additionally, Fourier transform infrared (FTIR) spectroscopy is used to detect and quantify other fire gases such as hydrogen halides (HF, HCl, HBr), nitrogen oxides (NO, NO₂), sulphur dioxide (SO₂) and hydrogen cyanide (HCN). Furthermore, four water cooled Schmidt-Boelter sensors arranged on each side of the test sample capture the radiant heat fluxes. The tests are documented on video and photo.
Results of the Main Tests and Derived Design Fire

In general, it can be observed that the fire behaviour of the individual luggage items appear very similar: After being exposed to the ignition source for 60 sec the fire spreads over the entire piece of luggage within a few minutes. This growth stage is followed by the fully developed fire which is characterised by a certain period of a comparatively constant and maximum heat release rate. Subsequently, the fire decays and the heat release rate decreases. Though, one exception occurs in substantially deviating from the typical burning behaviour as stated above: During main test number 3 “business trip” whose charge contains a laptop as well as multiple pressured cans, such as hair spray and deodorant (cf. Figure 3), there is no notable external fire spread and no measurable heat release rate within the first 15 minutes of the test. Nevertheless, the fire smoulders inside the trolley travel bag until a pressurized can bursts and discharges its flammable gas which results in an explosive flame and an escalating heat release rate (cf. Figure 6).

The new design fire for a burning piece of luggage is intended both to representatively cover the generated test data and being expressed mathematically as simple as possible. The three characteristic stages of the new design fire in terms of the heat release rate are specified as follows:

- **Growth stage:** $t^2$-squared increase of HRR, growth factor »slow« [14],
- **Steady stage:** constant HRR of 120 kW ($t = 200$ sec to $t = 1,200$ sec),
- **Decay stage:** linear decrease of HRR to 0 kW at $t = 3,600$ sec.

In this context, the »ignition model no. 5« described in EN 45545 can be taken into account which is intended to represent larger ignition sources as, for example, a burning piece of luggage. The heat release profile of 75 kW for two minutes followed by 150 kW for 8 minutes was derived from a burning railway seat in the context of the FIRESTARR project. Compared to the test results obtained in the present study it can be stated that this ignition model conservatively covers the heat release of real luggage within the first ten minutes which is deemed to be the decisive period in terms of fire development.

![Figure 6: Heat release rates of different pieces of luggage and the derived design fire curve](image-url)
To generate suitable input data for the design fire the measured volume fractions of the emitted gases are translated into mass flows for each component. Beside carbon dioxide and carbon monoxide a significant amount of hydrogen chloride is detected in several tests.

The shapes of the CO$_2$ release curves are similar to the HRR curves. Therefore, the same equations are used but with an adjustment of the numerical values corresponding to the CO$_2$ emissions (Figure 7).

For the fire growth and the fully developed stage of the CO release the existing mathematical expressions with respect to the numerical values are adapted as previously. However, there is no decay stage to be observed but the phase of maximum release continues and finally exceeds the considered period of 60 minutes (Figure 8).
For hydrogen chloride the emission curves are less specific than those obtained for the previous fire gases. As for the HRR and the CO₂ release rate the HCl design curve consists of a t-squared growth stage, a constant fully developed stage and a decay stage (Figure 9).

Figure 9: HCl release rates of different pieces of luggage and the derived design fire curve

To complete the required parameters for the new luggage design fire a soot yield of 0.03 gram soot per gram fuel is specified as an average from the experimental results.

The obtained results now enable to entirely describe the fire behaviour of luggage based on both the heat release rate and the emission of toxic and visibility impairing substances. By using the generated fire data a new ignition model for railway vehicles has been developed that represents the typical heat and smoke emission characteristics of a burning piece of luggage.

APPLICATION OF THE IGNITION MODEL IN NUMERICAL FIRE SIMULATIONS

Comparison with Test Results
At first, the experimental test configuration, together with the new ignition model, are simulated with the Fire Dynamics Simulator (FDS) in order to compare the simulation results for the radiant heat fluxes from the fire as well as the toxic gas concentrations and the light transmittance in the exhaust duct with the experimental data. The simulation findings show that the implemented design fire generates satisfying results and therefore, turns out to be appropriate for being used as ignition model for a railway vehicle in the subsequent numerical fire simulations.

Fire Simulations for a Double Deck Passenger Rail Carriage
The derived design fire from the experimental investigations now becomes an ignition model which is applied to a virtual passenger rail carriage. The fire simulations are carried out addressing two main aspects. On the one hand, the location of the ignition source and the fire parameters of the interior materials are varied to analyse their impact on the fire development. On the other hand, the toxic and visibility impairing effects, resulting from the ignition source itself and potentially from further materials contributing to the fire, on occupants inside the carriage are investigated. A double deck carriage, previously used in the European research project TRANSFEU [15][16], serves as geometric model. Assuming operation category OC3 for a required running time of 15 minutes to reach a safe refuge for an evacuation in case of fire, materials must meet the requirements of hazard level HL2 according to EN 45545. For selected HL2 materials (e.g. seats and side walls) simulation input data were generated and validated within TRANSFEU and the research conducted in [17]. Hence, these data are deemed suitable and applied in this study. Simulation input data for further combustible components with HL2 burning characteristics (e.g. ceiling panels) are taken from the internal data base.
Three different approaches are used to model the fire behaviour of the materials:

- **inert materials:**
  the materials do not release any heat or decomposition products.

- **imposed pyrolysis (method 2 in TRANSFEU):**
  after having reached the ignition temperature for a discrete material surface a predefined function for the specific heat release rate is applied whose profile is determined from cone calorimeter tests.

- **calculated pyrolysis (method 3 in TRANSFEU):**
  the decomposition of the solid material is modelled using reaction paths and kinetic parameters derived from thermogravimetric analyses.

In addition to the three different modelling approaches for the train components, the position of the ignition source is varied from the lower deck to the upper deck and to the single deck area at the front inter-carriage connection. For each case it is positioned on a seat in a seating group of four seats as shown in Figure 10. Furthermore, the influence of the ventilation conditions is analysed, assuming the front inter-carriage connection door as closed or open.

![Figure 10: Sectional view, highlighting the three analysed ignition source positions](image)

### FIRE SIMULATION RESULTS FOR THE DOUBLE DECK PASSENGER RAIL CAR

**Basis for Assessing the Safety of Occupants**

The objectives of EN 45545 are to minimise the probability of a fire starting and to control the fire development and through this, to minimise the impact on passengers [4]. Material and product requirements form the basis of this approach. In case of fire, occupants are supposed to leave the affected area and to stay in the adjacent passenger area which is protected by fire barriers. However, assuming a railway vehicle operating fully occupied, it is deemed unrealistic that the adjacent carriage offers the capacity to be a safe refuge for all passengers, particularly in case of a fire inside the end vehicle.

Thus, if a piece of luggage burns in a railway vehicle it is to expect that occupants remain in the affected carriage until the train reaches a place where evacuation becomes feasible.

To assess the tenability conditions for occupants on board a train in case of fire the concept of fractional effective dose and fractional effective concentration (FED/FEC) for toxic gases as described in ISO 13571 [18] is adopted. Using the FED/FEC concept values of 1.0 correspond, by definition, to compromised tenability for 50 % of the exposed population. Thus, a lower threshold value of 0.3 (or 0.1 for particularly susceptible subpopulations, e.g. children, asthmatics or elderly people) is recommended to be used in fire risk analyses [18] [19]. Additionally, gas temperatures, radiant heat fluxes and visibility play a role with respect to personal safety. In the simulation, the required data are calculated by sensors located in the lower deck and in the upper deck as well as in the front and the rear foyer. All devices are positioned at the centre line of the carriage in a height of 1.60 m, the assumed human face-level.
Simulations with Inert Train Materials
Generally, the smoke released from the burning piece of luggage behaves completely different depending on whether the source is located in the lower deck, in the upper deck or in the single deck area:

Lower deck: initially, the fire effluents appear in the lower deck and then flow, thermally driven, through both foyers into the upper deck. Accordingly, the smoke disperses into the entire volume of the carriage (Figure 11).

Upper deck: the fire effluents accumulate in the space of origin in the upper deck due to their lower density relative to the surrounding air. Hence, a stratification takes place with an upper layer of highly concentrated fire effluents and a lower layer almost free of smoke (Figure 12).

Single deck: The smoke behaviour can be seen as a mixture of the phenomena described above. There is a tendency of stratification to observe, but the lower layer shapes only very thin.

Concerning tenability conditions on board, the effect of asphyxiant gases, quantified by the FED, is most important. Other criteria, such as gas temperatures, heat fluxes and irritant gases play a minor role. They exceed the tenability thresholds, if at all, only close to the fire. Visibility aspects may become important, especially during evacuation, but are not considered in detail here.

The smoke dispersal, dependent on the fire source location as described above, is reflected by the FED curves at different measuring positions: For the fire in the lower deck, the sensors located in the lower and the upper deck as well as in the front and the rear foyer respond nearly identically, thus showing the homogeneous distribution of the toxic gases inside the entire carriage. In this scenario, the FED exceeds the thresholds of 0.1 and 0.3 after 15 min and 22 min, respectively (Figure 13, left diagram, black curves). For the simulation with the fire located in the upper deck, the FED curves differ considerably due to the smoke layering. Whereas FED values of 0.1 and 0.3 are reached after 8 min and 13 min in the upper deck, the FED in both foyers is less than half as large. Related to the smoke stratification, there are no FED values to quantify in the lower deck for the period under consideration (Figure 13, right diagram, black curves).

As can be seen from Figure 13, the exposure conditions in the vehicle are also affected by the ventilation conditions (inter-carriage connection door opened or closed). There are differences caused by the exhaustion of smoke in the simulations with the door opened. The FED values for these simulations stay below the values for the closed door, since the fire effluents partly flow out the door (Figures 13, grey curves). However, it is arguable whether these simulation results are transferable to real applications, due to the fact that in reality the fire effluents do not flow to the outer atmosphere but to the adjacent carriage.
Simulations with Imposed Pyrolysis of Combustible Train Materials

In these simulations, the approach of imposed pyrolysis is applied to the combustible train materials. In general, the dispersion of fire effluents inside the vehicle with the fire location in the upper deck and in the lower deck is comparable to the simulations with inert materials. At both ignition source positions, the seat with the burning piece of luggage placed on as well as parts of the side wall and the ceiling ignite. The amount of ceiling material contributing to the fire is higher in the simulations with the ignition source in the lower deck which results in a higher maximum heat release rate (Figure 14). Nevertheless, a significant fire spread does not take place in both scenarios. It becomes apparent that the materials contributing to the fire behave self-extinguishing and the fire decays. However, the scenario with the ignition source in the single deck area at the end of the carriage leads to completely different results: Here, the fire spreads rapidly from the burning piece of luggage to the seat on which it is placed and to large parts of the side wall as well as to the combustible parts of the partition walls which separate the seating groups from the front foyer. A short time later, the ceiling ignites, too, and the scenario results in flashover four minutes after the fire has started (Figure 14). The ventilation conditions (carriage end door open or closed) do not substantially affect the fire development (Figure 14).
With this modelling approach, it is also the dose of asphyxiant gases, which is the decisive factor for tenability. Here again, placing the ignition source in the lower deck results in a nearly homogeneous smoke distribution inside the carriage, whereas placing the ignition source in the upper deck leads to a distinct stratification of the smoke layer. Both phenomena are confirmed by the corresponding FED curves. But due to the vehicle components being modelled as combustible, a larger amount of fire effluents is generated in these simulations which leads to higher toxic doses for the period under consideration (cf. Figure 15). The scenario with the ignition source positioned in the single deck at the end of the carriage turns out to be particularly critical: Because of the early occurrence of a flashover, the conditions inside the car become untenable within the first five minutes of the fire (Figure 16). Improved ventilation conditions (opening of the carriage end door, thermal window collapse) attenuate the effect in the scenarios with the ignition source in the lower deck as well as in the upper deck.

Figure 15: FED for ignition source in the lower deck (left) and the upper deck (right) with the inter-carriage connection door closed (Ø) or opened (O)

Figure 16: Simulation at t = 213 s (left) and FED for ignition source in the single deck area with the inter-carriage connection door closed (Ø) or opened (O)
To further investigate the conditions that cause flashover with the ignition source located at the end of the carriage, a series of sensitivity analyses is carried out. This part of the carriage differs from the upper and lower deck area in the geometric configuration and the amount of combustible materials: The side wall next to the seat with the ignition source placed on is about 60 cm longer due to a smaller window in that area. Furthermore, there are partition walls with a combustible surface which separate the two seating groups from the foyer. These circumstances promote a vertical fire spread and limit the movement of hot gases away from the fire. The heat flux to the exposed material surfaces is thus increased. The small compartment heats up quickly, parts of the ceiling ignite and flashover occurs.

Further analyses show that the exposed surface area of the side wall plays an important role: Flashover also occurs within four minutes if the ignition source is placed in the upper deck and an equal configuration with a narrowed window and an expanded side wall is reproduced in this area.

Simulations with Calculated Pyrolysis of Combustible Train Materials
In these simulations, lower fire spread is observed than in the simulations with imposed pyrolysis for the train components. With the ignition source positioned in the lower as well as the upper deck, smaller parts of the wall panel and the seats ignite. In addition, only minor parts of the ceiling (temporarily) burn when the ignition source is located at the end of the coach. A heat release rate of 230 kW is not exceeded in these simulations and, therefore, flashover does not occur. Using the modelling approach with calculated pyrolysis, a rather moderate burning behaviour of products has also been observed in [17].

CONCLUSIONS
Based on experimental investigations, an ignition model representing the fire behaviour of a typical piece of luggage is developed. It is confirmed that the »ignition model no. 5« described in EN 45545 represents the heat emissions from larger ignition sources, such as a burning piece of luggage, within the first ten minutes of the fire. In addition to the heat release rate, the new developed ignition model takes into account the time-dependent emissions of gaseous and particulate matter as well.

The effect of a burning piece of luggage as ignition source to a rail vehicle is investigated by means of numerical fire simulations involving the new ignition model. It is observed that fire spread inside the vehicle is possible, depending on the position of the fire source, the fire load and the specific geometric configuration. It is found that the position of the fire source significantly influences the smoke dispersal inside the carriage. Concerning the tenability conditions on board, the toxic dose generated by the asphyxiant fire effluents represents the decisive criterion prior to thermal effects. The simulation results show that a burning piece of luggage can create hazardous conditions which increase in severity with further vehicle components contributing to the fire. The toxic potential of a burning piece of luggage inside a passenger rail car is not covered by standards and design codes at present. In order to reliably assess personal safety on board, the toxic potential of a burning piece of luggage should be considered in the design phase of a vehicle.
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Achieving higher fire safety in vehicles: the potential of phosphorus, inorganic and nitrogen flame retardants

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ABSTRACT
The need for higher fire safety requirements in transportation has been well exposed and discussed during the FIVE conferences in 2010 and 2012, in particular regarding the specifications that are valid for road vehicles (cars, busses), which can be regarded as obsolete today [1-6]. With the anticipated increased use of plastics and natural fibres (light-weight construction, fuel savings), the multiplication of onboard electronics (GPS, DVD etc) and related cabling, and the upcoming move towards electromobility, flammability problems in road vehicles are not expected to decrease, unless specifications would be upgraded [7, 8].

While many papers in Gothenburg and Chicago compared the fire performance of materials used i.e. in trains or planes (well regulated) versus those used in cars and busses (less stringent), little has been said on how to achieve such a high level of fire safety. Apart from using inherently less flammable materials (which are normally more expensive, and sometimes heavier and/or difficult to process or recycle), the use of flame retardants (FR) is a viable option to prevent fires from happening, and is thus totally complementary to smoke/fire detection and active firefighting techniques when considering a full-system approach.

On the other hand, FRs are often controversially discussed in the public in regard to the potential health and environmental effects of certain substances. As a consequence, even harmless substances need to demonstrate their benefits, both in terms of their contribution to fire safety as well as regarding their eco-tox profiles.

PINFA is the non-halogenated Phosphorus, Inorganic and Nitrogen (PIN) Flame Retardants Association, founded 2009, and is a Sector Group of Cefic, the European Chemical Industry Council.

The paper will introduce Pinfa as an industry association, presenting its members, vision and missions, and briefly review some of Pinfa’s activities, which include, among other things, a technical brochure on PIN FRs applied to plastics and textiles used in various modes of transportation. In a second part, the paper will explain the role of flame retardants in developing fires. Last but not least, the paper will also review the latest environmental and health studies of flame retardants, including results of the EU financed “Enfiro” project, which have been published in 2013.

KEYWORDS: flame retardants, halogen-free, ignition, flame spread, smoke, plastics, textiles

WHAT ARE FLAME RETARDANTS?
Flame Retardants (FRs) are substances that are added to flammable materials (plastics, wood, textiles) by physical means (compounding, blending) or chemical means (i.e. grafted onto the polymer backbone or reacted on the surface of fibres) to modify their combustion. While this term describes
their function, it says nothing about their chemical nature, their mode of action nor about their chemical nature. There are in fact more than 150 singles substances which can act as FR, and very often, combinations of different substances are used in order to benefit from synergistic effects (lowering the dosage for a given level of fire safety) or to optimize some properties of the treated articles (i.e. transparency, mechanical properties, electrical properties) or minimize costs.

FR substances can be roughly divided into five chemical classes:
- brominated FR
- chlorinated FR
- phosphorus based FR
- Nitrogen based FR
- mineral FRs, which covers diverse chemistries (aluminium or magnesium hydrates, borates, silicates, clays, graphite etc.)

This variety of substances includes liquid and solid substances (powders) of organic or inorganic nature, all having different chemical, physical and toxicological (both human and environmental) properties, and also a different FR efficiency (certain FRs requires less than 1% dosage to pass certain tests in certain substrates, others require very high loading, sometimes exceeding 60% by weight).

**WHO IS PINFA?**

Pinfa stands for non-halogenated Phosphorus, Inorganic, Nitrogen Flame Retardants Association. Founded 2009 by 6 members as a Sector Group of Cefic, the European Chemical Industry Council, it today brings together 24 members [9], including those affiliated to Pinfa North America [10], which has been established in 2013.

Pinfa members share the vision of an ideal flame retardant, which
- is not toxic
- does not migrate out of finished products
- does not release additional toxic or corrosive gases in the event of a fire
- does not impede the recycling of final articles
- is either degradable in the environment or remains neutral (as naturally occurring substances do, i.e. minerals)

Pinfa members recognize that all their substances may not be perfect, but are committed to improving the environmental and health profiles of their products, as well as improving their efficiency (reducing overall dosage) and developing new products to address market needs.

To the missions of Pinfa belong:
- promotion of the use of PIN FRs
- provide information to legislators, downstream user and other interested parties on safety, health and environmental issues related to PIN FRs
- work with industry partners, associations and other stakeholders to support the sustainable use of PIN FRs
- carry out research relevant to safety and sustainability

**HOW DOES PINFA ACHIEVE ITS MISSIONS?**

a) building networks

Pinfa engages dialogue with interested parties at different levels:
- regulators and politics (such as European Commission, US EPA, Environment Canada or national bodies)
- Ecolabel organizations
- industry associations: pinfa has agreed mutual membership with iNEMI (the International
Electronics Manufacturing Initiative – www.inemi.org) and collaborates with other organizations such as HDPUG (www.hdpug.org) for the development of guidelines to process halogen-free circuit boards, or GTFI in France (www.gtfi.org), which is more involved in passive fire safety in buildings & constructions.

- research organizations: Pinfa cooperates notably with the German IFV Bahntechnik (Interdisciplinary Railways Research Association, [11]) in Berlin, which brings together a network of more than 10.000 companies, academia and individuals having stake in railways business
- NGOs: pinfa dialogues with ChemSec, CleanProductionAction and others on FR relevant topics

b) communications

The websites maintained by Pinfa are of course one of the easiest way to get access to informations about PIN flame retardants:
Pinfa Europe: www.pinfa.org
Pinfa: North America: www.pinfa-na.org

Among other things, visitors can access Pinfa’s product selector, which is a searchable database allowing readers and materials scientist to get a first selection of suitable PIN FR for a variety of polymers and materials. Some basic regulatory informations, such as labelling or Reach status, are also included.

Pinfa is also glad to publish a bi-monthly Newsletter, trying to cover everything about FRs in general and PIN FR in particular. Pinfa's newsletter can be subscribed for free on www.pinfa.org

Pinfa also edited three brochures about PIN FR uses in E&E applications (3rd edition, 2012), Transportation (1st edition, 2010) and more recently Building & Construction (1st edition, 2013). Digital versions of these brochures can be downloaded directly from the website.

c) conferences and workshops

Apart from participating to exhibitions and conferences, Pinfa also organizes dedicated workshops, mostly in cooperation with other partners. Four workshops dedicated to electrical & electronic (E&E) applications have been organized between 2010 and 2014 in different locations (Brussels, Tokio, Taipei and San José), addressing challenges and opportunities linked to the transition to non-halogenated materials used in consumer electronics.

More recently, Pinfa North America co-organized with SAMPE and the Department of Ecology of the State of Washington a 1st workshop about Meeting High Performance Requirements for Aviation” [12] in Seattle, WA, gathering 90 participants representing the whole value chain.

ROLE OF FLAME RETARDANTS IN A FIRE

Flame retardants essentially act in the very early stage of a developing fire [Fig.1]. They prevent a fire to start by increasing the amount of energy needed to ignite the 1st item. If for some reasons the starting fire develops (i.e. forced ignition by arson, or presence of high fuel load near flammable items), FR will perturb the combustion, usually resulting in slower and/or limited flame propagation (best case: leading to self-extinguishment) and lower the heat release, which are important factors to prevent a small fire to develop into an inferno. When considering thermoplastics, FR, when properly formulated, can also prevent the formation of burning droplets, which can be another factor for a starting fire to spread over to other flammable items.
However, in case there is enough fuel, oxygen and energy involved, FR will unlikely be able to prevent a fire to reach the “flash over” stage, after which FR have no to little effect any longer. Only so-called intumescent FRs, and certain ceramic-forming additives, may have some potential to create a shield between the fire and the substrate, thus allowing cables or structural elements (fire rated walls, doors or load bearing structures, such as steel beams or even concrete) to maintain their function during a fully developed fire (“Fire resistance” as opposed to “reaction-to-fire”, for which most FR are usually only good for).

**HOW DO PIN FLAME RETARDANTS WORK?**

PIN FR develop their FR effect through different mechanisms, either through chemical reactions, physical effects or through a combination of both. These complex, sometimes polymer-specific reactions can take place in the solid (or condensed) phase, and/or in the melt and/or in the gas phase [13].

1) chemical action in the gas phase

This typically applies to halogen FRs, which release acidic gases (HBr or HCl) that will interact with hydrogen radicals in the flame through radical activity.

Some PIN FRs, notably phosphine oxide, red phosphorus and phosphonates to a lower extent, can also interfere in the flame by releasing PO radicals and/or by other mechanisms, that are not necessarily well understood. Unlike halogens, PIN FR will not release corrosive gases, but as all FR disturbing the combustion process within the flame, they will impede a complete combustion, which typically results in smoke production.

2) chemical action in the condensed phase

a) Char formation: most phosphorus FRs, typically phosphates and polyphosphates, which release non-volatile polyphosphoric acid that will in turn remove chemically-bound water from the polymer and create a carbonaceous layer via complex esterification, cyclization and crosslinking reactions. Nitrogen FRs can be useful to participate in the crosslinking reactions, thus enhancing the stability of the char. The thus created carbon-rich layer will act as a physical barrier to oxygen.

b) Formation of a glassy / ceramic-like layer can be obtained by using boron compounds, such as zinc borate, melamine borate, low-melting glasses and few others. The formed glassy layer can act as a physical barrier on its own, or be used together with char-forming additives to improve the char formation or reduce smoke formation.

3) chemical action in the melt phase

This is particular mechanism that only applies to specific FRs in given polymers. Typically examples
are melamine cyanurate in polyamides or amino-HALS structures in polyolefins. Upon decomposition of these FRs, the breakdown products will be released that will lead to a non-burning polymer decomposition. This mechanism basically removes fuel from the heat source and can be very helpful in certain fire tests.

4) physical action in the gas phase
Metal hydrates (ATH, MDH) are the main examples. Upon endothermic decomposition, they release water vapour, which absorb energy, release water vapour and reduce smoke formation.

5) physical action in the condensed phase
Intumescence is a particular mechanism based on the formation of a char foamed layer that thermally insulates the underlying substrate. This can be both used to protect plastics (preventing further decomposition and contribution to the developing fire) or non-flammable materials, such as metallic structures. When used in thermoplastics, intumescence effectively offers a “build-in” anti-dripping mechanism.

THE FLAME RETARDANTS CONTROVERSY
Despite the fact that there is little to no data or statistics available about how many fires are being prevented by the use of FR, there is a consensus in the industry and among fire safety experts that FR save lives and property. However, FRs have become a hot discussion topic since a couple of decades, raising questions about toxicity and their environmental footprint. Although a limited number of substances was under suspicion, this bad image affects all FR chemistries nowadays, and there is a need for clarifying the socio-economic benefits of FRs, as well as addressing environmental and health data gaps for many molecules.

pinfa and its members therefore co-operates with national & supranational organisations (EC, OECD, United Nations) & other industry associations, consumer organisations & non-governmental organisations in order to address these gaps. Pinfa members are committed to contribute to the development of scientific knowledge related to the whole life cycle of PIN FRs.

RECENT STUDIES ABOUT ENVIRONMENTAL & HEALTH ASPECTS OF PIN FRs
In this respect, it is worth to mention some of the recent studies, such the EU funded ENFIRO project [14] or the US EPA alternatives assessment programs [15, 16], which results have recently published.

The ENFIRO project chose a prototypical approach to study various polymer/FR combinations, comparing traditional halogenated FR solutions to their proposed non-halogenated alternatives.

Some key conclusions could be drawn from the studies performed under this project:
- for all polymer systems selected, alternative PIN FR could be identified
- all selected PIN FR fulfilled regulatory fire tests
- selected PIN FRs have similar fire performance and technical capabilities as their brominated/antimony containing reference formulation
- in general, PIN FR systems produce less smoke (only few exceptions) and less toxic components in smoke
- some PIN FRs showed lower risk for the environment and human health and a lower potential to bioaccumulate
- lower human and environmental risks are expected to be due to lower hazards from PIN substances, probably not due to lower exposure scenarios
- leaching from polymer into the environment seems to be polymer dependent, not FR dependent

In recent years, the US Environment Protection Agency (EPA) commissioned the evaluation of environmental and health properties of PIN FR alternatives to high volumes brominated FRs (TBBPA, Deca-BDE, HBCD). As a result, these studies could evidence that PIN alternatives with an
overall good profile are available. But they also highlighted that certain PIN FRs also have some chemicals hazard too. However, these studies have been focusing only on inherent hazardous of the substances without taking exposure (risk) into account, thus making difficult to have a conclusive picture.

Because such assessments are by nature not easy to perform and results difficult to exploit, there is a need from down-stream users to develop tools that would simplify the selection or de-selection of substances. Such a tool has been (and still is being) developed by Clean Production Action, a US based NGO, with support of US EPA: the “Green Screen” [17] uses a quick and simplified approach (based on available literature, no testing performed) to classify substances in 4 rating levels:
- benchmark 1 (=avoid): Chemical of High Concern
- benchmark 2 (=Use, but search for safer substitutes): Chemical with moderate hazard properties
- benchmark 3 (=Use but still opportunity for improvement): lower hazards than benchmark2
- benchmark 4 (=Prefer, safer chemical): chemicals with low eco-tox endprints

Pinfa members were involved in the early stage of the development of GreenScreen and could thus collect valuable experience about the assessment process. First results are expected to be made public in the course of 2014 or 2015.

CONCLUSIONS

Flammability requirements for materials used in road vehicles (cars, busses) rely essentially on specifications set in FMVSS302 (and equivalent standards) and can be regarded as obsolete. With the continuously increasing use of plastics and natural fibres (for weight saving reasons) and increasing electrification (onboard electronics, e-mobility etc), the need for fire resistant materials is expected to increase.

Flame retardant additives represent an economic alternative to inherently less flammable materials, which are often heavier (e.g metals) and/or more expensive (high performance plastics) and/or difficult to process or recycle at end-of-life.

In view of the controversial discussions about the environmental and health impact of flame retardants, non-halogenated PIN flame retardants represent viable options. Pinfa, as an association, and its members are committed to improve their products and provide information where needed.

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Computational Analysis of Ignition Source Characteristics on Fire Development in Rapid Transit Vehicles

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ABSTRACT

In this study the influence of ignition source characteristics, including initiating fire size and location, on fire development within a rapid transit vehicle under a range of tunnel ventilation conditions is evaluated using Fire Dynamics Simulator (FDS). A prescribed burning rate approach is implemented using material input parameters that were derived from cone calorimeter testing of select materials sourced from transit vehicles. Given the limitations of the modelling approach, it is expected that the model will result in some degree of over-prediction of the ignition of materials at early stages of the fire and subsequent flame spread in areas of relatively low radiant heat exposure. Four initiating fire sizes ranging from 25 kW to 350 kW are evaluated, which are representative of a range of possible materials that could be introduced and subsequently ignited within a rapid transit vehicle. Three ignition locations are assessed within a representative transit vehicle interior using four interconnected open-gangway cars. The train doors are assumed to be open along the walkway side of the train, and tunnel air velocities ranging from 0 to 3 m/s are considered.

The model predictions indicate that fire development for all four ignition sources remains localized to a portion of the incident car when no induced tunnel air velocity is considered. One ignition location (on the top of a seat) did not result in any significant flame spread for all ignition source sizes and tunnel ventilation conditions. For the other ignition locations a larger ignition source correlates with greater fire development at low tunnel air velocities. At increased tunnel air velocities of 2 -3 m/s, the models yield predictions of peak heat release rates (HRR) that are relatively independent of ignition source, although the predicted time to the peak HRR is observed to decrease with increasing initiating fire size. Given the predicted fire development behaviour and the anticipated over-prediction of early fire spread in the analysis method, the model results support the conclusion that an ignition source would have to be large to pose a significant risk of a serious fire event for the type of transit materials and train configuration considered in this study. Assessing the likelihood of large ignition sources within a rapid transit vehicle would assist in quantifying risk and evaluating appropriate design parameters for a particular vehicle and system.

KEYWORDS: rapid transit vehicle, fire development, initiating fire, heat release rate, tunnel ventilation

INTRODUCTION

Fire development within rapid transit vehicles is an important parameter for assessing risk relative to life safety and property protection for transit systems, and in specific design applications such as the development of performance criteria for emergency ventilation in tunnels and underground stations. A greater understanding of the various parameters that can influence fire development in transit environments would assist in quantifying corresponding risk context and facilitate selection of the most suitable design parameters for a particular vehicle and system. Pertinent variables that have an impact on fire development inside vehicles include the materials used, potential ignition sources, specific vehicle geometry, changes in ventilation (e.g. window failure and door position), and suppression. Under-prediction of the potential for fire development in transit vehicles could result in...
increased life safety risk in the event of a fire, while an over-predicted design fire would correlate with increased expenditure for excess ventilation capacity.

In a previous study [1] computational analysis of the impact of the tunnel ventilation system on fire development within a rapid transit vehicle in a tunnel was conducted using various configurations of interconnected open-gangway vehicles using Computational Fluid Dynamics (CFD) and a specified burning rate methodology [2,3,4,5]. The analysis results indicated that tunnel ventilation conditions and the extent of train interconnection had a significant effect on the predicted fire development behaviour and peak fire size. The objective of this analysis is to examine the impact of the ignition source strength and location on the predicted fire development behaviour in an open-gangway interconnected rapid transit vehicle under a range of ventilation conditions within a tunnel.

CHARACTERIZING POTENTIAL IGNITION SOURCES

The configuration and construction of modern rapid transit vehicles generally correlates with limited potential ignition sources. These vehicles typically do not have trash containers and are constructed with fire-hardened combustible materials that meet flame spread and smoke generation requirements of standards such as NFPA 130 [6]and EN 45545 [7]. Incidental accumulation of debris, such as newspapers, cups, and other garbage between cleaning cycles would not be expected to present a significant ignition risk.

Information regarding potential ignition sources is included in NFPA 130 and EN 45545. For example, Annex E of NFPA 130 (2014) provides guidance relative to identifying vehicle fire scenarios when conducting a fire hazard analysis for rapid transit and passenger rail applications. In this context, consideration of representative fire scenarios is suggested to include the potential for small sources of ignition (e.g. crumpled newspaper) underneath seats or on top of a vandalized seat, and the potential for ignition due to overheated vehicle equipment (e.g. electrical, HVAC).

Modern transit materials are generally very resistant to ignition with small incidental sources, such as cigarettes and lighters [8]. These minor ignition sources correlate with approximately 0.005 kW for a cigarette [9] and 0.1 kW for an open flame representative of a lighter/candle [10], and while they can easily ignite minor combustibles such as paper, they would not be sufficient for self-sustained ignition of the interior components typical of modern transit applications. Accordingly, such ‘nuisance’ ignition sources are mitigated from risk for life safety and train damage where appropriately fire-hardened materials are used.

Potential sources of fuel that could provide a larger ignition source in a train passenger compartment include small initiating fires involving more readily-ignitable materials that may be introduced into the vehicles through normal use by passengers include paper/cellulosic material, clothing, miscellaneous debris and bags/luggage. Peak HRR measurements for some examples of these materials are summarized below in Table 1 to provide context regarding initiating fire sizes associated with introduced materials. The burning characteristics of the individual materials directly influence the growth and decay phases of these potential incipient fires, and for most of the materials listed in Table 1 the peak HRR would be only achieved for a short duration.

The experimental ignition sources that have been utilized in various transit and passenger rail vehicle fire testing has varied considerably, ranging from the ignition of combustible materials such as those outlined in Table 1 to introduced distributed flammable liquids corresponding with malicious intents. Passenger rail fire testing that was conducted by NIST under a comprehensive fire safety research program [8,13,14] utilized ignition scenarios consistent with the guidance provided in NFPA 130 that included ignition under a seat by small source (representative of crumpled newspaper), ignition by a small gas burner on top of a seat, and a newspaper-filled trash bag fire on top of a seat. Using materials that met current Federal Railway Administration (FRA) requirements at the time of the testing in the 1990s, it was found a significant ignition source (such as a large trash bag along with a 25 kW gas burner) was necessary to sustain flame spread [14].
Table 1  Examples of approximate peak heat release rates for trash and other combustibles.

<table>
<thead>
<tr>
<th>Item</th>
<th>Peak HRR [kW]</th>
<th>Approximate Peak Burning Duration [s]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene wastebasket (0.6 kg) filled with shredded paper (0.2 kg)</td>
<td>15</td>
<td>100 - 200</td>
<td>[11] (p. Y3.4/10-12)</td>
</tr>
<tr>
<td>Pillow with 0.65kg of polyurethane foam</td>
<td>40</td>
<td>100</td>
<td>[11] (p. Y6/51)</td>
</tr>
</tbody>
</table>
| Luggage filled with clothes                                         | 120 (hard suitcase)  
25 (soft suitcase) | 300  
1000                                  | [12] (p. 3-28)      |
| Two men’s jackets                                                    | 75 - 85       | 10 - 20                              | [12] (p. 3-14)      |
| Trash bags filled with paper (1.17kg total)                         | 140 (1 bag - 1.17 kg)  
280 (2 bags - 2.34 kg)  
350 (3 bags - 3.51 kg) | 100  
20  
100                                  | [12] (p. 3-46)      |
| Amtrak trash bags from overnight trains (1.8 - 9.5 kg)               | 30 – 260      | 10 - 400                             | [8] (p. 41)         |

The ignition and fire spread behaviour of modern materials was further examined by Coles et al [15], using a coupled CFD/pyrolysis model in conjunction with bench-scale and real-scale fire testing. The analysis found that more extreme ignition sources (such as introduced flammable liquid spills with a minimum heat release rate potential of 500 kW) could cause fire spread beyond area of initiating fire, but it was unlikely that small localized fires (such as a trash fire) would lead to fire spread beyond the area of origin. Other examples of fire testing of rapid transit and passenger rail vehicles utilized various ignition sources including 6.2 kg of isopropanol (approximately 7.9 L) in the Eureka project [16], 1 L of petrol and a plywood board in the METRO project [17], a variable heat release propane burner generating 75 kW for 3 minutes before increasing to 150 kW for 8 minutes [18], and a travelling bag (duffel bag) with newspaper [19]. In fire testing that was conducted by the Bay Area Rapid Transit District (BART) ignition sources consisting of a 40 kW burner and a 160 kW burner were used for corner lining tests, and trash bags filled with 0.8 kg of paper and 0.2 kg of paper cups were utilized for full-scale fire tests [20].

The effect of fire hardening on trains is complicating the study of fire researchers and, in the context of rapid transit vehicles, correlates with introduced fire sizes that are disproportionate to materials that would normally be present in such an environment, implying security risk questions and implications that are not currently being addressed. This highlights the need to better understand ignition, fire growth, and the definition of credible design fires with consideration of operational control and security threats in order to establish overall risk and accepted practice for defining initiating fires.

**MATERIAL TESTING**

Samples of interior materials sourced from rapid transit vehicles were tested in a cone calorimeter at a fire testing laboratory in order to establish the time to ignition, soot yield, and heat release rate for a range of heat flux exposures. The testing was conducted in accordance with ASTM E1354-09. The materials that were tested included bellows material, floor covering, seat material (padding with cover), advertisement signs with clear plastic covers, light fixture covers (polycarbonate), and separator film from the glass windows and partitions.

The ignition properties of the materials that are required for the model, including ignition temperature and thermal inertia, were derived based on a heat conduction analysis using the time to ignition data obtained from the cone calorimeter testing over a range of exposure heat fluxes [21]. The model inputs for burning behaviour were obtained using averaged test data with a 50 kW/m² incident heat flux for the major interior components (seats, floor, and gang-bellows) and 35 kW/m² for the minor components with the propensity to fall out of position or melt during fire exposure (light fixture
covers and advertisements with covers). The use of 50 kW/m² in the cone calorimeter tests as a representative exposure for developing fires within transit vehicles is consistent with measured values obtained during 1984 Amtrak interior tests [8] and with the conclusions from the NIST passenger rail study relative to exposure from severe ignition scenarios [14]. The material properties used in this study are summarized in Table 2, and the input curves for heat release are presented in Figure 1.

### Table 2  Material ignition properties derived from cone calorimeter testing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ignition Temperature $T_{ig}$ (°C)</th>
<th>Thickness $\Delta$ (mm)</th>
<th>Conductivity $k$ (W/mK)</th>
<th>Density $\rho$ (kg/m³)</th>
<th>Peak Heat Release Rate $Q''_{max}$ (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat cover/padding</td>
<td>533</td>
<td>19.7</td>
<td>0.03</td>
<td>506</td>
<td>208</td>
</tr>
<tr>
<td>Floor cover</td>
<td>419</td>
<td>3.10</td>
<td>0.19</td>
<td>1637</td>
<td>342</td>
</tr>
<tr>
<td>Glass separator film</td>
<td>414</td>
<td>0.19</td>
<td>0.24</td>
<td>1368</td>
<td>84</td>
</tr>
<tr>
<td>Light fixture cover</td>
<td>518</td>
<td>2.03</td>
<td>0.43</td>
<td>1450</td>
<td>225</td>
</tr>
<tr>
<td>Advert and cover</td>
<td>518</td>
<td>2.45</td>
<td>0.43</td>
<td>1380</td>
<td>341</td>
</tr>
<tr>
<td>Bellows</td>
<td>447</td>
<td>2.00</td>
<td>0.43</td>
<td>1326</td>
<td>225</td>
</tr>
</tbody>
</table>

**Figure 1**  Comparison of material heat release rates (per unit area) from the cone calorimeter testing of the transit materials.

**ANALYSIS METHODOLOGY AND LIMITATIONS**

The current analysis utilizes prescribed burning-rate CFD methodology in order to evaluate the impact of ignition source location and strength on the predicted fire behaviour within open-gangway interconnected rapid transit vehicles under various tunnel ventilation conditions. The ignition and burning characteristics for select rapid transit vehicle interior materials were derived using small scale material testing. A three-dimensional representation of an interconnected open-gangway rapid transit vehicle was created, and the interior surfaces within the vehicle model were assigned effective material properties and ignition characteristics based upon the data obtained from the small scale testing. Each material was assigned an ignition temperature and prescribed heat release rate behaviour. Similar specified burning rate CFD methodology was applied by Chiam [2] relative to the Singapore’s Circle Line and has been utilized in the analysis of fires within buildings [3,4,5].

The prescribed burning rate modelling approach requires material-specific data which are not readily available for most materials. Accordingly, small-scale testing of the materials of interest and interpretation of test data is required in order to obtain representative model parameters. The material-specific heat release rate and ignition characteristics that are derived from these experiments serve to
establish the combustion behaviour for each of the interior components within the model. The model represents fire spread on the basis of a material surface reaching its specified ignition temperature, on a grid cell-by-grid cell basis. Once ignited, the material releases heat at a pre-defined experimental burning rate that has been selected from the cone calorimeter testing at a specific incident heat flux. This is an important limitation of the prescribed burning rate methodology. The burning rate of each material does not vary according to the level of incident radiation. As a result, the burning behaviour of an ignited material has the potential to be underestimated (where the actual incident heat flux is greater than the experimental heat flux), or overestimated (where the actual incident heat flux is lower than the experimental value).

By using material burning behaviour that is obtained at heat fluxes that are consistent with larger developing fires, the incipient ignition of materials at early stages of the fire and subsequent flame spread in areas of low radiant heat exposure are expected to be over-predicted. The use of experimental data from a higher incident heat flux would also not account for the effectiveness of fire hardened materials at resisting ignition and reducing the propensity for flame spread at low heat fluxes [2]. Accordingly, the model assumptions in this study are expected to correlate with increased propensity for materials to ignite and with the prediction of premature flame spread beyond the area of origin. However; the modelling methodology is expected to accurately predict the overall trends of fire development under various ignition and ventilation conditions. Evaluation and comparison of the trends of burning behaviour provides valuable insight into the influence of these parameters on fire development.

Pyrolysis modelling provides an alternative CFD methodology that allows for the effect of incident thermal radiation on the burning behaviour of materials to be accounted for in the modelling of flame spread with various materials [15,22]. However, pyrolysis modelling adds a significant level of complexity relative to the modelling approach adopted in this study in order, and subsequently requires additional input parameters for materials. These pyrolysis input properties require detailed derivation from experimental measurements using numerical optimization methods, which is beyond the scope of this study.

**COMPUTATIONAL MODEL SETUP**

The computational modelling in this study was conducted using Fire Dynamics Simulator (FDS) version 5.5.3. FDS is developed by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST). The model geometry consists of a 4 car interconnected open-gangway rapid transit vehicle, as shown in Figure 2. The car dimensions and seating configuration are intended to be representative of a typical open-gangway rapid transit vehicle.

![Figure 2](image_url)  
*Figure 2  Overview of the model geometry for the 4-car open gangway rapid transit vehicle (roof assembly hidden for clarity).*

The tunnel geometry is representative of a single-bore tunnel with a dividing wall between tracks. A tunnel length of 175 m is used within the computational domain, as illustrated in Figure 3. A sensitivity study was conducted with an increased length of the tunnel segment to confirm that the location of the simulation boundaries had a negligible impact on the prediction of peak heat release rate (HRR) and growth rate. The induced velocity of the tunnel ventilation system was modelled as a fixed-velocity vent across the tunnel area at the upstream boundary of the tunnel segment. The tunnel ventilation system was assumed to start 60 seconds after fire ignition and then ramp-up in a linear fashion over 60 seconds, establishing full velocity within the tunnel 120 seconds after ignition. A range of tunnel ventilation velocities from 0 m/s to 3 m/s were examined for each ignition location and initiating fire size, yielding a total of 46 simulations.
For all simulations the train was assumed to be stationary within the tunnel at the effective time of ignition. All passenger doors on the walkway side of the train were assumed to open 60 seconds after ignition and remain open for the remainder of the simulation. Initial ambient tunnel airflows due to piston effect were ignored. A grid cell size of 0.1 m x 0.1 m x 0.1 m was implemented for all simulations, yielding a total of 2.7 million grid cells in the computational domain. All scenarios in this study involve a flat (0% grade) tunnel segment. A total simulation period of 1800 seconds was used.

**Figure 3** Overview of the train and tunnel segment geometry.

Failure of the train windows during a fire influences the ventilation conditions within the train. Window failure is assumed to occur when the glass reached a temperature of 500°C, based upon experimental observations of the fallout temperature for tempered glass with no sprinkler protection [23]. Only ignition scenarios in the interior of the rapid transit vehicle are considered for this study. Three initiating fire locations (illustrated in Figure 4) were selected in three different areas of the most-upwind train car:

- Fire on the floor immediately adjacent to a group of seats (Ignition Location 1).
- Fire on a seat near the front of the train (Ignition Location 2).
- Fire on the floor immediately adjacent to the bellows at the interconnection between car 1 and car 2 (Ignition Location 3).

**Figure 4** Overview of the train car geometry illustrating the initiating fire locations (fire area for 350 kW initiating fire shown, roof assembly hidden for clarity).

Four different initiating fire sizes, ranging from 25 kW to 350 kW, are implemented in the computational model for each fire location. The ignition sources are described below:

- 350 kW: Based upon an experimental curve that was obtained for 3 burning trash bags filled with paper [12], with a total burning duration of approximately 600 seconds.
- 150 kW: Based upon an experimental fire curve for 1 burning trash bag filled with paper (scaled up from a peak of approximately 140 kW to a peak of 150 kW) [12].
- 50 kW: Assuming a 300 s burning duration using steady burning behaviour with no incubation, growth, or decay phase.
• 25 kW: Assuming a 300 s burning duration using steady burning behaviour with no incubation, growth, or decay phase.

The 25 kW and 50 kW fire sizes are selected to be representative of peak heat release rates of ignition sources such as smaller pieces of luggage, clothing, or small garbage bags. The steady burning behaviour for these two ignition sources is used to provide a conservative estimate of the thermal exposure to surrounding materials. The model inputs for each of the initiating fires that are considered in this study are presented in Figure 5.

**MODEL PREDICTIONS OF PEAK FIRE SIZE**

The model predictions of peak HRR for the ignition location 1 scenarios (on the floor adjacent to a group of seats) are presented in . For the 25 kW ignition source fire development was predicted to be limited to immediate vicinity of incipient fire for all tunnel ventilation conditions that were examined, yielding only localized fire damage to the adjacent seats with minimal contribution of the interior train materials to the fire.

With no induced tunnel air velocity the 50 kW, 150 kW and 350 kW incipient fires yielded predictions of fire development that was limited to a portion of the incident car, with predicted peak HRRs of approximately 5 - 7 MW. Increasing tunnel air velocity facilitated greater fire spread through the interconnected train cars, as the open doors and broken windows provided significant area for the tunnel air flow to enter the train. At 1 m/s tunnel air velocity, the predicted peak fire size increased for all three ignition sources, with a greater increase in peak HRR observed with increasing...
ignition source size. With the tunnel air velocity increasing to 2 m/s and 3 m/s the peak HRRs continue to increase, yielding approximately the same peak fire size for the three ignition sources. The predicted peak fire sizes for ignition location 2 (on top of a seat) are presented in Figure 7. For all four incipient fire sizes fire spread was predicted to be limited to the materials immediately adjacent to ignition source, with overall peak HRR values marginally above the peak HRR of the ignition source. Given the location of the ignition source in the front portion of the train, upwind of the first set of open train doors, the induced tunnel air velocity has a negligible impact on the incipient fire development, and as a result no flame spread beyond the immediate vicinity of the incipient fire is predicted for all tunnel ventilation velocities considered.

![Figure 7 Predicted maximum HRR for ignition location 2: on top of a seat.](image)

The model predictions for peak fire size for ignition location 3 are presented in Figure 8. With no forced tunnel air velocity the 25 kW, 50 kW, and 150 kW initiating fires resulted in minimal involvement of train materials. The 350 kW initiating fire was sufficient for fire spread to nearby combustible materials in the upstream and downstream car, yielding a peak fire size of approximately 8 MW. With increasing tunnel air velocity the results were similar to those from ignition location 1, resulting in increased fire spread through the interconnected cars and yielding a larger peak fire size. The 25 kW initiating fire resulted in minimal fire development for tunnel air velocities of 2 m/s or less; however, at 3 m/s the induced tunnel air velocity was predicted to be sufficient to cause significant fire development, resulting in a predicted peak HRR that was consistent with the larger ignition sources.

![Figure 8 Predicted maximum HRR for ignition location 3: train floor adjacent to bellows.](image)
MODEL PREDICTIONS OF FIRE DEVELOPMENT

The model HRR predictions for ignition location 1 are presented in Figure 9. The 25 kW ignition source [Figure 9(a)] yielded no significant fire development, resulting in the ignition of only localized materials after approximately 120 seconds of exposure. For the 50 kW ignition source [Figure 9(b)] two fire spread regimes were observed with increasing tunnel air velocity. With increasing air velocity, the early fire growth rate was observed to decrease (from approximately 250 seconds to 500 seconds), as fire spread to combustible materials located upwind of the ignition source was hindered by the airflow induced within the incident car. After approximately 500 seconds the higher air velocity (2 and 3 m/s) resulted in more rapid fire growth and flame spread into the downstream direction to the interconnected vehicles, in contrast to the 0 m/s and 1 m/s scenarios in which fire growth slowed down after 500 seconds, maintaining an approximately constant heat release rate.

The trends of fire development for the 150 kW and 350 kW initiating fires are similar to the 50 kW case, but with faster early fire growth at higher ventilation velocities and an earlier peak HRR with increasing ignition source size. The relative difference between the different ignition sources is most pronounced for the 1 m/s tunnel air velocity condition, in which the 350 kW initiating fire resulted in a significantly higher peak fire size at late stages of the fire.

For all four ignition sources, there was no significant fire development predicted at ignition location 2, resulting in only limited ignition of train materials. The model predictions of HRR for the 25 kW and 350 kW initiating fires are presented in Figure 10. Given the relatively sheltered location of this ignition location, upwind of the first set of opened train doors, the tunnel air velocity had limited impact on the predicted heat release for all four initiating fire sizes.
The model predictions of HRR for the ignition location 3 scenarios are presented in Figure 11. For the 25 kW initiating fire size, no significant fire development is predicted for tunnel air velocities of 2 m/s or less, but at 3 m/s the fire is predicted to eventually rapidly develop and spread to the downstream cars after a long incubation phase. Given that the burning duration of the incipient fire is 300 seconds for this case, and the observed incubation period is approximately 600 seconds, this prolonged period of negligible fire growth followed by significant fire development is most likely an artefact of the methodology and the expected over-prediction of burning behaviour at relatively low heat fluxes.
With 0 m/s tunnel air velocity the 50 kW and 150 kW initiating fires did not result in fire development beyond the immediate vicinity of the ignition location, while the 350 kW initiating fire yielded very slow fire development into areas of the train cars adjacent to the bellows. For these three largest initiating fires the predicted behaviour was similar to that observed for ignition location 1, with increasing tunnel air velocity yielding increased fire growth rates.

CONCLUSIONS

This study utilizes prescribed burning rate CFD methodology in order to evaluate the effects of initiating fire size and location on the trends of predicted fire development in rapid transit vehicles under a range of tunnel ventilation conditions.

For the ignition location on the top of a seat all four initiating fire sizes did not result in any significant fire growth. For the two floor fire locations (adjacent to seats and adjacent to the bellows), fire development was predicted to be limited to a portion of the incident vehicle for all ignition sources with no forced air velocity in the tunnel. Increasing tunnel air velocity facilitated increased fire spread through the interconnected vehicles, resulting in a higher predicted peak HRR that was relatively independent of ignition source strength at higher velocities. However; increasing the initiating fire size resulted in faster fire growth, with earlier achievement of peak HRR.

The analysis supports the following conclusions:

- Simulations of different initiating sources correlates with literature in that the location of the initiating fire is fundamental to the overall potential for fire growth;
- Smaller initiating fires are likely to remain localized unless a secondary sources of fuel can sustain prolonged burning at a modest heat release rate;
- Larger initiating fires were predicted to have fire development that was limited to one portion of the incident car where only natural ventilation was available;
- Larger initiating fires spread through the open-gangway train where forced push-pull ventilation was introduced.

Assessing the likelihood of large ignition sources within a rapid transit vehicle would assist in quantifying risk and evaluating appropriate design parameters for a particular vehicle and system. Anticipated future work in the Sereca research program will involve further evaluation of the important parameters influencing fire development in rapid transit vehicles, including ignition sources and ventilation conditions, within a risk framework. This would include derivation of probability density functions and cumulative density functions to provide a more holistic approach to assist in defining credible design fires for rapid transit emergency ventilation system design.

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An Investigation of the Electrical & Thermal Characteristics of Common Electrical Faults in a Fuse Protected Starting & Charging System

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Kidde Technologies
Colnbrook, UK

ABSTRACT
A significant proportion of fires occurring within transit vehicle engine compartments may be directly attributed to electrical faults. A fire suppression system cannot directly address and remove electrical faults only the fires resulting from them. Timely detection may provide a means to address the fault condition at an early stage of development thereby mitigating the fire risk. In this paper we consider the electrical and thermal characteristics of common electrical cabling faults that may occur within a fuse protected transit vehicle engine starting and charging system. Common fault scenarios that present a significant fire risk are identified and the experimental simulation of these faults is described. Experimental results from these simulations are presented. Based upon these results an attempt is made to characterise the thermal and electrical signatures associated with common cabling faults.

KEYWORDS: engine, fire, detection, electrical, cable fault

INTRODUCTION
A large percentage of reported transit vehicle fires originate in or around the engine compartment with reports suggesting that up to 60% of all transit vehicle fires originate in or around the engine compartment. Further analysis of the causes of engine fires suggests that at least 20% may be directly attributed to electrical faults within the engine compartment. [1], [2],[3],[4]

Fires caused by the ignition source presented by electrical faults may be readily detected and extinguished by a correctly configured automatic fire extinguishing system (AFES). It is however worth noting that even after successfully extinguishing the fire unless the electrical power supply is disconnected the ignition source is still present and re-ignition may occur.

Ideally, rapid detection of the electrical fault before ignition occurs would allow for disconnection of the electrical supply from the affected cabling, thereby significantly mitigating the risk of occurrence of a fire. The next most favourable scenario is rapid detection and extinguishing of any resulting fire before significant damage or risk has occurred, alongside disconnection of the electrical supply to prevent re-ignition.

Faults that occur in and around high current carrying cables, such as those found in vehicle starting and charging system, are considered by the authors to present a significant fire risk. Such faults therefore warrant further consideration and investigation. A clear understanding of the thermal and electrical characteristics of potential cable fault conditions is important for optimization and successful implementation of fault mitigation and rapid fire detection schemes. To this end experimental apparatus was developed to simulate and characterize fault conditions presented by intermittent shorts of damaged cables to the vehicle chassis and loose connections.
CABLE FAULT CONDITIONS WITHIN A STARTING AND CHARGING SYSTEM

The authors’ simplified interpretation of a fuse protected transit vehicle diesel engine start and charging system is shown below in Figure 1. The example shown in Figure 1 is a 24V system with two 12V automotive lead acid batteries connected in series. Such battery packs can typically supply >750 CCA (cold cranking amps) and peak transient currents in excess of 1200A.[5] A secondary power source is provided by two 24V alternators connected in parallel. Typical alternator output currents encountered in commercial vehicles vary between 160-300A with 275A or more being common in many transit vehicle applications.[6] All interconnecting cables should be rated for currents in the range of 250A-300A, i.e. SAE J1127 AWG 2/0 or equivalent.

In the example shown the fuse limits the continuous current from the battery pack to ≤300A and the output of the alternator is limited to ≤275A. The addition of a cut-off relay allows for disconnection of the electrical supply from the batteries. It is important to note that the circuit protection, both the fuse and the cut-off relay, only protect cabling and connections between the battery and the fuse. Cabling between the alternator and the fuse and/or master relay is not protected.

Previous work by the present authors has shown that a short to ground of the high current carrying cables can result in significant heating along the whole length of the affected cable.[7] It was also shown that such a fault could be readily detected with a correctly installed linear heat detector. This type of event is however an unrealistic scenario within a correctly designed fuse protected system where the fuse is expected to clear the fault before significant heating of the cable can occur.

Initial arcing may occur as the cable comes into contact with the ground and this may present a short lived ignition source. This however is a transitory event and these faults are not considered to represent a significant sustained fire risk. Similarly, a static short of cables carrying current from the alternator represent a minimal risk since the output from the alternator is below the rated current carrying capacity of the cables.

Continuous faults that occur at currents below the rating of the fuse or faults that generate high current transients may occur that are not cleared by the fuse. These faults can persist over a prolonged period of time and any associated heating or arcing can provide an ignition source. These faults may present a significant sustained fire risk. Common fault scenarios that have the possibility to cause such electrical faults are damaged cable sheathing and severed cables, resulting in intermittent and/or resistive shorts to the vehicle chassis and loose connections at cable terminations. These faults can result in significant heating of, and damage to, cables and connectors as well as causing sustained arcing. Both significant heating and arcing represent an ignition source which may lead to the occurrence of fires within the vehicle engine compartment.

Figure 1: Simplified schematic of a typical fuse protected transit vehicle start and charging system
EXPERIMENTAL SIMULATION OF FAULTS

Damage Cables Shorting to Chassis
A schematic of the experimental apparatus employed to simulate intermittent shorting of damaged cables to the vehicle chassis is shown below in Figure 2 and the practical implementation is shown in Figure 3. Additional details of the experimental test hardware are shown below:

- Cable Under Test: AWG 2/0 EPDM insulated battery cable
- Fuse: 32V, 300A Cut-Off Relay: Bosch 0 333 301 010, battery cutoff/changeover relay
- Batteries: 2 x Numax 663, commercial vehicle battery, 12V 110AH
- Current Transducers: LEM HTFS 800P, Hall effect current transducer, +/-1200A full scale

One end of the electrical cable under test was connected to the positive (+ve) terminal of the battery pack via a 300A slow blow fuse and a cut-off relay. The other end of the cable was connected to the negative (-ve) terminal of the battery pack via a 0.2Ω fixed load. An intermittent short to a grounded vehicle chassis was simulated by driving a contact plate up or down with a double acting pneumatic cylinder, to make or break contact with a section of the cable from which the insulated sheathing had been removed. Control of the pneumatic cylinder was achieved using two solenoid valves controlled via a LabView™ interface. The contact plate was connected to the -ve terminal of the battery via either an interconnecting cable with an associated resistance of approximately 0.001Ω or a fixed load resistance of 0.2Ω. The fixed load was introduced in an attempt to replicate an intermittent resistive short.

Two current transducers, I1 and I2, monitored the currents at the locations shown in Figure 2. The voltage was monitored at four points, V0, V1, V2 and V3 as shown. The voltage and current signals were acquired and logged at 1.0kHz using an NI 6008 USB data acquisition device in conjunction with LabView™ software. The temperature of the cable was monitored by 1mm diameter metal sheathed type K thermocouples, fixed to the cable with stainless steel cable ties at the locations shown in Figure 3. The data from these thermocouples was logged and recorded using an IMC Spartan™ datalogger at 5Hz.

Figure 2: Schematic of the experimental apparatus employed to simulate damaged cables shorting to the vehicle chassis
Loose Connections
The experimental apparatus employed to simulate damaged cable sheathing was adapted to simulate loose connections. These adaptations are shown in Figure 4 and Figure 5. Both static and chattering loose connections were simulated.

The terminal lug of the cable was loosely attached to a bolt fixed to a metal plate. This metal plate is connected via a fixed $0.2\Omega$ load to the -ve terminal of the battery. In this experiment the contact plate was driven up or down with a 50% duty cycle to chatter the cable terminal lug at the required frequency. The contact plate was electrically isolated from the conducting cable and connection under test.

Thermocouples T1 and T2 were attached as shown in Figure 5 to measure the temperature of the contact lug and the cable in close proximity to the lug. Thermocouples T3 to T8 were left in their original locations. The current and voltage were measured at the locations shown in Figure 4.
Figure 5: Experimental apparatus employed to simulate loose connections

RESULTS

Damage Cables Shorting to Chassis

Table 1: Tests conducted to simulate damaged cables shorting to the vehicle chassis

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Description</th>
<th>Contact interval</th>
<th>Dwell Interval</th>
<th>Test Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A1</td>
<td>Intermittent Short / Parallel Arc to ground</td>
<td>0.2s</td>
<td>5.0s</td>
<td>300s</td>
</tr>
<tr>
<td>Test A2</td>
<td>Intermittent Short / Parallel Arc to ground</td>
<td>0.2s</td>
<td>2.7s</td>
<td>300s</td>
</tr>
<tr>
<td>Test A3</td>
<td>Intermittent Short / Parallel Arc to ground</td>
<td>0.2s</td>
<td>1.2s</td>
<td>300s</td>
</tr>
<tr>
<td>Test A4</td>
<td>Intermittent Short / Parallel Arc to ground</td>
<td>0.2s</td>
<td>0.7s</td>
<td>300s</td>
</tr>
<tr>
<td>Test A5</td>
<td>Intermittent Short / Parallel Arc via 0.2Ω load</td>
<td>0.2s</td>
<td>0.7s</td>
<td>300s</td>
</tr>
<tr>
<td>Test A6</td>
<td>Intermittent Short / Parallel Arc via 0.2Ω load</td>
<td>0.2s</td>
<td>0.4s</td>
<td>300s</td>
</tr>
</tbody>
</table>

Figure 6: Temperature recorded at the four thermocouple locations that showed the highest increase during Test A4
Figure 7: Average of recorded values of T2 & T3 as a function of time during tests A1 to A6

Figure 8: Current readings during the first 2.5 seconds of Test A4

Figure 9: Voltage readings during the first 2.5 seconds of Test A4
Figure 10: Current readings during the first 2.5 seconds of Test A6

Figure 11: Voltage readings during the first 2.5 seconds of Test A6

Loose Connections

Table 2: Tests conducted to simulate loose connections

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Frequency</th>
<th>Test Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test B1</td>
<td>Static</td>
<td>4.5 minutes</td>
</tr>
<tr>
<td>Test B2</td>
<td>2Hz</td>
<td>12 minutes</td>
</tr>
<tr>
<td>Test B3</td>
<td>5Hz</td>
<td>5 minutes</td>
</tr>
</tbody>
</table>
Figure 12: Temperature recorded at the two thermocouple locations that showed the highest increase during Test B1

Figure 13: Temperature recorded at T1 as a function of time during tests B1 to B3

Figure 14: Current readings during the first 5.0 minutes of Test B1
Figure 15: Voltage readings during the first 5.0 minutes of Test B1

Figure 16: Current readings during the first 5.0 minutes of Test B3

Figure 17: Voltage readings during the first 5.0 minutes of Test B3
DISCUSSION

Damage Cables Shorting to Chassis

A list of the tests conducted to simulate intermittent short/arcs arising from damaged cable sheathing is shown in Table 1. A contact interval of 0.2s was determined experimentally to be the maximum contact time for which a repeatable fault could be generated without blowing the 300A fuse. The temperatures recorded at the four thermocouple locations that showed the largest increase during test A4 are shown in Figure 6. At all other thermocouple locations the recorded temperature increase was negligible over the duration of the test. In all tests the maximum temperature occurs at T2 and T3, either side of the fault location. The average of the temperature recorded at these two locations is shown in Figure 7.

Localised parallel arcing was visually observed as the contact plate made and then broke contact with the cable. Locally this generates an extremely high temperature event which caused serious damage to the cable. The temperature was high enough to cause melting of the copper cable and the ejection of molten fragments of metal was observed. It is the presence of arcs and molten fragments of metal which are considered to represent a fire risk.

During all tests the highest level of heating of the cable is observed at T2 and T3. An increase in temperature at locations T7 and T8 was also observed. T7 was located close to the fuse and T8 was located close to the positive battery connection. Both of these locations coincided with localized restrictions in current flow. Test A4 is the most extreme case having the highest voltage and current and shortest dwell interval. Even in this extreme case, the temperature of the cable did not exceed 100°C even for a continuous fault occurring over a 5 minute period.

A linear heat detector in close proximity to, and run along the length of the cable will always be in close proximity to any ignition sources and as such will provide the fastest response in the event of a fire. However, since no significant heating of the cable or its surroundings occurs this linear heat detector will not provide early pre-ignition detection of these types of event.

The current and voltage during the first 2.5 seconds of test A4 are shown in Figure 8 and Figure 9 respectively. The current and voltage data recorded during test A6 are shown in Figure 10 and Figure 11 respectively. The electrical characteristics associated with this type of fault are highlighted by the current and voltage measurements recorded during tests A4 and A6 shown in Figure 8 to Figure 11. The main characteristics for these types of faults are an anomalous increase in current and a large differential current measured between locations either side of the fault.

Simply looking for an anomalous increase in current would require a prediction of the normal running conditions to correctly identify a fault condition. For example large current spikes are a normal during startup and the fault detection system would need to account for events such as these. Faults with a resistive path to ground, as exemplified by test A6, may be particularly difficult to distinguish since the anomalous increase in current may be within the normal operating parameters of the cable and fuse.

A more reliable method may be monitoring for differential currents between the two ends of the cable and this has been described in detail in previous work on this subject.[8] This is a reliable method with a minimal risk of false alarm that can provide a zone of protection between the two current monitoring points. The practical implementation of this approach may however prove challenging in an environment where cables are routinely connected and disconnected in the performance of maintenance operations.

Loose Connections

A list of tests conducted to simulate loose connections is shown in Table 2. The temperatures recorded at the two thermocouple locations that showed the largest increase during test B1 are shown in Figure 12. At all other thermocouple locations the recorded temperature increase was negligible over the
duration of the test. The form of this temperature distribution is representative of the form of the temperature distribution recorded during test B1, B2 and B3. In each test the maximum thermocouple temperature occurred at T1. The temperatures recorded at T1 for all tests are shown in Figure 13. In all cases significant localised heating of the cable terminal lug and the cable close to the loose contact was observed. The high level of heating at the point of contact results in the cable terminal lug glowing red hot. In the case of chattering loose connections, significant arcing was also seen.

Over a period of several minutes the temperature recorded at point T1 close to the cable terminal lug steadily increases to temperatures in excess of 300°C. A slight increase in temperature was recorded at point T2. No significant heating occurred at any other point along the cable. In addition, after several minutes thermal decomposition and pyrolysis of the cable coating was also observed close to the contact. The high temperatures associated with these events suggest that correctly installed heat detectors may provide pre-ignition detection of these events. Due to the extremely localized nature of this heating event any heat detector must be in close proximity to, and preferably in contact with, the cable connector if it is to provide early, pre-ignition detection.

The current and voltage during the first 4.5 minutes of test B1 are shown in Figure 14 and Figure 15 respectively. The current and voltage during the first 2.5 seconds of test B3 are shown in Figure 16 and Figure 17. The electrical characteristics associated with this type of fault are highlighted by the current and voltage measurements recorded during tests B1 to B3 shown in Figure 14 to Figure 17. The main electrical characteristics of this type of event are an unusually high potential difference between the two ends of the cable prior to the series load. This is due to the increased resistance introduced by the loose connection. In this case no significant anomalies in the differential current are observed.

For loose connections current monitoring is unlikely to be successful however, measurement of the potential difference along the cable prior to the series load could provide a reliable means of pre-ignition detection of these faults. However, as with differential current sensing, the practical implementation of this type of detection scheme may prove challenging.

CONCLUSION

We have successfully simulated electrical cable faults which persist over a prolonged period in a fuse protected starting and charging system and characterised the thermal and electrical nature typical to these faults. This included simulation of both low current faults in the form of loose connections and transient high current events faults associated with intermittent shorting of damage cables to the vehicle chassis.

Intermittent shorting of damaged cables to the vehicle chassis is characterised by arcing with an associated ejection of molten fragments of metal. Due to the extremely localised nature of the arcing event no significant heating of the cable or its surroundings occurs. The main electrical characteristics for these types of faults are an anomalous increase in current and a large differential current measured between locations either side of the fault.

Heat detection is unlikely to be successful in providing pre-ignition detection of these events. However, a linear heat detector in close proximity to and run along the length of the cable will provide the fastest response in the event of a fire. Early/pre-ignition of these faults may be possible through current monitoring but the practical implementation of this type of detection scheme may prove challenging.

Loose connections present a fire risk due to significant heating of the cable terminal lug and also series arcing as a loose connection makes and breaks contact of a cable under load. Any heat detector must be in close proximity to and preferably in intimate contact with the cable connector to provide pre-ignition detection of these events. The occurrence of a high potential difference between the two ends of the cable measured at locations either side of the fault may also provide early detection of
loose connections however. As with, current sensing the practical implementation of this type of detection scheme may prove challenging.

Pre-ignition detection of loose connections faults may be best addressed with a heat detector whereas the pre-ignition detection of intermittent shorting to the vehicle chassis may be best addressed by current monitoring. As such the optimum choice for pre-ignition detection of these events is a combination of these two approaches.

If this is impracticable an alternative approach based solely on heat detection may be employed to provide early detection of fires arising from intermittent shorting and pre-ignition detection of loose connection faults. On detection of a fault condition it is imperative to disconnect the electrical supply to remove the ignition source and in some instance it may also be appropriate to deploy a fire extinguisher. This may be achieved in practice by locating a linear heat detector in close proximity to and run along the length of the cable. In addition heat sensing in close proximity, or preferably in intimate contact with the connection point, provides fast pre-ignition detection of loose connection faults.

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Fire Experiments of Carrier loaded FCV in Full-Scale Model Tunnel – Estimation of Heat release rate and Smoke Generation Rate -

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ABSTRACT

The present paper describes the estimation of heat release rate and smoke generation rate for fire of carrier loaded with vehicles in tunnel by CFD simulation and full scale tunnel fire experiments. The entire heat release rate was estimated by superimposing those of divided parts in exact timing. Additionally, fire of carrier loaded with 8 vehicles was investigated by extending this method.

KEYWORDS: Tunnel Fire, FCV, Heat Release Rate, Smoke Generation Rate, 3D-CFD

INTRODUCTION

In recent years, fuel cells (FC) are attracting attention as a new energy technology. To promote the use of FC, the Japanese government has investigated various regulations, one of which is the restriction on the transportation of hazardous materials through undersea tunnels and long tunnels. The quantitative restrictions are less than 200 L of inflammable liquid gasoline, less than 60 m³ or 120 L vessel volume of inflammable hydrogen gas, natural gas, etc., and less than 600 kg of liquefied gas. Although such regulations exist, the influence of fire caused by accident of a truck carrying fuelled FC vehicles on tunnel structure and evacuation environment has never been investigated. Therefore, in this study, fire experiments of carrier loaded with vehicles were held by using full scale tunnel in Japan Construction Method and Machinery Research Institute. Numerical simulations was also conducted to examine the heat release rates.

In the experiments, it was assumed that the fire occurred near the carrier and spread to the carried vehicles. Fire characteristics were investigated for various amounts of fuel in the carried vehicles. The fuel of the vehicles was assumed to be compressed hydrogen, as defined in the vehicle safety standard. The basic principles of the safety standard are as follows:

1. Hydrogen gas must not leak. The gas leaks, if occurred, must be immediately detected and be intercepted. The leaked gas must be immediately removed.
2. The gases including hydrogen must be discharged safely.

Since the technical requirements for the structure and performance of gas vessels, main stop valves, vessel check valves and safety valves should satisfy the standard, the carried vehicles are not considered as the initial source of fire by collision. The assumed scenario in the experiments was; 1) a fire was caused by the accident of another gasoline vehicle, and spread to the carried vehicles. 2) The vessel safety valves of the hydrogen tanks on the carried vehicles were then activated by heat, causing hydrogen discharge as a jet, which finally caught fire. The tested vehicles put on the carrier vehicle were loaded with hydrogen cylinders.
EXPERIMENT AND SIMULATION

The experimental tunnel is 80 m long, 12.4 m wide and 7.46 m high, and is horseshoe shaped. In the simulation, the tunnel was located in a computational wind tunnel of 120 m long, 20 m wide and 20 m high (see Figure 1). The origin of the Cartesian coordinate system is located at the centre of the left portal, with $x$ in the tunnel longitudinal direction (positive direction being from left to right portals), $y$ in the transverse direction, and $z$ in the vertical direction ($z = 0$ m at the floor). A uniform velocity of 2 m/s at inlet and free flow conditions at outlet of the wind tunnel were applied to simulate the longitudinal stream in the experimental tunnel generated by jet fans. The heat release rate used in the calculation was estimated from the experimentally obtained temperature variation near the fire as follows. In the experiments, longitudinal wind influenced the natural wind by some transverse winds was assumed to enter the tunnel; the transverse wind was ignored in the simulation due to the calculation load. The tunnel portals were in the free outflow condition. The horseshoe shaped tunnel space was divided into equal sections and the rectangular tunnel was divided into unequal sections to reduce the calculation load. The cell width was investigated; the total number of cells was 320 thousand ($181 \times 57 \times 31$ cells), each width in the horseshoe tunnel was $dx = 0.5$ m, $dy = 0.334$ m, and $dz = 0.355$ m, respectively. The centre of the fire source was located at $x = 35$ m and $y = -3$ m. In the simulation, there was no fire pan or carrier, but heat source was installed at the position corresponding to fires.

The highly quantitative 3-D CFD code, Fireles, using a LES turbulence model developed in 1998 was used. The reproducibility of smoke spreading, backlayering and descending calculated by Fireles has been confirmed by comparison with fire experiments in full-scale tunnels and a model-scale tunnel [1], [2].

Figure 1 Calculating area of tunnel fire experiments.
HEAT RELEASE RATE

Gasoline Vehicle (case 1)

Four vehicles, each of which contained 50 L of gasoline, burned in the experiment. When a passenger car containing 30 L of gasoline burns completely, 7 GJ of heat is produced [3]. The complete combustion of 20 L gasoline generates gross calorific value of approximately 690 MJ. The gross calorific value of the vehicle containing 50 L of gasoline was determined as the sum of these values, approximately 7.7 GJ. With assumption that convection component becomes 50% of the gross calorific value as it is 40–60% in case of a gasoline pool fire, the convective calorific value of the vehicle containing 50 L of gasoline was 7.7 GJ × 0.5 = 3.85 GJ ≈ 4 GJ.

The total gross calorific value of the pool fire which was substitution for initially crashed car was 1211 MJ. The convective calorific value, 50% of the total gross calorific value, was therefore approximately 600 MJ. The heat release of the tires was zero because they did not burn in the experiment.

Figure 2 shows the profile of the maximum temperature rise time at \(x = 60\) m and \(z = 6\) m. The time profile curve of heat release rate was assumed to be proportional to that of temperature between 0 to 2700 s with integrated value 16.6 GJ. The result of the heat release rate curve is plotted as grey line on the right vertical axis. Several blocks of heat source ignited sequentially had each heat release curve. Figure 3 shows vertical distributions of the temperature and smoke density at \(x = 10\) m, 60 m and 70 m. These figures show that the experimental data (dots) and the simulation data (solid lines) quantitatively match each other.

Inflammable Gas Vehicles (case 2, 3, 4)

The burning parts are divided into carried vehicles without fuel, fuels (gasoline, hydrogen and CNG), rear wheels, driver's seat of the carrier, and a 1 m\(^2\) pool fire, and the individual heat release rate of each part was determined. The total heat release rate curve was obtained by superimposing at the timing of the fire spreading each other.

The heat release rate of four ignited vehicles on the carrier was determined by superimposing heat release rates of a carried vehicle, a jetting flame igniting CNG or hydrogen, and so on. The heat release rate curves of the following parts are shown in Figs. 4 to 8:

1. One loaded vehicle without fuel
2. Fuel (gasoline, hydrogen and CNG)
3. Rear wheels of the carrier
4. Driver's seat of the carrier
5. Pool fire

Regarding the vehicle body, the heat release rate was obtained by dividing it into one vehicle and fuel. The gross calorific value of a passenger car combusting completely is 7 GJ [3], and the gross calorific value of 30 L of gasoline is 30 L × 34.6 MJ/L = 1038 MJ ≈ 1 GJ, that is, the gross calorific value of a vehicle without gasoline is 6 GJ. The convective thermal component of a passenger car containing 30 L of gasoline combusting completely is 3–3.9 GJ, which is 42–56% of the gross calorific value when combusting completely [3]. In the present study, the convective thermal component of a vehicle body was assumed to be 50% of complete combustion, i.e. 3 GJ. The heat release rate curve from ignition to completion of combustion is proportional to the square of time \(t\), and the maximum heat release rate of 3 MW continued to 900 s as shown in Fig. 4.

There were four cases of one vehicle containing various fuels: case 1: 50 L of gasoline, case 2: 12.55 m\(^3\) of CNG, case 3: 17.6 m\(^3\) of low-pressure hydrogen, and case 4: 43.6 m\(^3\) of high-pressure hydrogen. The heat release rates in complete combustion are: 1.73 GJ for gasoline, 0.53 GJ for CNG, 0.19 GJ for low-pressure hydrogen, and 0.47 GJ for high-pressure hydrogen, based on the experimental results.
Figure 2  Temperature rise and Heat release rate.

In the case of gasoline, the convective thermal component was assumed to be 50%, whereas CNG, and low- and high-pressure hydrogen evaporate and burn, and so the convective thermal component is assumed to be more than 50%. Hence, the convective thermal component of CNG, and low- and high-pressure hydrogen was assumed to be 80%, 0.4 GJ for CNG, 0.15 GJ for low-pressure hydrogen, and 0.4 GJ for high-pressure hydrogen. The heat release rate curve from ignition to completion of combustion is proportional to time; the maximum heat release rate is 4 MW for CNG, 1.5 MW for low-pressure hydrogen and 4 MW for high-pressure hydrogen, which continued to 80 s as shown in Fig. 5. To determine the heat release rate of the carrier, it was divided into the driver's seat and the rear and front wheels. In the present study, the left and right wheels were considered to be close enough to be treated as one burning object, whereas the heat release rates of the rear and front wheels...
were treated separately. The carrier has eight rear wheels and two front wheels, giving a total of 10. Assuming that each wheel weighs 28 kg and has a calorific value of 32.9 MJ/kg, or approximately 0.92 GJ/wheel, then the calorific value of the eight rear wheels is approximately 7.36 GJ. Assuming that the convective thermal component is 50%, the convective calorific value is approximately 3.68 GJ. The heat release rate curve from ignition to completion of combustion is proportional to time, and the maximum heat release rate of 2.4 MW continued to 1200 s as shown in Fig. 6. The calorific value of the front wheels and the driver's seat are 3 GJ, which is nearly the same as that of the body. The heat release rate curve from ignition to completion of combustion is proportional to the square of time $t^2$, and the maximum heat release rate of 2.4 MW continued to 900 s as shown in Fig. 7. 35 L of gasoline was consumed in the pool fire, which has a calorific value of approximately 1.2 GJ. Assuming that the convective thermal component is 50%, the convective calorific value is approximately 0.6 GJ. The combustion time of the pool fire was before and behind 6 min depending on the experimental case, therefore, the combustion time was assumed to be 6 min in this study. The heat release rate curve from ignition to completion of combustion is proportional to time, and the maximum heat release rate of 2 MW continued to 270 s as shown in Fig. 8.

First, the maximum heat release rate of 3 MW was reached at 150 s, continued till 1050 s, then the fire was extinguished at 1200 s.

Note: In case 2, corresponding to the experimental results, the maximum heat release rate was 4 MW.

The spread time was defined to be 120 s and the fuel was assumed to start spreading at 240 s. The maximum heat release rate was reached at 20 s from when the fire started to spread, and continued till 100 s. After 20 s from this spreading finished.
Note: There is only a small difference of 10% in the heat release rate between CNG and high-pressure hydrogen, so their heat release rates were assumed to be the same.

![Figure 6](image6.png)

*Figure 6  Rear wheels of the carrier.*

The rear wheels burned for a long time; the combustion time of the wheels was longer than that of the other items. The time taken to reach the maximum heat release rate of 2.4 MW was 300 s, and continued till 1200 s. After 300 s, the fire started to extinguish gradually.

![Figure 7](image7.png)

*Figure 7  Driver's seat of the carrier.*

First, the maximum heat release rate of 3 MW was reached at 150 s, continued till 1050 s, then the fire was extinguished at 1200 s.
First, the maximum heat release rate of 2 MW was reached at 60 s, continued till 300 s, then the fire was extinguished at 360 s.

Figures 9, 10 and 11 show the combustion area and heat release rate between numbers and each area respectively. Figure 10 shows the heat release rate for each part in case 2, and Fig. 11 shows that in case 4. The horizontal axis is elapsed time and the vertical axis is convective heat release rate; the heat release rate curve in case 2 is shown in Fig. 10. In case 2, the maximum heat release rate of the carried vehicles' body of 3 MW was used in some preliminary calculations, however, the experiment did not be simulated, the calorific value of three vehicles was 4 GJ, which the last burned vehicle was except in 4 vehicles, maximum heat release rate was determined 4 MW. Additionally, some part of the heat release rate became high locally, because the fuel heat release rate was added to the heat release rate of the vehicles' body. Actually, it is not shown that the heat release rate of the combustion area rose from 4 MW to 8 MW, but 4 MW heat occurred on 4 MW combustion area. Since this, the protrusion is same reason. Only in case 2, the driver's seat of the carrier burned, and the driver's seat was added to the heat release rate curve. Figure 11 shows the heat release rate curve in case 4. No. 6 was not used in cases 3 and 4 not to the driver's seat burned.

The spreading order was No. 1, 2, 3, 5 and 4. The experimental results were used for the timing of spreading, but were corrected accurately when there were big differences from the experimental heat release rate. A comparison between the experimental results and the total heat release rate by adding each part of the heat release rate at each time is shown in Fig. 12 for case 2 and Fig. 13 for case 4. Parts of the heat release rate rose rapidly, having good corresponding is shown these figures.

**SMOKE GENERATION RATE**

Optical smoke density was measured at 15 points on the grid of $x = 10\text{ m}, 60\text{ m},$ and $70\text{ m},$ and $z = 1.5\text{ m}, 3\text{ m}, 4.5\text{ m}, 6\text{ m}, 7.5\text{ m}.$

The experimental results of smoke generation rate and smoke generation ratio are summarized in Table 1, where $Q_{\text{max}}, M_{\text{max}}, S_{\text{max}},$ and $\beta$ denote followings:

- $Q_{\text{max}}$: Maximum theoretical heat release rate [MW]
- $M_{\text{max}}$: Maximum gasoline reducing rate [g/s], each case of heat release rate converted to pool fire.
- $S_{\text{max}}$: Maximum smoke generation rate [g/s]
- $\beta$: Smoke generation ratio = $S_{\text{max}}/M_{\text{max}}$ [-]

Figure 14, 15, 16, and 17 show the optical smoke density obtained by experiment and simulation; the horizontal axis is the optical smoke density and the vertical axis is the height from the floor. The experimental smoke generation rate was 1.4–3.4 g/s; comparing this value with the smoke
HEAT RELEASE RATE IN THE CASE OF 8 LOADED VEHICLES

By dividing the heat release rate into parts and using each part of the heat release rate at each time, the heat release rate was investigated in the case of increasing the number of carried vehicles. The calorific value of one vehicle and the combustion time was the same as in the case of four carried vehicles, all the materials are assumed to burn out, that is, comparing with three cases, which are:

Case A: Eight gasoline vehicles burn, and one vehicle contains 50 L of gasoline.
Case B: Eight FCVs burn, and one FCV contains 60 m³ of fuel.
Case C: Large bus of heat release rate [2]

As shown in Fig. 18. Figure 19 shows the temperature distribution obtained by 3-D CFD simulation for case B. The tunnel is rectangular, with no slope, natural wind velocity of 2 m/s, and the time is 10 min.
Figure 11  Parts of Heat release rate in case 4.

Figure 12  Comparison between the experimental result and the simulation heat release rates in case 2.

Figure 13  Comparison between the experimental result and the simulation heat release rates in case 4.

Table 1  Smoke generation rate and ratio

<table>
<thead>
<tr>
<th>case</th>
<th>$Q_{\text{max}}$ [MW]</th>
<th>$M_{\text{max}}$ [g/s]</th>
<th>$\beta$</th>
<th>$S_{\text{max}}$ [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Gasoline</td>
<td>11.0</td>
<td>125.0</td>
<td>0.0274</td>
<td>3.43</td>
</tr>
<tr>
<td>2 CNG</td>
<td>17.0</td>
<td>195.0</td>
<td>0.0097</td>
<td>1.88</td>
</tr>
<tr>
<td>3 Hydrogen (low)</td>
<td>11.0</td>
<td>125.0</td>
<td>0.0114</td>
<td>1.43</td>
</tr>
<tr>
<td>4 Hydrogen (high)</td>
<td>11.0</td>
<td>125.0</td>
<td>0.0142</td>
<td>1.78</td>
</tr>
</tbody>
</table>
Figure 14  Vertical profile of optical smoke density (case 1).

Figure 15  Vertical profile of optical smoke density (case 2).

Figure 16  Vertical profile of optical smoke density (case 3).
Figure 17  Vertical profile of optical smoke density (case 4).

Figure 18  Heat release rate distribution.

Figure 19  Temperature distribution by the simulation. The tunnel is rectangular, with no slope, natural wind velocity of 2 m/s, and the time is 10 min in Case B: Eight FCVs burn, and one FCV contains 60 m$^3$ of fuel.)
CONCLUSIONS
The heat release rate and smoke generation rate of a carrier loaded with vehicles filled with fuel were estimated both by fire experiments and numerical simulations for a full-scale model tunnel. The inflammable parts were divided into several parts, and heat release rate curves were determined for each part. The total heat release rate was estimated by superimposing the curves at the same timing. In addition, a fire of a carrier loaded with eight vehicles was investigated by extending this method. The following results were obtained:
1. The distribution of the heat release rate of the fire of the carrier loaded with eight vehicles filled with gasoline (total of 320 L) was smaller than that of a large bus fire.
2. In the case of a fire of the carrier loaded with eight FCVs (with $8 \times 60$ m$^3$ of hydrogen), compared with a large bus fire, the heat release rate was larger after 10 minutes and the maximum heat release rate was 1.5 times greater. However, the combustion time was short and the total calorific value of heat convection was almost the same.

REFERENCES
Rapid fire spread in a bus depot fire

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ABSTRACT

In a bus depot fire in Germany 69 buses were destroyed in 2011. The fire started in one bus. Investigations after the fire showed that most likely a technical defect was the cause of the fire. The fire spread very rapidly to the other buses. The bus depot was in a building, which was also completely destroyed. In recent years several fires occurred in bus depots in Germany. All these fires showed the same rapid fire development, though the 2011 fire was the most severe with a property loss of about 22 million Euro. Operation interruption also is a key issue after these fires. The fire development and fire spread was investigated numerically after the fire with FDS 5 (NIST). The predicted fire spread was in good agreement with the timeline, which could be reconstructed after the fire: a video was made by a monitored location nearby. Reasons for the rapid fire development and spread were investigated as well as fire safety measures in the building as smoke and heat ventilation. Extensive experimental investigations of bus materials showed that these materials have poor fire performance compared with materials of other transport vehicles, e.g. trains. The poor fire performance of the bus materials affect directly the fire and smoke development in bus fires. As well as the real cases as the numerical calculations show that is nearly impossible to save the building or other buses in a building, which is used as a bus depot if one bus is already fully in fire. Often the bus fires start in the engine compartment. Onboard suppression systems can significantly reduce the hazard of these fires. Different fire safety measures are discussed and recommendations are derived from the investigations to reduce the hazard of bus depot fires.

KEYWORDS: bus depot fires, numerical simulations, FDS, bus interior material

INTRODUCTION

The severe bus depot fire with the loss of 70 vehicles in one event in Germany in 2011 showed that bus depots should not planned like other industrial buildings without taking into account the special requirements a bus depot with a lot of busses in one building need. The development of the bus depot fire was investigated and the fire safety measures were assessed. Recommendations how to improve the fire safety of bus depots are given as the result of the investigations of Provinzial Insurance and BAM.

BUS DEPOT FIRES

A complete parking hall with 69 busses and other vehicles was lost in one fire in December 2011 in Bottrop, Germany. The parking hall was built in 1976 and had an area of approximately 5000 square meters. The building was a steel reinforced concrete construction. The roof construction contained structural decking elements, insulation and bitumen sheets. The roof contained skylights as well as integrated smoke and heat extraction [1], [2].

The fire developed extremely fast and left the fire service with very limited options to act although the
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fire service responded quickly to the emergency call. The fire was probably caused by an electronic defect in a battery box, which was below the engine area of one of the parked busses. Arson has been excluded by the investigators after extensive research. The amount of property loss was estimated as 22 million Euros, approximately 85% of the total amount had to be used to replace the busses [1], [2]. The parking hall was insured by the German insurer Provinzial, which is based in North Rhine Westphalia. The serious fire was the reason that the insurer made an assessment of all insured bus and tram/train depots. The assessment showed that bus depots were not seen as at major fire risk up to now and the insurer made no special requirements additional to the building regulations.

The assessment showed that the Bottrop case was not the only bus depot fire. Several other bus depots fires occurred in Germany in recent years: In 2007 and 2009 bus depot fires occurred in Heidelberg [3] and Darmstadt [4] and 2013 in Munich [5]. The other cases had less property loss but in all cases the fire started in the engine compartment and the fires developed very fast, the loss of the busses in the building or building section was the result.

In modern busses the engine compartment is crowded and the temperatures are very high [6] - so engine fires will probably occur more often in the future if no fire safety measures will be introduced. The Provinzial assessed not only bus depots but also train/tram depots as well as other parking spaces for public service vehicles like waste removal vehicles. The bus depots in buildings / halls showed the highest risk of severe fires because of the rapid fire development inside the busses. Many investigations on bus interior materials showed that because of low fire safety requirements the bus interior materials tend to burn very quick and release large amounts of smoke and heat.

In several German provinces the building regulations for bus depots are very similar to the regulations for car parks. The assessed bus depot halls had ground areas between 5000 and 12000 square meters and are very different from car parks.

In all assessed depots one or more buildings as parking area for the busses exist, additionally there are facilities for cleaning, maintenance, storage and staff rooms. The fire safety measures were on different levels. Some depots have several fire sections with fire walls but especially the older depots often have only one section and no separation of the bus parking area and the other facilities. The buses are normally parked with very limited space between the busses to get large numbers of busses in the depot. Often the distance from one bus to another is only 40 to 50 centimetres.

For newer depots fire safety concepts exist but in all assessed cases the extreme fire load of the buses were not taken into account. An additional difficulty is the containment of the well burning interior bus material in water safe body work. A bus obviously has to be safe against rain but that means that the positive effect of sprinklers is at least questionable.

The fire safety measures which were found in the assessment of the bus depots by the Provinzial seem not to be promising in preventing the total loss of the bus depot and the busses. It is necessary to develop fire safety measures that take the rapid fire development into account as well as the water repelling body work and the fact that most bus fires start in the engine compartment [7-10].

NUMERICAL SIMULATIONS OF BUS DEPOT FIRES

On the basis of a BAM project on fire safety of busses which was funded by the German Ministry of Transport a new model for a city bus was developed. First only one bus with typical bus interior material was modelled, Figure 1. The numerical simulations were performed by using the Fire Dynamics Simulator (FDS, version 5.3), developed by NIST. In the previous study a lot of experimental investigations had been performed on bus interior materials and bus seats and a whole bus. It could be shown that the fire safety requirements for bus interior materials are on a significant lower level than the fire safety requirements for train materials. As a result bus fires develop very fast and produce large amounts of toxic smoke [7-12].
In Figure 2 the rapid development of the fire is shown. The fire was assumed to have started in the engine compartment.

The next step was the numerical modelling of a bus row, Figure 3 and Figure 4. The rapid smoke filling of the bus depot hall can be clearly seen. The fire develops not only very fast inside the first bus but also spreads rapidly from one bus to the next. The smoke layer under the ceiling is very hot - the fire can also spread to other busses via the hot smoke gas layer.
The last step in the numerical simulation was the modelling of the bus depot, Figure 5. It was assumed that the bus in the left corner in the front started the fire by an engine fire. The fire spread very fast from one bus to the next, through the hot smoke gas layer the fire also spread to busses which were farer away from the first burning bus. Smoke extraction system were included in the roof. But it was not possible to reduce the hot smoke gas layer significantly. The burning of the complete area could not prevented by the smoke and heat extraction systems.

![Figure 5 - Numerical simulation of the bus depot fire.](image1)

**FIRE SAFETY CHALLENGES IN BUS DEPOTS**

The following challenges for the development of fire safety measures for bus depots are important:

- The fire load in busses because of the used interior materials is extremely high and normally the metal body work prevents suppression of the fire with sprinklers or other suppression systems.
- The space between the parked busses is normally extremely limited.
- The fire development in a bus is extremely rapid (a fully developed fire within 2 or 3 minutes).
- The bus fires release large amounts of heat and smoke.
- Reduction of the fire load in the busses will take time.
- The extraction of smoke and heat with extraction systems is not feasible.

**CONCLUSIONS AND RECOMMENDATIONS**

The investigations of the bus depot fire and the previous investigations about bus fires show clearly that a further enhancement of the fire safety requirements for busses is necessary to prevent future losses of lives and property. The still significant gap between requirements for bus interior materials in contrast to train materials has to be closed.

Because most of the bus fires start in the engine compartment suppression systems for the engine compartment have shown to be very effective. In Sweden the total loss of busses has decreased to nearly zero after most of the busses are equipped with engine suppression systems. The available time for escape for passengers is significantly increased when an engine suppression system is installed.

Fire safety concepts of bus depots have to take into account the above mentioned challenges. The bus parking hall must have either building sections with fire walls and a maximum number of 20 busses in
one section or a suppression system at the location where the most bus fires start: in the engine compartment. 20 busses are an insurable and organisational manageable number.

The measures of the fire safety concepts of the assessed bus depots are not adequate to prevent a total loss of the property like it happened in the severe fire in the bus depot in Bottrop, Germany in 2011 where 70 vehicles were lost in one fire. The experimental investigations in the previous projects as well as the assessment of the bus depots and the investigation of bus depot fires with numerical simulation showed that the bus parking halls are not comparable with car parks and that the usual smoke and heat extraction systems are not able to reduce the hot smoke gas layer enough to prevent a fire spread through the whole depot with the loss of all vehicles. Also the rain safe body work of the busses prevents an effective suppression of a fire by water which is applied from above (like a sprinkler).

The most effective and cost-effective measure is the equipment of the busses with engine suppression systems, which are connected to an alarm system of the bus depot. With this measure a large number of fires can be suppressed at the fire origin and the early alarm gives time for further actions. For operating busses the suppression systems also provides additional escape time for the passengers, which save lives.

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Simplified approach to predict heat release rate curves from multiple vehicle fires in car parking buildings

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ABSTRACT
A risk-based study of passenger vehicle fires in car parking buildings is on-going at the University of Canterbury. This paper discusses a simplified approach to obtaining heat release rate curves for multiple passenger vehicle fires. The approach employs the superposition of two or more probabilistic single vehicle design fire curves where vehicles are categorized by their curb weight and statistical distributions are used to characterize the growth rate, decay rate and peak heat release rate. These single vehicle design fire curves are then used to define regions of likely design fire curves for multiple vehicle fires. In order to assess the robustness of the simplified method, experimental data from a total of seven two-vehicle fires have been compared using the approach. The comparisons show that the simplified approach gives reasonable predictions for the accumulated heat release rate for multiple vehicle fires.

KEYWORDS: heat release rate, multiple vehicles, vehicle classification, parking buildings.

INTRODUCTION
Vehicle fires in car parking buildings can impact on the life safety of the vehicle occupants as well as the building occupants who are the vicinity of the fire. Vehicle fires in car parking buildings can also result in material losses in terms of the vehicles, to the building structure and contents as well as to neighbouring property. Recently there have been several significant fires in car parking buildings involving multiple vehicles and in some cases these have led to fatalities. One of the most serious incidents reported was in 2006 in Gretchenbach, Switzerland where seven fire fighters were killed in an underground car park due to structural failure caused by fire [1]. Again in the same year there was a car park fire incident in Bristol, United Kingdom where 22 vehicles were destroyed and one person died in the occupancy above the car park [1]. Therefore it is prudent to understand the risks of vehicle fires and the need to potentially reduce the probability of a fire starting and/or mitigate the severity if a fire does occur.

This work is part of a larger research investigation into risk-based fire safety of passenger road vehicles in car parking buildings being undertaken at the University of Canterbury. The definition of passenger vehicle used throughout the research is based on the New Zealand Transport Authority (NZTA) which states that it is a motor vehicle constructed primarily for the carriage of passengers, with not more than nine seating positions which include the driver's seating position, and either has at least four wheels or it has three wheels and a gross vehicle mass exceeding one tonne [2]. The research has developed a method of generating multiple vehicle parking scenarios using a risk analysis approach [3]. The research has also compiled data from 41 single passenger vehicle fire experiments from various available sources dating back from the early 1990s up until the 2000s [4]. Recent data from Okamoto et al. [5] adds three more vehicles to the total giving 44 single vehicle fire experiments. The experiments have been categorized into seven vehicle classes by their curb weight according to the ANSI classification system [6] i.e. Passenger Car: Mini, Light, Compact, Medium and Heavy; Minivan/MPV; and SUV and these data have been analysed to produce distributions of peak heat release rate.
**Passenger Vehicle Design Fires**

The design fire is an important concept which can be described as the characterization of the fire typically presented in terms of heat release rate as a function of time \[7\]. Design fires may also include other information such as an estimate of the area of burning and/or smoke and gaseous species production rates which are also typically expressed as a function of time. A design fire is a key component of performance-based design which is an approach adopted as rational means of providing efficient and effective fire safety. The design process gives flexibility to achieve defined objectives provided that safety can be demonstrated. There are guidelines, such as the International Fire Engineering Guidelines \[8\] and the SFPE Engineering Guide \[9\] which specify the tasks required for the design process i.e. defining the project scope; establishing objectives; developing performance criteria; identifying and selecting appropriate design scenarios etc. Therefore, the identification and selection of one or more design fires is deemed as an integral part of the process to ensure that a performance-based design will satisfy its objectives.

Design fires for passenger vehicles are important for fire safety design in car parking buildings and any other related structures which contain vehicles. From previous research by Tohir and Spearpoint \[4\], a detailed analysis was completed in an attempt to determine a reliable approach to characterize a passenger vehicle design fire. Out of the 44 single vehicle fire experiments identified, only 33 experiments have been analysed in detail. The other 11 experiments have been excluded due to incompleteness of the data where the cause was mostly due to the fire being suppressed before it reached its full potential. Table 1 shows the single passenger vehicle classification by curb weight and number of experiments available in each category.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Curb weight</th>
<th>Number of experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car: Mini</td>
<td>1500 – 1999 lbs (680 – 906 kg)</td>
<td>7</td>
</tr>
<tr>
<td>Passenger car: Light</td>
<td>2000 – 2499 lbs (907 – 1134 kg)</td>
<td>7</td>
</tr>
<tr>
<td>Passenger car: Compact</td>
<td>2500 – 2999 lbs (1135 – 1360 kg)</td>
<td>7</td>
</tr>
<tr>
<td>Passenger car: Medium</td>
<td>3000 – 3499 lbs (1361 – 1587 kg)</td>
<td>5</td>
</tr>
<tr>
<td>Passenger car: Heavy</td>
<td>$\geq$ 3500 lbs ($\geq$ 1588 kg)</td>
<td>1</td>
</tr>
<tr>
<td>Minivan/MPV</td>
<td>Unspecified</td>
<td>6</td>
</tr>
</tbody>
</table>

**Characterization of Design Fire Curves**

For this work the focus is on the heat release rate as this is often a key driver for a design analysis and could be sufficient for the determination of fire hazard in car parking buildings. The general features of a single vehicle design fire typically exhibit an incipient phase, growth phase, fully developed phase and decay phase. In this paper, design fires are represented by the combination of a growth and a decay curve. The growth is be defined as a t-squared function such that

\[
\dot{Q}(t) = \alpha_{peak} t^2
\]

where $\dot{Q}(t)$ is the heat release rate as a function of time, $t$ is time from ignition and $\alpha_{peak}$ is the peak method fire growth coefficient. The peak method fire growth coefficient is found by fitting a curve to single vehicle experimental data between ignition and the highest measured peak heat release rate. An exponential fire decay method is used such that

\[
\dot{Q}(t) = \dot{Q}_{max} e^{\beta_{exp} t} \quad (t \geq t_{peak})
\]

where $\dot{Q}(t)$ is heat release rate as a function of time, $\dot{Q}_{max}$ is the maximum heat release rate at time $= 0$, $\beta_{exp}$ is fire decay coefficient and $t$ is time from the peak heat release rate until the fire terminates. Figure 1 illustrates the combination of two equations i.e. Eq. (1) and Eq. (2) to form a single vehicle design fire curve. This approach gives fixed values for the coefficients for each individual experiment but it does not provide any distributions to the coefficient values across the curb weight classifications.
The question is then, how well do these single vehicle design fires produce reliable results for further use? The main objective of this work is to establish a simplified, reliable approach to represent multiple vehicle fire spread scenarios which could be used for the design of car parking buildings. To achieve this objective, comparisons of the simplified approach and seven two-vehicle fire spread experiments found in the literature are undertaken to demonstrate the capability of the approach. The outcome from the comparisons can then be used to produce a reasonable approximation of the heat release rate curve for multiple vehicle fire spread scenarios in an enclosure such as a parking building.

**Simplified Approach**

Although previous research by Tohir and Spearpoint [3] has shown that most fire incidents in car parking buildings around the world involved only a single vehicle, there have also been cases which involved two or more vehicles. Thus, it is useful to establish an approach to creating design fires which is not limited to only single vehicle fire scenarios.

Given the single vehicle design fires, how can they be combined to create multiple vehicle scenarios? There are a number of challenges that need consideration for combining multiple item design fires. Firstly, the ignition time for each item has to be obtained and this can be determined by calculation or obtained from experimental results. Secondly, there are numerous factors which can affect the heat release rate development in an enclosed space such as the burning enhancement due to the incident radiation flux from the hot gas layer and boundary surfaces.

A simplified approach is used here that employs the superposition of two or more single item heat release rate curves. This approach has been previously introduced by Mowrer and Williamson [10] which the concept is given as;

\[ \dot{Q}(t)_{tot} = \sum Q_i \]

where \( \dot{Q}(t)_{tot} \) is the combined total heat release rate of all of the burning items and \( \sum \dot{Q}_i \) is the summation of the heat release rate of each individual item. Mowrer and Williamson noted that the approach was limited by the lack of a methodology to characterize the challenges of multiple item fires which cannot be clearly isolated.

This simplified approach has been chosen here because the creation of a risk-based approach to the design of car parking buildings is already a complex problem and so it is important to keep the level
of detail consistent for each part throughout the whole research project. The approach uses a combination of several key probabilistic components of a single passenger vehicle design fire as explained in the methodology section.

**Multiple Vehicle Fire Spread Experiments**

There are several notable experiments involving multiple vehicle fire spread in which the complete heat release rate curves are reported. The work by Steinert [11] in 1998 and 1999 presents 10 experiments in a study of burning and fire spread to vehicles parked next to each other. There were three experiments with only a single vehicle involved, six experiments in which two vehicles were parked next to each other and a single experiment with three vehicles parked next to each other. In 1997, Joyeux [12] compiled a report of a series of vehicle fire experiments performed in 1995 and 1996. The main objective of this work was to study the heat release rate of vehicles where 10 experiments were conducted for this purpose. The experiments were conducted under a hooded calorimeter to simulate an enclosed car park. Out of the 10 experiments, four experiments involved a single vehicle and the other six involved a pair of vehicles parked next to each other. There is also a report published by the Building Research Establishment (BRE) [1] in 2010 which compiles the results of series of vehicle fire experiments. There were 10 experiments altogether in which four of the experiments involved a single vehicle fire scenario, two experiments involved a two vehicle fire scenario and four experiments involved a three vehicle fire scenario.

At this stage, only scenarios with two vehicles involved are considered for this work. This decision is to ensure that the simplified approach works for simpler scenarios before going to the more complex scenarios that involved three vehicles. The BRE experiments which involved the two vehicles have not been included in this work due to lack of information on the heat release rate curves. Only two of the six two-vehicle experiments presented by Joyeux have been considered due to the completeness of the heat release rate information against time. The selected experiments given by Steinert and Joyeux are compiled where the main parameters which are important for the comparisons are the heat release rate curve and the timeline of the experiment, i.e. the time of each vehicle ignition where in some instances the first vehicle is ignited by an external source at some time after the start of the experiment.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Manufacturer &amp; model of vehicle (ANSI classification)</th>
<th>Second vehicle ignition time relative to first vehicle (min)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Peugeot 309 (Light*) and Limousine Trabant (Mini)</td>
<td>35.0</td>
<td>Steinert, 2000</td>
</tr>
<tr>
<td>2</td>
<td>Limousine Trabant (Mini) and Volkswagen Polo (Light*)</td>
<td>22.5</td>
<td>Steinert, 2000</td>
</tr>
<tr>
<td>3</td>
<td>Limousine Trabant (Mini) and Citroen BX (Light)</td>
<td>12.0</td>
<td>Steinert, 2000</td>
</tr>
<tr>
<td>4</td>
<td>Fiat Ascona (Light*) and Volkswagen Jetta (Light*)</td>
<td>52.0</td>
<td>Steinert, 2000</td>
</tr>
<tr>
<td>5</td>
<td>Limousine Trabant (Mini) and Citroen BX (Light)</td>
<td>28.5</td>
<td>Steinert, 2000</td>
</tr>
<tr>
<td>6</td>
<td>Renault Twingo (Mini) and Renault Laguna (Compact)</td>
<td>10.0</td>
<td>Joyeux, 1997</td>
</tr>
<tr>
<td>7</td>
<td>Renault Laguna (Compact) and Renault Twingo (Mini)</td>
<td>10.0</td>
<td>Joyeux, 1997</td>
</tr>
</tbody>
</table>

* Classification based on year of report / experiment
For each experiment the make, model and the year of manufacture have been used to determine the appropriate curb weight classification for each vehicle. In some cases it has not been possible to directly identify the exact appropriate classification since the year of manufacture was not reported even though the make and model are known. The year of manufacture is necessary as the curb weights of some makes and models vary throughout the vehicle production run. Thus, where the year was not available, a decision has been made to select the appropriate classification by estimating the year of manufacture based on the date of published report or when the experiment was conducted. The details of the seven experiments considered are shown in Table 2.

METHODOLOGY
This section is divided into two main parts where the first part is to establish the distribution curves for the key components of a single passenger vehicle design fire and the second part is to use the simplified approach to compare these curves with the two-vehicle fire experiments.

Fire Growth and Decay Distribution Curves
The fire growth and decay coefficients for each of the 33 single vehicle experiments have been obtained by fitting appropriate curves to the experimental heat release rate data. Figure 2 shows the analysis in terms of fire growth coefficient against log-scaled fire decay coefficient for each classification. It can be seen that the Mini and Light classifications generally show the highest growth coefficients although there is a considerable overlap with the other heavier classifications. The results also suggest that vehicles with higher growth rates also exhibit faster decay rates.

The values shown in Figure 2 are used to establish distribution curves for fire growth and decay for each classification. To process the data sets, the BestFit capability in the @RISK software [13] is used. The outcome of the distribution fitting process is a ranked order of fitting statistics for each potential distribution shape where a smaller value indicates a better fit. For this particular analysis, the selections of distribution shapes are not only based on the ranking of the fitting statistics but also based on the distribution shapes that are commonly used and likely to be available in other software tools for further analysis, and also on selecting consistent distribution shapes for the growth and decay coefficients.

Figure 2 The growth and decay data for the different vehicle classifications.
Explanation of the Simplified Approach

With the distribution shapes for the fire growth coefficient, the peak heat release rate (found previously in Tohir and Spearpoint [4]) and fire decay coefficient for each of curb weight classification in place, a probabilistic design fire can then be formed. To form the design fire probabilistically, a suitable range of limits from the distribution shapes needs to be used. One option is to consider the 5th and 95th percentile values as the border for each distribution meaning most of the possible design values lie in this range. Having limits lower than 5th and larger than 95th percentile would mean that the design curves would encompass almost any possible value in the range and would mean there would be no distinct differentiation between the classification groups. Another range of limits for the distribution shapes is to consider the standard deviation in which is the lower limit gives the 33rd percentile and the higher limit gives 66th percentile. This range of value is smaller than using the 5th and 95th percentiles but is sufficient to cover 66% of the range of possibilities. The upper and lower distribution limit values taken from the three distributions are sufficient to form an envelope of possible design fires for a given curb weight classification where the design fire is formed by the combination of the peak method equation for the growth (Eq. (1)), the exponential method for the decay (Eq. (2)) and a maximum heat release rate.

With the design fire region available for every classification, the comparison with the two-vehicle fire spread experiments results is then performed. However, the comparison requires some further information from the original literature source such as the time of ignition of the first and second vehicle. With the curb weight classification for each experiment known, the design fire region can be superpositioned from the single vehicle design fire curves offset by the ignition times measured in the experiments.

Peacock et al. [14] has introduced a technique to quantify the differences between experimental measurements and model predictions. However, the technique is only applicable for comparison between two distinct single datasets whereas for this work, the comparison is made with the probabilistic region against the single dataset from an experiment. The quantification of the comparison of the design fire region with the experimental data is introduced here as a normalized indicator. Thus, the quantification of the fit is calculated as the percentage of points in the experimental heat release rate that intersect with the design fire region.

RESULTS

Fire Growth and Decay Distributions

Tables 3 and 4 shows the ranked order distribution shapes for the t2 fire growth coefficient and exponential fire decay coefficient for each classification with the exception of Heavy since data is only available from a single experiment.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Mini</th>
<th>Light</th>
<th>Compact</th>
<th>Medium</th>
<th>Minivan/MPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shape</td>
<td>Val.</td>
<td>Shape</td>
<td>Val.</td>
<td>Shape</td>
</tr>
<tr>
<td>1</td>
<td>BG</td>
<td>0.30</td>
<td>W</td>
<td>0.19</td>
<td>G</td>
</tr>
<tr>
<td>2</td>
<td>LL</td>
<td>0.30</td>
<td>T</td>
<td>0.21</td>
<td>E</td>
</tr>
<tr>
<td>3</td>
<td>G</td>
<td>0.31</td>
<td>G</td>
<td>0.22</td>
<td>W</td>
</tr>
<tr>
<td>4</td>
<td>W</td>
<td>0.31</td>
<td>LL</td>
<td>0.22</td>
<td>LL</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>0.31</td>
<td>E</td>
<td>0.24</td>
<td>LN</td>
</tr>
</tbody>
</table>

BG = Beta General; LL = Log Logistic; G = Gamma; W = Weibull; T = Triangular; E = Exponential; LN = Log Normal

For the growth coefficient (Table 3), the fitting statistics show a range of results in which Compact has a relatively low and narrow range of 0.17 to 0.19 for the top five rankings whereas Minivan/MPV
has a top ranked distribution that has a fitting statistic that is greater than the 5th ranked Compact
distribution as well as a greater spread in the fitting statistics between the top and bottom ranked
distributions. From the analysis of the five classifications, the Gamma (G) distribution has been
chosen as the single distribution shape for the fire growth coefficient due to its high ranking i.e. top
three ranking for each classification and low statistical value throughout.

Table 4  Ranked order distribution for the exponential method fire decay coefficient.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Mini</th>
<th>Light</th>
<th>Compact</th>
<th>Medium</th>
<th>Minivan/MPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shape</td>
<td>Val.</td>
<td>Shape</td>
<td>Val.</td>
<td>Shape</td>
</tr>
<tr>
<td>1</td>
<td>E</td>
<td>0.18</td>
<td>LL</td>
<td>0.12</td>
<td>T</td>
</tr>
<tr>
<td>2</td>
<td>W</td>
<td>0.19</td>
<td>LN</td>
<td>0.14</td>
<td>W</td>
</tr>
<tr>
<td>3</td>
<td>LL</td>
<td>0.19</td>
<td>G</td>
<td>0.16</td>
<td>G</td>
</tr>
<tr>
<td>4</td>
<td>LN</td>
<td>0.23</td>
<td>W</td>
<td>0.17</td>
<td>LN</td>
</tr>
<tr>
<td>5</td>
<td>T</td>
<td>0.40</td>
<td>E</td>
<td>0.22</td>
<td>BG</td>
</tr>
</tbody>
</table>

BG = Beta General; LL = Log Logistic; G = Gamma; W = Weibull; T = Triangular; E = Exponential;
LN = Log Normal

In Table 4 it can be seen that even though Weibull (W) is ranked 5th for the Minivan/MPV
classification for the decay coefficient fitting statistic it is still similar to the other classifications.
Therefore the Weibull distribution is chosen due to its reasonably low statistical fitting value
compared to other distribution shapes.

A summary of the distribution analyses for peak heat release rate, fire growth coefficient and decay
coefficient is shown in Table 5 where it contains the parameters to characterize the Gamma and
Weibull distribution shapes for each classification. There is no obvious pattern for the fire growth
coefficient and fire decay coefficient statistics as a function of classification, so it is difficult to form a
more general design fire curve. However for the peak heat release rate, there is an increasing trend as
the function of classification apart for Minivan/MPV. This is partly due to Minivan/MPV
classification having an unspecified curb weight range which means that the experimental results may
contain Minivan/MPV vehicles with wide range of curb weights. The distribution using these
parameters gives suitable values for peak heat release rate, fire growth and decay coefficients that are
used for the characterization of the single vehicle design fires.

Table 5  Summary of the single vehicle distribution analyses for peak heat release rate, fire
growth coefficient and decay coefficient.

<table>
<thead>
<tr>
<th>Class</th>
<th>Peak heat release rate (kW)</th>
<th>Fire growth coefficient (kW/min²)</th>
<th>Fire decay coefficient (kW/min²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distribution shape</td>
<td>α</td>
<td>β</td>
</tr>
<tr>
<td>Mini</td>
<td>Weibull</td>
<td>5.19</td>
<td>3809</td>
</tr>
<tr>
<td>Light</td>
<td>Weibull</td>
<td>1.66</td>
<td>5078</td>
</tr>
<tr>
<td>Compact</td>
<td>Weibull</td>
<td>2.40</td>
<td>5879</td>
</tr>
<tr>
<td>Medium</td>
<td>Weibull</td>
<td>3.18</td>
<td>7688</td>
</tr>
<tr>
<td>Minivan/MPV</td>
<td>Weibull</td>
<td>4.25</td>
<td>4588</td>
</tr>
</tbody>
</table>

Application of Simplified Approach
Figure 3 shows an example of an envelope of the possible range of design fires for Passenger Car:
Mini classification. The dashed line is the range of possible design fires region within the 5th and 95th
percentile of the distributions. The bold line is the range of possible design fires region for higher and
lower standard deviation of the distribution. In each case the upper and lower limits for the growth
have been selected and allowed to reach the upper and lower range of the peak heat release rate values respectively. For the upper limit, the peak heat release rate is maintained constant until it reaches the time where the slowest possible growth is able to reach the peak while for the lower limit, the slowest possible growth crosses the earliest possible decay from the peak thus creating the earliest possible duration of the item to finish burning. By forming this region, one can expect that for corresponding vehicle classification to burn within the possible region.

Figure 3 Range of possible design fires for Passenger Car: Mini classification.

Also shown in Figure 3 are scatter of dots which represent the possible peak heat release rate at certain time to peak generated by using a Monte Carlo simulation. Ten thousand random values from the fire growth and peak heat release rate distributions have been generated to compare with the two ranges of possible design fires. It is found that 90% of scatter dots fall inside the 95th/5th probabilistic design fire region and 68% of the scatter dots are inside the standard deviation probabilistic design fire region, as might be expected. Similar envelopes can be obtained for the other vehicle classifications and for this current work, it is decided that only the standard deviation design fire region will be used for comparison with the experiments.

The application of the superposition method has been completed for the seven two-vehicle fire spread experiments. Three comparisons of the superpositioned design fire region with experiments heat release rate history data are selected for detailed explanation. The selected experiments for comparison are Experiment 1, Experiment 4 and Experiment 6. These experiments are selected due to their unique combinations of two different vehicle curb weight classifications. In each comparison the dotted line indicates the combination of the probabilistic design fire region and the bold line indicates the heat release rate history data from the original experiment. The ignition times of the vehicles are indicated where a vertical line indicates the time of ignition of the second vehicle.

Figure 4 shows the comparison of superpositioned probabilistic design fire region with the Experiment 1 heat release rate data. In this experiment the first vehicle was not ignited directly but was exposed to an external flame. Thus, the time of ignition for the first vehicle; a Passenger Car: Light class was recorded at 16 minutes and the ignition of the second vehicle; a Passenger Car: Mini was recorded at 35 minutes. The probabilistic design fire region starts after the first vehicle was ignited and it can be seen that the measured heat release rate values mostly lie inside the probabilistic design fire region. The peak heat release rate for the experiment reached around 6200 kW and starts to decay afterwards. The calculation of the quantification of the fit gives 90% of the experiment data points intersecting with the standard deviation probabilistic design fire region.
Figure 4  Comparison of superpositioned design fire region with Experiment 1 heat release rate data.

Figure 5 shows the comparison of the superpositioned probabilistic design fire region with Experiment 4 heat release rate data but this time as an example of the combination of two Passenger Car: Light vehicles. From the information given by the literature source, the time of ignition for the first vehicle is after 42 minutes and the ignition of the second vehicle ignites 10 minutes later at 52 minutes. It can be seen that the experimental heat release rate grows quicker than the design fire region up until it reaches peak and then begins to decay. The experimental data points only start to intersect with the probabilistic design fire region during its decay phase at is around 57 minutes. Since both of the vehicles were of the same classification, the ignition of the second vehicle does not significantly alter the growth combination, hence keeping the experimental growth outside of the design fire region until it just passes the peak. For this comparison the calculation of the quantification of the fit gives 28%.

Figure 5  Comparison of superpositioned design fire region with Experiment 4 heat release rate data.

Figure 6 shows the comparison of superpositioned probabilistic design fire region with Experiment 6 heat release rate data for Passenger Car: Mini and Compact class vehicles. From the information
given in the literature source, the first vehicle ignites just after the data recording was started and the ignition of the second vehicle was at 10 minutes. The beginning of the experiment shows the heat release rate growth rise to within the range of the probabilistic design fire up until around 9 minutes where rapid growth occurred to reach peak at around 7500 kW. Then the experimental heat release rate starts to decay up until 19 minutes where it starts to lie within the probabilistic design fire range. Interestingly, there was a second peak which reaches around 6600 kW and lies within the probabilistic design fire range. The calculation of the quantification of the fit gives 70% of the experiment data points intersecting with the standard deviation probabilistic design fire region.

![Graph showing heat release rate over time](image)

Figure 6 Comparison of superpositioned design fire region with Experiment 6 heat release rate data.

Table 6 shows the percentage of fit between the experiment data and the corresponding probabilistic design fire region. Five of the scenarios have minimum percentage of at least 62% and two have exceeded 90% however Experiment 2 and Experiment 4 both exhibit a low percentage fit of 28%. Examination of the comparison shows a relatively small difference between the experimental data and design region (e.g. as can be seen in Figure 5 during the initial growth) and by having a broader region i.e. 5th/95th percentiles, would increase the fit percentage. This analysis shows that the simplified approach can be considered to be a reasonable method to predict heat release rate for a two vehicle fire scenario.

### Table 6 The percentage of experiment data within the probabilistic design fire region.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Percentage of experimental data within the standard deviation probabilistic design fire region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>85</td>
</tr>
<tr>
<td>4</td>
<td>28</td>
</tr>
<tr>
<td>5</td>
<td>91</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>62</td>
</tr>
</tbody>
</table>
DISCUSSION AND CONCLUSION
This paper has presented a simplified approach of using single vehicle design fire distributions to represent multiple vehicle fire spread scenarios. The probabilistic design fire region shows the possible range of heat release rate curves of multiple vehicles without considering a limit on the total energy that can be released by each single vehicle. The total energy could be included as part of forming a probabilistic design fire in which the shape of heat release rate curve is modified by the maximum total energy that could be released. For example, an analysis of the total energy released in single vehicle experiments can be obtained from Tohir and Spearpoint [4]. However such an approach would need to consider whether the cumulative energy release is tracked for each individual vehicle of whether only the total energy release is assessed. It is also possible that should a combination of lower growth and decay coefficients be selected from the distributions then the total energy release from the subsequent design fire will be less than the expected range obtained in experiments. These factors add more complexity to the proposed risk-based approach particularly where greater numbers of vehicles are involved in the analysis.

The current comparison of the proposed design fire curves with the two-vehicle experiments has used the measured ignition time of the second vehicle rather than attempting to calculate it. In order to extend the methodology to include a probabilistic assessment of multiple vehicle ignition times it may be possible to use experimental data to create distributions in terms of measured times or by using heat release rate values at the time a new vehicle ignites. Alternatively it might be necessary to try to calculate ignition times from material properties and incident radiation similar to the approach taken by Baker et al. [15].

In conclusion, the simplified method of using the superposition of single vehicle design fire curves is considered to be a reasonable approach to assess the heat release rate of two-vehicle fire scenarios as shown by the comparisons with the seven experiments illustrated. The results suggest that there is value in continuing with the on-going research to determine suitable design fires for multiple vehicles scenarios. The next step is to expand the number of vehicles involved in the fire spread scenarios beyond two and to couple the fire spread with the multiple vehicle parking scenarios described elsewhere [3].

REFERENCES


Motorcoach Fire Safety Evaluation

Jason Huczek, Alexandra Joyce, Christopher Wray
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Keith Friedman, Rhoads Stephenson, Dennis Mihora
Friedman Research Corporation (FRC), USA

Ashok Nedungadi, Future is Now Consulting (FiNC), USA

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) has contracted with Southwest Research Institute (SwRI) to develop test apparatuses and test procedures to evaluate candidate fire detection and suppression systems for motorcoach engine compartments, and hot wheel warning systems to prevent tire fires in the wheel well.

The project team has conducted inspections of the three largest-selling motorcoaches in the U.S. and used this information to design a typical engine compartment and a typical tag axle assembly in a simulated wheel well. The fabrication of these two test apparatuses has been completed and draft test procedures have been written. Calibration and commissioning of each apparatus was conducted in the spring of 2014.

During the summer of 2014, suppliers of fire detection and suppression systems and of hot wheel sensing systems have brought their hardware to SwRI for evaluation in the test fixtures. Final procedures for evaluation of these systems will be prepared and provided to DOT/NHTSA in September of 2014 and the project will be concluded in November of 2014.

KEYWORDS: Motorcoach, Fire Safety, Detection, Suppression, Engine Compartment, Wheel Well

INTRODUCTION

Regulatory Background

The Department of Transportation (DOT) Motorcoach Safety Action Plan of 2009, charges NHTSA to evaluate the feasibility of more-stringent flammability requirements for interior and exterior materials, and regulations requiring installation of fire detection and protection systems. The Motorcoach Enhanced Safety Act of 2011 calls for standards to improve fire safety through evaluation of flammability criteria for exterior components of motorcoaches, smoke suppression to prevent inhalation of toxic gasses through improved fire resistance of interior components covered under FMVSS 302, prevention of and resistance to wheel well fires to mitigate propagation into the passenger compartment, and evaluation of automatic engine compartment detection and suppression systems.

Based on this legislation, NHTSA has funded research to develop test apparatuses and test procedures to evaluate candidate fire detection and suppression systems for motorcoach engine compartments, and hot wheel warning systems to prevent tire fires in the wheel well.

Literature Review

Motorcoach fires without injury are fairly common. However, in 2005 a motorcoach that was being used to transport assisted living facility residents in the Hurricane Rita evacuation effort caught fire killing 23 of the elderly occupants of the vehicle. This event was documented in a highway accident report by the National Transportation Safety Board (NTSB) [1].
Estimates range from 160 reported motorcoach fires to 2200 total bus fires per year in the United States. The majority of these fires start outside the occupant compartment, in the wheel well or engine compartment, as shown in Figure 1. The components that have been identified to be the most common ignition points are the brakes, turbochargers, tires, electrical sources, and wheel/hub bearings [2].

![Figure 1 Percentage of Motorcoach Fire Records by Fire Origin Location, (2004-2006) [2].](image)

In 2009 NHTSA funded the National Institute of Standards Technology (NIST), Building and Fire Research Laboratory (BFRL) to conduct research to:

1. Understand the development of motorcoach fires and its subsequent spread into the passenger compartment,
2. Evaluate and identify bench-scale material flammability test methods,
3. Test the effectiveness of fire hardening of motorcoach exterior components around the wheel well, and
4. Assess tenability within the passenger compartment in the event of a wheel-well fire.

Conclusions from the NIST assessment were [3]:

1. Materials designed to meet FMVSS 302, Flammability of Interior Materials, do not meet the more stringent Federal Aviation Administration (FAA) and Federal Rail Administration (FRA) requirements (i.e., vertical burn rate, heat release, smoke density, etc.).
2. Fire-hardening to isolate a tire fire from surrounding combustible materials delayed fire spread.
3. The time from fire penetration to untenable conditions in the vehicle interior was from 5 to 9 minutes.

There has been prior research focused on the development of test procedures to evaluate engine compartment detection and suppression systems.

Kidde has published research on development of a standard test for transit vehicle (motorcoach) extinguishing (suppression) systems [4] and in comparing various fire detection systems for engine compartment fires [5]. At the 2006 SAE Congress there was a session devoted to fire suppression research needs, which was summarized by Hamins [6].

SP Technical Research Institute of Sweden has published several reports [7-10] on this research topic and has also developed a standard test methodology [11] for evaluating suppression systems installed in a motorcoach engine compartment.
Research Objectives

The major objectives of the current research project are the following:

1. Develop a test fixture and test procedures for evaluating fire detection and fire suppression systems for motorcoach engine compartments.
2. Develop a test fixture and test procedures for evaluating tire fire warning systems for motorcoach wheel well areas.

The secondary objective of the current research project was to further investigate the topic of fire hardening of a bus and propose a standard test method that would be useful to compare potential fire hardening materials for this purpose. This part of the project will not be discussed in this paper.

METHOD AND RESULTS

Engine Compartment and Wheel Well Characterization

In February of 2013, the SwRI team conducted a survey of three model year motorcoaches sold in North America (one each from three different manufacturers) at their respective maintenance facilities. The purpose of this survey was to characterize the engine compartments and wheel well areas. The goal of this task was to fully characterize these areas and then use that information to design a representative test fixture for both the engine compartment and wheel well fire scenarios. Figure 2 shows a photograph of each motorcoach engine compartment surveyed (view from rear of coach).

The interior gross volume of the engine compartments surveyed varied between approximately 6-9 m³. Table 1 provides a summary of where several of the major components in the engine compartment are located. During the motorcoach survey, the wheel well area was also inspected for each motorcoach and photographs and measurements of these areas were documented. In general terms, the wheel well areas were much more similar between motorcoaches, as compared to the engine compartments. In this regard, the task of developing a representative test fixture for wheel well warning system evaluation is more straightforward than for engine compartments.

<table>
<thead>
<tr>
<th>Component Description</th>
<th>Motorcoach A</th>
<th>Motorcoach B</th>
<th>Motorcoach C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine assembly</td>
<td>Middle</td>
<td>Middle</td>
<td>Middle</td>
</tr>
<tr>
<td>Two coolers and fan</td>
<td>Left</td>
<td>Left</td>
<td>Left</td>
</tr>
<tr>
<td>Air filter</td>
<td>Top - middle</td>
<td>Top - right</td>
<td>Left – Middle</td>
</tr>
<tr>
<td>Lavatory equipment</td>
<td>Right</td>
<td>Right</td>
<td>Right</td>
</tr>
<tr>
<td>Emissions control</td>
<td>Left - Lower</td>
<td>Left - Middle</td>
<td>Left - Top</td>
</tr>
<tr>
<td>A/C Compressor</td>
<td>Lower right</td>
<td>Lower right</td>
<td>Lower right</td>
</tr>
<tr>
<td>Turbo</td>
<td>Left side of engine</td>
<td>Left side of engine</td>
<td>Left side of engine</td>
</tr>
<tr>
<td>Surge tank – engine coolant</td>
<td>Above engine cooler</td>
<td>Above engine cooler</td>
<td>Above engine cooler</td>
</tr>
<tr>
<td>Alternators</td>
<td>Left side</td>
<td>Left side</td>
<td>Right side</td>
</tr>
</tbody>
</table>
Engine Compartment Test Fixture

Based on the survey task, three-dimensional models of each motorcoach were developed so that they could be overlaid and compared and contrasted. Figure 3 shows each of these motorcoach representations.

Based on these models, a single representative model was created, which is shown in Figure 4. This final model was then transformed into a final test fixture design. Several views of this test fixture can be seen in Figure 5.

The purple shaded boxes in Figure 4 are modules that are used to represent clutter in the engine compartment and also to incorporate ignition sources and secondary combustibles that will be utilized in a given fire scenario. These modules are depicted as racks of cylindrical and rectangular obstructions colored white/silver in Figure 5.
Engine Compartment Fire Scenarios

The scope of the project requires the development of test procedures to evaluate both detection and suppression systems in the engine compartment. As such, it is planned to include fire scenarios which incorporate both the detection and suppression system in a given test. In addition to this integrated testing, there will be the option or requirement to conduct one or more tests with the detection system assumed to either have failed or not be present. In this way, the final test protocol will be applicable to both detection and suppression system evaluation.

In order to identify the most common fire scenarios for the engine compartment, detailed discussions with the NHTSA Office of Defects and Investigation (ODI) were held in addition to discussions with motorcoach manufacturers, suppliers and operators. As a result, the following fire scenarios will be included in the testing protocol for evaluating engine compartment detection and suppression systems:

1. Hot Surface Re-Ignition Test (One Test)
   a. Real Bus Hazard: hot surface in engine compartment such as turbo and exhaust manifold.
   b. Ignition Material: continuous feed of lube oil through Hago Model 1.50/80°H nozzle to drip oil at nominally 7 ml/min.
   c. Ignition Source: steel plate representing hot surface of turbo/exhaust manifold. Heated from behind by quartz IR panel heater.
   d. Location: upper left (hot) side of engine.
   e. General Procedure: raise nominal temperature of hot plate to 750 ºC, open oil valve, observe dripping fire, after 15 seconds, turn off power to heaters for hot surface, after additional 15 seconds, discharge suppression system and record time to re-ignition, if any.
   f. Ventilation: conduct test without the fan running.

Figure 4 3-D Models of ‘Average’ Motorcoach Engine Compartment.

Figure 5 Motorcoach Engine Compartment Test Fixture Design Drawings.
2. Diesel Spray Fires (Four tests)
   a. Real Bus Hazard: diesel spray fire as a result of a leak in the Diesel Particulate Filter (DPF) system. The diesel flow rate will nominally equate to a 1.25-mm leak diameter with nominal operating conditions per motorcoach OEM for diesel line on DPF.
   b. Ignition Material: continuous feed of diesel fuel through Monarch F-80 nozzle, 10.0 gal/hr flow rate, and 80° spray angle. The diesel spray nozzle is mounted in a small flame stabilizer (metal can nominally 3-in diameter and 3-in long).
   c. Ignition Source: tell-tale cup (details below) positioned below the spray nozzle.
   d. Locations: lower left (hot) side of engine and upper left (hot) side of engine.
   e. General Procedure: ignite the tell-tale cup, after 30 seconds, discharge the diesel, after an additional 30 seconds discharge the suppression system and record observations.
   f. Ventilation: perform tests with and without fan running.

3. Power Steering Fluid (PSF) Fires (Two tests)
   a. Real Bus Hazard: PSF spray fire as a result of a leak in the power steering system. The PSF flow rate will nominally equate to a 0.375-mm leak diameter with nominal operating conditions per motorcoach OEM for PSF line.
   b. Ignition Material: continuous feed of PSF through Monarch F-80 nozzle, 15.5 gal/hr flow rate, and 80° spray angle. The PSF nozzle is mounted in a small flame stabilizer (metal can nominally 3-in diameter and 3-in long).
   c. Ignition Source: tell-tale cup (details below) positioned below the spray nozzle.
   d. Location: middle right (cold) side of engine.
   e. General Procedure: ignite the tell-tale cup, after 30 seconds, discharge the diesel, after an additional 30 seconds discharge the suppression system and record observations.
   f. Ventilation: perform tests with and without fan running.

4. Distributed Pool Fires (Two tests)
   a. Real Bus Hazard: multiple fire locations after incipient fire has spread through compartment. This fire scenario also evaluates the ability of the system under test to adequately cover the full volume of the test fixture.
   b. Ignition Materials:
      i. 8 tell-tale cups, nominally 3-in diameter and 2-in high, each filled with 130 ml of heptane (approximate 1-in. depth)
      ii. 2 rectangular pans, each measuring 8 x 18 x 1-in. high, filled with 1750 ml of heptane (approximately 0.5-0.75-in. depth).
   c. Location: throughout the entire test fixture, eight tell-tale cups in nominal eight corners of primary compartment space (not including battery compartment), one rectangular pan in left (hot) side clutter and one rectangular pan in right (cold) side clutter.
   d. General Procedure: The cups and rectangular pans are ignited within 30 seconds (pan is the last to be ignited) and 30 seconds after ignition of pan, the suppression system is manually discharged and observations are recorded.
   e. Ventilation: perform tests with and without fan running.

5. Plastics Fire (One Test)
   a. Real Bus Hazard: Class A material (plastics) fire close to the toilet holding tank and air filter housing components.
   b. Ignition Materials:
      i. 8 vertical strips of plastic, 4 ABS and 4 Polypropylene, each measuring 2-in x 28.75-in. long (nominally 1/8-in. thick)
      ii. 4 horizontal strips of plastic, 1 of each type of plastic on lower two shelves of clutter rack adjacent to vertical strips and ignition pan.
   c. Ignition Source: 1 rectangular pan (same as pool fire test) with 120 ml of heptane used to ignite the plastic.
   d. Location: lower right (cold) side of engine.
e. General Procedure: Ignite the pan fire, after 105 seconds of pre-burn, discharge the suppression system and record observations.

f. Ventilation: conduct test without the fan running.

6. Battery Compartment Fire (One Test)
   a. Real Bus Hazard: overheated cable in battery compartment, which leads to a growing Class A fire.
   b. Ignition Materials:
      i. 1-in diameter pipe insulation – two horizontal sections 30 inches in length and one vertical section 25 inches in length. Each section is sprayed lightly with diesel fuel. These sections are mounted just above the egg-crate foam and over the overheated cable.
      ii. Egg-crate foam plastic insulation – one 16 x 18-in panel applied to back wall of battery compartment directly over the overheated cable.
      iii. Plastic toolboxes – these are used to approximate battery boxes. Four of these boxes are placed in the compartment and 10 ml of grease is applied to the top surface of the back two boxes.
   c. Ignition Source: 23.5-in long thermoplastic cable overheated to ignition by discharging a 300-amp load from two bus batteries in series (24 volts). The cable also has approximately 5 ml of lubricating grease applied evenly over the surface of the cable insulation.
   d. Location: battery compartment.
   e. General Procedure: discharge battery current into test cable and allow cable to ignite, 30 seconds after cable ignition, discharge suppression system and record observations.
   f. Ventilation: conduct test without the fan running.

Based on discussions with the motorcoach manufacturers, it is recommended that the fan speed be set to a “nominal” representative speed (volumetric flow rate), typical to the majority of motorcoach driving time. This equates to an average air velocity of approximately 6 m/s at the outlet of the fan after the louvered radiator enclosure and nominally 4 m$^3$/s of volumetric airflow.

Wheel Well Test Fixture and Fire Scenario

The project team has determined, based on discussions with experts in the wheel well fire area (manufacturers, carriers, etc.), that the major heat sources for tire fires are (in order of importance):

1. Dragging brakes;
2. Failed bearings (these are becoming less frequent with the new “maintenance free” bearings which do not require addition of lubricant oil). However, there still are a significant number of coaches on the road with the older style bearings that fail more readily without good maintenance
2. Underinflated tires (especially the inner tire of a set of dual drive axle tires). The NTSB/Greyhound track tests were not able to cause a fire this way (they stopped the test at thread separation) [12]. However, NTSB has implicated underinflated tires in another motorcoach fire, and most experts still believe that under inflation can cause fires;

The most vulnerable tires to overheat are on the tag axle (un-driven axle), followed by the drive axle, and then the steering tires. An early warning sensor system would have a higher likelihood of success than an active detection and/or suppression system in the wheel well area. This is due to the fact that the wheel well area is an extremely challenging fire area, due to its relatively open geometry, harsh environment, and the aggressive nature of a tire fire. If an impending fire event can be detected prior to heating the tire to its ignition temperature, then it should be possible to avoid the event before it starts. A wheel well fire early warning system test procedure has been developed, which evaluates sensors and algorithms that can detect a hot wheel in advance of a tire fire.
This test procedure is based on a single tag axle that is supported at one end with a bearing structure and driven by an electric motor connected to the wheel lug nut assembly. The wheel is heated by partially engaging the brakes on the tag axle, causing heat to be transferred through the rotor and wheel assembly and into the tire. The goal is to show that some quantity can be measured and used to predict an abnormal wheel heating condition, and to warn the driver before a tire fire would develop.

Based on the work conducted by NIST, tires are estimated to ignite at approximately 400 °C [3]. Currently available Tire Pressure Monitoring System (TPMS) sensors measure the temperature and pressure of the air inside the tire. These existing sensors can be set to issue a high temperature alarm at a specific temperature (adjustable by user). This alarm temperature is considerably higher than what is encountered during hard braking and thus should not result in excessive false alarms.

It is important to show that the heat stored in the metal components is not enough to exceed the ignition temperature and allow a fire to start even after the wheel (motorcoach) has stopped. Therefore, two extended tests were conducted until a tire fire/blowout was observed. This demonstrated that the test fixture is sufficient to add enough heat into the system for a dangerous event, and also allow the study of the temperature distributions up to that point. Finally, this information can be used analytically to quantify the margins between false alarms and an actual tire fire. Figure 6 provides several views of the final wheel well test fixture.

**Figure 6**  *Motorcoach Wheel Well Test Fixture Design Drawings.*

**Baseline Testing on Engine Compartment Fixture**

After the engine compartment fixture was fabricated, a series of tests for each fire scenario was conducted to gather baseline information about the conditions in the engine compartment during each standard fire. The measurements primarily consisted of temperatures throughout the fixture and close to each ignition source, as well as video for each scenario. Figure 7 shows the final fabricated engine compartment test fixture. Figure 8 shows photographs from the baseline tests of selected fire scenarios. Figure 9 shows a typical graph of the temperature plots from a series of baseline tests (diesel spray fires depicted in this case).

**Figure 7**  *Motorcoach Engine Compartment Test Fixture.*
Baseline Testing on Wheel Well Fixture

After the fabrication and installation of the final test fixture was complete, a series of baseline tests were conducted to checkout instrumentation and to map the variable frequency drive current (VFD) to the motor to the applied torque to the system.

The applied torque was measured as a function of the current draw from the motor and applied brake pressure for a variety of wheel speeds. This allowed for the development of a calibration curve that correlates amperage and brake pressure to applied torque.

Subsequent to these tests, the torque meter was removed from the system and replaced with a shear coupling that accounts for the physical space, as well as adds a measure of safety to the system in case of a catastrophic event. Figure 10 shows the fabricated test fixture from above and from the side.
Figure 11 shows the relationship between torque, motor current draw and applied brake pressure.

Figure 10  Wheel Well Fixture (Left: Plan View, Right: Side View).

Figure 11  Torque as a Function of Motor Current Draw and Applied Brake Pressure.

A baseline test was performed without a tire sensor to determine how the wheel assembly heats up when a nominal 2000 N-m of torque was applied. During this baseline test, a phenomenon called ‘brake fade,’ or ‘brake glazing’ was observed. This phenomenon occurs when the brakes are brought to a significantly elevated temperature without any burnishing, or breaking-in, of the brake pads.

Figure 12 shows the brake pad installation location and a photographic comparison of brake pads that have and have not been glazed. As a result of this observation during the first test, the heating rate was modified and the final procedure includes a cycling heat exposure, rather than a constant exposure.

Figure 12  Left: Brake Pad Installation, Right: Brake Fade Comparison (Left: Faded, Right: New).

An additional baseline test was taken to tire failure and subsequent fire. In this test, instead of attempting to apply maximum torque for maximum duration, maximum torque was applied for shorter durations and the entire assembly was brought to an elevated temperature more slowly and brake fade
was avoided. This allowed the development of a much higher temperature of the overall wheel assembly than observed in the first test.

At the end of this test, while the wheel was coasting to a stop, a catastrophic blowout of the test tire was observed, which led to a small fire as a result of the tire being blown onto the hot components of the brake assembly, as well as the grease from the failed bearing. This fire was immediately suppressed and not allowed to develop. This event provides input to the development of a reasonable upper limit to observe sensor activation. Figure 13 provides a photograph of the stationary thermocouple locations on the torque plate and also various photographs of the wheel well test fixture components after this event. Figure 14 provides selected data from this test.

![Figure 13](image1.jpg)  
Wheel Well Test Photographs: Top Left: Torque Plate Thermocouple Locations, Top Right: Just After Blowout, Bottom Left: Wheel Removed, Note Sheared Rotor Hub Assembly, Bottom Right: Rotor Hub Removed, Note Failed Bearing.

![Figure 14](image2.jpg)  
Selected Data from Tire Blowout/Fire Test.
CONCLUSIONS

Test fixtures have been designed and fabricated to represent a motorcoach engine compartment and wheel well space. The engine compartment fixture is used to evaluate detection and suppression systems and the wheel well fixture is used to evaluate hot wheel early warning devices.

The engine compartment fixture considers several realistic scenarios, which will challenge the ability of an active fire protection system to detect and extinguish these fires. The wheel well test fixture considers one primary failure scenario that could represent either a dragging brake or failed bearing.

The final recommendations for each test procedure as well as the results of the fire hardening aspect of this research project will be provided to DOT/NHTSA in September of 2014 and the project will be completed in November of 2014.

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CONTACT INFORMATION

For more information about this project, please contact Jason Huczek, at jhuczek@swri.org or (210) 522-3632.

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VULCAN-The next step in Fire Suppression Integration
FIVE 2014

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Dafo Brand AB
Stockholm, Sweden

BACKGROUND

The Need
Bus and coach fires are a global concern. According to reported bus fire statistics, around 1% of all buses are involved in some form of fire incident each year. In Finland, a total of 57 bus fires were reported to rescue authorities in 2010 and 69 in 2011, injuring people and damaging property worth thousands of Euros. The occurrences of bus fires is believed to be considerably higher than this as some incidents go unreported. One reason is that some large bus/coach operators do not insure their buses against fire, preferring to bear the risk themselves; this therefore lowers the incentive to report incidents. In fact, a study of bus and coach fires undertaken in Sweden and Norway in 2006 estimated unreported fires to be two-thirds of reported incidents. These incidents typically result in huge financial and property losses and in the worst cases injuries or fatalities. The financial losses incurred include physical damage to the coach, applicable insurance deductibles, lost property of the passengers as well as lost productivity of the bus itself. In 2004 alone, the public fire department of USA responded to 297,000 vehicle fires which caused an estimated €1 billion ($1.3 billion) in direct property damages, 550 civilian deaths and 1,500 civilian injuries. In Australia, the projected losses for 2012 are nearing €12.8 million (AUS $16 million) and we estimate the figure for Europe to be much higher, given that a bus in a European state (Sweden) is considered 10 times more likely to experience a fire compared to one in Australia.

The tighter vehicle emissions legislation (Regulation (EC) 715/2007) and noise emission limits in Europe are believed to significantly increase the risk of engine bay fires. Euro 4, 5 and the coming Euro 6 vehicle emission standards and the proposed EC Regulation to lower vehicle sound emissions, will typically result in:

- Engines running at higher temperature and pressures; particle filters are now operating at 80ºC.
- Increased sound insulation being introduced to vehicles which can become soaked with flammables such as diesel oil and ignite at such high temperatures.

Most buses that experience engine bay type fires are either severely or totally burnt out costing the European community huge financial and property losses, and posing great danger to the safety of the travelling public.

Because of this the professional sector of bus and coach operators and legislators is becoming increasingly concerned with the fire risks of coaches and buses and many have actively encouraged the installation of automatic fire detection and suppression systems (AFDSS). Insurance companies have also made it a requirement for mass transit vehicles such as passenger buses to have fire detection and suppression systems. These systems have proved to be effective in managing bus fires, allowing precious time for passengers to evacuate the bus. In Sweden, where AFDSS’s have been strongly encouraged by insurance companies, there has not been any reported case of complete burnouts of insured buses since 2005. Undoubtedly, passenger safety can be improved and some financial and property savings achieved across Europe through the installation of AFDSS in bus and coaches.
Although these AFDSS’s have proved effective in preventing complete loss of property, greater financial benefits can be achieved by making them predictive of potential fire problems and not just reactionary.

This is particularly important in engine bay fires where around 38% of the fires are fuelled by leakages in the fuel- and oil-systems and can be very instantaneous and large in magnitude. Even with a functional AFDSS in place, considerable levels of damage can be incurred in a short time before the fire is detected and acted upon and many, if not all, the compartment’s contents may be damaged by the fire or the extinguishing process employed resulting in loss of operational capability.

This situation is compounded by the slow reaction times of heat detectors used in existing systems. Fire detection systems based on twisted wires detect flame and/or heat only and take up to 40 seconds to respond to the fire. These time delays in responding to a fire lead to unnecessary damage of property considering the high flammability of some engine components and liquids like fuel, engine oil, hydraulic oil, coolant, rubber hoses, casings, cables, and plastic containers. The presence of high air flow from the cooling fan makes heat detection even more difficult. In a study titled, ‘Fire Detection in Engine Compartments of Buses: A pilot study’, computer simulation in fire dynamics showed that heat detection is a lot more difficult with high air flow than without forced air flow.

Furthermore, air from the fans to cool the running engine, introduces oxygen contributing to the progress of any on-going fire. Consequently, engine fires often spread rapidly. The German Motor Vehicle Association DEKRA, conducted fire tests to investigate the variation of temperatures against time, as a fire spreads on a bus seat exposed to half a litre of fuel. Their results showed that it only took 44 seconds for smoke to completely fill the bus and a self-rescue was impossible after only 84 seconds. This suggests that engine fires can spread in similar times bearing in mind the sufficient oxygen supply from the fan. That being the case, detection times of existing systems renders them virtually ineffective in preventing loss of operational capability of various engine components. There is certainly a need for predictive detection of potential fire problems to ensure minimal property damage and prevent loss of operational capability of buses/coaches.

The need is exacerbated by the fact that existing AFDSS are not integrated into the central bus (CAN-bus) control system and therefore some automatic rapid response actions such as cutting off fuel supply and locking fans stationary cannot be completed. Such quick response actions are necessary in preventing the spread of fires and are currently being advocated by some transport regulating authorities in Europe. For instance, Transport for London (TfL), an integrated body responsible for the city’s transport system, advocates AFDSS that locks stationary any fans in the engine bay, cuts off fuel supply and automatically shuts down the engine within 10 seconds of fire detection. These actions can only be achieved with AFDSS that are integrated into the central control system of the vehicle.

Moreover, existing AFDSS operate as ‘stand-alone’ systems which alert the driver via an alarm and rely on him to control the vehicle and switch on the suppression system. This can increase the burden on drivers who are already exposed to added pressure of having a large number of people that are directly influenced by their own actions. Depending on a particular incident, panic reactions may occur as the driver jostles to maintain control of the bus and switch on the suppression system, resulting in unnecessary delays in implementing the response measures. This underscores the need for an automatic system to respond with the appropriate suppression measures.

Current fire suppression systems are either on or off. Consequently, they give exactly the same response to fire problems irrespective of whether it is necessary or not. This means that a small fire in a less dangerous portion of the engine attracts the full multi-point dispensing of the extinguishing agent all over the engine just as a huge fire will. While this might be a good safety precaution, it is costly to bus and coach operators. A system which locates the position of potential fire problems and can quantify the actual problem will enable a proportional or graduated response and deliver safety at a lower cost.
For quick extinguishing of fires, current AFDSS require nozzles to be located very close to vital points in the engine resulting in a large number of nozzles and complex delivery system. Additionally, current agent tanks are expensive and heavy. With a clear understanding of how nozzles work, optimal nozzle design can be achieved and minimal number of nozzles can be used resulting in cost savings.

The Solution
In response to this need, DAFO, one of the leading SME suppliers of vehicle fixed installation fire detection and suppression systems in Europe, proposed the development of fully automated, intelligent fixed installation fire/smoke detection and extinguishing system for buses and coaches. Together with 4 other European SMEs, they formed a fully integrated supply chain capable of delivering this solution to the market. However, the delivery of such a solution requires expertise in adaptation and integration of smoke detectors, design and development of agent tanks, nozzles and intelligent response control systems; which expertise they do not possess. Therefore they intend to contract 3 RTD performers (RTDPs) (EII, NOVAMINA and SP) with world-leading knowledge in their areas of speciality, to undertake the required research and development activities. EII are dedicated experts in software development, electronics and control systems design, NOVAMINA in pressure vessel design, fluid dynamics and modelling, while SP are highly experienced in fire dynamics, fire detection and suppression and test design and specification. These RTDPs will develop and integrate the 3 vital component technologies of this solution which are smoke detection system (SP), agent tank, and nozzle and piping system (NOVAMINA) and intelligent response control system (EII).

A fully automatic and intelligent fire detection and suppression system combining signals from heat and flame sensors, and smoke detectors will be developed in this project to detect small amounts of smoke preceding fire, rapidly warn and take suppression measures. Nearly 25% of all engine bay fires are caused by electrical faults, resulting in a small amount of smoke being released. Detection of that smoke with the smoke detector and implementing appropriate suppression measures prevents it from growing into a fully-fledged fire. Through this kind of early detection, almost 25% of potential fire problems are prevented and significant bus damage by fires avoided resulting in significant financial savings. Not only will the savings come from the prevention of physical damage of the bus but also in the avoidance of negative publicity, potential for lost revenue based on public perception, lost productivity of the bus itself and inconvenience costs of passengers if the bus loses operational capability.

Fires caused by any other means are detected by both heat, flame and smoke detectors and an immediate response implemented by the intelligent control system. The most appropriate sensor will be placed on engine components on which fires are most likely to be ignited. Off-the-shelf vehicle heat and flame detectors will be used together with smoke detectors. Robust smoke detector systems currently used in main avionics compartments (computer room / electrical energy centre) of aeroplanes which operate at temperature ranges of -40 to 86°C will be adapted to vehicle applications and modified to withstand diesel, dust particles and hydraulic oils.

When a fire or potential fire problem is detected, the system will immediately give the driver audible and visual notifications as the intelligent response system automatically determines the extent of the problem, size and location of the fire through a smart sensor grid. As soon as the level of problem is ascertained, the system will automatically implement the most appropriate response to the problem. The responses will vary depending on the extent of the problem and may include switching on the fire suppression system, sending a message of the fault to the operator and requesting remedial action, cutting off fuel or oil supply, shutting down the cooling fan and so on. In order to enable the combined operation of the engine, fuel and hydraulic oil flow as well as the suppression system, the AFDSS controls will be integrated into the CAN-bus control system. Driver manual activation or override option will be provided to delay the specific actions such as cutting off of the fuel supply to allow for movement of the bus to a safer place.
The system control unit will be individually connected to and communicate to both peripheral equipment like detectors of different kinds, alarm devices, actuators, etc. and the vehicle communication system. This arrangement will allow for faster responses and the location of the position of a problem in the engine and permit the issuing of a proportional response. The control unit will be able to function as a “stand alone” unit with built-in battery giving it the necessary liberty to function in the event of certain system responses such as remote electrical isolation by removal of electrical power. The system will distinguish between the individual detectors and initiate response measures accordingly – for example, detection of fire in luggage compartments gives alarm while detection in the engine compartment actuates extinguishing system.

Components of the extinguishing systems that will be designed and fabricated are agent tank, nozzles and other fittings such as pipes and hoses. The size of existing nozzles and piping systems will be reduced to allow for easy installation and fitting into the limited engine space. Nozzles will be optimised to the actual extinguishing agent at operational temperatures and pressures to enhance system performance using minimum number of nozzles. A low cost and weight agent tank (< €120) will be designed to withstand internal pressures of up to 150bar and a reduced of diameter 160mm which is easy to maintain and service.

The VULCAN SMEs have collectively undertaken a meticulous study of the extent of the work required to deliver this proposed solution. By breaking down the work into specific activities and pairing them with the needed expertise to successfully accomplish them, we are sure to select the most appropriate RTDPs for the project.

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9  http://www.trailways.com/resources/docs/2010-11-28%20Fire%20Technology%20-%20Fire%20suppression%20of%20bus%20engine%20compartments%5B1%5D.pdf
13 http://www.trailways.com/resources/docs/2010-11-28%20Fire%20Technology%20-%20Fire%20suppression%20of%20bus%20engine%20compartments%5B1%5D.pdf
Detection of fires in Heavy Duty (HD) vehicles

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ABSTRACT

Detection of fires in the engine compartments, toilet compartments, baggage bays and sleeping cabins of Heavy Duty (HD) vehicles is arduous. The elevated air flows, concentration of pollutants and wide range of surface temperatures in the engine compartment together with the complicated geometries of the latter spaces complicate the operation of all types of detectors. These lead to difficulties defining the optimal type of detection technologies to be used as well as the adequate location of each detector. This paper presents research for understanding the challenges and necessary characteristics of detection systems in compartments with high air flows, large temperature variations and complicated geometries. In particular, this work reports about literature surveys of existing standards, legislations and research in the field as well as experimental findings.

KEYWORDS: fire detection in vehicles, fire tests & smoke characterisation.

INTRODUCTION

Fires in the engine compartments of surface and underground non-rail heavy duty (HD) vehicles are unfortunately still common around the world [1]. For instance, fires in the media drift and distribution level sections of Swedish non-coal mines and German potash and rock salt mining are predominantly caused by service vehicles, drilling rigs and loaders [2–4]. Furthermore, statistical data indicates that nearly one percent of the buses registered in northern Europe will suffer an incident related to fire during a one year period and that one in ten will have an incident related to fire during its life cycle [5]. Although this quantity is alarmingly high, it does not necessarily denote that all these fires lead to fatalities or total property loss. However, statistical data do indicate that almost two thirds of the reported fires commenced in the engine compartment and that these fires were, in most cases, not promptly detected by the drivers. Late detection causes that nearly one in five of the aforementioned fires spread outside the firewall of the engine compartment putting in risk the security of its occupants [6, 7].

Engine compartments of heavy duty vehicles are, in general, spaces where detecting fires with inexpensive and simple detection systems is arduous. High air flows and large amounts of suspended pollutants in the compartment, together with the complicated geometry and the wide range of surface temperatures typically occurring during the normal operation of the vehicle, complicate the operation of all types of detectors. The deposition of pollutants on the components of optical detectors can impair their operation as well as obstruct the channels of aspirating systems, thus hindering their operation or shortening their service interval. In addition, thermal point detectors can have an extremely limited effectiveness under high air flow conditions unless these are located in the vicinity of an eventual fire where these can be effectively heated by the ensuing smoke and fire plumes [8].

UNECE Regulation No. 107 regulation stipulates that engine compartments of buses and coaches with rear mounted engines must be equipped with a fire detection system and that coaches should have fire detectors in the toilet compartments and sleeping cabins, but the regulation is unfortunately not specific about the performance and effectiveness of the employed detection system. This inaccurateness allows the employment of detection systems which would be incapable of detecting fires under high air flow conditions, providing a vague improvement regarding fire protection [9].
Although the engine compartment is the most common place of origin of fires in these types of vehicles, toilet compartments, baggage bays and sleeping cabins are not excepted of this problem. Although detecting fires in these compartments is not as difficult as detecting fires in engine compartments, the differences in geometries among vehicle fleets may lead to difficulties defining an optimal detection technology and location of a detector to be installed in these compartments. Even though the mandatory implementation of detection systems is a fact, the effectiveness of the detectors will be highly suspected to their correct selection and placement.

Research for understanding the challenges and necessary characteristics of detection systems in compartments with high air flows, large temperature variations and complicated geometries is necessary. SP Fire Research conducts active research in the field of detection of fires in HD vehicles where different detection technologies and strategies are evaluated and compared. This paper reports experimental findings and a literature study about the existing standards, legislations and research in the field.

CURRENTLY VALID LEGISLATION AND STANDARDS

To the best of our knowledge there are no international standards or test methods currently in force for evaluating the performance of fire detection systems in HD vehicles. Even though there are some standards available highlighting minor requirements or risk assessment methods, there are no approval test methods meant to holistically evaluate the performance of systems meant to be installed in this type of vehicles. For instance, the Australian Standard AS 5062 and the guidelines SBF 127 and SBF 128 prepared and published by the Swedish Fire Protection Association provide some lineaments about fire protection in vehicles. While the AS 5062 is a comprehensive standard regarding fire protection in vehicles focused on risk analysis including some counted requirements on fire detection in HD vehicles the SBF 127 and SBF 128 provide environmental tests requirements, such as resistance to vibration, ambient temperature variations, and corrosion. Furthermore, the standards EN 14604 and UL 217 set out requirements for recreational vehicles and the NATO standard STANAG 4317 have relevant environmental requirements for mainly applicable to military battle tanks.

For general use, the main standards for fire alarm systems in Europe and North America are EN 54, ISO 7240, NFPA 72, FM (3210, 3230, 3232, 3260), and UL (268, 521). All of these, except NFPA 72, include approval test programs for different types of detectors. However, these should not be used for approval of detectors for use in e.g. the engine compartment of vehicles. There are several important parameters that are not adapted for vehicle application in these standards, such as ambient temperature, vibrations, high air flow, fire sources, and false stimuli or background noise levels.

The European automotive legislation has very vague requirements on fire detection. For buses and coaches the regulation UNECE 107 specifies some minor requirements, but the regulation is not specific about the performance or installation of the system.

The following two sections present fire detection tests conducted in the toilet compartment and in the engine compartment of a bus. The present work is a basis for future work for improving standards and legislation of fire detection in HD vehicles.

EXPERIMENTAL STUDIES

Fire detection tests in the toilet compartments of a bus

A standardised toilet compartment was constructed based on the input from 26 buses from a variety of models and suppliers. The standardised toilet compartment is depicted in Figure 1. It was identified that the most important influencing parameter affecting the performance of a fire detection system is the ventilation characteristics, which differed dramatically among the studied buses. However, most
buses have a fan positioned in a concealed space under the sink that extracts air from the compartment. The air enters the concealed space via air vents and in some cases also via the trash can opening (the largest hole to the left hand side in Figure 1). Gaps around the toilet door work as air inlet to the compartment and in the standardise compartment these gaps are summed up in a larger gap at the upper right hand side corner of the toilet door. Some real toilet compartments also have a fresh air intake from the air conditioning system.

![Figure 1. Standardised bus toilet compartment.](image)

Five different fire detection systems were tested at different placing positions. The detectors included linear heat detection, point heat detection, point smoke detection, and aspirating smoke detection.

Seven fire tests were conducted in accordance with Table 1. Although a heptane pool is not a realistic fire source in a toilet compartment, it was used because of good repeatability compared to the other fire sources. Rubber and plastics materials were placed in the concealed space of the fan representing a pump, cables and other electronics normally contained there.

<table>
<thead>
<tr>
<th>Test</th>
<th>Fire source</th>
<th>Fire position</th>
<th>Ventilation condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cigarette</td>
<td>Seat level</td>
<td>Low fan speed</td>
</tr>
<tr>
<td>2</td>
<td>Paper</td>
<td>Trash can</td>
<td>Low fan speed</td>
</tr>
<tr>
<td>3</td>
<td>Paper</td>
<td>Trash can</td>
<td>High fan speed</td>
</tr>
<tr>
<td>4</td>
<td>Heptane pool</td>
<td>Floor level</td>
<td>Low fan speed</td>
</tr>
<tr>
<td>5</td>
<td>Heptane pool</td>
<td>Floor level</td>
<td>High fan speed</td>
</tr>
<tr>
<td>6</td>
<td>Plastics/rubber</td>
<td>Above fan</td>
<td>Low fan speed</td>
</tr>
<tr>
<td>7</td>
<td>Plastics/rubber</td>
<td>Above fan</td>
<td>High fan speed</td>
</tr>
</tbody>
</table>

An example of the scenarios described in Table 1 is shown in Figure 2 where paper is burning in the litter bin of the standardised toilet compartment.
Discussion of partial results

The results of these tests show that the position and ventilation characteristics of the compartment clearly influence the performance of the installed fire detection system. These partial results are discussed here:

a) Smoke detectors are generally much faster than heat detectors. Heat detectors should only be used in narrow spaces where the detector is close to a potential fire source, e.g. above the trash can.

b) The impact of the ventilation fan is very relevant. In several fire scenarios a detector in the ceiling of the toilet compartment would not give a fire alarm in the early stage of a fire, as the one shown in Figure 2 showing a paper fire in the litter bin and where the smoke did not spread across the toilet compartment.

c) Because of the importance of the ventilation and ventilator, it seems appealing to recommend the installation of fire detectors also in the concealed space of the fan. It is worth to highlight that aspirating systems may be considered as more effective than other systems due to their capability to simultaneously sample air from several spaces while the detector can be easily concealed and protected in better suited areas than the toilet itself.

d) Aspirating smoke detectors are not affected as much as point smoke detectors by high air flows.

e) It was only the most sensitive aspirating smoke detector that was activated by cigarette smoke.

Fire detection in the engine compartments

The performance of various fire detection systems for engine compartments of HD vehicles were tested in the engine compartment of the city bus shown in Figure 3. The tested systems were simultaneously tested and compared with regard the time for detecting the induced fires. The detectors that were included in this study included heat, smoke and flame detectors. The choice of detectors was
based on the fact that heat detection is the most broadly used fire detection technology in the engine compartments of HD vehicles. Although flame detectors commence to be employed for detecting fires in these applications, smoke detectors are seldom used.

Discussion of partial results

Three linear heat detectors with fixed activation temperature ranging from 139 °C to 180 °C which are customarily used by fleet operators were tested together with an IR/IR flame detection system and one aspirating optical smoke detection system. The detection systems were installed in the engine compartment of the bus as it could have been installed in a real case with the aim of covering the entire engine compartment. Three fire scenarios were designed to simulate realistic fires and consisted of both slow developing electrically generated fires as well as a fast developing fuel leakage fire. A photograph of a spray fires is presented in Figure 4. The air flow through the engine compartment represented a stationary bus on idle speed. The rear hatch of the engine compartment was replaced with glass windows for increasing the visibility into the engine compartment during the tests.

Figure 3. City bus prepared for performing fire detection tests.
The detection ability varied among systems and fire scenarios. While the flame detector gave extremely fast response on the fast developing fuel spray fire, it did not respond at all to the small and slow propagating electrically generated fires. The flame detector used in the test was designed to automatically adjust its detection alarm level to avoid false alarms, i.e. the detector does not respond if the radiation level increases too slowly. The results from the linear heat detectors shows that the tested systems have to be close to an open flame in order to activate, which may considerably delay the alarm time for small fires occurring at some distances from the detection system. Moreover, the air flow from the engine compartment fan had a great impact on the heat transport by transporting hot gases from the fire area. It underlines the importance of covering the entire area potentially affected by fire with detectors and considering the heat and mass transport to the detectors. The tests did not show any significant differences in detection times between the different fixed temperature heat detectors. The results from the aspirating smoke detection system showed that the tested system was able to detect the fire at an early stage, i.e. already at small concentrations of smoke. The test results show the importance of appropriate fire detection system design in order to avoid unwanted consequences in case of engine compartment fires.

**SUMMARY**

The work presented in here is part of the project “Fire detection & fire alarm systems in heavy duty vehicles – research and development of international standard and guidelines”. The project will continue until the end of 2015 and the aim of the project is to develop an international test method for fire detection systems in the engine compartment of buses and other heavy duty vehicles. Most work packages in the project are mainly focused on producing background material for the overall goal of defining an international test standard for engine compartments, but the project also includes work leading to recommendations on which type of fire detection system that is most suitable in e.g. toilet compartments and how the systems should be installed.

The remaining work consists on laboratory testing, both full scale and small scale testing, thoroughly investigations regarding background noise and fire causes, and of course the development of an international test method. The background includes normal variation of temperature, airflow, vibration, particle concentration, and particle distribution in the engine compartment of heavy duty vehicles operating e.g. in different road environments, in mines, or at construction sites.

Acknowledgements

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REFERENCES


Battery Aspects on Fires in Electrified Vehicles

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ABSTRACT

Safety issues concerning the use of large lithium-ion batteries in electrified vehicles are discussed based on abuse test results of lithium-ion cells together with safety devices for cells. The presented abuse tests are; propane fire test, external heating test (oven), overcharge and short circuit. It was found that in a fire, cells with higher state of charge (SOC) gave a higher heat release rate (HRR) while the total heat release (THR) had a lower correlation with SOC. One fire test resulted in a hazardous projectile from a cylindrical cell. Toxic gas emissions of hydrogen fluoride (HF) were measured in the fire tests and it was found that the total amount of HF released increased with lower SOC.

KEYWORDS: lithium-ion battery, electrified vehicle, safety, thermal runaway, fire, toxic gases

INTRODUCTION

The lithium-ion (Li-ion) battery technology can enable a broad introduction of electrified vehicles mainly due to its high energy capacity. Li-ion batteries also have other important properties, e.g. long life time and the possibility of fast charging. However, lithium-ion batteries have a drawback compared to most other battery technologies in that the electrolyte is flammable and the battery may go into a thermal runaway, that is, the battery may self-heat, resulting in a rapid pressure and temperature increase in the cell, which will release flammable and toxic gases but can also cause projectiles and fire [1-2]. This may happen moving out of the stable operating window of the Li-ion cell and can be caused by e.g. short circuiting, overheating, overcharging or mechanical damage.

Lithium-ion batteries are used in very large numbers for consumer products like cell phones, laptop computers etc. Incidents have happened with these batteries but the consequences are in most cases not that serious due to the limited size of the batteries. With the increased number of electric vehicles on the roads the safety issues of the lithium-ion technology have become more important taking into consideration the large size of the batteries in automotive applications. Incidents involving electric vehicles have indeed happened some of them resulting in fires. But luckily these fires have not resulted in any more serious consequences yet.

One example is three car fires involving the battery electric vehicle (BEV) Tesla Model S that occurred in 2013. In two of them the driver hit road debris at highway speed while one was caused by a crash into a concrete barrier and a tree resulting in significant deformations. The first fire was a result of penetration from beneath of the battery pack. Mass media attention was high regarding these incidents and the fires made the stock price of Tesla to decrease. Anyhow, compared to the annual average number of automobile fires in the USA, of the order of 1/1000 automobiles [3], the number of car fires in Tesla Model S (estimated as 1/1000 cars) is significantly lower. This comparison does not take into account the age of the cars involved, older cars may be more prone to fires, but it still shows that the risks involving electric vehicles should not be overstated. National Highway Traffic Safety Administration (NHTSA) investigated the fires and did not find any defect trends [4] but Tesla did voluntarily chose to reinforce the underbody of their cars by arming plates [5] in order to lower the frequency and the effect of hitting road debris.
Other incidents include the Fisker Karma plug-in hybrid electric vehicle (PHEV). In October 2012 hurricane Sandy caused flooding of a harbor in Newark, New Jersey. The flooding lasted several hours and thereafter 16 brand new Fisker Karma were destroyed by fire. The cars were completely covered with salt water during the flooding, an extreme situation where electrical short circuits are likely to occur. Again mass media attention was high even though other vehicles including other PHEV/HEV also burnt. Prior to hurricane Sandy some other fires incidents occurred involving Fisker Karma, one of them outside a supermarket shortly after the driver left the car. Fisker Karma is now no longer produced, possible partly due to the fire problems but also due to other causes. These incidents are examples where electric vehicle fires have been in the focus of the mass media. Other fires have happened, during charging or as spontaneous fires, but have not gained as much media interest. The fires and their consequences clearly demonstrate the necessity of putting safe vehicles on the market, not only for the safety of humans in or near the vehicles but also for economical and environmental reasons.

The electrified vehicle (xEV) has a potential to be safer than conventional combustion engine cars, simply because the main fire source, gasoline/diesel is removed [6]. Anyhow, the safety of a battery system depends on several things, e.g. cell chemistry, cell design and system design, including thermal management system and control strategies. Common cathode chemistries contain cobalt, e.g. lithium cobalt oxide (LCO), LiCoO₂, lithium nickel manganese cobalt (NMC), LiNiₓMn₁₋ₓCo₂O₂, and lithium nickel cobalt aluminum (NCA), LiNiₓCo₁₋ₓAl₂O₂. Lithium phosphates [7] are also used, e.g. lithium iron phosphate (LFP), LiFePO₄. For the anode, various forms of carbons are dominant while lithium titanate oxide (LTO), Li₄Ti₅O₁₂, is used in lower volumes. This paper focuses mainly on carbon-LFP cells which are seen currently as state of the art on the market when it comes to safety, although many battery systems for automotive applications use less stable chemistries in order to obtain e.g. higher energy density. Abuse test results from cell level are presented and their impact is discussed on battery system and vehicle level.

CELLS STUDIED

Cylindrical cells as well as pouch and soft-can prismatic cells have been tested. In the pouch cell, the layers are stacked on top of each other and sealed by an aluminum-polymer bag. The pouch cell is often called a coffee bag cell or a polymer cell. Figure 1 shows an X-ray photo of the EiG pouch cell. The layered structure is clearly visible, where the white/grey colored layers are the separator material.

![Figure 1](image.png)

Table 1 shows the cells and their specifications for the abuse tests presented in this paper. Most of the cells have a LFP-cathode and a carbon based anode as seen from Table 1. The initial state of charge (SOC) level of the cells was achieved by charge/discharge procedures using a Digatron battery test equipment or an ordinary laboratory power aggregate. The cells had not been used prior to the measurements but had different calendar ageing. The EiG and Lifetech cells had approximately 2-3 years of calendar aging while the European Battery cells were less than 6 months old and the Samsung, EVE and GBS cells were about 1 year old. Cylindrical cells of type 18650, i.e. 18 mm in diameter and 65 mm long, are produced in very large volumes and are traditionally used in laptops. Besides the use of 18650 cells in laptops, Tesla Motors has chosen the 18650 cell format as a basis for
its serial-production of electric vehicles, while other vehicle manufacturers have chosen the prismatic or pouch cell type. Panasonic is the cell supplier for the Model S battery which uses cells with NCA as cathode material [8].

Table 1  Cell and test specifications.

<table>
<thead>
<tr>
<th>Cell</th>
<th>Nominal cell capacity (Ah)</th>
<th>Nominal cell voltage (V)</th>
<th>Cathode/ anode</th>
<th>Cell packaging</th>
<th>Test type presented in paper</th>
<th>Initial SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EiG ePLB-F007A</td>
<td>7</td>
<td>3.2</td>
<td>LFP/carbon</td>
<td>Pouch</td>
<td>propane fire, overcharge</td>
<td>0-100</td>
</tr>
<tr>
<td>Lifetech X-1P</td>
<td>8</td>
<td>3.3</td>
<td>LFP/carbon</td>
<td>Cylindrical</td>
<td>propane fire</td>
<td>100</td>
</tr>
<tr>
<td>European Battery</td>
<td>45</td>
<td>3.2</td>
<td>LFP/carbon</td>
<td>Pouch</td>
<td>short circuit, overcharge</td>
<td>100</td>
</tr>
<tr>
<td>Samsung ICR18650-24F</td>
<td>2.4</td>
<td>3.6</td>
<td>Cobalt based/carbon</td>
<td>Cylindrical</td>
<td>External heating (oven)</td>
<td>100</td>
</tr>
<tr>
<td>EVE F7568270</td>
<td>10</td>
<td>3.2</td>
<td>LFP/carbon</td>
<td>pouch</td>
<td>overcharge</td>
<td>100</td>
</tr>
<tr>
<td>GBS LFMP40Ah</td>
<td>40</td>
<td>3.2</td>
<td>LFMP/carbon</td>
<td>prismatic</td>
<td>overcharge</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 2 Photo of tested cells, not same physical scale.

THERMAL RUNAWAY

The thermal runaway was studied by external heating abuse test for a commercial 18650 laptop cell. The cell is produced in large quantities by Samsung. The cell was fastened to a brick and placed inside a thermostatically controlled oven, Binder FED 115, and heated up in about 1 hour to the thermal runaway temperature. The cell voltage and the cell surface temperature (measured by four type K thermocouples) as well as the oven air temperature (measured with one type K thermocouple) were measured with 1 Hz. Figure 3 shows the cell voltage and the differential temperature, ΔT, as a function of the oven temperature. The differential temperature is the difference between the average cell surface temperature and the oven temperature. Before the thermal runaway the cell voltage breakdown occurs due to melting of the separator, an endothermic process which is observable as a small local decrease of ΔT. ΔT has negative values up to 220 °C due to higher oven temperature than cell temperature, while the thermal runaway occurs at 220 °C. The cell surface temperature increases to close to 800 °C (ΔT above 500 °C), with a maximum rate of around 5000 °C/min. Observations from the video recording showed that the thermal runaway is accompanied with a pressure wave and instant ignition. The duration of the fire is approximate 1 minute.
Figure 3  External heating test of a Samsung 18650 laptop cell.

FIRE CHARACTERISTICS ON CELL LEVEL

The fire tests were conducted using the measurement and gas collection system of a Single Burning Item (SBI) apparatus that is normally used for classification of building materials according to the European Classification scheme EN13823 [9]. The experimental setup is shown in Figure 4. The battery cells were placed on a wire grating. A 15 kW propane burner was placed underneath the cells and was ignited two minutes after the start of the test.

Tests were performed on EiG and Lifetech cells. Five cells were tested at the same time. The EiG cells were fastened together with steel wire while the Lifetech cells were placed inside a protection box made of walls of non-combustible silica board and steel net at the bottom and top. Additionally, a secondary layer of steel net was used at the top nailed to the wire grating to protect from hazardous projectiles, see Figure 5. A blank test was conducted at the beginning of each test day in order to be able to subtract the burner influence on the heat release rate (HRR) values and to make a blank for the gas analysis. HRR values were calculated by the oxygen consumption method and corrected for CO₂ [9]. The fire emissions from the test object were collected in a duct flow. In the tests of EiG cells with
100% SOC a duct flow of 0.6 m$^3$/s was used but in order to increase emission concentrations in the ventilation duct the flow was decreased to 0.4 m$^3$/s for the other tests of EiG cells and for the Lifetech cells. All tests were video recorded. A heated (180 °C) sub-flow was taken out to an FTIR, Thermo Scientific Antaris IGS analyzer (Nicolet), with a gas cell (heated to 180 °C), that measured gases, e.g. hydrogen fluoride (HF). Each test used a fresh primary filter (heated to 180 °C) which was analysed for fluoride content after the test. All fluoride found was assumed to be in the form of HF. For a detailed description of the experiment, see Andersson et al. [10].

The heat release rate for various SOC levels for a five-cell-pack of EiG cells is shown in Figure 6. A strong dependence between SOC and HRR can be observed and lower SOC values result in lower heat release rate peaks. For 100% SOC there are rapid heat releases, outbursts, one per cell, while no outburst or HRR peak can be seen for cells with lower SOC. For an example of an outburst see Figure 7. The total heat release (THR) has a relatively low dependence on SOC and was roughly 8 MJ for the five-cell-pack, corresponding to 6.5 MJ/kg battery. Ribière et al. [11] found, based on a 11 Wh pouch cell with LiMn$_2$O$_4$ (LMO) cathode, a heat of combustion of 4 MJ/kg, which is in the same order as that measured in our study.
The nominal energy content of the five-cell-pack is 112 Wh. Electrified vehicles typically have 10-30 kWh of batteries and an extrapolation of our values to the energy released for this size of battery pack gives a THR of 700 - 2100 MJ, which corresponds to a fire of about 20-50 liter of gasoline.

PROJECTILE HAZARDS

Batteries can also cause projectile risks which was demonstrated in one of the fire tests. Even though the cells were equipped with a safety valve this did not prevent the explosion of one of the five Lifetech cylindrical cells as shown in Figure 8. Material from the cell interior was expelled while the cell moved backwards with a clear bang and a pressure wave forming a crater in the bed of small stones in the propane burner. No visual flaws of any kind could be observed for any of the five Lifetech cells before the test. A simple tear-down was conducted but no indications were found to understand why that cell exploded. Figure 9 shows photos during tear-down. No separator could be observed in the cell, which was expected due to the high fire temperatures. The positive current collector of aluminum foil seemed to have melted completely. The copper foil was still present. The weight loss of the cell was 27%.
CELL VENTILATION AND TOXIC GASES

The gases released from a Li-ion battery cell can be toxic, e.g. CO, but the fluoride emissions are of most concern. Hydrogen fluoride (HF) is one of them, but there are also others, e.g. phosphorous oxyfluoride (POF₃). They are formed from the fluorine content used in the Li-ion cell, the binder (e.g. PVdf) and the commonly used Li-salt, hexafluorophosphate (LiPF₆). The reaction formulas for the salt decomposition can be seen in the following equations [12].

\[
\begin{align*}
\text{LiPF}_6 & \rightarrow \text{LiF} + \text{PF}_5 \\
\text{PF}_5 + \text{H}_2\text{O} & \rightarrow \text{POF}_3 + 2\text{HF} \\
\text{LiPF}_6 + \text{H}_2\text{O} & \rightarrow \text{LiF} + \text{POF}_3 + 2\text{HF}
\end{align*}
\]

HF has a relatively well-known toxicity [13] while the toxicity of POF₃ is unknown. However, POF₃ might be even more toxic than HF as in the case of the chlorine analogue POCl₃/HCl [14]. POF₃ could not be observed in the fire tests on Li-ion cells reported here. A fire study on electrolytes in a Cone calorimeter by Andersson et al. [10] indicated that the POF₃ production might be approximately 1:20 of the HF production, which indicates that POF₃ may have been released also in the present tests but the concentration was below the detection limit (6 ppm). Figure 10 shows the real-time HF production rate for EiG cells with different SOC during the fire tests. The highest rate is for 50% SOC while 100% SOC has the lowest rate. The total amount of HF from both FTIR and the sampling filter is shown in Table 2 and values are between 4.9-13.9 g HF for a five-cell-pack. Ribière et al. [11] measured HF in their studies of another type of pouch cell and if we normalize their values against the cell electrical energy we obtain 37-69 mg/Wh, with the higher HF amounts for lower SOC. These amounts are in the same order as our results, 50-120 mg/Wh, however, in contrast to our study, Ribière et al. [11] found the highest HF production rate for the fully charged (100% SOC) cells.

<table>
<thead>
<tr>
<th>SOC (%)</th>
<th>Max rate of HF production (mg/s)</th>
<th>Total amounts of HF (g)</th>
<th>Total amount of HF (mg/Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Our measurements</td>
<td>Calculated from</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ribière et al. [11]</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>8.3</td>
<td>5.6</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>16</td>
<td>14</td>
<td>120</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>11</td>
<td>100</td>
</tr>
</tbody>
</table>
Extrapolation of our data to a larger battery pack size typically used in electrified vehicles gives an indication of the potential amount of released HF. A battery pack for an electrified vehicle, based on the tested EiG cell, could, for example, have 432 cells. This corresponds to 108 cells in series and four cells in parallel which results in a battery pack with 9.7 kWh and 346 V nominal voltage. The extrapolation factor is then 432/5 = 86.4, resulting in 400-1200 g HF depending on the SOC level. These values are in the same order of magnitude as those reported by Lecocq et al. [15] for fire tests on a complete electric vehicle.

![Figure 10](image1.png)

*Figure 10*  The rate of HF production for a EiG five-cell pack for 0%, 50% and 100% SOC.

**CELL SAFETY MECHANISMS**

Cylindrical 18650 cells for consumer products typically have a cobalt based cathode which is not as thermally stable as LFP [16]. A number of safety mechanisms [17] are often included in 18650 cells used in consumer products for low voltage systems. An example of such a safety mechanism is the current interruption device (CID). The CID is a disc which is part of the current pathway. In case of overpressure in the cell, the CID is mechanically released due to the pressure, letting the cell go into open circuit mode. The CID is typically activated at a predesigned stage, before the cell can go into thermal runaway, by using shutdown additives [18]. PTC (positive temperature coefficient) is another safety mechanism, which protects the cell by rapidly increasing the resistance in the current pathway when triggered by an overtemperature, significantly lowering the current passing through the cell. Anyhow, the CID and PTC do not work that well in battery systems with multiple cells electrically connected in series and thereby a higher voltage [19] e.g. in batteries used in electrified vehicles. Figure 11 shows a cross-section X-ray photo of a 18650 cell where PTC and CID are shown.

![Figure 11](image2.png)

*Figure 11*  X-ray photo of a 18650 cell with the PTC and CID marked.
Shutdown separators are widely used in commercial Li-ion batteries as a safety protection for some abuse situations, e.g. overcharge and short circuit. The pores in the separator are closed at overtemperatures which lead to a hindered ion transport between cathode and anode and thus an open circuit. The shutdown separator usually consists of a layered structure where one layer has a lower melting temperature than the other layer. When the first layer melts the pores in the separator are closed, while the second layer sustains the cell integrity thereby prohibiting internal short circuit. Figure 12 shows DSC measurements of a polypropylene (PP) separator and of a shutdown separator with polyethylene (PE) and PP, the latter exhibits two melting temperatures, corresponding to the two materials. In case of e.g. an overcharge leading to an increased cell temperature, the PE will melt at around 130 °C, lowering the current and thereby the heating process. It may work less well in some situations e.g. when the current is interrupted too late or when the cooling is poor due to the battery system design. In those cases the melting temperature, around 160°C, of the second layer of PP can be reached leading to the total disintegration of the separator followed by an internal cell short circuit. The use of shutdown separators in large battery systems has shown not to have the same safety benefits as in small batteries. When many cells are electrical connected in series (forming a cell string) it causes the voltage to increase which in turn can also lead to separator breakdown [20].

![DSC measurements of two different separator materials, one shutdown separator with PE-PP and one with only PP. The DSC measurements used a liquid N₂ cooled Mettler DSC-30, the samples were purged with N₂, and heated between 25 °C and 185 °C with a heating rate of 5 °C/min.](image)

In order to account for the drawback that some of the typical safety devices used in cells for consumer products cannot be used in Li-ion cells for electrified vehicles, other safety mechanisms such as special additives in the electrolyte are used. Li-ion cells for xEV typically uses cells which higher quality in manufacturing with more pure raw materials and safer chemistry like the LFP which can withstand abuse better. Figure 13 shows 2 C-rate overcharging of four LFP based cells with a capacity between 7-45 Ah. The GBS cell has a cathode of LFMP, i.e. LFP with manganese. The charger voltage was max 15.3 V and the charger was active during the complete test. The temperatures reached less than 80 °C, well below the onset temperature of the thermal runaway. However, the cells swell and gases are emitted. Four European battery cells were tested and the result from one of them is shown in Figure 13. Actually one of the European Battery cell unexpectedly caught fire. A situation of an overcharge abuse in the field might occur in case of a failure in the battery management system (BMS). High charge currents can occur e.g. during fast charging or during breaking (recuperation) of a xEV which makes those cases especially sensitive to errors in the overcharge protection. In principle, the consequences for overcharging of LFP cells are less dramatic than for other Li-ion chemistries but the temperature increase starts at a lower state of overcharge [16].
In case of a short circuit of a Li-ion battery the current can be very high. Measurements of a low-ohmic short circuit on a single pouch cell from European Battery are shown in Figure 14. The voltage and current were measured with 1 kHz by an oscilloscope and cell surface temperatures (by eighteen type K thermocouples on both sides of the cell) by a data logger at 1 Hz. The short circuit peak current is close to 1100 A and then lowered to a plateau of about 700 A. High currents generates a lot of heat but for this cell the temperature increase is only about 5 °C since the short circuit is stopped when the positive terminal burns off from the cell. In case of a large battery pack with cell terminals that do not burn off, the current and the generated heat can be substantial and in case of burnt off terminal tabs the flames might ignite vented flammable battery gases or plastic parts inside a battery system.

**Figure 13** Overcharge tests of LFP and LFMP cells, with charge current of 2 C-rate.

**Figure 14** Short circuit of a European Battery pouch cell.

**BATTERY SYSTEM AND ELECTRIFIED VEHICLE LEVEL**

High battery safety is accomplished by using many layers of actions of various safety techniques. Figure 15 shows the safety-onion with examples of diverse safety actions used to ensure a low probability for fault and to minimize the consequences of a fault. Firstly, the cell chemistry is essential since this is the basis of the thermal stability. Secondly comes the cell design and packaging. In principle there are three main levels; cell, battery system and vehicle level.
Figure 15 The safety-onion showing examples of layer by layer of different safety actions that can be used to establish a safe battery system in electrified vehicles.

CONCLUSIONS

There is a relatively good knowledge about the safety risks and safety devices used in consumer cells. Using Li-ion in the automotive sector puts higher demands on the battery since the batteries are significantly larger and with harsher environmental conditions, e.g. vibrations, humidity, larger temperature variations. The different Li-ion chemistries show diverse hazards where the LFP is less reactive but still safety measures are needed for all Li-ion batteries. High safety is achieved by adding several safety layers from cell to vehicle level, however the risk for a cascading fire in a complete battery pack starting from a single cell is not yet well studied and the knowledge about possible counteractions is thus also limited. Sometimes things go wrong even though smart safety strategies are used. The exploded cylindrical cell due to a cell vent malfunction showed this and this fact underlines the importance of using many safety layers.

The toxic gas emissions from Li-ion batteries, e.g. HF and POF₃, can pose a serious risk for persons. A replacement of the Li-salt LiPF₆ to a non-fluorine salt and change of fluorine binder could resolve this risk. Intense research is ongoing in this field but the required properties for a Li-ion battery in a xEVs are complex and demanding.

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Fire Fighting of Battery Electric Vehicle Fires

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ABSTRACT

The growing number of battery-electric and hybrid-electric vehicles increases the risk of an accident involvement and that of a fire event of such a vehicle. The fire brigades and other groups involved in the emergency response sector need to be trained in handling such situations. To provide information about the burning behaviour of traction batteries and the influence of different extinguishing agents on the fire-fighting success three fire tests were carried out, other tests were analysed.

KEYWORDS: Li-Ion, Traction Battery, BEV, Fire test, Fire Fighting

INTRODUCTION

The number of battery-electric and hybrid-electric vehicles equipped with high voltage traction batteries is rapidly growing in most countries. A changing environmental awareness, rising fuel prices, and political motives are some of the key reasons for this trend. The new market is not only a playground for start-ups and the traditional automobile manufacturers and their suppliers, but also for energy providers, battery manufacturers, and IT-companies. Enormous sums are invested in research and development of such vehicles and the necessary infrastructure.

The large variety of players leads to a dazzling array of different systems, approaches and finally vehicle concepts found on the streets. The electric drive has always had a shadowy existence since the beginnings of the automobile, the last decade's developments justify referring to it as a new technology. As such, it has raised questions and even concerns. The electrical safety and fire safety of the electric drive are subjects of heated debate on internet platforms. More or less funded reports about single events like those of the crash test related fire of a Chevrolet Volt or the post collision fire series of the Tesla Model S even more fired up the debate. In view of the present low registration figures of electric and hybrid-electric vehicles, their involvement in accidents and fire events is accordingly small. Nevertheless, law enforcement agencies, emergency medical services, recovery services and, last but not least, fire departments need to be prepared.

But also among rescue services there is much uncertainty about the right techniques to free trapped occupants after an accident. The same applies to vehicle fires. Can car fires involving vehicles with a lithium ion traction battery be handled in the same way as conventional vehicle fires? Is water the right extinguishing agent? Is there a risk of explosion? Some of the published knowledge guides do not only provide information but do also cause confusion.

Independent, freely available, and scientifically grounded information is required. To service the fire departments DEKRA conducted a series of Li-Ion-battery fire fighting tests. Combined with data from other fire tests the results provide basic information.

STATISTICS

Alternative fuelled and/or propelled road vehicles are the talk of town. The registration figures are fast growing. Nevertheless, the overall number of such vehicles still is very small. According to the German Kraftfahrt-Bundesamt (KBA) – the Federal Motor Transport Authority – just about 1.5% of
all registered vehicles (January 1st, 2013) were driven with alternative fuels, as shown in Figure 1. Gasoline and Diesel are still the unchallenged first, [1][2].

Narrowing the scope on the alternative fuels, liquefied petroleum gas (LPG) and compressed natural gas (CNG) have the lion’s share. Including plug-in-hybrid vehicles the number of electric vehicles grew to about 15,800 in Germany. 7,114 of them were battery electric cars, about 3,000 battery electric trucks. The share of battery electric vehicles (BEV) of the overall vehicle population was thus at 0.019%, Figure 2, [1][2].

Information about the number of vehicle fires is rare. Most European countries do not have a statistic on vehicle fire incidents. Insurance data is also very limited with only reporting fires in insured vehicles (comprehensive coverage).

The German National Traffic Accident Statistics [3] do not include the category “vehicle fire”. The statistic is based on accident reports by the police. The official form used by the police all over Germany does not contain a query regarding fire.

Large in-depth databases like GIDAS are representative for the traffic accident occurrence, but reliable data about vehicle fires can not be deduced. The data is limited to post collision fires [4]. More reliable data is provided by the statistics of the Association of the German Insurance Companies GDV. Round about 21,000 vehicle fires have been reported to the German insurance companies in 2006 [5]. The weak point of that statistic is – as mentioned above - that fire cases are only registered if the cars had a fully comprehensive coverage.
The German Automobile Club ADAC states the number of 40,000 vehicle fires per year in Germany in a 2002 publication [6]. The Swiss Automobile Club TCS and the Austrian club ÖAMTC state the number of 3,000 vehicle fires per year in their countries [7][8].

Up to date data is available from the Austrian Federal Fire Service Association. In 2004 they counted 1,844 vehicle fires. 1,621 of them were car fires [9]. The vehicle population was 5,575,677, that of cars 4,109,129 [10]. Thus in Austria 0.03% of all registered vehicles and 0.04% of all registered cars were involved in a fire incidence requiring the fire brigade.

Comparatively extensive data is provided by the US American NFPA. According to that data the number of vehicle fires was 258,000 in 2007. Those lead to 385 civilian deaths, 1,675 civilian fire injuries and a property damage of $1.4 billion [13]. Compared to the 2006 data with 278,000 reported vehicle fires, 490 civilian deaths, 1,200 civilian injuries and a property damage of $1.3 billion, a decreasing number of fires faces an increasing amount of property damage [14].

DEKRA FIRE FIGHTING TESTS

To gather additional information about the burning behavior of Li-Ion-traction batteries and the possibilities of fire fighting, three tests were carried out within a test series. The temperatures of the batteries and the necessary amount of water for fire fighting were recorded. HD videos and extensive pictures were taken to generate schooling material.

The similar type of Li-Ion traction battery (hereafter referred to as LiB) manufactured by Deutsche ACCUmotive has been used in all three tests. The type of battery is used on a current electric vehicle. The LiB uses stacks of pouch cells. The LiBs had a capacity of 17.6kWh and a weight of about 175kg each. There is no metallic Lithium in that type of battery. The state of charge (SOC) was at a 95% level.

The LiBs housing is made of two completely sealed parts of body-sheet metal. The thickness of the pan is 2.4 mm, that of the upper cover 1 mm. The housings had no openings for a direct flooding with water.

The LiBs were placed in a support frame according to their mounting orientation in an electric vehicle (EV). The support frame was located inside a tray, Figure 3. Two sides of the frame were covered to simulate the vehicles’ chassis beams. The tray was filled with 45 litres n-heptane as ignition source. The initializing fire burned for about 11 minutes, Figure 4. The fire-extinguishing was started in minute 20.
Six thermocouples were fixed on the LiB housings. The temperatures of the thermocouples were then recorded with a data acquisition system at a sampling rate of 1 Hz. The ambient temperature ranged between 20 °C and 26 °C.

With water being the extinguishing agent primarily used all over the world by fire brigades LiB 1 was extinguished with water. The water was supplied through a standardized hydrant. For delivery an AWG type CM nozzle (DIN 14365) was used. The front limiter was fixed, limiting the water flow to a rate of 100l/min at maximum full jet. The water flow rate can be regulated stageless through a control lever between 0l/min and 100l/min, full jet and spray jet are possible.

For LiB 2 the F-500 additive was used. This has shown a good performance in vehicle fire fighting and it is suggested to be used for fighting fires involving LiBs by the independent Baden-Württemberg State Fire School [13]. It uses an encapsulating technology and has a good cooling performance. The water was supplied by the same hydrant like in Test 1. For delivery an AWG TurboSpritze 2000 Venturi 75 – C 2L, specially designed for F-500, was used. The nozzle, working on the venturi principle, has an attached 2l container for the additive. The maximum water flow rate is limited to 75l/min. The admixing ratio was set to 1%. The water flow rate can be regulated stageless through a control lever between 0l/min and 75l/min, full jet and spray jet are possible.

For LiB 3 the Firesorb® additive was used. This has shown a good performance on fire tests with small Li-Ion tool batteries done by the Robert Bosch GmbH [14]. Mixed with water it forms a heat-shielding gel with good cooling capacity and a reduced evaporation rate of the water. To add the additive an inline inductor Z2R according to DIN 14384 with a flow rate of 200l/min and an admixing ration of 1.8% was used. For delivery the same nozzle was used as in test one. The limiter was removed; the theoretical maximum flow rate was 200l/min. Due to the increased friction (inductor + generated gel) the real flow rate was at a maximum of 90l/min.

After igniting the n-heptane it took about 8 minutes in all three tests for a first visible action of the LiBs. The visible effects were small holes in the LiB-housings with inflammable gas/steam escaping through, igniting immediately. The holes were caused by short circuits. Arc flashes were visible through the holes, Figure 5.
In the following course of fire the pressure release devices (PRD) opened several times. The escaping gas led to flash fire like flames with a length of about 200 cm while the n-heptane was still burning, Figure 6. Short circuits led to bright white flames, comparable to welding flames. The LiBs housings were locally damaged caused by that, resulting in a few little holes. A few grams of liquid aluminum were thrown out of the holes, coming up within a radius of less than 2 meters.

After the n-heptane was burnt away after about 11 minutes the LiBs burnt on self-contained. The flames appearing at the pressure release devices were clearly smaller in that phase without the supporting heptane fires. Flames with a length of up to 40 cm were permanently burning around the electric connectors (one per LiB), at the holes in the housing, and at the bottom side at the cooling system connections. Light-colored smoke was emitted by the burning LiBs. The amount of smoke was far less than that emitted by burning gasoline.

Immediately after igniting the n-heptane the temperatures measured rapidly rose. The sensor mounted under the LiB and thus directly above the fire measured temperatures around 750°C. With the n-heptane no longer burning all temperatures decreased. With starting fire fighting the temperatures dropped immediately to below 100°C on the housing and to temperatures around 130°C on the bottom side, Figure 7.

The fires were extinguished well-directed with the approach of using as little water as necessary. The first battery was extinguished with water. Starting in second 1,260 it took about 40 seconds and 70 liters to get the flames extinguished. Several short water pulses followed to cool the heavily smoking (white smoke) LiB. 144 seconds after starting to extinguish the fire the LiB reignited. After extinguishing that fire the battery was cooled with reduced water flow within the next minutes to avoid another reigniting. Then a reduction of white smoke was clearly visible. Within the first 4 minutes about 200 liters of water were used. The LiB heated up and emitted large amounts of smoke again. Another 200 liters of water were necessary to cool down the LiB to a level of little smoke emission. The extinguishing took 17 minutes and 30 seconds and a water amount of 400 liters.
The second fire was extinguished with a 1% F-500 mixture. With the first contact between the F-500 and the LiB the flames immediately disappeared. It took about 14 seconds and 15 liters to get the flames extinguished. The temperatures dropped like in test 1. In contrast to test 1 they did not rise again. Similar to test 1 the LiB emitted an enormous amount of a white smoke/steam mixture, Figure 8. To reduce that also in test 2 several F-500 pulses were used to reduce the amount of smoke. All together less than 80 liters of water were necessary in test 2.

The third fire was extinguished with a 1.8% Firesorb® mixture. Also here the flames were extinguished very fast. It took about 5 seconds to have no more flames visible. The first phase of fire fighting all together took 12 seconds and about 40 liters. The temperatures dropped and stayed on a
low level like in test 2. Also here large amounts of white smoke/steam were emitted. The total amount of water used in test 3 amounted to about 120 liters.

In all tests samples of the water running off have been taken and analyzed in an environmental laboratory. A discharge of the water into the canalization connected to a sewage treatment plant would have been possible in all three cases (according to the limits set by the State of Baden-Württemberg legislation). Table 1 gives a key-data overview of the three tests. The detailed description of the tests and the results are published in [15].

**Table 1 Overview of the three tests**

<table>
<thead>
<tr>
<th></th>
<th>Test 1 Water</th>
<th>Test 2 F-500</th>
<th>Test 3 Firesorb</th>
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</thead>
<tbody>
<tr>
<td>Type of cell</td>
<td>identical</td>
<td>Pouch-cell</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td></td>
<td>175kg</td>
<td></td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td>17,6kW/h</td>
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</tr>
<tr>
<td>Amount of water</td>
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<td>80l</td>
<td>120l</td>
</tr>
<tr>
<td>Additive</td>
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<td>F-500</td>
<td>Firesorb</td>
</tr>
<tr>
<td>injection rate</td>
<td>-</td>
<td>1%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Extinguishing time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Flames</td>
<td>40s</td>
<td>7s</td>
<td>6s</td>
</tr>
<tr>
<td>Re-ignition</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>stop of extinguishing</td>
<td>1050s</td>
<td>689s</td>
<td>456s</td>
</tr>
<tr>
<td>time of flowing water</td>
<td>447s</td>
<td>100s</td>
<td>91s</td>
</tr>
<tr>
<td>Temperatures</td>
<td></td>
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<tr>
<td>max temp on top side</td>
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<td>577°C</td>
<td>409°C</td>
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<tr>
<td>max temp on bottom side</td>
<td>823°C</td>
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<td>751°C</td>
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<tr>
<td>max temp on side</td>
<td>780°C</td>
<td>1294°C</td>
<td>934°C</td>
</tr>
</tbody>
</table>

**OTHER TESTS AND APPROACHES**

Several other companies, organisations, and institutions have carried out fire tests within the last few years. Oftentimes the tests were limited to small battery packs or single cells. The burning behaviour of BEVs has also been the focus of tests. Little information is available about the best ways of fire fighting and the influence of additives on the effectiveness of the extinguishing water.

**Exponent Study**

A very interesting study was carried out by the U.S. American Exponent Incorporation commissioned by the Fire Protection Research Foundation. The title of the study published in 2013 is: Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results [16]. The authors use the results to confirm or supplement the recommendations given in the 2012 NFPA Electric Vehicle Emergency Field Guide [17]. Full scale battery fire tests with the batteries located inside a vehicle dummy led to valuable information about the possibilities of fire fighting, the amounts of water required and effective fire fighting tactics.

**Studies Comparing the Burning Behaviour**

To get information about the necessity of changing fire fighting tactics, the differences between a burning vehicle with an internal combustion engine (ICE) and a battery electric vehicle needs to be analysed. Within several studies such comparisons have been done. The analysed Japanese and French studies led to comparable results. Overall the burning behaviour, the heat release rate and the
emitted gases are very similar [18][19][20]. For a study in Norway a Peugeot iOn was set on fire by igniting the traction battery with a gas burner. No comparison vehicle was used for that test. The description of the burning behaviour and the measured values do not show relevant deviations to fires of vehicles with an ICE [21].

Guidelines for Emergency Personnel

With the fire authorities call for information getting louder, several guidelines have been published. Most vehicle manufacturers published guides in the style of the existing rescue data sheets. Besides providing basic information many of those publications also contain directions to use the service disconnect, limitations about the persons allowed to disconnect and so on. Thus the confusion of the emergency personnel grew. Also did the extend of comments on various internet platforms.

The guideline of the State Fire School of Baden-Württemberg was one of the first independently published information in the German speaking part of the world [13]. The NFPA Guideline is now published in its 2013 Edition [22]. Unfortunately that is not available free of charge. The valuable content is thus not getting the desirable wide distribution.

The BGI 8686 standard published by the DGUV received such a good feedback, that it is also available in English now. The main focus here is not the accident or fire situation, nevertheless the basic information given about electric vehicles is very good for teaching purpose [23].

Vehicle sided Approaches

The main problem in fighting BEV fires with burning batteries is the poor accessibility of the batteries. Usually it is not possible to get water directly to the battery cells. The vehicle manufacturer Renault is following a passive approach. Current models have a fire fighter access for the battery. The battery’s housing has sealed openings on the top side. In case of a fire inside the battery the seal is melting away. The resulting holes can effectively be used to flood the battery with extinguishing water.

Daimler and Behr have a patent on a suppression system. The patent text reads as follows: “The method involves connecting an interior of a lithium-ion battery with a fire extinguishing agent storage by an emergency line, where the interior of the battery comprises individual cells of the battery. A fire extinguishing agent is temporarily introduced from the storage into the interior for fire prevention and/or firefighting. A tempered cooling circuit of the battery is selected as a storage that contains carbon dioxide as a refrigerant. The line is temporarily and fluidically connected with the interior by an emergency opening. An independent claim is also included for a device for fire prevention and/or fire-fighting for a lithium-ion battery of a vehicle i.e. motor vehicle” [24].

CONCLUSIONS

The own tests and those analysed have shown differences in the burning behaviour of conventional ICE vehicles and vehicles with Li-Ion traction batteries. Nevertheless the differences do not require to “re-invent” fire fighting tactics or the fire fighting equipment.

In all analysed tests the batteries burned without any explosions or parts being thrown away. The overall heat release rate is comparable between conventional vehicles and BEVs. With not using large amounts of combustible liquids in BEVs there are no burning liquids flowing away contributing to a fast fire spread to close by objects like seen at gasoline or diesel fires.

In case of a fire the fire brigade can use water for fire fighting. The amount of water required to extinguish such a fire is, according to the test results of the published tests, a lot larger than that used for fire fighting of conventional driven vehicles. Additives can effectively help to reduce the required amount of water. Both substances used in the DEKRA tests showed a very good performance.
Additives reducing the water’s surface tension are expected to easily enter deeper structures of the vehicle and thus better reach the LiB’s casing than just water. The effect can be expected for conventional foaming agents mixed to the water at a similar low rate like used for the F-500 in the DEKRA tests. Here nothing can be said about the effectiveness of extinguishing, because such an agent was not used in any of the analysed tests.

An important factor that has to be kept in mind by the fire-fighters is the enormous amount of smoke emitted as soon as the flames are extinguished. This is worsened by the long time that dense smoke is emitted. The areas to be blocked off are expected to be enlarged. The long time required to extinguish the fire may also need more SCBAs at the scene. The usual personal protective equipment is sufficient.

In many tests the Batteries re-ignited. In one of the Exponent tests the re-ignition occurred 22 hours after extinguishing the battery. Rescue personnel but also towing companies and garage workers need to be informed about that problem.

None of the tests has shown an endangerment of the rescue personnel due to the electricity.

An effective fire fighting of BEVs is possible. A few specific characteristics need to be considered – but that is the case in any incident the fire brigade is responding to.

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Responding to Electric Vehicle Battery Fires

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ABSTRACT
Fires involving cars, trucks, and other highway vehicles are a common concern for emergency responders. Fire service personnel are accustomed to responding to conventional vehicle fires and generally receive training on the hazards associated with various vehicle subsystems. For fires involving electric drive vehicles (a.k.a. electric vehicles), a key question for emergency responders is: “what is different with electric vehicles and what tactical adjustments are required?”

A major test project was initiated in 2012 to directly address this question, resulting in a report in the summer of 2013 titled “Emergency Response to Incidents Involving Electric Vehicle Battery Hazards”.[1] This project is part of a larger on-going effort to proactively address the concerns of fire protection professionals and emergency responders. The intent is to support the proliferation of electric vehicle technology by addressing unwanted fires and other emergency events before they occur, while also effectively mitigating them once they do. The inherent unknown hazards of emerging technology has been a motivating influence for this activity, including questions relating to lithium-ion battery technology that have generally been of interest to the broader fire protection community.[2]

The overall goal of this project was to conduct a research program to develop the technical basis for best practices for emergency response procedures for electric vehicles involving large format lithium-ion batteries. This included consideration of certain details such as suppression methods, personal protective equipment (PPE), and overhaul/clean-up operations.

Figure 1: Large Format Battery Fire Test

Basic hazard concerns that were examined during this project included: (a) thermal characteristics, (b) respiratory and dermal exposure, (c) electrical conductivity, and (d) projectiles. A key component of this project was the full-scale testing of large format lithium-ion batteries used in these vehicles, with suppression of the vehicle fires by qualified fire fighters.

This research activity summarizes these tests and includes discussion on the key findings relating to best practices for emergency response procedures for electric vehicle battery incidents. This research work was primarily conducted by Exponent Inc. on behalf of the Fire Protection Research Foundation, with funding from U.S. Dept. of Energy - Idaho National Laboratories, U.S. Dept. of Transportation, and Alliance of Automobile Manufacturers.

KEYWORDS: electric vehicle, fire, fire fighter, lithium-ion battery

INTRODUCTION AND BACKGROUND
Fire departments and fire brigades are familiar with motor vehicle fires, and fighting such fires is a generally expected part of their normal duties and tasks. These are among the more common fires they
For example, in the United States, between 2009 and 2011, there was an average of approximately 187,500 highway vehicle fires per year.[3] Despite being on a downward trend from earlier years, the number of incidents is still noteworthy. A typical fire fighter can realistically expect to fight a highway vehicle fire at some point in their career.

Vehicle fires that occur in the open (e.g., not within a garage or building) are generally classed as highway vehicle fires in the statistical literature. Further, a highway vehicle is defined as a vehicle intended for highway use and is classified as either a passenger road vehicle or truck/freight road vehicle.[4]

Passenger road vehicles are designed with the primary purpose of transporting people using roads, and include cars, buses, recreational vehicles, and motorcycles. Truck/freight road vehicles include pick-up trucks and larger transport vehicles.[5] The most common highway vehicles involved in fires are automobiles (a.k.a., cars), accounting for over 70 percent of the highway vehicle fires in the United States during the five year span of 2003 to 2007.[6]

New technology is becoming available in the transportation sector that is changing the characteristics of automobiles commonly found on the roads today. The landscape of new motor vehicles is changing and national government policies are promoting the use of certain new technologies, like electric vehicles, to alleviate the dependence on foreign energy resources.

These technologies are providing significant improvement in vehicle efficiencies, but at the same time they are introducing new potential hazards requiring tactical adjustments and a need for awareness by emergency responders. This project takes into account the following key characteristics:

- The landscape of modern automotive vehicles is changing, with a renewed focus on electric and hybrid electric vehicles.
- Large format lithium-ion batteries are one of multiple available technologies serving as an alternative to internal combustion engine powered vehicles, and at this time they are among the more common alternative energy approaches for motor vehicles.
- Fires involving internal combustion engine vehicles are relatively common, and this serves as a baseline since today’s fire service has widespread experience and familiarity with fighting these fires.

There has been some effort to provide standardized operating approaches for emergency responders fighting fires involving large format lithium-ion batteries such as those used in electric vehicles. However, a solid technical basis for these requirements has not been well-established, reinforcing the value of a research project to address these issues.

At the time of this study, a primary emergency operating guidance document of interest has been interim guidance provided by the National Highway Traffic Safety Administration (NHTSA), which is a federal agency under the U.S. Department of Transportation. NHTSA states the following in their Interim Guidance for Electric and Hybrid Electric Vehicles Equipped with High Voltage Batteries: “If the fire involves the lithium-ion battery, it will require large, sustained volumes of water for extinguishment. If there is no immediate threat to life or property, consider defensive tactics, and allow the fire to burn out.” [7] Among the questions lingering around this guidance, is the amount of water that equates to “…large sustained volumes…”

Another example of efforts to provide standardized operating approaches for emergency responders fighting vehicular lithium-ion battery fires is underway with the Society of Automotive Engineers (SAE) International. In 2012 they released their document J2990-12, Hybrid and EV First and Second Responder Recommended Practice, which describes the potential consequences associated with
hazards from electric drive vehicles and suggests common procedures to help protect emergency responders, tow and/or recovery, storage, repair, and salvage personnel after an incident has occurred with an electric vehicle.[8]

Notable among these various efforts to address standardized operating approaches for emergency responders fighting vehicular lithium-ion battery fires projects has been a major initiative to develop training materials for all emergency responders in a three year project funded by the U.S. Department of Energy. This has been led by the National Fire Protection Association (NFPA) in partnership with a wide range of other interested organizations, and is currently available at the website www.evsafetytraining.org.[9]

RELATED RESEARCH
Around the 2008 to 2009 time frame, a renewed focus emerged to address the inherent fire protection and emergency responder safety concerns relating to the proliferation of electric vehicles, and to clarify long term solutions in support of this technology. The underlying intent of this activity was to support the proliferation of electric vehicle technology by addressing unwanted fires and other emergency events before they occur, and effectively mitigating them once they do.

There were several spin-off research efforts and summit/workshops to address specific issues of concern. The following summary highlights certain pertinent related research initiatives, as well as several summits/workshops that further clarified fire protection related issues for electric vehicle related technology:

- **“Fire Fighter Safety and Emergency Response for Electric Drive and Hybrid Electric Vehicles – Final Report”**: A background research study that assembled core principle and best practice information for emergency responders to assist in their decision making process at emergencies involving electric drive and hybrid electric vehicles. It included a one-day workshop of applicable subject matter experts to review and evaluate the topic.[10]
- **“Assessment of Powered Rescue Tool Capabilities with High-Strength Alloys and Composite Materials”**: A research study that assessed the capabilities and existing field inventory of powered rescue tools and their ability to handle high strength steels found in electric vehicles and other new vehicles now proliferating on the highways.[11]
- **”Electrical Vehicle Charging and NFPA Electrical Safety Codes and Standards”**: A research study that facilitated the safe integration of electric vehicles into the electrical safety infrastructure, by reviewing the technologies likely to impact electrical safety, and presenting an assessment of needed changes to codes and standards along with a roadmap for needed additional research.[12]
- **”U.S. National Electric Vehicle Safety Standards Summit Summary Report”**: The proceedings for a summit held on 21-22 October 2010 in Detroit, Michigan to address safety related codes and standards issues, with a focus on the fundamental codes and standards centric areas of: vehicles, built infrastructure, and emergency responders. This was intended to develop the base elements for an action plan for the safe implementation of electric vehicles using safety standards as the primary mechanism for this action plan.[13]
- **”2nd Annual Electric Vehicle Safety Standards Summit – Summary Report”**: The proceedings for a summit held on 27-28 September 2011 in Detroit, Michigan to bring together the appropriate stakeholder groups to further refine a shared implementation plan to ensure that fire and electrical safety standards impacting electric vehicles do not serve as a barrier to their deployment.[14]
- **”Lithium-Ion Batteries Hazard and Use Assessment“**: A research study to develop the technical basis for requirements in codes and standards to support the protection requirements for hazards involving lithium-ion batteries. This report provides a literature review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution. It additionally provides a research approach
toward evaluating appropriate facility fire protection strategies for the bulk storage of lithium-ion batteries.[15]

- "Personal Protective Equipment for Hybrid and Electric Vehicles": The proceedings for a workshop held on 1 May 2012 in Quincy, Massachusetts to bring together emergency responders and other stakeholders to develop guiding principles and recommended action steps to address the proper PPE for emergencies involving hybrid or electric vehicles, with a focus on minimizing the risk to emergency responders due to hazards involving electrically energized equipment.[16]

- "Lithium-Ion Batteries Hazard and Use Assessment Ph. IIB": A research study that provides results of full scale empirical fire tests of high rack storage of common lithium-ion batteries, to clarify their flammability characteristics as compared to standard commodities in rack storage. This addressed various sizes of lithium-ion batteries, including batteries for electronic devices such as laptops, power tools, cameras, and cell phones.[17]

- "Electric/Hybrid Vehicle Safety Training for Emergency Responders": A training materials development project focused on providing comprehensive awareness and emergency response training for fire fighters and other emergency responders to prepare them for widespread implementation of advanced electric drive vehicles, with objectives to enhance general awareness training and emergency response tactical training, as well as to establish a centralized resource for ongoing technology transfer.[18]

- "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results": A research study involving full scale fire tests of large format lithium-ion electric vehicle batteries to develop the technical basis for emergency response best practices, with consideration for certain details such as suppression methods, PPE, and clean-up/overhaul operations.[19]

The last of the aforementioned reports and proceedings is the focus of this paper. Several comprehensive research efforts by others are directly related to the topic of emergency response to incidents involving electric vehicle battery hazards. The following summarizes several of the more pertinent and applicable studies:

- **Electrical Conductivity**: The electrical conductivity of fire hose streams is a well-studied topic. Some technical reports date back to the early 20th century, and are still valid today, recognizing that electricity and hose streams have changed little since their work was conducted. It’s noted that the electrical characteristics of salt water (e.g., for ship board fire fighting) has different electrical conductivity characteristics than fresh water, and requires different consideration.[20]

- **Respiratory and Dermal Exposure**: Exposure to fire by-products is an explicit concern with vehicle fires. The National Institute for Occupational Safety and Health (NIOSH) evaluated chemical and particulate exposures to fire fighters during vehicle fire suppression training. NIOSH is the U.S. federal agency that conducts research and makes recommendations to prevent worker injury and illness. Their research evaluated the exposure hazards from conventional passenger vehicle fires to fire fighters and other emergency responders. Their work underscores the importance of wearing full respiratory and dermal protection when fighting vehicle fires of all types.[21]

- **Full-Scale Electric Vehicle Fire**: Full-scale empirical fire tests in Japan provided a comparison of fire behaviour of an electric drive vehicle versus a comparable internal combustion engine vehicle. Measurements included the total heat release rate of the burning vehicles based on calculations using mass loss rates. In this case, the vehicles were not identical models, thus making a side-by-side comparison difficult. Despite these difficulties, the issues of concern to emergency responders were noted to be similar between the two vehicles.[22]

- **Water Additives**: A research study by DEKRA in Germany clarified the use of water additives for the control and extinguishment of large format lithium-ion batteries used in electric vehicles. Full scale fire tests were conducted to evaluate the use of different water
additives (e.g., encapsulator agents), as compared to hose streams with fresh water. This research work demonstrated the effectiveness of fresh water for fire fighting and the additional effectiveness of certain water additives.[23]

- **Vehicle Fire Comparison**: A research study by INERIS in France involving full scale vehicle fires is of particular interest because it provided side-by-side comparisons of similar model vehicles. In this case, four vehicles were burned using two pairs of different models of vehicles, with each pair including an electric vehicle and a comparable internal combustion engine (ICE) vehicle of the same model. Thus the vehicles in each pair were similar other than their propulsion systems. From the perspective of emergency responders responding to a fully involved vehicle fire, the results showed little difference in terms of fire intensity, need for PPE, and concern for projectiles.[24]

**BASIC APPROACH**

The primary focus of this paper is a major test project to directly address emergency responder concerns when responding to fires involving electric vehicle battery hazards.[25] This project is part of a larger on-going effort relating to large format lithium-ion batteries, to proactively address the concerns of fire protection professionals and emergency responders.

The overall goal of this project is to conduct a research program to develop the technical basis for best practices for emergency response procedures for electric vehicle battery incidents, with consideration for certain details such as suppression methods, PPE, and overhaul/clean-up operations. The basic hazard concerns that were examined are the following:

- a) thermal characteristics,
- b) respiratory and dermal exposure,
- c) electrical conductivity, and
- d) projectiles.

The scope of work included, but was not limited to, the following six primary tasks:

i. A review of industry best practices for fire fighting tactics for electric vehicles and internal combustion engine vehicles (to serve as a baseline);

ii. Identification, categorization, and prioritization of battery technologies and representative battery types for full-scale testing;

iii. Identification of the key required elements of electric vehicle emergency response, including tactics, PPE, and overhaul operations;

iv. Development of a full-scale fire testing program for each battery to be tested;

v. Full-scale fire testing per the program developed above, including one unsuppressed heat release rate test and six manual suppression tests; and

vi. Report of final results and summary of the best practices for emergency response to incidents involving electric vehicle battery hazards.

**METHODS AND MEASUREMENTS**

Initially, three different styles of batteries were sought for testing from three different car manufacturers. Due to field-related technical difficulties, related to the charging one of these battery types, only two styles were ultimately used by the project. Of the two styles, both were based on lithium-ion technology and are currently widely used in production vehicles in the United States. These batteries were all tested under fire conditions at a 100 percent state of charge.

These battery styles were designated for this project as Battery A and Battery B. Overall, the project involved the testing of seven large format lithium-ion batteries, with three Battery A type batteries and four Battery B type.

Battery A had a 4.4 kWh electrical storage capacity that is normally installed under the rear cargo compartment of the vehicle. Battery B was a 16.0 kWh battery normally installed under the vehicle...
floor pan spanning nearly the entire length of the vehicle, from the rear axle to the front axle in a T-shaped configuration. Conveniently, Battery A and Battery B cover the spectrum of typical large format lithium-ion batteries in terms of battery size and vehicle installation positions, and were thus seen as being representative of the varying hazards emergency responders could face in the field during actual electric vehicle fires.

This project involved full-scale testing of the seven large format lithium-ion batteries as follows:

- **Heat Release Rate (HRR) Test**: Prior to the manual suppression tests, a single 16.0 kWh battery (Battery B) was burned in a full-scale HRR test at Southwest Research Institute (SwRI) in San Antonio, Texas. This was conducted with full measurement and without any fire fighting intervention. The intent was to clarify the free burning characteristics of the large format battery and provide confirmation of the ignition scenario that would be used in the manual suppression test series. This battery was fully instrumented to monitor essential parameters, and test measurements recorded the following: HRR, products of combustion, temperature, heat flux, projectile observations, battery internal temperature, battery internal cell voltage, thermal imaging, still photography, and high definition video.

- **Manual Suppression Tests**: Six large format batteries were used for the manual suppression tests. These were conducted in two sets of three batteries each. The tests were conducted at the Maryland Fire and Rescue Institute (MFRI) in College Park, Maryland. MFRI is the fire service training academy for the State of Maryland, which satisfied one of the project requirements to conduct the tests at a nationally recognized fire service training site. The first set of tests involved three separate burns using Battery A, and the second set involved three with Battery B. These six batteries were each installed within a generic vehicle fire trainer “prop” (a.k.a., the “mule”) that was intended to replicate an actual electric vehicle. Figure 2 provides an illustration of the vehicle used in the MFRI test series. Each test also included manual fire suppression involving fire fighters with fresh water hose streams.

All manual suppression tests subjected the batteries to simulated exposure fires originating underneath the vehicle chassis using gas burners that could be remotely controlled. The tests were conducted without opening, altering, or manipulating any of the internal features of the large format batteries. Consequently, an external ignition source was chosen using four propane fuelled burners that could be remotely controlled. This was intended to replicate the scenario of a flammable liquid pool fire beneath the electric vehicle, which was considered a realistic scenario based on a collision and resulting fire involving a more common internal combustion engine powered vehicle with the electric vehicle. This ignition scenario allowed for a repeatable and reproducible battery ignition that was credible and could be measurably applied to all the batteries.

The manual suppression tests were conducted with and without vehicle interior finishes. All fire suppression activities were conducted by qualified active duty fire fighters, with no special instructions provided other than to fight the fire according to their normal tactical operations and procedures. The data measured during the manual suppression tests included: temperatures, heat fluxes, projectile observations, suppression water sampling, volume of suppression water flow, nozzle voltage and current measurements, battery internal temperatures, battery internal cell voltage measurements, thermal imaging, still photography, high definition video, and MFRI staff and fire fighter observations.

The intent of the testing was to provide a repeatable and reproducible scientific experiment that evaluated water-based suppression tactics of an electric vehicle fire involving the large format lithium-ion battery. The deliverables from this research project and the data collected were used to bolster current guidance,
such as that provided by NFPA through their Electric Vehicle Training Program and Electric Vehicle Emergency Field Guide.

RESULTS

The initial free-burn test at SwRI of the single Battery B provided important information to establish a baseline of the burning characteristics for the large format lithium-ion batteries. In addition, this test provided proof of concept for the ignition scenario to replicate an external pool fire that would cause the battery to become fully involved in combustion.

In this SwRI test, the single 16.0 kWh battery (Battery B) at 100 percent state of charge was allowed to free-burn without any suppression. This burned for approximately one and one half hours (1:34) with an open flame, but then continued to smoke for an extended period of time. The maximum exterior temperatures at the 1:34 mark were approximately 401 °C (753 °F). Two hours later, maximum observed exterior temperatures were approximately 181 °C (358 °F). Three hours after all visible flaming ceased, the maximum observed exterior temperatures were approximately 156 °C (312 °F). The maximum HRR was 698 kW at just under 18 minutes, and the total heat release was 720 MJ.

It was noted that this free-burn did not result in any concerns relating to projectiles or explosions.

The MFRI manual suppression tests were conducted in two separate series, with the first series involving three Battery A tests (designated A1, A2, and A3) and the second series with three Battery B tests (designated B1, B2, and B3). A wide range of measurements were recorded, and are detailed in the project report. Figure 3 provides an example of one of the MFRI Test Series.

The following is a summary of the overall observations from the manual suppression tests:

- Water was used to successfully extinguish all fires during the suppression tests; however, the amount of time required applying water and the total volume of water necessary for extinguishment was significantly larger than what is typically required for extinguishing a traditional internal combustion engine vehicle fire.

- Fire tests involving vehicle interior finishes (A3 and B3) produced significantly more intense fires with overall greater flame heights than battery only fires. At a standoff distance of five feet from the test vehicle, maximum heat flux measurements for tests without interior finishes (A1, A2, B1, B2) were between 2.1 and 3.7 kW/m2. In comparison, maximum heat flux measurements for tests with interior finishes (A3 and B3) were between 8.1 and 11.9 kW/m2. Overall, the heat flux was comparable to what would be expected for a conventional internal combustion engine vehicle.

- No adverse electrical conditions were noted. Test data indicated that the chassis and nozzle current and voltage levels were negligible. All batteries were tested at 100 percent state of charge.

- No projectiles were observed from the battery pack in any of the tests. None of the batteries tested “burst” or “exploded” in any manner. However, in all tests “popping” and “arcing” sounds and off gassing of white smoke consistent with internal battery cells from the battery pack undergoing thermal runaway were recorded.

- In one test, the battery reignited 22 hours after the battery was fully extinguished and the test concluded, and with the fire deemed to be “out” in accordance with available measurement techniques and observations. Once this test had been completed, this battery showed no signs of visible flaming, no signs of significant off gassing or smoking, and surface temperature readings on the battery were approximately ambient. Following each individual fire test the subject battery was isolated on a remote concrete pad for extended monitoring. The re-ignition was attributed to the stranded electrical energy, and for all batteries there was no way to measure remaining electrical energy due to the fire damage to the battery.
In general, from the perspective of fire fighters and other emergency responders, a fire involving an electric vehicle with a large format lithium-ion battery is comparable to a fire involving an internal combustion engine vehicle. A common question asked by fire fighters is what is different with an electric vehicle fire (with large format lithium-ion batteries) versus a conventional vehicle fire? The answer: they are relatively similar but require certain tactical adjustments.

The fires are not necessarily more intense, though they tend to burn longer and can be difficult to access with a hose stream. One tactical adjustment involves not manually breaching or penetrating the high energy electrical battery during fire fighting (e.g., with a pike pole or haligan bar), and being cautious and respectful of the possible stranded electrical energy in the large format battery. Thus the fires are more difficult to fully extinguish and require more water, but otherwise the fire fighting tactics with fresh water are generally the same. As a result, an aspect requiring special consideration is overhaul and dealing with damaged batteries that may include stranded electrical energy.

It was mentioned earlier that a detail of particular interest is the volume of water required to control and extinguish the fire. This relates back to already established guidance information, which simply indicates that copious amounts of water are required for extinguishment. Thus it is helpful to examine the amount of fresh water used in these tests. Table 1 summarizes the duration of the fire fighter use of hose streams and the volume of water used.

The degree of variability of the results in Table 1 is partially attributed to different fire fighting crews. Interestingly, the fire tests with interior components (A3 and B3) produced significantly more intense fires and appeared to more completely consume the large format batteries, resulting in less stranded electrical energy and arguably more rapid fire extinguishment.
Table 1: Duration and Amount of Water Used During the MFRI Suppression Fire Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Fuel Load</th>
<th>Suppression Time (minutes)</th>
<th>Water Flow Time (minutes)</th>
<th>Total Water Flow (liters (gallons))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Battery only</td>
<td>5:88</td>
<td>2:20</td>
<td>1,041 (275 gal)</td>
</tr>
<tr>
<td>A2</td>
<td>Battery only</td>
<td>36:60</td>
<td>3:53</td>
<td>1,673 (442 gal)</td>
</tr>
<tr>
<td>A3</td>
<td>Battery &amp; interior components</td>
<td>49:67</td>
<td>9:77</td>
<td>4,013 (1060 gal)</td>
</tr>
<tr>
<td>B1</td>
<td>Battery only</td>
<td>26:52</td>
<td>14:03</td>
<td>6,640 (1754 gal)</td>
</tr>
<tr>
<td>B2</td>
<td>Battery only</td>
<td>37:60</td>
<td>21:37</td>
<td>9,990 (2639 gal)</td>
</tr>
<tr>
<td>B3</td>
<td>Battery &amp; interior components</td>
<td>13:88</td>
<td>9:32</td>
<td>4,410 (1165 gal)</td>
</tr>
</tbody>
</table>

SUMMARY OBSERVATIONS

The control and extinguishment of fires involving electric vehicles equipped with lithium-ion batteries requires a response similar to those involving internal combustion engine vehicles, with certain tactical adjustments. For emergency responders this is welcomed news. They are already familiar with fighting a fire involving internal combustion engine vehicles, and the differences between fighting fires involving conventional vehicles versus newer electric vehicles (using standard large format lithium-ion batteries) can be readily addressed.

Specifically, the differences with basic hazards involves consideration of the following four characteristics: (a) thermal characteristics, (b) respiratory and dermal exposure, (c) electrical conductivity, and (d) projectiles.

The tests showed that thermal concerns have attributes requiring certain additional consideration to address fire duration, while the other three characteristics are similar to conventional vehicles. For example, the need for PPE to protect against respiratory and dermal exposure was deemed to be minimally different than a conventional vehicle, requiring full PPE protection. Likewise, there were no projectile hazards that met or exceeded what is already seen from regular vehicle fires due to the sudden release of energy from tires, shocks, or airbag deployment systems. Prior to the tests the stray electrical energy was a question, though the study results indicated no adverse measurements of concern, including at the hose line nozzles during fire fighting operations.

The thermal characteristics was the one subject area with an identifiable difference between electric vehicle fire fighting and internal combustion engine vehicles. The fires were arguably similar in terms of overall HRR, temperatures, and other general parameters, but the one noteworthy difference was that the fires were difficult to suppress and extinguish from a time duration standpoint. They continued for longer periods of time and therefore required more water to complete the fire fighting task.

It is noted that the amount of water in some cases exceeds what is normally carried on modern fire apparatus, and thus fire fighters responding to electric vehicle fires in remote locations with limited water supply will need to consider alternatives. For example, in cases such as those with no exposures in remote areas, the alternative of letting a fully involved large format lithium-ion battery burn may be a viable option, especially with regard to the challenges of overhaul and addressing batteries with stranded electrical energy.

In summary, due to the prolonged nature of fires involving large format lithium-ion batteries, one aspect of fighting these fires that requires additional focus is overhaul and post-fire handling of the vehicle. Further, the batteries likely will have some level of stranded electrical energy, and the phenomenon of re-ignition is a genuine concern. This is particularly challenging when it is no longer possible to measure the electrical energy within the battery due to the damage from the fire. In all cases, the vehicle and battery manufacturers should be consulted for the proper protocol and special directions for handling damaged batteries that may include stranded electrical energy. Fire damaged
batteries should be isolated in a fire safe area after a fire until all stranded electrical energy is deemed to no longer be a concern.

Interestingly, this is introducing a concept in fire protection engineering that is relatively unusual, with arguably extinguished batteries coming back to life much later after the event has been normally considered “closed”. In these tests, fire fighting operations initially suppressed the battery fires, and proceeded to extinguish the fires until there was no measurable indication of excess temperatures or other typical “fire” indicators. However, in one case, a large format vehicle battery re-ignited 22 hours after the completion of the test on an isolated concrete holding pad, after being declared out from a fire fighting standpoint. Thus, isolation of a post-fire damaged battery with potential stranded energy, which can potentially re-ignite, is a relatively new requirement for emergency responders dealing with electric vehicle fires.

In summary, fighting fires in electric vehicles equipped with large format lithium-ion batteries is manageable and well within the capabilities and resources of modern fire fighters. This research focused on specific large format lithium-ion batteries, and further testing of additional battery configurations and technologies is warranted. Of particular interest are new battery technologies like the lithium metal polymer (LMP) batteries in production in Europe, that have dramatically different burning characteristics than the large format lithium-ion batteries in production for vehicles in North America.

Further, this study focused on the use of fresh water in basic manual fire fighting tactical operations, since this is anticipated as being the most probable fire fighting scenario. The use of water additives to improve effectiveness, or the use of other than fresh fire fighting water (i.e., the use of ocean or salt water), is likewise an area that requires further study.

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2011.


20) Sprague C. S., “Electrical Conductivity of Fire Streams”, Research Series #53, Engineering Experiment Station, Purdue University, Lafayette IN, Jan 1936.


EVERSAFE - Overview of Battery Safety and Safe Handling of Damaged Electric Vehicles

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ABSTRACT

EVERSAFE is a Swedish-German project funded by the Seventh Framework Programme Era-Net Transport Electromobility+ and runs from 2012 to 2014. The overall objective of the project is to provide safety requirements and research needs for electrically propelled vehicles. Safety issues are categorized into two groups; active and passive safety and each addresses relevant aspects of safety of electric vehicles. Although fully electric vehicles are the main focus, results of the project also have applications to other electric vehicles variants including hybrid electric vehicles, fuel-cell electric vehicles and plug-in hybrid electric vehicles.

This paper focuses on the passive safety part of the project including cell level component tests as well as comprehensive simulations evaluating battery vulnerability. Special considerations were set to investigate crash cases that are most likely to be relevant for post-crash handling of the battery (or Electrical Storage System – ESS). Electro-chemical behaviour of the ESS was studied in cell tests where fire risks and chemical releases were evaluated. As a consequence recommendations for the safe handling of an ESS for post-crash scenarios were compiled to give proposals to adapt existing or develop new regulations as well as update existing rescue guidelines appropriately. A full scale test of a fully electric vehicle was conducted and the ESS handling recommendations were evaluated.

KEYWORDS: battery, electro-chemical risks, post-crash, handling procedures

INTRODUCTION

The EVERSAFE project (Everyday Safety of electric vehicles) is funded under the Era-Net transport Electromobility+ program. It started in April 2012 and ended in September 2014. The scope of the project is broad and addresses both the active and passive elements of electric vehicles. The project has three technical work packages and one for project management and dissemination. The project is made up of three Swedish and three German partners with a broad range of expertise covering psychology, vehicle safety, material and electro-chemical technology, and vehicle dynamics. The partners included research institutes (BASt, Fraunhofer, and VTI), vehicle manufacturing (Volvo Car Corporation), and universities (TU Chemnitz and Royal Institute of Technology).

The passive safety research activities in the project addressed vehicle structural performance, battery cell behaviour, and post-crash handling issues. The following sections describe the parts of the project related to the physical safety of the vehicle occupants, the Electrical Storage System (ESS), and issues for post-crash handling.

DEFINING RESEARCH QUESTIONS

The project objectives were refined in the first months of work through a literature review, focus
group study, and brainstorming session. The literature review addressed both the active and passive
safety elements in the project and the focus group exercise was oriented on the user perception of the
electric vehicle safety. During a brainstorming session, the subsequent research focus was used to
finalize some critical load cases so that an accident analysis could be conducted and answer the
specific questions raised. The focus groups provided a taxonomy of user concerns that defined
scenarios depending on the role of the individual (Figure 1). The users came from groups with some
or no experience with electric vehicles. It is interesting that both groups identified the release of
battery chemicals and the battery mass as points of concern.

![Figure 1: Taxonomy of User Concerns](image)

**Literature Review**
The literature associated with general safety issues for electric vehicles was divided into different
subgroups: Users, Accidents-Incidents, Electrical Issues, Technical Standards, and Generalist
information. At the beginning of the project there were a few studies of user expectations or
interactions with electric powered or alternative fuel vehicles.

Safety was the most common concern of the consumers although the top concern was range anxiety.
In a telephone survey conducted in USA in 2012 with collected survey data from 1,702 adults, 77%
of interviewed were concerned about the limited range of electric vehicles. The remaining concerns
centered on safety, led by fire risk during home charging (42%), pedestrian safety (40%), crash
protection (39%), and post-crash fire (35%) [2].

In an earlier study, only 1% of 481 respondents ranked safety as the most important issue for electric
vehicles. However, only 57% of the respondents agreed or strongly agreed that EVs are a safe mode
of transportation while 26% indicated they were unsure [3].

There is likely to be adaption of driving styles to the new technologies applied in electrically driven
vehicles [4] as well as the silent operation [5] of the vehicles. The latter was related to how the driver
interprets their interaction with road users outside the vehicle.
The penetration of electric vehicles in the vehicle fleet is still low and this is reflected in the analysis of vehicle crashes based on national data sources such as police reports. The most relevant report describing electric vehicles was that provided by Daimler [6]. Although electric vehicles could not be directly analyzed, they used conventional vehicles as a surrogate and identified deformation maps that could identify the most risky areas for battery placement in real crashes and compared to deformation from standard crash tests (Figure 2). Also, given that electric vehicles will tend to operate in a similar manner in the road system the accident configurations most commonly observed should also be relevant for the near future. A study by NHTSA [7] and Japanese statistics (IATSS, 2007) show that the most common accident types are rear end and intersection collisions.

**Standards and regulations**

Regulations and industry standards have developed dramatically in the last five years to address safety concerns of electric vehicles on both vehicle and battery level. Both UNECE (United Nations Economic Council for Europe) and US FMVSS (Federal Motor Vehicle Safety Standards) have been updated to address vehicles with electrical propulsion. The UNECE regulations, of particular relevance for Europe, have Regulation 100, which addresses the electrical safety for vehicles. Frontal and side impact regulations (Regulations 94 and 95) have been amended to include electrical component safety. FMVSS 305 is the US regulation specifying the test and performance requirements for electrically propelled vehicles. There are similarities between the US and UNECE regulations in that electrical components must always be isolated from the chassis during the test and electrolyte spillage shall be limited to less than 5 l.

At the battery pack level, several standards such as SAE J2929, UL 2580, ISO 12405 have been developed to ensure that high-voltage battery pack can withstand certain mechanical, thermal, and electrical abuse test including vibration, impact, shock, short circuit, etc.

A substantial review of electric vehicle safety requirements was conducted by TRL [8] where occupant, fire, and electrical safety were addressed. The report describes existing and future issues for electrical vehicle regulations in Europe. One interesting issue that was implied by [8] was that fire protection requirements for electric vehicles did not include a rear impact test if the batteries were located outside of the passenger compartment as it was not a flammable fuel storage tank.

**Scenario Definitions**

Following the initial literature review, a project meeting and brainstorming session was used to define the specific areas of interest for the project. Included in this was a definition of critical impact conditions. In terms of battery safety and risk for post-crash issues, pole side impacts and rear impacts were considered those most critical to investigate. Pole side impacts have the most potential for directly deforming an ESS and a rear impact also has the risk for deforming an ESS as well as being a
load case not applicable if all recommendations in [8] were to be followed. While these two crash scenarios are the main research issues, other impact types were open for investigation.

Following this initial groundwork, the project initiated a research program than had following research questions:

1. Are electrically driven vehicles particularly vulnerable to different crash types, especially the chosen scenarios?
2. Do electric vehicles pose new risks compared with conventional vehicles in crashes in terms of emissions of poisonous or flammable gases in a crash?
3. What special post-crash handling procedures are needed?
4. What new regulations and standards are needed?

RESEARCH METHODS

Accident Analysis
While electric vehicles contain different components than conventional vehicles, there are essential safety elements that these vehicle groups share. Both must protect the same human occupants in a crash and both operate on the same roads and thus share the same crash risks in terms of configuration and severity (within the operational capability of the vehicles). This allowed the EVERSAFE researchers to review previous studies without restricting the analysis to only accidents with electric vehicles. While this was an appropriate method to review the crash load cases, it did not allow the research team to study the outcome of a crash with an electric vehicle.

As described in the literature review, the study by Justen et al [6] provided an overview of the damage patterns and extent that conventional vehicles may experience in a crash. This information is a general indicator of the risk for battery deformations, but there is also the risk for high decelerations that may introduce battery safety issues. An investigation of recent crashes in the US with Event Data Recorders (EDR) was undertaken. EDRs contain the crash pulse information for frontal and side impacts in most modern US vehicles and are downloaded in the National Automotive Sampling System (http://www.nhtsa.gov/NASS ) by US accident investigators. Running a query for the two main scenarios – side impacts and rear impacts – a set of crashes was collected to analyse acceleration and deformations from vehicles. These cases are still limited to vehicles with conventional drive trains.

The number of cases matching the selection criteria (rear or side impact, EDR data available) was limited. Only 3 rear impact cases and 26 side impact cases were collected. The results of rear end impacts showed that considerable deformations were observed for low acceleration crash pulses. The vehicles shown in Figure 3 only had accelerations around 10 gs even though there was more than 45 cm of deformation or more. What is interesting in car-car side impacts is that the bumper of the striking car tends to deform the struck vehicle over the sill as seen in Figure 3. This is likely to miss any batteries placed under the floor unless the direct contact is sufficiently large to pull the neighbouring structures and induce structural damage to the batteries through indirect loading.
The EVERSAFE project also had an interest in vehicle crash compatibility for new electric vehicles and there was a need to determine what compatibility issues could be important for the emerging electric vehicle population. One of the main conclusions from the EUCAR project [9] was that side impact compatibility was more dependent on vehicle geometry, while frontal impact was dependent on both mass and geometry. This work was continued in a recent 7th Framework project FIMCAR where an extensive review of modern vehicle compatibility was conducted. In particular the accident analysis report [10] gave a breakdown of important crash outcomes and determined that high overlap impacts, particularly for smaller vehicles, caused high accelerations and produced significant injuries in occupants. Thus, vehicles in the smaller segments were the most at risk. Recent sales information shows that the most sold electric and hybrid vehicles are under 1600 kg[11].

As mentioned earlier, there is limited crash information for electric or hybrid electric vehicles. The Swedish Project “Räddningskedjan” reviewed 165 crashes with hybrid vehicles, the majority being the Toyota Prius[12]. In these 165 cases there were no fires directly after the crash. Crashes that were of special interest were those with small overlaps where the damage was close to some high voltage components in front of the driver. There were also rear end collisions with some hybrid vehicles with similar damage levels as seen in Figure 3.

From the available accident data it was concluded that side impacts and rear impacts are relevant impact scenarios to pursue. The side impacts with poles were given the priority as the deformation extends below the sill and is more likely to damage the batteries. Rear impacts with significant deformations are also a concern.

**Testing – cell Level Tests**

**Cell Level Tests**

Two different experimental test approaches were used in the project. An investigation of battery cell behavior was conducted by two Fraunhofer institutes: Ernst Mach Institute (EMI) and Institute for Chemical Technology (ICT). Both institutes conducted mechanical damage testing to the cells and EMI also performed some material characterization tests to facilitate numerical modeling of the battery. ICT conducted electrical abuse tests.

The cells tested were pouch cells and a series of nail penetration, shear, and external short circuits test. Nail penetration are part of the standard tests being conducted on cells but the nail penetration tests differed between the institutes. The EMI probes were limited by the fixture back plate and did not fully penetrate the cell as specified in the standard procedures while the ICT nail penetrator passed through a hole in the back plate allowing full penetration. The EMI test can be considered more of a localized crush test. The ICT nail penetration tests had a metallic nail to promote internal short circuits while the EMI nails were non-conducting. Both institutes applied a new abuse test, a shear test that cleanly sliced the cells with metallic knives.
In general the tested pouch cells were quite resistant to the abuse. Only 1 of 19 cells resulted in thermal events. A special area of concern is the reproducibility and the robustness of these tests, as the results might strongly differ depending on the testing conditions. The EMI nail (crush) tests produced some cell swelling and each time, a thermal activity was observed (see Figure 4) where temperatures up to 300°C were recorded. The nail used at EMI was made of plastic and could widen during the test, resulting in a local compression of the cell compared to the full nail penetration of the cell at the ICT facility (Figure 4). None of the ICT nail tests produced any significant cell swelling although there were traces of toxic substances. Temperatures did not exceed 60°C. The comparison of these tests shows that a clean penetration with a thin nail doesn’t lead to a reaction of the cell (test performed at ICT), whereas an intrusion with a wider object leads to a local compression and a short-circuit (test performed at EMI). Simulations and full car crash results showed that some current cell abuse tests, e.g. SAE J2464, might not be representative of what may happen in a vehicle crash as the intruding object would probably be wider as a thin nail.

Both institutes conducted shear tests (Figure 5) where there was no significant thermal activity (under 30°C) but with some toxic substance release. Even after the cells had been cut, there was a stable voltage developed by the cell. The lack of reaction in these tests could confirm that a clean cut of the cell will not lead to a failure of the separator and thus no direct contact appears between the cathode and anode.

ICT also conducted external short circuits. No significant thermal activity (temperatures under 50°C) was observed.

**Full Scale Tests**
A full scale test of a Mitsubishi iMiEV was conducted at the BASt test facility. Given the interest in pole side impacts, a trolley with a rigid pole was used to strike the side of the iMiEV. The impact configuration is shown in Figure 6. The test speed was 35 km/h and the trolley mass was 2500 kg.
compared to the 1000 kg iMiEV. The impact location was chosen as the most vulnerable for the vehicle due to battery placement and surrounding protection.

Figure 6: Pole Side Impact

The results of the test are shown in Figure 7 where the characteristic pole deformation is apparent on the vehicle. The damage caused minor damage to the battery casing but nothing was visually obvious in the battery tray after the crash. The orange circle on the top of the figure shows the point of impact. The vehicle was monitored for several weeks after the test. As a result of the undamaged battery housing, no emission of battery chemicals outside the car and inside the battery pack could be detected by the highly sensitive and selective mobile Fourier Transformation-Infrared Spectrometer (FT-IR) provided by Fraunhofer ICT nor by the on-site handheld analytical devices provided by the fire brigades.

Figure 7: Results of Crash Test - Vehicle damage (left) and Battery Pack After Test (right)

Simulation
The simulation activities in the project were intended to analyze the battery protective structures in a second generation electric vehicle. It became apparent early in the project that the planned activities were not possible for the given resources in the project and the lack of a true second generation vehicle. As a result, an existing small car, Toyota Yaris, was used as it is a public domain Finite Element model available from the National Crash Analysis Centre in the US. Previous literature study showed that the tunnel area is statistically the safest place to build a battery. Thus, the model was modified to include a tunnel battery pack with a battery mass anticipated for this vehicle size. The resulting model is shown in Figure 8. The model was used to simulate a number of crash scenarios also shown in Figure 8. However, as the Toyota Yaris was not designed specifically as the platform for electric vehicles, caution should be taken to interpret the simulation results,
The battery was modeled with a simplified cell, module, and pack structure to duplicate the mechanical interactions between the different battery components. The simulation environment allows each module to be monitored during the crash so that force, acceleration, strain, etc. were reviewed in each case. An envelope representing the maximum output from each module was used to determine the worst case (Figure 9).

The worst case forces on the batteries occurred in frontal pole impacts followed by undercarriage (Figure 10), pole side and rear impacts. In terms of accelerations, the front pole impact was worst followed by vehicle side impacts. The results indicate the scenarios identified at the start of the project were relevant for investigation and that some critical scenarios were not belonging current regulations. The pole front and the undercarriage impacts were not considered earlier and are important to monitor in future research.

Figure 8: Modified Toyota Yaris and Load Cases Investigated

Figure 9: Output from All Battery Modules and Resulting Maximum Envelope (black line)

Figure 10: Undercarriage impact simulation
A second set of simulations were explored by EMI using the mechanical tests from the battery cells. A model of the cell structure was constructed using the mechanical information available for the different components. The model was developed at both a detailed and simplified level as shown in Figure 11. The main components are the envelope (aluminum), copper, and a plastic separator.

![Figure 11: Numerical Model of Battery Cell (1-Detailed, 2-Simplified)](image)

The model was validated against the mechanical tests with reasonable results as shown in Figure 12. The metallic components fail first, followed by the envelope and separator, and finally the pouch casing. The detailed model of the cell was useful in understanding some of the cell behavior in the component test. Several cases (shear, nail) involved electrically conductive materials penetrating the cell and bridging the different electrode layers. The expected internal short circuit and resulting thermal activity was not observed in many cases and the different failure thresholds for the materials may explain the robust behavior. The pouch outer case (coating) and separator are essentially plastic, non-conducting materials. As they are more ductile, they may be following the intruding structure and electrically isolating it from the remainder of the cell, reducing the likelihood of an internal short circuit.

![Figure 12: Validation of Cell Model](image)
Post Crash Handling

The EVERSAFE project is currently reviewing the post-crash handling requirements for rescue services in Germany and Sweden. There is also an on-going activity in Sweden in the “Räddningskedjan” project that is working closely with rescue services to develop training information for electric vehicle handling after a crash.

Rescue services need to consider how electric vehicles influence the following steps when approaching any vehicle after a collision:

1) Information on the way to the scene
2) Appraisal of the vehicle on the scene, identification of vehicle
3) Securing/stabilizing the vehicle (if it not all wheels, submerged),
4) Fire control/ control of battery fluid
5) Shut down electrical systems (to prepare for cutting the vehicle if needed for step 6)
6) Occupant extraction
7) Hand-off to towing company

In steps 1) and 2) it is important to determine early on if the vehicle has electric propulsion and significant electrical storage capacity. It is important that electrical vehicles can be easily identified from conventional vehicles. When appraising the vehicle at the scene it is important to be aware of the critical impact conditions and which deformation/damage patterns need to be flagged as most hazardous.

Although not covered by testing or analysis in EVERSAFE, other research has determined that securing/stabilizing the vehicle is not significantly different for electric and conventional vehicles. The main issue is that the main electrical shutoff should be activated earlier for electric vehicles even if this should occur automatically for crashes producing damage to the vehicle. Electric shock protection is required by existing safety requirements (UNECE Regulation R100, R94, R95).

Fire control with water is not dangerous. The main issue that may arise is the increased potential for toxic substances even when thermal activity is not observed. Thus there may be a need to have portable detectors of common battery substances available to monitor a vehicle as well as monitors of battery temperature to identify the risk of imminent gas generation.

Once the vehicle has been stabilised, then occupant extraction can proceed as normal, however the cutting and deformation of the vehicle should be closely monitored to avoid mechanically abusing the battery components, particularly if the battery has been damaged. Once the occupants are extracted, the disposal of the vehicle needs to follow the manufacturer’s handling guidelines and the vehicle structure should be stabilized to not induce further mechanical damage to the batteries.

DISCUSSION

The EVERSAFE project has a broad mandate to investigate the “everyday” safety of electric vehicles. From the passive safety activities in the project, important information and guidance for the post-crash handling of electrical vehicles was developed. One of the main findings to note is that the battery is a relatively robust structure for most situations that may arise during or after a crash. Mechanical abuse testing beyond the standard test condition (shear, local crush) showed the tested cells were robust and required considerable provocation to produce thermal activity of concern for vehicle fires. A special area of concern is the reproducibility and the robustness of these tests, as the results might strongly differ depending on the testing conditions. The simulation, testing, and accident analysis indicate that most crash scenarios involve damage to the vehicle that produce little or no damage to the battery because of low accelerations or deformations to the vehicle. However, some scenarios might be critical for the battery and are not belonging current crash regulations. This is important to realize as it will allow most crashes to be addressed with little consideration for serious fire or electric shocks that may be expected by the lay person.
Only one cell type was tested in the project and the results are indicative only for this particular cell construction and chemistry. The cell tests demonstrated that visually observable damage to the cell was needed to cause the emission of small amounts of toxic gases or thermal activity. Although many of the tests involved visual damage to the cell, not all cases directly led to what one can consider as dangerous conditions. The mechanical loading conditions explored in the cell tests are extreme cases that should be readily identifiable at the scene. Dramatic shearing or penetration of different structures into the battery modules would be required to produce the gas or thermal activity observed. As external short circuits were not hazardous at the cell level, an intact battery system should be considered as safe for all individuals at a crash site.

The main issues that are apparent from the EVERSAFE activities are if hidden damage is caused within a battery pack or module. It is obvious that visible damage to a battery pack could indicate a need to treat the battery carefully. However any internal damage to the battery (within the cell, module, or pack) that occurs without observable external damage to the casings (ie acceleration based) is still an issue to consider. The resources in EVERSAFE were not able to investigate all load cases but high accelerations leading to internal battery deformations should be considered for future standards to reduce the risk of this failure model.

CONCLUSION

The EVERSAFE project had a number of research questions that should be addressed. These questions and the answers to date are:

1. Are electrically driven vehicles particularly vulnerable to different crash types, especially the chosen scenarios?
   Answer: In practical terms, manufacturers using the existing state of the art for vehicle crashworthiness should be able to protect the battery system for expected crashes and certain crash severities. This is obvious from the current databases where new hybrid vehicles have not exhibited any extra issues over conventional vehicles.

2. What special post-crash handling procedures are needed?
   Answer: It appears that there is a need to:
   a) easily identify electric vehicles and their shutoff units.
   b) be aware of sensitive impact configurations and damage patterns that could be detrimental to batteries
   c) have access to portable detectors of toxic substances likely to be released by batteries
   d) ensure that any occupant extrication, towing, or storage activities do not further damage the batteries mechanically

3. What new regulations and standards are needed?
   Answer: This is still under development but there is a need to identify if existing mechanical abuse tests for acceleration induced damage (beyond those specified in UN38.3, ISO 12405) are sufficient. It will also be useful to have standards or regulations that promote robust cell performance so that mechanical damage does not automatically generate internal short circuits within a battery cell or module.
REFERENCES


E-Vehicle Safe Rescue
Investigation of risk factors and rescue tactics in a traffic incident event involving an E-Vehicle

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ABSTRACT
The aim of the research project E-Vehicle Safe Rescue is to form the basis for a new online training program for Swedish rescue personnel concerning how to act when encountering a traffic crash incident involving an E-Vehicle (i.e. any type of electric and hybrid electric vehicle). This program will be based on a revision of existing recommendations complemented with results from a variety of physical abuse tests and traffic related crash tests on battery cells, modules and packs.

KEYWORDS:
e-vehicle; electric; hybrid electric; rescue; risk assessment; li-ion; battery; abuse test; crash; fire; water immersion; gas analysis; rescue tactics; training; first responders

INTRODUCTION
In the event of an E-Vehicle crash, quick and competent rescue of the vehicle occupants requires new knowledge and up-dated training to minimize the time from crash to final treatment for injured occupants. The necessity for better understanding for E-Vehicle behavior in a traffic incident was proved evident through a survey that was sent out to Scandinavian first responders during spring 2011 by the Swedish Civil Contingencies Agency (MSB). In 100% of the survey answers, people of this profession expressed uncertainties in terms of how to act when encountering a crashed E-Vehicle. (1) As a response to these uncertainties MSB together with Umeå University initiated a pre-study 2011 and gathered a group of partners covering academia, industry and research institutes aiming at a research project that would investigate relevant risks and myths related to E-Vehicles in traffic incidents. This research project started in spring 2012 and constituted of the organizations represented as authors for this article.

It is today commonly known that the introduction of Li-ion batteries into the market for E-Vehicles not only offer increased voltage, electric capacity, power density and energy density, but also carry significant amounts of combustible contents due to the use of organic electrolyte in these types of battery cells.. (2) (3) (4) (5) (6) (7) (8) Moreover, in the event of critical battery failure a Li-ion cell is commonly designed to ventilate any critical pressure build-up (9) (10) so as to impede explosive behavior. This ventilation releases electrolyte vapor and other gaseous species generated during critical battery cell failure, which not only presents risk for flammability but research also show that harmful gases can be generated during such a critical failure. (11) (12) (13) (14) (15)

Consequently, concerns are frequently raised about what countermeasures to use among first response teams when encountering E-Vehicle in a traffic accident in terms of personal protection as well as best practice for safe rescue of vehicle occupants and minimizing impact on the surrounding of such a damaged vehicle. Training programs and research projects for this purpose are being developed around the world by governmental agencies, universities and other actors. Most known worldwide is the work done by NFPA and their training program (16), but other examples of programs and projects, beside the research project described in this article, can be found – e.g. AFV (Alternative Fuel Vehicle) Safety Training (17), as well as OEM based such as material released by TESLA (18).
Safety of E-Vehicles, their Rechargeable Energy Storage System (REESS), and Li-ion cells has been under particular scrutiny for the last decade. Research stretch, from fundamental research (academic and/or industrial) on key materials and transport phenomena on nano level for enhanced battery cell safety, to applied research (academic and/or industrial) on power electronics and safe guard systems of cells, battery subsystem and complete REESS. From this perspective, the research project E-Vehicle Safe Rescue is best described as Applied Industrial as illustrated by Figure 1.

This project has been characterized by an investigative nature with focus set on analysis of general properties of an E-Vehicle battery system and its constituent parts from a safety perspective. The project partners have also experimented with test and evaluation methods due to the lack of customized testing of these types of systems on the market. The test and evaluation methods were developed without the purpose of ascertaining a specific test method.

The main focus of this project has been how to implement research findings into practice on the field. Its emphasis has not been on identifying and understanding all the underlying mechanisms leading to various characteristics and failure consequences of batteries and cells; hence, the high position on the applied scale, i.e. y-axis, in Figure 1.

As the E-Vehicle market has consolidated the range of commercial battery chemistries throughout the past five to ten years, Li-ion batteries have proven to present the most viable choice for traction batteries in E-Vehicles due to its high energy and power density. Throughout this time and consolidation process the broad range of Li-ion battery chemistries initially offered to the E-Vehicle market have been reduced to two market dominating Li-ion (cathode) chemistries by preference of the large vehicle manufacturers. (19) (20) (21) In this project, these two chemistries – commonly denoted as LiFePO₄ and NMC – have been exposed to abuse testing on cell, module, and pack levels.

METHOD

Fundamental Analysis to form the Basis
The research project E-Vehicle Safe Rescue started in 2012 by launching two fundamental analysis – on one hand focusing on E-Vehicle tech/chem parameters through industrial technical literature and
academic research literature, and on the other hand focusing on crash statistics and review of existing first responder recommendations. This in order to establish a first overlook on evident risks or potential myths debated by professionals and the public and, based on this overlook, decided what physical abuse testing should be prioritized.

A simplified failure pathway model on cell level was defined and thereafter served as fundamental guidance for project discussions about traffic accident risk assessment. The latter was summarized by three crash event phases – In-Crash Phase; Post-Crash Phase; and Rescue Phase – within which the simplified failure pathway was integrated together with potential failure events on the level of the E-Vehicle and basic actions to consider during rescue actions by professionals. This mapping process, together with the output from the fundamental analysis on E-Vehicle tech/chem parameters resulted in the following selected physical abuse testing on REESS and subsystem units. This selection of physical abuse testing involved:

- **Mechanical Abuse**
  - Crash testing of REESS and subunits as those units experience the crash when mounted in complete E-Vehicle
    - Sled crash test for acceleration exposure
    - Sled crash test for deformation and intrusion exposure

- **Electrical Abuse**
  - Short circuit and battery failure by water immersion – fresh and 3% salt water

- **Thermal Abuse**
  - External fire exposure through bonfire tests – Variable State Of Charge (SOC) and configuration of cells (i.e. numbers of battery cells per test and subunit vs. complete REESS)
    - Analysis of Heat Release Rate
    - Analysis of gaseous species concentrations

- **Fire Suppression and Tactics**
  - Investigation of usability of ten fire suppression agent
  - Investigation of fire suppression tactics

**Mechanical Abuse Testing**

In order to define relevant crash cases of an E-Vehicle to be investigated in terms of crashworthiness and protection of market available REESS, two studies on crash statistics were performed based on data from two of the world’s largest crash statistics databases – the USA National Automotive Sampling System (NASS) and The German In-Depth Accident Study (GIDAS). The NASS study focused on crashes involving E-Vehicles and their documented behavior after crash. The GIDAS study focused on crashes involving E-Vehicles and their documented behavior after crash. The GIDAS study focused on crash patterns of passenger vehicles in general based on filtering criteria:

1. Only passenger cars of limousine-, hatchbacks-, van/suv, and station wagon-shape
2. Only vehicles which got the worst deformation in an Object- or Vehicle-collision
3. The deformation depth in each regarded zone must be known
4. Only vehicles built between the years of 2000 and 2010 or equipped with ESP

Analysis of the two set of data (NASS respectively GIDAS) resulted in case studies of crashes that were considered as representative for E-Vehicle crashes.

The aggregative crash pattern presented to the left in Figure 2 was derived based on the filter criteria above. A terminology for “significant intrusion” was defined on basis of the intrusion patterns seen in high crash-energy accidents (see photo to the right in Figure 2) causing intrusion within the 2 percentile limit. The GIDAS data was collected based on conventional passenger vehicles since no E-Vehicle with relevant crash damage was available in the GIDAS database at the time of this study (i.e. 2012).
Based on data from collision case studies, E-Vehicle simulation models for a selection of crashes were defined. CAE simulations were conducted (Figure 3 left) and the data generated were converted to mechanical abuse tests on complete REESS and subsystems using the sled test laboratory at Autoliv in Sweden (Figure 3 right).

**Figure 2** Identification of relevant crash cases to investigate based on GIDAS data showing collision patterns of significant intrusions, i.e. within the 2-percentile boarder.

**Figure 3** Investigation of crash cases by simulations and the crashworthiness of conventional traction batteries

**Electrical Abuse Testing**

Electrical abuse of a battery system can be caused amongst others by mechanical abuse or failing power electronics. The potentially harmful parameters are hazardous voltage, field strengths in liquids and direct contact with overcurrent in none-controlled circuits. Water immersion was chosen as the most relevant electrical abuse test in relation to a potential E-Vehicle incident.

REESS (about 400 Volt maximum) of two brands respectively two cell chemistries (i.e. LiFePO₄ and NMC) were tested by being immersed into a 400 liter tank with fresh water or 3% salt water (see Figure 4). Field strengths in the water close to the REESS was investigate and the SOC before and after test was documented. The temperature of the water before and after test was documented. The test was performed outdoors for good ventilation in order to avoid accumulation of any H₂ and Cl₂ generated by potential electrolysis of water.

The REESS containing LiFePO₄ chemistry was a prototype REESS acquired from an OEM while the one containing NMC chemistry was a commercial REESS acquired from another OEM.
Figure 4 Water immersion in fresh water and in 3% salt water

Figure 5 show the test setup and points of measurements – the reference point GND respectively point 1 to 6. GND represent a measuring point on the metal housing of the REESS which is transferred to the metal surface of the water tank as illustrated by the orange conductor in Figure 5. The location of the GND point on the water tank surface was used in order to simplify the physical data acquisition. The measuring points 1-6 represent sensors positioned in place by fixations in order to assure precise location in the water outside the REESS.

Figure 5 The outer measurements represent the water reservoir (1300 x 900 mm). The center dark rectangle is the REESS which is being immersed into the water reservoir. The numbered dots – from 1 to 6 – are measuring points for detecting field strength in the water nearby the REESS. GND represents a point of contact with the REESS metal housing.

Thermal Abuse Testing
Bonfire tests were conducted in order to simulate a battery failure cause by external heat source. Tests were performed by SP in dedicated fire test laboratories. Li-ion cells of the two chemistries mentioned in the Introduction were bonfire tested at different SOC and different numbers within bundles of [1; 5; 10] while data about Heat Release Rate (HRR), total heat energy, and concentrations of gaseous species were collected. Also a complete battery pack was exposed to external heat source and the same type of data was collected for analysis.

Fire suppression and Tactics
An investigation of usability of ten fire suppression agents was performed on Li-ion cells, based on output and test setup from bonfire tests done at SP. The three best performing agents were further tested on larger battery units. Fire suppression tactics were also investigated in terms of best means to get readily access to the traction battery which is commonly hidden inside the E-Vehicle structure.
The limited access to the REESS is a key hurdle. (22) (23) A tactics using an cutting extinguisher capable of distributing high pressurized water (above 250 bar) was investigated in terms of its efficiency to quench the fire as well as the thermal runaway inside an REESS, due to its ability to penetrated sheet metal vehicle structures. In this test, a regular vehicle was used as carrier of the REESS which was positioned in the trunk of the vehicle in order to simulate an E-Vehicle with an REESS located at the rear center of the vehicle.

The scenario simulated was a vehicle fire on a highway with busy traffic which would require the vehicle fire to be suppressed as fast as possible in order to have the vehicle removed as soon as possible. Similar tests show that such a battery fire tends to reignite sequentially which prolongs the completion of the extinguishing mission. (23) The intended result was to investigate the consequences seen when cutting into a battery system with high pressurized water. In preparation for this test the REESS was charged to above 80% SOC. The vehicle fire was initiated using propanol. After about five minutes the intensity of the fire was considered large enough to commence fire suppression using regular tactics with regular firefighting equipment. At this point the REESS had reached beyond thermal runaway and consequently contributed to the fire. The first responder action tactics to be tested was to first apply regular fire suppression tactics and equipment in order to push down the fire of the burning vehicle, and then approach the burning REESS with the cutting extinguisher attacking the fire inside the REESS and cooling down its interior to the point where venting and gas generation is significantly reduced.

RESULTS

Mechanical Abuse Testing
The material acquired from analyzing crash statistics of NASS (USA) showed that among the 165 E-Vehicle crashes between 2004 and 2010 no high energy crashes with REESS led to critical battery failure. Average Delta-v was 20-25 km/h in all impact directions. As a consequence of being first out of the market for E-Vehicles, 66% of all of these crashed E-Vehicles between those years were Toyota Prius. (24)

The number of vehicles selected by the filter applied to the GIDAS (Germany) database was weighted in comparison to German federal statistics, and the weighted number of vehicles was 4127 passenger cars. The final weighted number of vehicles presenting “significant intrusions” was 83 cars. Cases studies of this range of cars were conducted and the results were compiled in a report. (25)

Based on the detailed investigation of crashes from NASS and GIDAS, relevant cases to study further were concluded to be represented by cars exposed to:

- Frontal crash in 64 km/h into rigid barrier. E-Vehicle with REESS mounted in the trunk.
- Side impact by Movable Deformable Barrier (MDB) traveling at 88 km/h with vertical center line of hit through the center of the gas cap close to the right rear wheel. E-Vehicle with REESS mounted in the trunk.
- Rear end impact by MDB traveling at 88 km/h offset 70%. E-Vehicle with REESS mounted in the trunk.
- Side impact by Pole at 58 km/h with vertical centerline of the pole impacting at the center of the driver’s door. E-Vehicle with REESS mounted in the center tunnel.

Those cases were subsequently studied by CAE simulations on E-Vehicle and the crash environment exposer to the REESS and its sub-components (e.g. battery modules) were analyzed.

The data derived from the CAE simulations describing the crash environment of the REESS and its sub-components formed the basis for sled crash tests on the corresponding battery parts. The results from all four crash scenarios were positive in terms of crashworthiness and no critical battery failure was experienced despite the statistically proven high severity of each of the crash scenarios.
Electrical Abuse Testing
Water immersion of REESS was performed in a water reservoir with more than 400 liter of water. Table 1 presents data from water immersion test performed on the prototype REESS of LiFePO4 chemistry. The corresponding data from the test on the commercial REESS of NMC chemistry is held confidential on request by the OEM supplying the REESS, but the results was very much similar to that presented in Table 1.

Table 1 Table of measured field strength between the points of measuring. Comparison of results acquired from test with fresh water versus 3% salt water performed on the prototype REESS of LiFePO4 chemistry.

<table>
<thead>
<tr>
<th>Volt dc</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
<th>U4</th>
<th>U5</th>
<th>U6</th>
<th>U12</th>
<th>U23</th>
<th>U34</th>
<th>U45</th>
<th>U56</th>
<th>U61</th>
<th>U+ to GND</th>
<th>U- to GND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Water</td>
<td>3,2</td>
<td>1,6</td>
<td>0,9</td>
<td>0,3</td>
<td>1,1</td>
<td>2,1</td>
<td>1,4</td>
<td>2,7</td>
<td>1,0</td>
<td>0,8</td>
<td>0,9</td>
<td>1,3</td>
<td>161,3</td>
<td>188,4</td>
</tr>
<tr>
<td>Salt Water</td>
<td>0,2</td>
<td>4,1</td>
<td>5,6</td>
<td>0,5</td>
<td>1,3</td>
<td>2,3</td>
<td>2,6</td>
<td>2,2</td>
<td>1,2</td>
<td>2,6</td>
<td>0,2</td>
<td>0,1</td>
<td>41,0</td>
<td>17,0</td>
</tr>
</tbody>
</table>

Data cells U1-U6 in Table 1 represent the field strengths measured between the GND point (i.e. metal housing of the REESS) and each U point, while U12-U61 represents the field strengths measured between each neighboring U point. “U+ GND” and “U– GND“ represent the voltage measured between the GND point and each one of the REESS pole.

Table 2 Final voltage change of the two REESS after immersion in fresh water and salt water

<table>
<thead>
<tr>
<th>REESS using Li-ion cells with cathodes of material</th>
<th>REESS #1 LiFePO4</th>
<th>REESS #2 NMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water</td>
<td>Test time 7:10 min</td>
<td>30 min</td>
</tr>
<tr>
<td>Δ Volt</td>
<td>Δ−4 V</td>
<td>−Δ 2 V</td>
</tr>
<tr>
<td>3% salt water</td>
<td>Test time 7:25 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Δ Volt</td>
<td>Δ−300 V</td>
<td>Inoperative</td>
</tr>
</tbody>
</table>

In **fresh water**: No significant electric discharge activity was detected in the battery or the water (see Table 2). The only activity detected was the fact that the power electronics of the commercially available REESS (i.e. the NMC) immediately did disconnect the poles of the REESS from the battery modules as a safe guard measure and therefore the “U± GND” showed no Volt. In tests of both two types of REESS measured field strengths in the water represented less than 0.5 Volt per meter at a distance of 100mm from the REESS.

In **3% salt water**: Immediately when each REESS was immersed into salt water the cells of the battery was short circuited and the water was electrolyzed generating H2 and Cl2 but no hazardous concentrations were detected in this test setup.

The total voltage after the immersion test of the prototype REESS had fallen down by 300 Volt dc as presented in Table 2, while the commercial REESS voltage did not offer such figures since its safe guard system had disconnected the battery at the time of contact with the water. However, after the test both of the two REESS proved to be discharged to the point of being inoperative.

The field strengths detected in the water was moderate and offered less than 0.5 Volt per meter at a distance of 100mm from the REESS. The heat generated during the discharge of the REESS were absorbed by the 400 liter water and in the second test series using the commercial REESS the temperature of the water reservoir increased from 4°C to 23°C in 15 minutes.

Thermal Abuse Testing
As mentioned above in the section of Method the results of the bonfire tests performed is presented in a separate Poster at the FIVE conference, 2014. Readers are guided thereto.
Fire suppression and Tactics
The ten fire suppression agents tested on bundles of 5 cells (LiFePO4 cathode chemistry) are presented in Table 3.

Table 3 Matrix of fire suppression agents tested on bundles of 5 cells (LiFePO4 cathode chemistry)

<table>
<thead>
<tr>
<th>Agent:</th>
<th>Water</th>
<th>Salt Water</th>
<th>Foam type AB</th>
<th>Foam type AF</th>
<th>Foam type fluoro free</th>
<th>Powder type ABC</th>
<th>Carbon dioxide</th>
<th>Novec 1230</th>
<th>Nitrogen</th>
<th>Halotron II</th>
</tr>
</thead>
</table>

All types of fire suppression agents tested were able to extinguish the flames of the readily accessible battery cells burning. The fire suppression agents providing the highest specific heat capacity and mass proved to be best at cooling the device under test. Hence, none of the gaseous agent continued to the next level.

The agents chosen to be tested on larger battery systems such as battery modules as well as complete battery packs were water and foam type AB. The results indicated that both water and water-based foam are good coolants. As generally recommended, e.g. by NFPA, copious amounts of water was proven to be required to reduce the heat inside an extinguished battery system. For these tests means of applying the two fire suppression agents were the same as most often used by Swedish first responders, i.e. low pressure water mist applied onto the surfaces of device under test.

The findings from the fire suppression tests on Li-ion battery cells, modules and battery pack, show that water and water based foam are preferable fire suppression agents. Therefore such mediums were used during the investigation of the cutting extinguisher capable of both cutting through several layers of sheet metal (e.g. vehicle floor or mid-tunnel structure) and thereafter introduce cooling water/foam to the interior of a REESS. The high pressurized water/foam inserted into the battery was able to continue penetration of Li-ion cells and thereby allowing channeling cooling water/foam through the REESS regardless of existing voids and distribution channels.

After the fire of the vehicle were suppressed, using regular tactics for burning vehicles, the fire fighter successfully cut open entries to the REESS through its sheet metal housing using the cutting extinguisher and cooling of the battery cells could start.

The tests on the complete REESS showed promising results as the battery fire stopped reigniting and the ventilation and generation of gases was reduced in magnitude. Directly after the cutting extinguisher had been deployed into the REESS the temperature of its metal housing presented a maximum temperature of only 95°C with no sign of increasing.

The consequences of using a cutting extinguisher were also investigated on the REESS’s battery modules. The results proved successful since the penetrating high pressurized water was able to cool down the battery cells to a temperature level below the one demanded for continuous propagation of thermal runaway through the battery module. To reach such result firm and dedicated tactics were required. Otherwise the battery unit soon reignited. The fire fighter using the cutting extinguisher had to be persistent and attack the battery unit at the location proven to be the hottest by IR camera until the REESS was completely flooded by the coolant, and the battery cells were cooled down to temperatures below their limit of thermal runaway. In these tests, while applying the high pressurized water/foam, no evidence that arcing would present a risk to the fire fighter was observed.
CONCLUSIONS

A fundamental analysis of existing recommendations, crash statistics, and E-Vehicle tech/chem parameters provided the foundation for this research project. On that foundation a risk assessment study were performed offering, amongst others, a simplified Li-ion battery failure pathway and the three crash event phases. A strategy for physical abuse testing was then formulated and four fundamental abusive conditions were defined together with relevant physical abuse tests. Those four abusive conditions and their related physical abuse tests generated the following conclusions:

Mechanical Abuse Testing
No critical battery failures were generated in these mechanical abuse tests despite the tough load.

Electrical Abuse Testing
None of the REESS experienced any significant electric activity when being immersed into fresh water. The commercial REESS’s safe guard system automatically disconnected the power electronics as well as the connection between the external poles of the battery and the interior battery modules. Both REESS experienced short circuits between their battery cells as the salt water provided current path in the proximity of the cells. As a consequence, both REESS were discharged below operative levels and electrically terminated. At the same time the 400 liters of water were heated up.
Thermal Abuse Testing
These conclusions are presented separately in a Poster presentation at the FIVE conference, 2014.

Fire suppression and Tactics
All ten fire suppression agents were able to extinguish the flame of the battery. Nevertheless, it is crucial to provide sufficient cooling to a burning battery. This was best achieved by using water and water based foam as fire suppression and coolant. The results support the common recommendation to supply large amounts of water in order to suppress an E-Vehicle battery fire.

A test series performed to investigate how the use of a cutting extinguisher could provide quick and easy access to an REESS which most often are expected to be hidden behind vehicle structure and sheet metals. Extinguishing the fire of the regular vehicle materials could be achieved using regular fire suppression tactics and equipment. Thereafter, the fire fighter using the cutting extinguisher approached the burning REESS and by means of the high pressurized water cut through the shielding metal structures and penetrated into the core of the battery without risk of arcing outside the REESS. The temperature of the REESS was reduced faster than experienced when regular fire suppression equipment was used. Nevertheless, the use of cutting extinguisher requires persistent action and attack on REESS. In order to sufficiently cool the REESS interior it needs to be readily cut through and flushed by the cutting extinguisher.

FINAL REMARK
E-Vehicle Safe Rescue have offered the project partners a successful joint research activity uniting the work of the governmental Swedish Civil Contingencies Agency (MSB) with the work of academic and industrial partners based on the co-funding by the Swedish Governmental Agency for Innovation Systems (VINNOVA). This innovative and constructive collaboration between these partners have generated both generalizing as well as detailed knowledge on battery risks and myths associated with E-Vehicle traffic incidents in order to form the basis of the web based educational material for Swedish first responders under development by the MSB.

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Fire Spread due to Thermal Runaway in a Lithium-ion Battery Cell

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²Applied Physics, Chalmers University of Technology, Göteborg, Sweden

ABSTRACT

The risk of spreading of fire between Lithium-ion battery cells is assessed using Finite-Element (FE) modelling of the heat transfer initiated by a thermal runaway. The results are contrasted to experimental data where the heat release rate (HRR) is utilized as an input to the simulation. It is found that the temperature increase in a neighbouring cell can be quantitatively estimated during the early stages of the fire taking into account the anisotropic thermal conductivity of the cells.

KEYWORDS: Lithium-ion battery, thermal simulations, fire test

INTRODUCTION

The thermal environment of lithium-ion battery cells is of interest since it is known that a thermal runaway may propagate to neighboring cells causing further spreading, e.g. the thermal runaway in a lithium-ion cell produces a significant amount of thermal energy that easily may cause thermal runaways in neighboring cells. The thermal runaway is caused by exothermic reactions in the lithium-ion cell that will further increase the temperature resulting in a rapid temperature increase that is very difficult to directly control by e.g. cooling. Along with the thermal runaway a number of hazardous events may happen such as rapid gas release, electrolyte leakage, fire and rapid disassembling/explosion [1].

To understand and avoid fire spreading it is of high interest to assess the impact on a neighboring cell of the cell undergoing thermal runaway. In this work simulations are performed as a complement to previous experimental work where temperatures at key locations between and around the battery cells have been monitored. In order to achieve this a simplified geometrical model has been constructed in the Finite-Element software COMSOL with homogenized battery cells in such a way that each cell is considered as one layer of material and simulated for two cases; either isotropic or anisotropic thermal conductivity in the plane and across the layers.

EXPERIMENTAL SET-UP

Fire tests on EiG ePLB-F007A 7 Ah pouch cells have been performed and some of the results in terms of toxic emissions and heat release rates are already published [2]. The tested EiG cell had a lithium-iron phosphate, LiFePO₄, cathode and a carbon based anode. Each of the tests consisted of five cells tightly packed together with steel wires, see Figure 1. The cell terminals (tabs) was cut-off prior the tests for all but the middle cell. In the tests the thermal runaway was initiated by a LPG burner of approximately 15 kW placed underneath the packed cells, see Figure 1. During the test temperatures between some of the cells were carefully monitored in two positions, see Figure 2. The five cells were fully charged, 100% state of charge (SOC).
The resulting HRR have been reproduced in Figure 3 for completeness as it is used as an input into the numerical work presented below. In Figure 3-4, the burner is started after 120 seconds. It is interesting to note that in Figure 3 five distinct peaks are visible signifying the thermal runaway of the five different cells in the pack. In the simulations, results obtained from the first peak will be used.

**NUMERICAL DETERMINATION OF THE TEMPERATURE FIELD**

In addition to using the HRR measurements, the temperatures between the cells in a battery pack of five cells are computed. The EiG cell has a pouch packaging which has a multilayered repeatable structure; negative current collector of copper, anode, separator, cathode, positive current collector of aluminum; where the thermal physical parameters vary significantly in terms of thermal conductivity, density and specific heat along and across the cell. The purpose of the simulation work is to gain better understanding under what conditions a fire is spreading between cells and thus also when there is a risk of cascading thermal runaways. It is assumed that a simple temperature condition is what initiates a thermal runaway where the limit is somewhere above 120 °C. To be able to accurately compute the temperatures in the pack shown in Figure 1 at the locations shown in Figure 2, we have constructed a simplified 2D geometrical model similar to that of Figure 2. In the model the battery cells are in the same ambient conditions ($T_0=28^\circ\text{C}$) as the surrounding in the experiment and are assumed to always be in perfect contact to each other although this may be rather far from the actual situation when a thermal runaway is well underway and the cell pouch is prone to swelling, which also was observed during the experimental tests. However, the steel wires partly inhibited the swelling.
Figure 3  Heat release rates from fire test of EiG F007 cells where 5 cells are exposed to a LPG burner (the power of the burner has been subtracted from the graph).

The ambient conditions give the proper boundary conditions for the thermal exchange between the cells and the surroundings by conduction, convection and radiation. The model is built in the multiphysics software COMSOL suitable for studying heat transfer problems. In the model the five cells have been implemented where bulk values of the density, specific heat and thermal conductivity is specified. The COMSOL software solves the heat transport taking into account heat conduction and radiation as well as solving for the Navier-Stokes equations to assess the convection around the cells coming from the fluid movement of air around the cells. The software is Finite-Element (FE) code and we have assumed that the Reynolds number is small such that turbulent fluctuations can be neglected. The model consists of around 10000 elements to have sufficient convergence and accuracy. The model takes about 10 minutes on an ordinary personal computer. In order to have reliable results, good input data are needed and values of the density, specific heat and thermal conductivity were in this case estimated from Spotnitz and Franklin [3] and Wu, Xiao and Huang [4]. Ideally, careful measurements of these quantities at elevated temperatures are needed but difficult to obtain. Here the values of density, $\rho=1895$ kg/m$^3$ and specific heat capacity, $C_p=700$ J/(kgK) have been used throughout the temperature range. The heat conductivity coefficient, $k$, was varied in the simulations since the structure of the battery cell allows for this value to be highly anisotropic. The first peak in the HRR measurement in Figure 3 is used as a heat source and it is assumed that the thermal energy is deposited homogenously into the bottom cell.

Figure 4  A comparison of the temperatures found in the experiment and the simulations using an isotropic thermal conductivity (a) and anisotropic thermal conductivity (b).

The simulation results are shown in Figure 4. In Figure 4a, the thermal conductivity $k = 6$ W/(m K) is used for T1 SIM and T2 SIM and conductivity $k = 3$ W/(m K) is used for T1 SIM MIN and T2 SIM MIN. In Figure 4b, the thermal conductivity $k_x = 27$ W/(m K) and $k_z = 0.8$ W/(m K) is used for T1
SIM and T2 SIM and conductivity $k = 13 \, \text{W/(m K)}$ and $k_z = 0.4 \, \text{W/(m K)}$ is used for T1 SIM MIN and T2 SIM MIN. A simple sensitivity study was made varying the thermal conductivity by $\pm 50\%$ in both the isotropic and the anisotropic cases. The results from the lower values are showed in Figure 4, however the results from the higher thermal conductivity have been omitted since they generally gave much lower values of the temperatures at the given points. It can be noted that the temperature T2 in the early stages (up to 400 s) of the fire development can be predicted to some extent by the simulation using anisotropic thermal conductivity. However, to be able to predict for longer times a temperature dependent thermal conductivity seems to be needed. Nevertheless, using the temperature condition for thermal runaway the model predicts a further thermal runaway in the adjacent cells which is corroborated in the test. Furthermore, the thermal energy released by the LPG burner is not taken into account into the thermal transfer calculations although it would yield elevated values of the temperatures in the simulation. The LPG burner was omitted in the model since it was found that the model then was prone to instabilities.

**DISCUSSION AND CONCLUSIONS**

The aim of the present work is to be able to quantify the conditions of battery cells neighbouring to a cell undergoing thermal runaway. The temperatures inside the closest cells determine when and if a cascade process of thermal runaways may happen. There is naturally a great interest to be able to predict and mitigate effects of single cells experiencing such an adverse event. The temperatures inside the neighbouring cell are predicted by a Finite-Element model constructed in the COMSOL software. The software solves for the Navier-Stokes fluid properties and the heat transfer within the cells. Obtaining adequate data of the battery cells is crucial for the computational model since precise measurements of these data are not available; data from the literature is used in combination with sensitivity studies of the thermal conductivity. In the first model a homogenized battery cell with isotropic thermal properties is used. However, the layout of the cell indicates that the thermal properties are indeed highly anisotropic and it is showed that this anisotropicity in the thermal conductivity is of importance. The results from the test and the simulations follow each other relatively well up to around 400 s and then the results diverge. There are several possible reasons for this discrepancy among them is that the mechanical changes, i.e. swelling of the pouch, changing the area of direct contact to the neighbouring of the cell pouches is not taken into account. Other factors such as the changes to the material compounds during thermal runaway in the cell is not considered, this changes the thermal properties of the battery cells. The thermal conductivity of the battery cell materials is most likely temperature dependent, a feature which is neglected due to the lack of knowledge of precise measured data of this quantity. To this end, the conclusion is that using rather simplified methods with accurate material data input, a cascade process of thermal runaways is possible to predict under the current situation.

**ACKNOWLEDGEMENTS**

Swedish Energy Agency and Swedish Fire Research Board are greatly acknowledgment for its support. Several technical staff colleagues at the Fire technology have contributed to this work.

**REFERENCES**

Fire in electric cars

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Norway

ABSTRACT
Electric cars are more popular than ever in Norway. With new Lithium-ion battery technology the battery packages in new electric cars are more popular because of its increased capacity.

The purpose of this bachelor assignment was to look into questions about fire safety in this type of vehicles, and to find out what happens when the battery package in an electric car ignites.

The worst-case scenario was chosen, fire in the battery package, and an industrial propane burner was used to ignite the battery. The experiment was documented on video and thermocouples were used to measure temperature.

INTRODUCTION
In Norway the total of electric cars is higher than anywhere else in the world. Today there are more than 25 000 electric cars in Norway, and the goal is to reach 200 000 by 2020. The high interest in these cars has lead to a big discussion about fire safety in the new electrical cars.

It has been developed different types of battery packages that are being or has been used in electric vehicles. Earlier, it was common to use battery packs of nickel cadmium, nickel metal hybrid or lead. Today, lithium-ion batteries are most common. These batteries have greater capacity and lower weight than the older battery types.

The project lasted for six months and this was some of the topics that was looked into:

- The fire safety of Lithium-ion battery packages
- How a fire will develop in an electric car
- Most common causes of fire in electric cars
- The best way to extinguish fire in electric cars
- Firefighters and police procedures

METHOD AND RESULTS

Method
During the preparations for the experiment, information was collected from various agencies, including the fire department, The Directorate for Civil Protection and Emergency Planning (DSB) and the Defense Research Establishment (FFI). It was also necessary to look at results from research work done abroad and search for information from different fires and accidents, not only in Norway but also from all around the world.

Fire experiment – electric car
February 2013 it was preformed a full-scale fire experiment with an electric car, Peugeot iOn 2012 model. For the experiment the “worst case scenario” was chosen, which was considered to be a fire that starts in the Lithium-ion battery package. The car was burned out without any attempt to
The battery package in Peugeot iOn consists of 88 series-connected battery cells with Lithium-ion manganese oxide. The battery has a total weight of 240 kg, energy of 16 kWh and a voltage of 33 Volts.

For the cells in the battery pack to ignite they had to reach a temperature of 150 – 200 degrees. It was assumed that the cells at this temperature would either burst, or the safety valve would open. This was one of the experiences FFI got from their fire experiments on lithium-ion battery cells.

To ignite the battery cells an industrial propane gas burner was used. The burner was placed under the car directed against cells in the right side of the battery pack, to provoke thermal runaway and internal short circuit in one (or more) of the battery cells.

A total of 15 thermocouples were mounted inside and outside of the car. Two of the thermocouples were placed on the top of the battery package through the ventilation system.

![Figure 1 - Placing of the thermocouples](image)

**Observations**

During the experiment the cells in the car battery ventilated one by one. It was possible to hear them ventilate and see burning electrolyte released from the cells.

Although the car was completely burned out after 60 minutes, the fire in the battery package kept going on at least 90 minutes the after ignition.

![Figure 2 - Fire experiment](image)
Results

These graphs show the results from the thermocouples that were placed on the right side of the electric car, on the back tire, under the drivers seat and on the windshield. The highest temperatures that were measured was 1049 and 1026 °C. The flashover occurred after approximately 30 minutes.

![Figure 3](image1.png)

**Figure 3** - Temperature measurements on the right side of the car: 1. Back tire 2. Windshield side 3. Drivers seat

Readings in following graphs show the results from the two thermocouples on the battery pack. The propane burner was pulled away after 11 minutes and explains the high temperatures in the beginning of the experiment. The measurements after 11 minutes is the one we have considered.

![Figure 4](image2.png)

**Figure 4** - Temperature measurements battery pack: 1. Under the passenger seat 2. Under the drivers seat 3. Between the battery and the hull
CONCLUSION

It was observed that the fire in the Lithium-ion battery cells consists of two phases. The first phase is when the battery cells ventilate out the electrolyte because of high temperatures and pressure, and with a nearby ignition source the ventilated electrolyte will ignite.

![Figure 5 - The first phase](image)

The heat from the electrolyte fire in the first phase can help the cathode ignite. We call this the second phase. The fire in the cathode is different from the electrolyte fire because the cathode contains oxygen. The oxygen will maintain the fire in the cell, and this can let the metals in the cells positive pole start to burn. This could be observed as flashes of light from under the car.

![Figure 6 - The second phase](image)

It had to be supplied a lot of heat during the experiment from the external heat source to achieve the thermal runaway and the short circuit in the battery cells. It was desirable to increase the temperature in the battery cells to 150 – 200 °C, to be sure that this would happen. The amount of heat that must be added depends on the battery characteristics and cell chemistry. Cell content, apart from the burnt electrolyte, was still inside the burned out battery cells which is a sign of good design and high security of this type of battery pack.

The conclusions after the fire experiment is that there was no high flame pillars, and no explosive fire as rumored has anticipated. The temperature measurements from this experiments indicated higher temperatures than results from an earlier experiment done in the same test area on a regular vehicle in 2011. This may be due to the battery package in the electric vehicle.

There are still several unanswered questions regarding fire in electric cars and it should be performed several experiments with different scenarios to increase knowledge in this area.
The way to more sustainable flame retardant solutions for automotive use.

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INTRODUCTION:
Modern car makers make extensive use of lightweight polymers and plastics. Sophisticated, embarked electronics contain numerous plastic parts that are exposed to heat and might be sources of fire. To mention a few of them: engine parts made of engineering thermoplastics; communication and data cables; connectors, relays and electrical assembly parts; safety features such as head protectors, safety belts. In addition, modern cars offer improved driving and journey comfort, thanks to high quality cushioning, upholstery and textiles. Many of these materials – either of synthetic or natural origin - making cars lighter and more comfortable are highly flammable. Electro-mobility will provide additional risk of flammability. Therefore, fire safety is an increasing necessity for cars, busses and coaches and it is crucial for our quality of life. Flame retardants help to reduce the risk of fire. In a sustainable approach, one looks for reducing and controlling the potential risk of the use of flame retardants and at the same time meeting the demand of consumers for a fire safe environment. For many of its flame retardants ICL-IP serves as an industry leader for both REACH registration deadlines in 2010 and 2013. All flame retardants supplied by ICL are fully REACH-compliant. Hence, these flame retardant chemicals are based on today’s knowledge on what is acceptable from a point of view of human health and environment. Moving towards sustainability is, however, an on-going challenge and requires the involvement of the whole value chain. Sustainability became an intrinsic part of ICL-IP’s R&D programs at a very early stage and new substances are assessed according to an internal ICL sustainability index. In this way we increase our efficiency in developing more sustainable products. ICL-IP, as a major producer of chemicals, follows high safety standards in its plants. Risk for emission to the environment of chemicals is often located at direct users and at the End of Life of the parts.
ICL FRAMEWORK

ICL’s sustainability approach is the development of a framework which helps the complete value chain to assess the sustainability profile of flame retardants. Building on existing hazard criteria, the approach comprises a risk based methodology to assess the extent to which potential hazards translate into potential risks due to possible exposure to humans and/or to the environment during the service life of substances in consumer goods. The framework provides a rigorous evaluation of the flame retardants in their applications, thus providing downstream users a tool for selecting the most sustainable system solution for the intended use. We explain below the methodology more in detail.

Furthermore, ICL cooperates with the downstream value chain, e.g. for our main flame retardants carbon footprint data based on cradle to gate analysis following internationally accepted methodology and is made available for our customers or downstream users to support them in the carbon footprint calculation of their end products.

ICL cooperates actively with its customers in life cycle assessment programs.

ICL also participates actively in large scale recycling programs in cooperation with OEM’s, polymer producers, waste management and recycling companies.

Sustainability has also an economic component. ICL works closely with its customers to develop more efficient flame retardant solutions by taking advantage and/or combining different flame retardants or by developing new synergists.

ICL-IP FR Framework Overview Guiding Principles

- Objective: ICL-IP is creating this framework in an effort to help OEMs and other value-chain stakeholders evaluate the appropriate use of FRs across diverse applications.
- Expanding on hazard-based approach: This framework expands upon existing hazard-based approaches by incorporating a risk-based framework to assess the extent to which potential hazards translate into actual risk of exposure to humans or the environment.
- Scope: This framework is intended to address hazard and exposure during FR intended use.
- Past precedent: ICL-IP’s approach aims to be globally applicable and scientifically robust, while remaining executable for all value-chain members; it builds off of existing standards and/or regulatory frameworks in North America and Europe (e.g., REACH, GHS, GreenScreen).

Progress to date:

- Over the past year, ICL-IP has begun to share the FR Framework with a range of value chain members, from direct customers to OEMs, and refined the approach based on their feedback and priorities.
- ICL-IP received strong support from the value chain for its approach, particularly for the addition of exposure alongside hazard to create a risk-based framework, and the ability to evaluate all FRs regardless of chemistry.
- ICL-IP and value chain members are currently discussing next steps and opportunities for cooperation in outreach and execution.
FLAME RETARDANTS FOR AUTOMOTIVE APPLICATION

Halogenated as well as non-halogenated flame retardants can be assessed following the framework methodology. Every substance can be assessed on its own risk profile. Potential hazard and exposure is strongly reduced in most cases when using polymeric or reactive flame retardants. These substances show in general low water solubility, no leaching, no migration and no volatiles. The high molecular weight avoids penetration in living tissues and assures low potential for bioaccumulation. Several studies showed the better performance of thermoplastic polymeric flame retardants during recycling and low toxicity potential during incineration at the end of life. Examples of flame retardant solutions with an improved sustainable profile used in automotive applications:

**Engineering Polymers and TPU:**
- Brominated Polystyrene: FR-803P
- Brominated Polyacrylate: FR-1025
- Low antimony/ antimony-free solutions: Fyrolflex Sol-DP
- Non-halogen solutions: Fyrolflex RDP-HP, Fyrolflex HP+, Fyrolflex Sol-DP
- Surface treated Magnesium Hydroxide: FR-20 series

**Polyolefin Cables: (non-halogen)**
- Magnesium Hydroxide: FR-20 series
- Borate based: FR-1120

**Flexible Polyurethane: (non-halogen)**
- Low VOC, polyether foam: Fyrol PNX, Fyrol PNX-LE
- Low VOC, polyether, polyester foam: Fyrol HF 10

**Textiles:**
- Additive, low leaching: TexFRon 9000 series
- Polymeric, low leaching: TexFRon 4000, TexFRon P series

**VECAP:**
Another initiative the “Voluntary Emission Control Action Program” VECAP was set up under the umbrella of EFRA, the European Flame Retardant Association, in cooperation with sector groups of users of flame retardants and to promote environmental best practices. It received the explicit support of some automotive OEMs. Below the principles of this program and some of its results are described. ICL is a raw material producer at the beginning of the value chain. The VECAP program is an example of our cooperation with our direct customers primarily.

VECAP is a program for reducing emissions into the environment by:
- Increasing the understanding of chemicals
- Management in the value chain: promoting and facilitating open and constructive dialogue with industry, regulators and other stakeholders
- Raising awareness among all those involved in the process, from site personnel to company top management
- Implementing and disseminating best practices identified through the program

The VECAP program now celebrates the 10 years anniversary showing a strong decrease in emissions mainly for empty packaging now going to incineration or controlled landfill.
References and guidelines

To get more information on our sustainability program, the framework, VECAP and our FR portfolio, go to

www.iclfr.com  www.vecap.info

KEYWORDS: Flame Retardants, Sustainability, Framework, VECAP

VECAP 2013 HIGHLIGHTS

• One additional brominated flame retardant reported for the first time
• Significant decline of potential emissions of the three main brominated flame retardants surveyed since 2008
• 93% coverage of the four brominated flame retardants sold in common by EFRA member companies
• Zero potential emissions of HBCD to land on nearly 100% of volume sold
• Reporting on EBP revealed that potential emissions to water and air are already at default values obtained when VECAP best practices are applied
• Potential emissions of TBBPA remain very low
• Consistent decrease of potential emissions to land of flame retardant Deca-BDE
• The full volume of HBCD, Deca-BDE and TBBPA empty packaging surveyed was responsibly disposed of
The Challenges Associated with using Gaseous Extinguishing Agents for the Protection of Transit Vehicle Engine Bays

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ABSTRACT
Most incumbent extinguishing systems installed on commercial transit vehicles currently rely on either dry chemical or aqueous extinguishing agents to provide fire protection within the engine compartment. This paper focuses on the relative merits and concerns of using gaseous extinguishing agents either as a complete or partial extinguishing solution.

KEYWORDS: Engine compartment, fire protection, extinguishing agents

SUMMARY OF EXPERIMENTAL FIRE TESTS
The challenges facing any extinguishing agent include parameters such as, open volumes, high and variable degrees of clutter, airflow and different fires challenges. Over the past years Kidde have carried out an extensive series of fire tests within a simulated bus engine bay (See Figure 1). These fire threats included a variety of Class A and Class B fires, some fuel spray fires and a pre-heated turbo-charger with fuel spray flowing onto the surface. This provided a re-ignition challenge. The study compared the relative performance of existing extinguishing agents such as dry chemical and water mist with gaseous extinguishing agents (See Table 1).

Figure 1: Summary of fire tests within Kidde simulated bus engine fire test rig.
Table 1: Summary of fire test results.

<table>
<thead>
<tr>
<th>Agent Type</th>
<th>Mass Flow Rate</th>
<th>Fire Threat</th>
<th>Presence of Airflow?</th>
<th>Hot Surface Re-ignition?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Chemical</td>
<td>Medium</td>
<td>Small</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large</td>
<td>Challenged</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>Gaseous Agents</td>
<td>High</td>
<td>OK</td>
<td>OK</td>
<td>Fail</td>
</tr>
<tr>
<td>Aqueous Agents</td>
<td>Low</td>
<td>Challenged</td>
<td>OK</td>
<td>Fail</td>
</tr>
</tbody>
</table>

From the results of this study it is clear that no extinguishing agent offers a perfect solution for this type of application. In many respects gaseous extinguishing agents compare favourably with commonly used agents such as dry chemical and water mist. They also offer some improvements in terms of physical characteristics. One of the key feature benefits gaseous extinguishing agents have over incumbent agents is that following a discharge no residue remains within the engine compartment. This in most circumstances would negate the requirement for clean-up from the effects of discharging the extinguishing system. However, this lack of residence time also creates poor extinguishing performance against fire challenges that have a tendency to re-strike. An example of such a fire threat would be fuel leaking onto a hot surface such as the turbo charger.

INVESTIGATION INTO A FIRE TEST WITH RE-STRIKE POTENTIAL

Kidde carried out a series of tests using a pre-heated turbo charger as the fire threat. The turbo was heated, using an internally mounted propane torch, to 600°C. After removing the heat source diesel was sprayed onto the hot surface at 15 s time intervals followed by a delay of 10 s. In a test where no extinguishing agent was applied successful re-ignitions occurred between 2 min and 3 min or until the measured temperature fell below 550°C. This typically allowed between 5 and 8 re-strikes to occur before the heat within the turbo could no longer support auto ignition of the fuel.

Test 1: In the first extinguishing test scenario fuel was applied to the turbo for 2 x 15s intervals prior to discharging the extinguisher. This simulated a typical detection time and allowed an additional 15 s for engine shutdown to occur. Just prior to actuating the extinguishing system the diesel fuel supply was switched off. Gaseous extinguishing agent was then discharged into the engine compartment and the flames were completely extinguished. Despite the presence of residual fuel in the vicinity of the hot turbo no significant re-strike event was observed (see Figure 2: Test 1) though some occasional flashes of flame did occur as some residual fuel came into contact with the hot turbo.

Test 2: As with Test 1 fuel was applied to the pre-heated turbo for 2 x 15s intervals to simulate detection and engine shutdown times. The fuel spray was then initiated a third time and remained on for the duration of the test. 5s after flame was observed on and around the turbo charger the extinguisher, which was filled with gaseous extinguishing agent, discharged into the engine bay. The fire was successfully extinguished but re-ignited back to a fully developed fire within 5s after the extinguisher had completed its discharge.

This testing has highlighted that simply using any extinguishing agent or indeed extinguishing system without giving due consideration to the vehicles operating conditions can provide a dramatic difference in the outcome to fire suppression within a bus engine compartment.
DISCUSSION

Gaseous Extinguishing Agents – Complete protection

When considering the use of gaseous extinguishing agents within a bus engine compartment it is important that all systems are assessed in terms of risk, then adequate control measures put in place following a fire detection signal. Effective mitigation of risks will dramatically increase the likelihood of successful suppression for all extinguishing agents and for some applications will allow the use of gaseous extinguishing agents to be considered also. A flow diagram showing an example of a sequence of events which could provide a successful outcome using gaseous extinguishing agents is shown in Figure 3. Each set of boxes along the horizontal axis represent a fixed point in time.

Immediately after detection of a fire event there are non-essential systems such as HVAC that can be switched off. Although it may not be safe for a driver to stop a vehicle immediately, they need to control when this happens, de-rating the engine and turning off cooling fans will reduce the spread of fire and increase the probability of successful extinguishment within the engine bay if activated at this time. When safe to do so and as rapidly as possible stopping the bus and isolating the electrical power to non-essential equipment, plus giving some consideration to other measures, will minimise the risk from ignition sources and start the process of cooling hot engine components down. Fast reaction to fire detection also allows rapid evacuation of passengers and the driver from the bus. In this example in a very short time the bus engine bay is now optimised in terms of likely hood to achieve successful suppression of the fire event. If the engine is switched off and the flow of fuel stopped then like the test described above a gaseous extinguishing system could provide a successful outcome and should at least be considered as a viable alternative to extinguishing systems with other more commonly used extinguishing agents.

Figure 2: Two hot surface re-ignition fire tests showing the effect of turning fuel flow off prior to extinguishing.

Figure 3: Use of gaseous extinguishing agents for complete fire protection
Gaseous Extinguishing Agents – Partial Protection

In a second example shown in Figure 4 a system is described where a customer may wish to use a clean gaseous agent but may not be satisfied that all the risks were adequately mitigated. In this case the initial steps of the block diagram replicate the scenario described in Figure 3. However after the gaseous extinguishing system is operated, in this case the detection system would continue to monitor the engine compartment. If the threat is successfully extinguished and it is deemed safe to do so it may be possible for the vehicle to be transported back for maintenance under its own power. This of course would need careful planning and consideration prior to doing so. If a fire event was once again detected then a second extinguishing system could then be operated. At this time it is known that a serious problem is present so justifications for engine clean up and controlled towing of the vehicle could be made.

Figure 4: Use of gaseous extinguishing agents for partial engine bay protection

In both scenarios described above it would be possible to utilise gaseous extinguishing agents and provide suitable extinguishing systems. However, as with all fire detection and suppression equipment the level of residual risk that is required or in some cases permitted for each individual vehicle dictates the level of protection provided. No extinguishing system can protect against all fire scenarios but some have a higher probability of success than others. It is just a question of how this probability is measured.

CONCLUSIONS

If all the stakeholders in buses such as manufacturers, operators and users work together with fire suppression companies and interested independent test facilities then further improvements can be made in understanding the causes and effect of overheat and fire events. This knowledge can be used to carry out a thorough risk analysis for each vehicle preferably during the design and prototype stage and will help to identify the best means of prevention, detection and extinguishing against a wide variety of events and vehicle circumstances. Rapid detection and planned control of the vehicles operational conditions following an event will help to minimise damage to the vehicle, allow rapid and safe evacuation from the vehicle and maximise the performance of the fire extinguishing system. Once the performance requirements for extinguishing systems and agents are better understood it is hoped that where appropriate gaseous extinguishing agents will be part of the next generation of extinguishing solutions for this market.

REFERENCES


Fire Tests on E-Vehicle Battery Cells and Packs

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ABSTRACT

Four series of fire tests were performed on Li ion battery cells and battery packs. Heat Release Rate (HRR) data and concentrations of toxic gases were acquired by oxygen consumption calorimetry and Fourier Transform Infrared Spectroscopy (FTIR), respectively. The test results indicate that SOC affects the HRR as well as the amount of HF formed during combustion. A larger number of cells increases the amount of HF formed. There is a significant difference between the NMC and the LFP cells in this study. The LFP cells generate a lot more HF per cell, but the overall reactivity of the NMC cells is higher.

KEYWORDS E-vehicle; Li ion battery; Fire test; Gas analysis; Thermal energy/power analysis

INTRODUCTION

Li ion batteries contain high electric energy and power density and comprise combustible materials and fluorine-based salts [1-3]. Risk analysis identifies thermal abuse as a key failure pathway [4]. Gases emitted during a thermal event in Li ion batteries contain a variety of organic and inorganic species including flammable constituents like hydrogen and hydrocarbons (e.g. methane and ethane) as well as vaporized electrolyte (alkyl carbonate) [5]. The emitted gases may also contain varying concentrations of highly toxic CO and HF. The organic solvents in the Li ion battery electrolyte and the conductive salt LiPF₆ are the major source of the gaseous species. Yang et.al. [1] have shown that the rate of gas evolution increases at abput170 °C and that the generation of HF is limited below this temperature.

A conventional ICE vehicle fire generates toxic gases. Lecocq et al. [6] have compared relative amounts of HF generated by the conventional cars and e-vehicles (i.e. any type of vehicle with electric propulsion) to evaluate the contribution made by the traction battery. Their results show that an increase in HF generation can be seen after 25-30 minutes when the traction battery has started to burn.

A research project named E-Vehicle Safe Rescue has been performed by The Swedish Civil Contin- gencies Agency (MSB) together with industry and academic partners. The purpose was to investigate the effects of abuse conditions, including realistic crash scenarios on Li ion battery systems in e-veh- icles. The present work uses results generated within the E-Vehicle Safe Rescue project for in-depth analysis of parameters affecting the battery when exposed to external fire.

EXPERIMENTAL

Fire test have been conducted on Li ion cells designed for E-vehicles. Two types of pouch cells of similar geometry and size were studied, however the electric capacity differs between the cells due to different cathode materials: 7 Ah LFP (LiFePO₄) and 14 Ah NMC (Li(Ni₁/₃Mn₁/₃Co₁/₃)O₂). Four series of tests have been performed as described in Table 1. For the multi-cell configurations, the cells were physically but not electrically connected. The cell bundles were held together with metal wire. Additionally, one complete E-vehicle battery pack was tested.

In the bonfire tests on cells a SBI (Single Burning Item, EN 13823) equipment were used, and the pouch cells were placed horizontally on a metal net with the burning flame on the flat side facing down. In the multi-cell bundles, the rest of the cells were stacked on top of the first cell (see Figure 1).

In all the four series, the heat release rate (HRR) and heat energy generated from the cells and pack
were quantified by oxygen consumption calorimetry. The emitted gases were identified and the specific concentrations of CO₂, CO, and HF were quantified by means of Fourier Transform Infrared Spectroscopy (FTIR). The weight loss of cells was studied in order to provide a base for analysis and comparison to the gases emitted.

Table 1 Description of test objects and fire exposure regimes during tests.

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Cell type</th>
<th>Geometric Configuration</th>
<th>SOC</th>
<th>Number of tests</th>
<th>Fire exposure regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>LFP, 7 Ah</td>
<td>Single cell and bundles of 5 and 10 cells, respectively</td>
<td>0% or 100%</td>
<td>10</td>
<td>Test objects were exposed to a bonfire with a 15 kW flame for 15 minutes followed by 30 kW for an additional 5-25 minutes.</td>
</tr>
<tr>
<td>B</td>
<td>LFP, 7 Ah</td>
<td>Bundles of 5 cells</td>
<td>25%, 50% or 75%</td>
<td>4</td>
<td>Test objects were exposed to a bonfire with a 15 kW flame for 10 minutes followed by 30 kW for an additional 15 minutes.</td>
</tr>
<tr>
<td>C</td>
<td>NMC, 14 Ah</td>
<td>E-vehicle battery pack: 200 cells arranged in 10 modules, total pack voltage 402 V</td>
<td>80%</td>
<td>1</td>
<td>The burner underneath the pack supplied a Heat Release Rate (HRR) of 1.5 MW (comparable to a burning passenger car generating approximately 4 MW). The burner was on for 15 minutes. The battery pack was allowed to self-burn for an additional 15 minutes before extinguishing with water. Thermocouples were used to measure temperatures in 20 different locations in the pack.</td>
</tr>
<tr>
<td>D</td>
<td>NMC 14 Ah</td>
<td>Bundles of 5 cells</td>
<td>25% or 75%</td>
<td>4</td>
<td>Test objects were exposed to a bonfire with a 15 kW flame for 10 minutes followed by 30 kW for an additional 15 minutes.</td>
</tr>
</tbody>
</table>

Figure 1 SBI test setup for bonfire tests on battery cells (left) and complete battery pack (right).

RESULTS AND DISCUSSION

Test results are presented below. Tables 2 and 3 shows the amount of HF released from burning cells as a function of SOC. Figure 2 shows the release of HF as a function of time for LFP and NMC cell bundles. Table 4 shows the total energy released for LFP and NMC cells, respectively, and Figure 3 shows the rate of heat release for the two cell types.

Burning the complete NMC battery pack generated 0.5 MW in addition to the 1.5 MW supplied by the burner. There were no fluor-containing components in the emitted fumes detectable by FTIR nor were there any traces of HF found in the ventilation filters after the test. Fire extinguishing was performed in 2 steps. First water was sprayed for 2 min on the outside surface, which quenched the flames. The battery was observed for 18 min with no reigniting occurring. The battery was then flushed thoroughly with water for 7 min. The battery continued to generate fumes and the internal temperature stayed at about 300-350 °C for hours following the fire quenching procedure. After six hours the thermocouples inside the battery showed 80°C.

This investigation shows that the amount of toxic emissions per cell increases with the number of burning cells (Table 2). A possible explanation is that the highly reactive HF and its intermediary PF₅ are
able to accumulate before being vented in the cells not directly exposed to the flame while the bottom cell acts as a thermal shield. A higher SOC also results in more HF released per cell, indicating that the higher SOC increases the overall reactivity inside the cells. However, the sample size is too small to derive a quantitative relationship between SOC and HF generation. There is a significant difference in the amounts of HF released from the LFP cells compared to the NMC cells (Table 3). Considering that commercial Li ion cells currently on the market have similar electrolyte compositions, the difference in HF generated can be interpreted as an indication that the formation of HF and/or the decomposition of LiPF₆ have been impeded. It is possible that this difference can be explained by the NMC electrolyte containing additives that are effective suppressants of HF formation.

<table>
<thead>
<tr>
<th>Bundles</th>
<th>HF total (g)</th>
<th>HF per cell (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% SOC</td>
<td>100% SOC</td>
</tr>
<tr>
<td>1 cell</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>5 cells</td>
<td>12.4</td>
<td>14.3</td>
</tr>
<tr>
<td>10 cells</td>
<td>37.6</td>
<td>41.1</td>
</tr>
</tbody>
</table>

**Table 3** HF generated during bonfire tests of LFP and NMC cells (5 cell bundles).

<table>
<thead>
<tr>
<th>Cell type</th>
<th>HF total (g)</th>
<th>HF per cell (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25% SOC</td>
<td>50% SOC</td>
</tr>
<tr>
<td>LFP, 7 Ah</td>
<td>5.6</td>
<td>11.7</td>
</tr>
<tr>
<td>NMC, 14 Ah</td>
<td>1.55</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1 Heat energy released during complete burnout of LFP and NMC cells in bonfire tests.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Energy released per cell (kJ)</th>
<th>Energy released per Ah (kJ/Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25% SOC</td>
<td>50% SOC</td>
</tr>
<tr>
<td>LFP, 7 Ah</td>
<td>1378</td>
<td>1405</td>
</tr>
<tr>
<td>NMC, 14 Ah</td>
<td>1426</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3 shows a comparison of HRR between the 7 Ah LFP and the 14 Ah NMC cells. The NMC cells have a significantly faster HRR than the LFP cells in these tests. It is apparent that at medium (i.e. 50%) and high (75%) SOC leads to a higher HRR than at lower (25%) SOC, but the relationship is not linear. However, the difference between the total energy released per cell is small. Consequently the energy released per Ah is almost double for the LFP cells compared to the NMC cells. This may be explained by the 2 cells having almost the same volumes despite the large difference in capacity. A possible conclusion is that the LFP cells and the NMC cells contain similar amounts of electrolyte, which is the main contributor of heat energy released during combustion. It is common to refer to the cathode material when discussing parameters of safety and thermal runaway [7]. However, the cathode material may not be the weakest link in all cell types. Instead focus is currently set on the composition of electrolytes [2,3]. The organic electrolyte is claimed to contain more combustible energy per unit mass than the Li ion battery cell offers in electric energy [8-10]. The manufacturers’ use of flame retardants and additives further add to the diversity in results when it comes to fire propagation, heat evolution and amounts of toxic species generated under thermal abusive conditions [11].

**CONCLUSIONS**

The larger number of cells involved in the fire, the more HF can be generated and released to the ambient. The NMC cells tested generate significantly less HF gas than the LFP cells tested. However, only one cell type from a single supplier was tested for each chemistry so it is impossible to conclude if this is a general characteristic of NMC cells. Higher SOC levels results in more HF released although the relationship does not appear to be linear.

The total amount of electric energy stored in the cells did not significantly affect the total amount of heat energy released. This indicates that the chemical energy per unit weight of Li ion cells is higher than the electric energy. However, the HRR was faster at medium and high SOC than at low SOC and
the NMC cells generate heat at a much faster rate than the LFP cells, indicating a higher reactivity in the NMC cells.

Figure 2 HF generation vs. time for LFP (left) and NMC (right) for varying SOC levels.

Figure 3 HRR when burning bundle of 5 LFP (left) and NMC (right) cells at varying SOC levels during bonfire test.

ACKNOWLEDGEMENTS
SP Fire staff – Francine Amon, Magnus Bobert, Per Thureson, Petra Andersson and Richard Johansson – are gratefully acknowledged for their work on performing the fire tests. The Swedish Governmental Agency for Innovation Systems (VINNOVA) is gratefully acknowledged for financial support to the E-Vehicle Safe Rescue project within the FFI framework.

REFERENCES
Statistics on Vehicle Fires in Finland in 1996-2013

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ABSTRACT

In Finland, data on every vehicle fire the rescue services are called out for is registered in PRONTO - The Statistical Data System for Finnish Rescue Services. Data covering the whole country is available from year 1996. The data includes, for example, assessment of cause of fire and human or property losses. Also, data includes information of actions in first extinguishing.

The number of registered vehicle fires has varied from 1 900 fires to 2 700 fires between the years 1996 and 2013. Almost all vehicle fires registered are road vehicle fires. Only a few off-road, water, rail or air vehicle fires are registered in the PRONTO system.

Two-thirds of the road vehicle fires are car fires. Other common road vehicle fires are truck, van and bus fires. Two-thirds of the vehicle fires are known to be caused by the failure of a machine or device. Of car fires 22 percent are arson.

In half of the vehicle fires portable fire extinguishers were used. In 83 % of the cases, the fire was extinguished or restricted when a portable extinguisher was used.

A total of 43 persons were injured and one person died in vehicle fires in 2013. The property losses were estimated to be 18 million euros in 2013.

KEYWORDS: vehicle type, cause of fire, first extinguishing, human losses, property losses

BACKGROUND

In Finland, the responsibility for the functions of the rescue services is divided between 22 rescue services regions. In the Rescue Act it is written: regional rescue services may preserve registry on action for monitoring and developing of the rescue services, and for the clarifying of an accident. Data on accidents the rescue services were called out for is stored in PRONTO - The Statistical Data System for Finnish Rescue Services [1]. The overview of the process on data formatting is described in Figure 1. The PRONTO system is a web-based system generated by the Ministry of Interior in 2000. Since 2006 the Emergency Services College has been responsible for the maintenance and development of the PRONTO system.

The PRONTO system includes data of over 1.5 million accidents and operations in the whole country since 1996. The data includes accidents the rescue services were called out for. For example, fires extinguished without the help of the rescues services are not included. For vehicle fires the following details are reported:

- type of vehicle
- description about the development of accident,
- cause of fire,
- human losses,
- property losses,
- actions in first extinguishing,
- actions in rescuing.
VEHICLE FIRES

The number of vehicle fires has varied from 1,900 fires to 2,700 fires between the years 1996 and 2013. Almost all vehicle fires registered are road vehicle fires; 95 percent of vehicle fires were road vehicle fires in 2013 (Table 1). Only a few off-road, water, rail or air vehicle fires are registered; in 2013 the percentages were 0.7, 1.4, 0.4, 0.0 and 0.9, respectively.

![Incident](image1)

**Figure 1** The overview of process on data formatting in the PRONTO system.

**Table 1** The number of vehicle fires by the type of vehicle in 1996-2013 in Finland.

<table>
<thead>
<tr>
<th>Year</th>
<th>Road vehicle</th>
<th>Off-road vehicle</th>
<th>Water vehicle</th>
<th>Rail vehicle</th>
<th>Air vehicle</th>
<th>Other vehicle</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>1,843</td>
<td>0</td>
<td>37</td>
<td>17</td>
<td>1</td>
<td>5</td>
<td>1,903</td>
</tr>
<tr>
<td>1997</td>
<td>1,900</td>
<td>3</td>
<td>29</td>
<td>15</td>
<td>1</td>
<td>12</td>
<td>1,960</td>
</tr>
<tr>
<td>1998</td>
<td>1,965</td>
<td>4</td>
<td>29</td>
<td>8</td>
<td>1</td>
<td>11</td>
<td>2,018</td>
</tr>
<tr>
<td>1999</td>
<td>2,165</td>
<td>6</td>
<td>41</td>
<td>8</td>
<td>1</td>
<td>10</td>
<td>2,231</td>
</tr>
<tr>
<td>2000</td>
<td>2,300</td>
<td>7</td>
<td>40</td>
<td>6</td>
<td>0</td>
<td>16</td>
<td>2,369</td>
</tr>
<tr>
<td>2001</td>
<td>2,560</td>
<td>8</td>
<td>26</td>
<td>12</td>
<td>1</td>
<td>19</td>
<td>2,626</td>
</tr>
<tr>
<td>2002</td>
<td>2,549</td>
<td>4</td>
<td>30</td>
<td>6</td>
<td>1</td>
<td>24</td>
<td>2,614</td>
</tr>
<tr>
<td>2003</td>
<td>2,579</td>
<td>4</td>
<td>24</td>
<td>3</td>
<td>1</td>
<td>25</td>
<td>2,636</td>
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<td>2004</td>
<td>2,539</td>
<td>10</td>
<td>18</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>2,596</td>
</tr>
<tr>
<td>2005</td>
<td>2,570</td>
<td>10</td>
<td>22</td>
<td>8</td>
<td>1</td>
<td>19</td>
<td>2,630</td>
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<tr>
<td>2006</td>
<td>2,638</td>
<td>19</td>
<td>33</td>
<td>6</td>
<td>2</td>
<td>27</td>
<td>2,725</td>
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<td>2007</td>
<td>2,453</td>
<td>16</td>
<td>41</td>
<td>16</td>
<td>1</td>
<td>22</td>
<td>2,549</td>
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<tr>
<td>2008</td>
<td>2,280</td>
<td>25</td>
<td>37</td>
<td>10</td>
<td>2</td>
<td>25</td>
<td>2,379</td>
</tr>
<tr>
<td>2009</td>
<td>2,298</td>
<td>35</td>
<td>33</td>
<td>8</td>
<td>1</td>
<td>25</td>
<td>2,400</td>
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<tr>
<td>2010</td>
<td>2,309</td>
<td>34</td>
<td>39</td>
<td>13</td>
<td>1</td>
<td>41</td>
<td>2,437</td>
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<td>2011</td>
<td>2,280</td>
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<td>37</td>
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<td>4</td>
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<td>2,395</td>
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<tr>
<td>2012</td>
<td>2,146</td>
<td>42</td>
<td>38</td>
<td>13</td>
<td>1</td>
<td>36</td>
<td>2,276</td>
</tr>
<tr>
<td>2013</td>
<td>2,223</td>
<td>30</td>
<td>39</td>
<td>11</td>
<td>0</td>
<td>29</td>
<td>2,332</td>
</tr>
</tbody>
</table>
The most common road vehicle fire is a car fire (Table 2). In 1996, 74 percent of road vehicle fires were car fires. In 2013, the share was 56 percent. Other common road vehicle fires are truck fires, van fires and bus fires. The number of truck fires has increased; in 2013, 13 percent of road vehicle fires were truck fires. The number of van fires has been quite stable the last six years; about 7 percent of road vehicle fires have been van fires in 2008-2013. Moreover, in 2013, 2 percent of road vehicle fires were bus fires.

Compared to the number of registered vehicles [2], bus fires are the most common type of road vehicle fires (Table 2). The number of bus fires was 47 per every 10 000 registered bus on average in 1996-2012. The number of truck fires was 24 per every 10 000 registered truck. Meanwhile, the number of car fires was only 7 per every 10 000 registered car.

Compared to transport performance [2], bus fires are also the most common type of road vehicle fires (Table 2). The number of bus fires was 9 per every 10 000 automobile-kilometres on average in 1996-2012. The number of truck fires was 7 per every 10 000 kilometres. Meanwhile, the number of car fires was 4 per every 10 000 kilometres.

Table 2  The number of and percentage of fires and the number of fires compared to automobile stock and to transport performances on average in 1996-2013.

<table>
<thead>
<tr>
<th></th>
<th>Car</th>
<th>Van</th>
<th>Truck</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fires</td>
<td>1 599</td>
<td>140</td>
<td>208</td>
<td>52</td>
</tr>
<tr>
<td>Percentage of road vehicle fires</td>
<td>67</td>
<td>6</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Fires / 10 000 registered vehicles*</td>
<td>7</td>
<td>5</td>
<td>24</td>
<td>47</td>
</tr>
<tr>
<td>Fires / 10 000 automobile-km*</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

*) The number of registered vehicles and the transport performances available in 1996-2012.

Figure 2  The effect of first extinguishing in vehicle fires in Finland in 2008-2013.
CAUSES OF VEHICLE FIRES

Two-thirds of the vehicle fires are known to be caused by the failure of a machine or device. Most of these are an undefined machine or device under the hood of which 4 percent are localized in electric cables and 3 percent in heaters. One fourth of car fires are known to be caused by human activity. Of these 75 percent are arson, i.e., 22 percent of car fires are arson. One seventh of other vehicle fires are known to be caused by human activity.

FIRST EXTINGUISHING

First extinguishing in vehicle fires has increased annually. Data has been documented since 2008. In 2013, in almost half of the fires an attempt was made to put it out with portable first extinguishing equipment. Half of the fires were extinguished when first extinguishing was attempted (Figure 2). In 17 percent of the attempts first extinguishing had no effect.

HUMAN AND PROPERTY LOSSES

The number of persons injured in vehicle fires has varied being around 40 persons during the last ten years. In 2013, 43 persons were injured in vehicle fires. The number of fatalities has varied around 4 victims during the last ten years. In 2013, one person died in a vehicle fire. The average of estimated property losses has varied between 5 000 and 10 000 euros annually. The largest property losses are on motor engine work vehicle fires: over 30 000 euros on average (Table 3). Property losses were estimated to be 18 million euros in total and 7 800 euros on average in 2013.

<table>
<thead>
<tr>
<th></th>
<th>Motor engine work vehicle</th>
<th>Caravan, Camper</th>
<th>Train</th>
<th>Motorboat</th>
<th>Truck</th>
<th>Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fires</td>
<td>108</td>
<td>45</td>
<td>9</td>
<td>17</td>
<td>252</td>
<td>1 546</td>
</tr>
<tr>
<td>Property losses (€)</td>
<td>30 734</td>
<td>25 521</td>
<td>23 702</td>
<td>22 823</td>
<td>18 209</td>
<td>3 789</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In Finland, data on every vehicle fire the rescue services are called out for is gathered in a national web-based register. The number of registered vehicle fires is 2 400 per year on average. Almost all vehicle fires registered are road vehicle fires. The most typical vehicle fire is a car fire. Most of the vehicle fires are caused by the failure of a machine or device. Of car fires 22 percent are arson fires. In half of the vehicle fires portable fire extinguishers were used. On average 40 persons get injured and 4 persons die in vehicle fires a year. The property losses are 19 million euros per year on average.

REFERENCE LIST

Development of a Fusible Access for Extinction of Lithium-ion Battery by Firefighters

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² Brigade de Sapeurs-Pompiers de Paris, Paris- France
³ RENAULT, Guyancourt - France

INTRODUCTION

For Paris and its close suburbs, the Police Prefect is in charge of the public safety and it is consequently essential to anticipate and address risks associated to new technologies. For issues related to fire, a partnership exists between two organisms of the Police Prefecture: the Paris Fire Brigade (BSPP) for fire extinction and intervention, and the Central Laboratory (LCPP) as a scientific and technical advisor.

The number of electric cars is planned to increase drastically in the next ten years. An exhaustive reflection had to be performed to anticipate the new risks induced by the different technologies going along with these electric cars: charging stations and networks, integration of these charging stations in buildings, sockets and cables, etc.

In Paris, the number of cars per 1000 inhabitants is about 330 which is relatively low compared to other parts of France where this number can be twice higher. However, all these vehicles are gathered over a smaller area, thus creating a dense concentration in streets and all related infrastructures (e.g. tunnels, underground car parks, etc.). It is therefore important for the BSPP to extinguish any fire as quickly as possible to decrease the consequences this accident could have on people and buildings. Collaboration has therefore been launched in Paris and suburbs between LCPP, BSPP and Renault to adapt firefighter intervention protocols to electric cars. Starting in 2012, a series of experiment has been performed on seven vehicles till today (Kangoo ZE, Fluence ZE, ZOE and Twizy).

All Renault electric cars were equipped with lithium-ion batteries.

KEYWORDS: thermal runaway, electric vehicle, fire extinction

THERMAL RUNAWAY

When the heat absorbed by a lithium-ion battery exceeds the rate at which the heat can be dissipated to the environment, a thermal runaway may occur. This would lead to the emission of highly flammable and toxic gases. An important number of safety devices exist to reduce the probability of occurrence of thermal runaway during the standard use of a lithium-ion battery in a car. However, in case of fire, the heat generated by combustion may be sufficient to modify the thermal balance and lead to a thermal runaway.

It was shown in a previous study [3] that the general behaviour of electric and thermic vehicles, exposed to a same external heat exposure, are close regarding maximal heat release rate and effective heat of combustion. The efficiency of firefighters to put out a vehicle fire is however highly dependent on its energy (gasoline, LPG, natural gas, li-ion, lithium metal polymer, etc.).

It is worth noticing that, for all the fire experiments performed by LCPP/BSPP on Renault EV, the energy from the combustion of the vehicle alone was never sufficient to observe a thermal runaway; an extra amount of fuel (wooden pallet for instance) had to be added below the car to reach the
purpose. In a real situation, this extra fuel may be provided by the load of the car, a vehicle parked beside, etc.

**PREVIOUS EXPERIMENT - A NEED OF FUSIBLE ACCESS**

A first experiment was performed on an electric vehicle prototype to assess the possibility for firefighters to extinguish a battery during a thermal runaway process.

The car battery was fully charged at the beginning of the test and equipped with thermocouples to measure the temperatures of its modules and vicinity.

In order to reach thermal runaway condition, a gas burner was placed under the car to heat up the battery. The heat provided from the burner and the combustion of the rest of the vehicle was however too low to increase the battery temperature efficiently. It was therefore decided to place the car over burning wooden pallets and thermal runaway finally occurred more than ten minutes later.

Temperature measurements are plotted in Figure 1. The exposure of the battery to the gas burner is not visible in this figure but only the thermal stress from wooden pallets starting at 1050s. The thermal runaway is observed from about 2200s until more than 5000s.

After a quick extinction of the passenger compartment and wooden pallets (less than 90 s), firefighters struggled to extinguish exhausting flames from the battery electrolyte. It is clearly visible in Figure 1 that firefighter intervention were failing to decrease temperatures measured on the battery casing. After 2750 s of test, temperatures decreased around the battery but then started increasing as soon as firefighters stopped cooling the vehicle.

![Figure 1 Temperature measurements around the li-ion battery.](image)

It was therefore necessary to develop a system to allow the extinction of li-ion batteries.

**FIREMAN ACCESS DEVELOPMENT**

As a consequence of first EV fire tests conducted, Renault decided to create a fireman access, to allow firefighters to drown 400V battery with water, the only way for first responders to extinguish it definitively. This fireman access is a piece of polymer located below the back seat – near the 400V battery casing holes – especially designed to melt at high temperature. The first EV in the world which benefits of this innovation is Renault ZOE. Renault Fluence ZE ph2 received it afterwards.
VALIDATION OF FIREMAN ACCESS

Impact on vehicle passengers

By design, the passenger compartment is only separated from the battery pack by a plastic membrane, melting around 150°C. After a risk assessment, it appeared that the most critical scenario for passenger safety was an electric fault on a cell that the battery management system would fail to detect and prevent. This would generate heat which may cause the decomposition of electrolyte and produce toxic gases dangerous for passengers stuck in the car [2, 3].

To reproduce the aforementioned scenario, an experiment was designed to: a) determine the condition inside the passenger compartment after an accident involving a thermal runaway; and b) estimate the time available for firefighters to rescue (first aid, car extrication, etc.) a passenger.

A thermal runaway of the battery was created by overcharge. Its occurrence was confirmed by an increase of temperature from 85 to 800°C in the overcharged module (named D in Figure 4), a decrease of battery tension at about 0.0425V/s and the generation of toxic and flammable gases from the battery pack to the environment. No ignition of these gases was however observed during the first stage of the experiment as no activation energy was present around exhaust zones.

The safety of passengers would no longer be guaranteed if one of the conditions listed in bold in Table 1 was reached.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Values</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen concentration</td>
<td>15%</td>
<td>Disorientation</td>
</tr>
<tr>
<td></td>
<td>12%</td>
<td>Loss of consciousness, permanent cerebral lesion</td>
</tr>
<tr>
<td>Carbon dioxide concentration</td>
<td>20%</td>
<td>Narcosis</td>
</tr>
<tr>
<td>Carbon monoxide concentration</td>
<td>0.1%</td>
<td>Death between 1 and 3 hours</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>Death in 3 minutes</td>
</tr>
<tr>
<td>Gas temperature</td>
<td>150°C</td>
<td>Incapacitation in 5 min, death in 30 min</td>
</tr>
<tr>
<td></td>
<td>190°C</td>
<td>Immediate incapacitation and death in 15 min</td>
</tr>
</tbody>
</table>

Temperatures measured inside the battery are plotted in Figure 4. It is observed than the thermal runaway spread relatively slowly from a module to another, highlighting an efficient compartmentalisation between these modules. Temperature measured on the fireman access increased to 150°C after about 1600s and 200°C at 2400s. The membrane kept part of its mechanical properties and still acted as a barrier till 1800s. After that, gas concentrations (O₂, CO and CO₂) started increasing but the values stayed relatively small (0.07% of CO₂, 0.02% of CO and a depletion of 0.7% for O₂). No increase of temperatures inside the vehicle was observed until 3500s nor flames. Toward the end of the test, smoke spreading in the passenger compartment was white and light.
Efficiency during extinction stage

After 3500 s of test, it was decided to ignite the flammable gases produced by the decomposition of electrolyte during the thermal runaway. Shortly after this ignition, the fire spread to the passenger compartment whose door was open. Twenty minutes later, once the fire was fully developed, the extinction phase was ordered. The passenger compartment was first extinguished and the battery pack was then drowned with water from the rear of the car. Temperature measurements during this stage are plotted in Figure 4 and the extinction phase should be compared to Figure 1. It is clearly visible that temperatures measured inside the battery and on its casing instantaneously decreased from about 600˚C to less than 100˚C highlighting consequently the efficiency and convenience of the fireman access to extinguish the fire located on the battery.

CONCLUSION

This study presented some experiments carried out by BSPP and LCPP with Renault. This collaboration between a vehicle manufacturer and authorities is necessary for an efficient development of intervention procedures, public and vehicle safety. Conclusions of this work will also be disseminated to other public services (firefighters from other French departments, legislators, etc.).

It is finally important to notice that gases produced by the battery during the thermal runaway are flammable. It is therefore necessary for firefighters to adapt their material (wear correct PPE, no activation energy, explosimeter, etc.) for this particular intervention.

REFERENCES


ACKNOWLEDGMENT

Authors would like to thank for their help during the project: Lieutenant Colonel Olivier Labadie and Adjudant-Chef Pedro Calado from SDIS 78, Sylvie Dupont, Adissa Traore and Delphine Garcia from LCPP, Aurelien Thiry during the writing process, Caporal-Chef Demandre from BSPP, and Renault EV Program Department.
New Extinguish Technics for Firefighting in new technology Vehicles

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Abstract
To improve extinguishing of fires in Electric and Hybrid Vehicles, and Vehicles in generals, an extinguish testing combining Water and Powder is under currently successfully testing. The purpose here is to create an extinguish mixture and technics, with high extinguishing effects on Fires involving Flammable Liquids, High Voltage Fires special metals like Magnesium and Aluminums or Machinery.

In the testing faces two types of Nozzles fore technics are proven. A regular Fog Nozzle (Akron) and the AWG Water spray nozzle with twist nozzles (Monsun Nozzle), which is a special Nozzle with a high cooling effect.

Besides testing the Nozzles extinguish effects with mixture on various materials and situations, also cooling effects, nozzle flows and operation distances, handling etc. Do to testing and effects it believed, the principle will be usable in wider perspectives also.

Types of Fires, where the extinguish method could be usable for are
• Vehicle Fires with Electrical and Gas driven Systems
• Vehicle Fires with Special Metals and Components
• Buses, Heavy Trucks and Entrepreneur Machinery a.o.
• High Heat Fires, like Tunnels and Parking Garages Fires

Subjects presented below;
- Principle of extinguish
- Equipments
- Special Nozzle and effects
- Testing faces, tested materials
- Fires in Parking Garages, New Technology Vehicles

Mixing Principle
The purpose here is to combine the Monsun Nozzles special extinguishing – and cooling effects with combined extinguishing agents. This can achieve a very good extinguishing effect, by mixing the water and the powder for extinguishing special Fires. – Testing here is not made with a foam mixture. In addition, a regular Fog Nozzle where also used to test effects and principle.

By connecting a foam mixer in the stretch line, it is possible to inject a combination of extinguishing agents; the use of water does not have enough extinguish effect on materials. The foam mixer can be placed as normal, as a foam attack line, and with the same operating personnel. Or, it can be placed directly at a pump outlet, allowing the Technician to operate the foam mixer, and adding powder by need.
Alternative use of principle
The principle can also be used on smaller scales, when combined extinguishes not is needed all the time. - Place the powder fire extinguishers nozzle tip close to the water flow of hose nozzle, and shout powder directly in the flush.

Equipment used under testing
- Attack Hose
- AWG Monsun Nozzle
- Akron Fog Nozzle
- Foam mixer and foam suction hose
- Powder ABC

Monsun Nozzle
This Nozzle is normally used for High Voltage, Paint and Liquid Fires. Also, its special cooling effect also provides greater protection for the crew do to heat stress and close contact to objects. Do to use in electricity the Nozzle is isolated for high voltage, up till 380,000 Volts.
It also provides good protecting do to leaking Gasses and explosion dangers with Gas driven Vehicles and technics like H2 and CNG, but also toxic gasses from Battery Packs.

Used here on Vehicle/Machinery Fires, and especially New Technology Vehicles, the idea is to combine its special extinguishes – and cooling water effect, with other extinguishing agents. These for more effective extinguish results and a wider use. Either with a light foam mixture, but especially Powder, this can be dosed into the water through a regular foam mixer and its suction hose.

Nozzle effects with a water/powder flush
- Extinguishing length between 8 - 10 meters, depending on the water pressure and wind conditions.
- Very high cooling effects and improved extinguishing effects on liquids and metals.
- Very good compact water flush (cone), which provides good thermal protection of personnel.
- Powder stays in water flush and has full effects.

The nozzles cooling effects also provide a greater protection for the crew by heat stress. The flush can also lower impacts of flammable or toxic smoke and gasses.

Regular Fog Nozzle
Regular nozzles can also be used for this combination, with almost same use and extinguish effects on Fires. But with a lower cooling and extinguish effects on some materials, and with other protection levels, if used on High Voltage systems.

1. Testing face
RESC Korsoer, Denmark, August 8. 2013/ Jess Millner and Instructor Carsten Nielsen
- Testing of equipments and nozzle flows.
- Testing, extinguishing of liquid Fires.

2. Testing face
RESC, Denmark, December 9, 2013 / Jess Millner, and Instructor Carsten Nielsen
- Testing, extinguishing of special Metals and Vehicle Fire.

3. Testing face
MSB Revinge, Sweden (2014) / Jess Millner, Instructors Stefan Haggö and Göran Valentin
- Planning of testing extinguishes principle and nozzle usability for various types of fires incl. Vehicles.

Issues to address do to Parking garage fires with new technology vehicles

Fire Tactical Approaches
When approaching new technology vehicle Fires in buildings, like parking garages etc., are we here well prepared, and do we have the right tactics for these Vehicles? Are we meeting new challenges, do to technics like Battery Packs and Gas systems, and how can we improve if needed?

How are the working conditions at a Fire round a parking bay for these Vehicles? What about free-pulling of vehicle to avoid Heat and Fire spreading, or blocking of wheels?

**Toxic gasses and fire spreading**

Toxic Gasses from Battery Packs, Dangers for exploding Batteries, or sudden movement from the Vehicle are also important Safety and Tactical issues. Leaking Gasses from CNG/H2 Vehicles do to heat effects from a close by Primary Fire is another important issue to look into. Fx. will leaking gasses from close by gas driven Vehicle ignite into a Secondary Fire?

Fire conditions and spreading in underground parking areas, especially do to heat, smoke and ventilation conditions, can be special challenges. Fire Hazards do to high heat and flames form these vehicles. What can here be seen as special Hazards do to building structures, PPE, equipments etc.?

**Suggestions**

Could High Pressure Ventilations in combination with heavy Water Fog here be used different or better by approach and attacks? Also the use of a Thermal Imager and Gas Meters combined on CNG/H2 Vehicles.

- When extinguishing vehicles with new technology systems, and especially with gas technologies, always use a Thermal Imager to measure temperatures of various techniques, including battery. Use a Gas meter approaching vehicles with gas technologies, here to measure leaks in systems for not ignited gases. If leaking gases are measured use a heavy water mist to stop gasses for inflaming.

_Safety First!_
Research of the vehicle accident detector using the accident noise

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TEL +81-76-240-4979 Fax +81-76-240-4991
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*2:Prof. Kanazawa University

ABSTRACT
It is very important to detect vehicle accident and vehicle fire on the expressway as soon as possible to inform the operator and drivers of the emergency.

We have started to research on the possibility of detecting the accident and fire by the noise. We introduce the method in this report.

KEYWORDS:
vehicle fire, vehicle accident, expressway, detector, accident noise, FFT, frequency, fire noise, traffic control center

INTRODUCTION
About 100-140 vehicle fires occur every year on the expressway.

Especially the vehicle's fire in the expressway tunnel is dangerous. The vehicle’s fire in the expressway tunnel is approximately 10% of all vehicle’s fires. It is so much important to detect the accident as soon as possible for safety.

At the moment, the traffic control center gets the information of accidents through the emergency call from driver. The control center instantly informs the accident to each station and tries to manage and control the traffic safely by supplying the information to the drivers.

Vehicle failure is one of the most causes of vehicle fires. If the operator notices the sign immediately, it could be possible to react (figure-1) before the accident would become worse. So we decided to research on the method of detecting traffic accident automatically by the characteristic noise.

MEASUREMENT AND RESULT
We tried to measure some cases of the noise located at the Hokuriku-expressway and Tokaihokuriku Expressway in Japan. (Table-1). The accident noise measured at the Crash Test Facilities.
Table 1: Expressway noise

<table>
<thead>
<tr>
<th></th>
<th>Passenger car</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expressway Case-1</td>
<td></td>
<td>Case-2</td>
</tr>
<tr>
<td>Expressway Tunnel Case-T1</td>
<td></td>
<td>Case-T2</td>
</tr>
</tbody>
</table>

Table 2: Accident noise

<table>
<thead>
<tr>
<th></th>
<th>Full-shot Crash Test (Passenger car)</th>
<th>Full-shot Crash Test (Truck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crash Test Case-FS1</td>
<td></td>
<td>Case-FS2</td>
</tr>
</tbody>
</table>

Figure 2: Case-1

Figure 3: Case-2

Figure 4: Case-T1

Figure 5: Case-T2

Figure 6: Case-FS1

Figure 7: Case-FS2
The peak noise level of the truck is larger than the vehicle. And, the peak noise level in the tunnel is larger than the open section. It will affect by the reflection of the noise. However that the frequency properties has the same tendency at the peak level noise. (Figure-8).
For detection the accident we focused on the noise. Figure-9 shows the vehicle’s traffic noise and the vehicle’s accident noise on the expressway. Figure-10 shows the truck’s traffic noise and the track’s accident noise on the expressway. These figures are performed Fast Fourier Transform (FFT) of the noise. There is no correction of auditory sensation. The sampling frequency is 44100Hz. The frequency resolution is 46.875Hz. Figure-9 and 10 shows that it compare traffic noise with accident noise. Almost all Frequency, the level of the accident noise is larger than the traffic noise. The traffic noise is mainly composed of the 0-13KHz band. The level of high frequency band is low. But the accident noise is composed of the wide-band and high-level, especially the high frequency is characteristic. We think that it is possible to detect the difference between the accident noise and the traffic noise by analysis of the high frequency band.

CONCLUSIONS

We have been collecting the many cases of traffic noises and many cases of accident noises like about vehicle accident, breakdown, vehicle fire to analyse the features. In this report, we will report the results of analysis.
Car Bumpers Reaction to Fire

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and

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Paris, France

ABSTRACT

This research focuses on the reaction to fire of plastic car bumpers and aims at providing assistance to fire investigators especially when it is assumed that the fire was set on a car bumper plastic material using an open flame.

Small scale-tests were first planned to better define the inflammation conditions of these materials and the ignition delay according to their chemical composition. Then, full-scale tests were undertaken to determine whether the flame of a cigarette lighter could provide enough energy to set fire to a car bumper. The purpose was also to verify whether the combustion reaction could persist and spread the fire to the engine compartment before reaching the passenger compartment of the vehicle, and within what timeframe.

KEYWORDS: car bumper, plastic, time to ignition

INTRODUCTION

This research conducted at the “Laboratoire Central de la Préfecture de Police” (LCPP) of Paris, in France, studies the reaction to fire of plastic car bumpers. The LCPP is endowed with an investigation team on call 7 days a week and 24 hours a day. An engineer and a technician are available on request of police officers and firefighters for risk assessments (following spills of dangerous products, carbon monoxide poisonings or even electrical incidents leading to an electrocution) and fire or explosion investigations (origin and cause determination, on-site detection and also different types of sampling including fire debris sampling). Vehicle fire investigations represent more than 20 % of this response unit activity.

In order to provide data to the fire investigators of the LCPP to evaluate the potential hypothesis of a fire set on the bumper of a vehicle, experiments were undertaken to determine whether an open flame could provide a sufficient activation energy to set fire to a car bumper, whether the combustion reaction could persist and spread the fire to the whole vehicle.
EXPERIMENTS

Twelve car bumpers from five different car manufacturers were collected. The twenty-five different plastic materials considered in this research were analyzed using FTIR (Fourier Transform Infrared Spectrometry) and XRF (X-Ray Fluorescence Spectroscopy) to identify their chemical composition and compare the analytical results to the information provided by manufacturers. The main polymers found in these plastic materials were Polypropylene (PP), Polyethylene (PE) and Polycarbonate (PC), sometimes added with Benzoyl Peroxide (BPO), Acrylonitrile Butadiene Styrene (ABS), Ethylene Propylene Diene Monomer (EPDM), and/or even talcum.

Small-scale experiments

Small-scale experiments were undertaken in order to observe the reaction to fire of these car bumper materials and assess the factors that may influence it.

1) The first round of tests was led in experimental conditions copying as closely as possible the commission of an arson: the tests were performed outdoor using a lighter, on a minimum of two 9 x 9 cm² samples for each of the twenty-five car bumper materials. The average time of flame impingement until ignition of the plastic material samples were recorded:

<table>
<thead>
<tr>
<th>Type of plastic material</th>
<th>Time of flame impingement [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean value</td>
</tr>
<tr>
<td>PP</td>
<td></td>
</tr>
<tr>
<td>Recycled PP</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM + ABS</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + ABS</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td></td>
</tr>
<tr>
<td>PE + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + ABS</td>
<td></td>
</tr>
<tr>
<td>P/E + BPO</td>
<td></td>
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<tr>
<td>T10</td>
<td></td>
</tr>
<tr>
<td>PE + BPO</td>
<td></td>
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<tr>
<td>PC + ABS</td>
<td></td>
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</tbody>
</table>

Graph 1  Small-scale experiments results in outdoor conditions

2) The second round of tests was settled in laboratory conditions, with a normalized 20 mm gas burner flame (based on the requirements of the NF P 92-504 standard) to ensure controlled and repeatable conditions and favour comparisons between the reaction to fire of the different polymers. At least three 10 x 5 cm² samples were here considered for each material and the average time of flame impingement needed to achieve the ignition of the samples were noted:

<table>
<thead>
<tr>
<th>Type of plastic material</th>
<th>Time of flame impingement [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean value</td>
</tr>
<tr>
<td>PP</td>
<td></td>
</tr>
<tr>
<td>Recycled PP</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>PP + EPDM + ABS</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + ABS</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td></td>
</tr>
<tr>
<td>PE + EPDM + BPO</td>
<td></td>
</tr>
<tr>
<td>P/E + EPDM + ABS</td>
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<tr>
<td>P/E + BPO</td>
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<tr>
<td>T10</td>
<td></td>
</tr>
<tr>
<td>PE + BPO</td>
<td></td>
</tr>
<tr>
<td>PC + ABS</td>
<td></td>
</tr>
</tbody>
</table>

Graph 2  Small-scale experiments results in laboratory conditions
Outdoor experiments indicated that coated materials consistently took longer to be ignited. However, the results obtained in laboratory conditions do not suggest any significant difference between coated and non-coated materials. It was found that the coating needed to be previously degraded by the flame before igniting the polymer.

The differences observed between the two sets of experiments might primarily be explained by the used flames. Indeed, the flame of the lighter was almost 4 cm high and yellow, whereas the flame of the gas burner was 2 cm high and blue. The hypothesis of a higher flame temperature from the gas burner was first raised but both reached 1100°C, although the flame temperature of the lighter was less stable by its manual control. Nevertheless, the lighter used a combustible gas mixture made of propane and isobutane, whereas the gas burner was fuelled with propane on a constant pressure of 40 kPa, thereby generating a flame with a higher heat rate release.

Generally, these small-scale experiments showed that all plastic material samples started burning within the range of one to three minutes. Nevertheless, two of them behaved differently from the others: a non-coated recycled PP burned after a thirty seconds flame impingement, as well as a coated polymer made of PC and ABS could never be ignited even after a five minutes flame impingement.

**Full-scale experiment**

This research was completed with a full-scale experiment. The flame of a lighter was used to ignite a vehicle front grille panel, a plastic material that may be of some interest for any incendiary willing to set fire: the circulation of oxygen is more important in perforated than unperforated component parts of vehicles, thereby facilitating their ignition.

The ignition of the material was observed after a thirty seconds flame impingement. Drops of ignited plastic materials were noticed at $t_0 + 3\text{ min } 45\text{ s}$ and the front grille panel was completely melted at $t_0 + 4\text{ min}$: the fire started spreading to the engine compartment. The whole engine compartment of the vehicle was in the clutches of flames at $t_0 + 12\text{ min}$ and the car bumper felt on the ground after $t_0 + 14\text{ min}$. Fire-extinguishing tasks started at $t_0 + 19\text{ min}$ and were completed at $t_0 + 25\text{ min}$.
The initial hypothesis of this research was corroborated: the ignition of a vehicle plastic material with an open flame may cause a generalized car fire.

**DISCUSSION**

This study led to the introduction of an experimental protocol as a tool to assist fire investigators to make decisions and evaluate hypotheses on a possible car bumper fire-setting using an open flame. The use of this protocol in real cases relies on an experimental process that requires the survival of enough undamaged material. Moreover, it sometimes requires the collection of samples by cutting into hard matrices, a particularly difficult task.

This research highlighted the significance of several factors on the ignition of car bumpers plastic materials. During the small-scale experiments in outdoor conditions, some factors adversely affected the ignition of materials, such as the wind that sometimes hindered attempts of fire setting. Coated materials can require a longer flame impingement than non-coated materials to be ignited, depending on the heat rate release of the flame used. Some factors helped the inflammation, such as the material thickness; the thinner the material, the faster the ignition. Moreover, the geometry of the material where the flame is applied also plays an important role, especially on the edges and the rounded areas of car bumpers. Other factors that may influence the reaction to fire of these materials have been raised but have not been detailed in this study. Indeed, the presence of flame retardants in polymers or coatings could not be confirmed by the FTIR and XRF analyses and, accordingly, their effect on the ignition of plastic materials could not be assessed. Flame retardants should not only limit the spread of the fire but also prevent the ignition of the material. Furthermore, the manufacturing process of a car bumper (by injection or by compression) influence its density and therefore its flammability. This factor should be mentioned even if it could not be evaluated in this experimental research insofar as no information was provided on that issue by manufacturers.

**CONCLUSION**

The results obtained in this research should not be considered as reference data and have to be used with caution in examination with real cases: some factors may influence the ignition of a car bumper plastic material such as its composition, its potential chemical treatments, its painting, its geometry and thickness, as well as the heat source provided and its application. Due to the limited number of experiments that were undertaken, the subtle influence of each of these parameters could not be unveiled.

This research should led to the development of a technical data base related to plastic car bumpers containing circumstantial information (manufacturer, model, color, etc.), experiments results using a gas burner in laboratory conditions, as well as FTIR and XRF analyses results. This library is not yet effective but the data collected in this study will be the foundation stone of its creation. In the future, samples collected on the field when fire investigators raise the hypothesis of a fire set on the bumper of a vehicle will ensure its fulfilment.

**REFERENCES**

Development of a solid propellant gas generator (SPGG) system for fire suppression in aviation – Design of a combustion chamber

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ABSTRACT
This paper describes an approach to design the so called combustion chamber of an innovative concept for a Solid Propellant Gas Generator (SPGG) to suppress fire in the aircraft cargo hold. The concept is inspired by a rocket engine: a solid compound reacts in a combustion chamber to form a hot aerosol /gas stream that is expanded via a nozzle. Ambient air is sucked into the attached injector for cooling this stream before feeding it into the fire protected area. The combustion chamber design is the key driver for the layout of the following injector stage and depends on multiple parameters such as pressure, temperature and composition. For parameter variation of the generator in order to identify the optimum design case it is essential to determine the combustion chamber properties analytically and validate these with respective test values.

INTRODUCTION
In commercial civil aircraft the passenger cabin, engines, auxiliary power unit and cargo compartments are protected from fires this way. Currently, extinguishing systems based on the effective and common quenching gas Halon (CBr3F). Due to prohibition of fluorine hydrocarbons with the Montreal Convention [1] in 1987, the use of Halon will be also prohibited for aviation from January 2019. Therefore, alternative extinguishing agents are researched that can be used as commonly and effectively as Halon. The most determining factor for the use of a system in aircraft is weight. Although alternatives such as water mist systems are considered, they tend to be rather unsuitable due to their heavy weight (up to a factor of three compared to Halon). Therefore other methods are required.

A method that seems to meet the special requirements for aviation applications is found in solid propellant gas generators (SPGG). The minimum requirements (so-called „minimum performance standards“– MPS [2]) define the suppression efficiency of alternative fire extinguishing systems for cargo compartments. In these MPS four fire scenarios are included that relate to both solid and liquid fires in cargo compartments and are evaluated according to temperature criteria in the area of fire. Commercially available solid propellant gas generators were reviewed in tests and have shown their general applicability for the replacement of Halon. A variety of studies were carried out on the behavior of aerosols which focused on the composition of the solid propellant, the distribution of the extinguishing aerosol and the mechanism of condensed aerosols [3], [4]. As for the structure of such a generator information was published in patents [5] which differ in the type of cooling material and housing design. A weight and performance optimized system is proposed in the following chapter.

DERIVATION OF AN ANALYTIC METHOD TO DETERMINE THE DESIGN PARAMETER OF A COMBUSTION CHAMBER
The requirements for aerosol generators from international standards are used to develop SPGG [8] [9] but they do not include construction details. With the help of findings from the field of engine development [6] and air bag technology [7] a method of a calculation seems feasible. The approach for the present study is that SPGG is based on the same principles as a rocket engine but with different target. The main function of a rocket engine is to provide maximum impulse which is
dependent on the nozzle output mass flow. In contrast to that the SPGG shall generate an optimally
distributed fire extinguishing medium under special requirements for the use in aircraft. The derived
requirements for such a generator are:

- Stable burning process
- Constant pressure and burning rate
- Increased burning time
- Weight and space optimized system
- Decrease of temperature output

**Calculation of the optimized design of SPGG**

The thermochemical aspects of propellant combustion are described in [6]. For that the mass balance
in a rocket motor is the calculation basis. The values which influences this balance are illustrated in
Fig. 1. Here is \( r \) the burning rate, \( A_b \) the burning surface area, \( V_c \) the free volume of the combustion
chamber, \( p_c \) the chamber pressure, \( T_c \) the temperature in the combustion chamber, \( m_g \) the mass
generation rate in the chamber, \( m_c \) the rate of the accumulation in the combustion chamber, \( A_t \) the
nozzle throat area and \( m_d \) the mass discharge rate from the nozzle.

![Figure 1 Mass balance in a rocket motor, from [6]](image)

The stability criterion of a rocket motor is derived from this mass balance. Fig. 2 clarifies the
dependence of pressure and the mass flow. The stable burning point is where the mass generation rate
in the chamber (\( m_g \)) and the mass discharge rate from the nozzle (\( m_d \)) are equal.

![Figure 2 Mass balance and stable burning point in a rocket motor, from [6]](image)

Using the stability criteria the first derived requirement (stable burning process) is fulfilled. Eq. (1)
describes this criterion relating to the pressure inside the combustion chamber (\( p_c \)).

\[
p_c(t) = \left( p_i^{1-n} - \frac{a \cdot \rho_p \cdot K_n}{c_D} \right) \exp \left( \frac{(n - 1) \cdot R \cdot T_c \cdot c_p}{L^*} \right) t + \frac{a \cdot \rho_p \cdot K_n}{c_D} \right]^{\frac{1}{1-n}} \tag{1}
\]

Here is \( p_i \) the initial pressure, \( a \) the constant dependent on the propellant chemical composition and the
initial propellant temperature, \( \rho_p \) the density of the propellant, \( K_n \) the ratio of the burning surface
area (\( A_b \)) and the nozzle throat area (\( A_t \)), \( c_D \) the nozzle discharge coefficient, \( n \) the pressure exponent
of the burning rate, \( R \) the gas constant, \( T_c \) the temperature in the combustion chamber, \( L^* \) the
characteristic length and \( t \) the time of the process. If the pressure exponent of the burning rate is less
than 1 – which is the case for most solid propellants – the chamber pressure tends to the equilibrium
pressure. This is illustrates via Eq. 2.

\[
p_{eq} = p_c = \left( \frac{a \cdot \rho_p \cdot A_b}{c_D \cdot A_t} \right)^{\frac{1}{n}} \tag{2}
\]

The ratio of the burning surface area (\( A_b \)) and the nozzle throat area (\( A_t \)) gives a dependence from the
geometry of the combustion chamber. Transposing this formula enables to generate geometry data for the combustion chamber.

\[
K_n = \frac{A_b}{A_t} = \frac{p_c \cdot c_D}{\rho_p \cdot a \cdot p_c^n}
\]

(3)

Fig. 3 shows the impact of other geometry parameters on pressure and burning time for internal burning type for constant \(K_n\). This value \((L/D)\) is the ratio of the length \((L)\) and the diameter \((D)\) of the propellant. Increasing this ratio yields a higher maximum pressure and decrease of the burning time.

![Figure 3](image)

**Figure 3**  Effect of \(L/D\) for constant \(K_n\) on a rocket motor on erosive burning [6]

To fulfill the above mentioned for the SPGG in aircraft applications it is mandatory to achieve a significantly lower value of this ratio \((L/D)\).

**EXPERIMENTAL VALIDATION OF THE ANALYTIC METHOD BY SETTING UP A CORRESPONDING COMBUSTION CHAMBER**

**Test campaign of the designed combustion chamber**

A basic gas generator prototype (GG 1) is designed and tested in order to set up a database for temperature and pressure values inside the combustion chamber. These tests are carried out with different nozzle diameters and a various range of propellant load. Using the measured values from this test campaign and the described equations a second gas generator prototype (GG2) is designed and tested. The second gas generator is more optimized – especially with regards to weight which allows fulfilling the last derivate requirement. Both prototypes are illustrated in Fig. 4.

![Figure 4](image)

**Figure 4**  SPGG prototypes of the combustion chamber, GG1 (left) and GG2 (right)

The values obtained from testing of GG 2 are compared with results of a scientific calculation program for liquid propellant rocket engines (Rocket propulsion analysis – RPA) [10] in order to validate its applicability to SPGG.

**Results of the testing**

The comparison between the calculated data from the program (RPA) and the test results with solid propellant by using temperature and pressure values at various propellant charges result in a median difference of 4 %. This demonstrates that the calculation for rocket motor achieves a high level of accuracy for the design of the combustion chamber for SPGG. Fig. 5 shows the variation of these values and the median of the variation.

![Figure 5](image)
With knowledge of the combustion phenomena in a rocket motor it is possible to shift the SPGG design in direction of an optimal use for aircraft application. In order to realize a stable burning process the ratio of the mass generation rate in the chamber and the mass discharge rate from the nozzle. With a small value for the ratio of the length ($L$) and the diameter ($D$) of the propellant a constant pressure, a constant burning rate and an increase in the burning time can be achieved. These detailed values enable the optimized structure of the second gas generator which includes a weight benefit of 50%. The envelope shows means to develop a weight competitive system with respect to the replacement candidates of the existing Halon System.

**CONCLUSION**

Thus a database of parameters is generated which serves for further improvement and simulation to generate a light weight system and solve the high temperature impact. The combustion chamber is the core of the fire extinguishing system. With respect to general requirements a cooling system is needed. To solve this challenge an injector system seems to be useful which is based on the patent [11]. Furthermore, reference values from the tests described above can be deduced with an injector. The injector is used to replace the current cooling unit (built-in cooling media). With the final solid propellant gas generator – combustion chamber, injector and brackets – a system design for the cargo holds of commercial civil aircraft is planned.

**KEYWORDS:** Solid propellant gas generator, Aircraft cargo compartment fires, rocket motor

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Thermotolerance of Automotive CFRP Cylinders in Case of Fire and Their Handling Method After Fire

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ABSTRACT
To examine a safety correspondence method of the hydrogen fuel cell vehicle after the extinguishment of a fire, the carbon-fiber reinforced composite cylinder (CFRP cylinder) for automobile with the filling gas of maximum working pressure was heated by electrical oven, when a cylinder burst or leak, the limiting temperature and the internal pressure of cylinder were investigated. As a result, a cylinder (Working Pressure 20MPa, Type III) burst at 200°C on cylinder surface with 38MPa. Another cylinder (Working Pressure 25MPa, Type IV) began leak from liner at approximately 150°C on the liner surface with 40MPa. The above result showed that the survival temperature of the CFRP cylinder is approximately 150 °C as low to be on the safer side.

KEYWORDS: CFRP cylinder, limiting temperature, extinguishment, first responders

INTRODUCTION
In the Global Technical Regulation on hydrogen and fuel cell vehicles, the maximum hydrogen filling pressure for a carbon-fiber reinforced plastic (CFRP) cylinder is expressed in terms of a cylinder inner pressure based on an environmental temperature of 15°C, while the maximum working temperature of a cylinder is set at 85°C[1]. The internal pressure varies according to environmental temperature; for example, if the environmental temperature rises from 15°C to the maximum allowable working temperature of 85°C, the internal pressure increases 1.25 times. Consequently, CFRP cylinders should have sufficient thermal and pressure resistance to meet the environmental.

Assuming fire accidents, the hydrogen fuel cell vehicle is equipped with a thermally activated pressure relief device (TPRD) which detects heat from fire and releases the stored hydrogen gas into the atmosphere for the prevention of cylinder rupture. If the fire is put off before TPRD activation, the CFRP cylinder retains a high-pressure hydrogen gas.

To move and keep such a fire-struck hydrogen fuel cell vehicle safely, it is important to diagnose the soundness of the hydrogen cylinder and, if judged necessary, release the hydrogen gas as promptly as possible. Nevertheless, there have been few studies on proper handling of a post-fire CFRP cylinder. To derive a proper handling method, research needs to be carried out on the cylinder ‘limit temperature’ at which the heated cylinder finally ruptures leading to gas leak. No researcher has reported on the limit temperature of CFRP cylinders before, while estimation has been made that the limit temperature is identical with the heat decomposition temperature of the epoxy resin impregnated in carbon fibers[1][2], the material for CFRP cylinders.

In this study, two types of CFRP cylinders filled with gas to the maximum working pressure were heated, and their limit temperatures and corresponding internal pressures were investigated. Based on the obtained data on cylinder rupture strength, on limit temperatures and on cylinder condition, discussion was made concerning a proper post-fire method of handling CFRP cylinders whose TPRDs remained unactivated throughout and after the fire-fighting process.

TEST METHOD
The designed maximum filling pressures of automotive CFRP cylinders are 20–25 MPa for compressed natural gas and 35–70 MPa for compressed hydrogen gas. When the maximum filling pressure is lowered, there are tendencies to reduce liner thickness and lower heat resistance of CFRP cylinders.
In order to ensure greater safety of CFRP cylinder heating tests, cylinders for compressed natural gas were employed in the present study for the lower maximum filling pressure requirement. Table 1 shows the test cylinders. Types III and IV cylinders for compressed natural gas were used, having a liner made of aluminium and plastic. Figure 1 shows the design diagram and photograph of a test cylinder placed in an electric oven.

Each of the two test cylinders was filled with nitrogen gas to its maximum filling pressure; then was heated in the electric oven in which temperature was measured at an upper and a lower point on the cylinder surface and at an aerial point in the center of the oven, using K-thermocouples. The temperature reading in the center of the oven was considered as oven temperature. The oven was heated to reach its preset temperature; then was additionally heated for 100 minutes or more to maintain the preset temperature and to enable a full permeation of heat throughout the nitrogen gas to an equilibrium inner pressure. Where the cylinder ruptured in the heating process, the cylinder surface temperature at rupture was defined as the limit temperature. The reasons for the selection of nitrogen gas were: (a) it becomes possible to thoroughly heat the cylinder to an equilibrium gas temperature while keeping the cylinder inner pressure constant, and (b) greater safety can be ensured at the time of cylinder rupture. On the other hand if the cylinder did not rupture during the heating process, a rupturing test using water pressurizing equipment was conducted to determine the residual strength of the cylinder which was cooled immediately after the heating process to minimize its thermal deterioration. Cylinder A (Type III) was cooled until its inner pressure returned to the maximum filling pressure and then was degassed so as not to affect its self-shrinking function[4] provided for the improvement of fatigue strength.

**RESULTS AND DISCUSSION**

**LIMIT TEMPERATURE AND PRESSURE OF CYLINDER A**

Figures 2 show the measured temperatures inside Cylinder A when it was heated to an oven preset temperature of 300°C. In the oven preset 300°C test, the cylinder ruptured when both lower and upper cylinder surface temperatures were approximately 205°C and the cylinder inner pressure 38 MPa. In the oven preset 250°C test, the cylinder ruptured approximately 100 minutes after the oven temperature had reached the oven preset temperature, and the lower and upper cylinder surface temperatures were both approximately 210°C and the cylinder inner pressure 38 MPa at rupture.

Figure 3 shows the cylinder temperatures and pressures when the electric oven was preset to 200°C. Both lower and upper cylinder surface temperatures rose to approximately 150°C while the cylinder inner pressure reached 34 MPa, but leak or rupture did not occur. The cylinder underwent a cooling by water 223 minutes after the test start; then, after the inner pressure had declined to the initial test start level, the cylinder was degassed. An additional test was performed to determine the rupture strength of Cylinder A, and it was found that when the cylinder surface temperature was approximately 150°C, Cylinder A ruptured at a rupture pressure of 95.1 MPa.

![Fig.1 Appearance of test equipment.](image1)

![Fig.2 Internal pressure / temperature to an oven preset 300°C (Cylinder A)](image2)
A new cylinder of the same type was found to rupture at an equivalent pressure of 91.7 MPa, proving that Type III cylinders had sufficient pressure resistance at their surface temperatures of 150°C. Consequently, the limit temperature and the corresponding inner pressure were considered to be 205°C at 38 MPa for Cylinder A.

Figure 4 compares the surface condition of a CFRP cylinder between when the surface temperature was approximately 150°C (oven preset to 200°C) and when it was 200°C (oven preset to 250°C). As cylinder surface temperatures exceeded 200°C, the resin impregnated in the CFRP was observed to have discolored to light brown and swellings had developed. The results suggested that if a Type III cylinder shows surface discolorations after the fire was extinguished, the rupture strength of the cylinder might have declined.

**Fig. 4 Surface of Cylinder A (comparison between surface temperature 150°C and 200°C)**

LIMIT TEMPERATURE OF CYLINDER B

Figure 5 shows the temperatures at three points and inner pressure of Cylinder B when heated to an oven preset temperature of 250°C. During heating to an oven preset temperature of 250°C, Cylinder B began leaking when its upper and lower temperatures measured approximately 150°C and its inner pressure 40 MPa. As the leaked gas spread in the electric oven, the oven temperature temporarily declined, but the heating of the oven was continued for 50 minutes after the start of leak. The oven continued leaking without rupture while the cylinder inner pressure fell below 15 MPa, whereby the cylinder was cooled by water and its gas was forced out. Subsequently the same test was repeated under the same conditions, indicating the same cylinder temperatures and inner pressure at leak start.

Figure 6 shows the temperatures at three points and inner pressure of Cylinder B when heated to an oven preset temperature of 200°C. Although the upper and lower cylinder surface temperatures reached approximately 100°C and the inner pressure approximately 37 MPa, Cylinder B did not generate leakage. In the subsequent rupture test, Cylinder B recorded an inner pressure of 137.1 MPa at rupture. A new cylinder of the same type measured a similar 123.1 MPa inner pressure at rupture, and maintained sufficient pressure resistance at a cylinder surface temperature of 100°C. Accordingly, the limit temperature and the corresponding inner pressure were considered to be 150°C at 40 MPa for Cylinder B. A pinhole produced by a melting of the plastic liner of Cylinder B heated to an oven preset temperature of 250°C was found, and the gas was considered to have
leaked from this pinhole.

**LIMIT TEMPERATURE OF CFRP CYLINDERS**

With the above-reported limit temperatures of Cylinders A and B taken into account, the general limit temperature for all CFRP cylinders was estimated at 150°C on the safe side. This temperature is clearly lower than the 312~316°C[4] which is the starting temperature of epoxy resin heat decomposition in air and an indicator of CFRP heat decomposition. Consequently it is necessary for the limit temperature of CFRP cylinders to reflect the effect of inner pressure increase on the pressure resistance of the cylinder.

**DISCUSSION ON CYLINDER HANDLING AFTER FIRE EXTINCTION**

Based on the automotive CFRP cylinder limit temperature determined in the present study, post-fire methods of safe CFRP cylinder handling were discussed. When molten plastic parts are found near the CFRP cylinder in trying to diagnose its soundness, it can be assumed that the cylinder has been exposed to an environmental temperature of as high as 150°C. Accordingly it is necessary to degas the cylinder as promptly as possible.

In the case of fire extinction using foam or powder, the CFRP cylinder may have to be left at an environmental temperature of 150°C or higher for hours after the extinction of fire due to a lack of cooling by water. On the other hand, the thermal deterioration of CFRP can be minimized and the cylinder inner pressure can be lowered by cooling the cylinder with water. As reported in Figures 3 and 6, it is safe to cool a cylinder immediately after its heating. Furthermore, the authors found that the forced cooling of a cylinder with water immediately after a fire exposure test increased the strength of the cylinder as compared to natural cooling[5]. Consequently it is recommendable to expedite the cooling of cylinders, using water after the extinction of fire.

**CONCLUSIONS**

To better understand the automotive CFRP cylinder’s limit temperature taking account of cylinder inner pressure at the time of a fire accident, CFRP cylinders filled with nitrogen to the maximum working pressure were heated, and the minimum temperature at which the cylinder ruptured or started leaking was measured along with concomitant inner pressure. The results indicated that Cylinder A ruptured at approximately 200°C at 38 MPa. Cylinder B started leaking from its liner when its temperature measured 150°C at 40 MPa. Consequently the limit temperature for all automotive CFRP cylinders was estimated at approximately 150°C on the safer side, and it was concluded necessary to actively prevent the cylinder temperature from reaching 150°C by cooling the cylinder with water as soon as the fire is extinguished. The other conclusion was that the soundness of a cylinder may be judged from the absence of discolored, molten or deformed plastic parts in the vicinity of the cylinder.

**ACKNOWLEDGEMENTS**

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**REFERENCES**

INFLUENCE OF THE PASSENGER VOLUME ON THE SMOKE LAYER IN TRAINS

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ABSTRACT

Because of the limited air volume in trains passengers can significantly reduce the space for the smoke spreading in case of fire. This compared to an empty train being considered in normative assessments or classification systems respectively. In fire experiments the influence of passengers on the smoke movement cannot be considered without endanger the test persons. By using the computational fluid dynamic model FDS the influence of the volume of passengers on the smoke layer height is examined. The analysis was done both with FDS 5 and 6.

KEYWORDS: smoke layer, fire simulation, double decker coach

METHOD AND RESULTS

By conducting fire experiments in trains stratification and movement of smoke is one focus of investigation. The results and outputs of real scale tests are necessary to implement the relevant conditions in a numerical fire simulation and to validate the computational procedure for the respective scenario as well. The following figure 1 shows the positions of some optical units (OU), which measured the transmission of a real scale test during the Transfeu project [1].

![Figure 1 Measuring points of the optical units](image)

Compared with the real scale test, the results of the simulations with FDS 5 and 6 are more conservative as the measured transmission, shown in figure 2. The input conditions of the simulations are the same by using the mixture fraction and accordingly single step combustion to examine the smoke movement.
Figure 2   Results of the real scale test compared with FDS

In general, the simulation with FDS 6 shows a greater transmission than the simulation of the scenario with FDS 5. The values of the simulation with FDS 5 are lower as FDS 6. The reasons of the discrepancy between the simulations and the experiment are discussed in [2]. The double-decker coach has a volume about 180 m³. While this space volume fills up with smoke, the smoke cools down at the interior and the surrounding walls of the coach, hence the thermal buoyancy is reduced. Experiments of fire spreading or smoke movement are conducted without any participant persons inside the train. Because of that, the influence of the human volume on the smoke layer height will not be measured. The presence of passengers reduces the space for smoke spreading. The time between ignition and exposing of passengers depends on the heat release rate of the fire, the fuel, fire spread, ventilation etc. For investigating the influence of the human volume on the smoke layer and the exposure time, different numbers of passengers are modelled as a construct of additional obstacles (fig. 3).

Figure 3   Passengers in the double-decker coach

For the first impression passengers with an assumed and uniform volume of 0.08325 m³ are build and multiplied, based on [3]. There is no distinction between male and female, children and adults. The focus lies exclusively on the replacing of the space for smoke spreading. Therefore, two scenarios are considered. The first scenario is build up with 77 passengers sitting distributedly in the coach and for
the second one; most of the 77 passengers are located near the entrance area, fig. 3. The position and the number of modelled passengers are not changing. Because of the limitation of FDS [4] the developed local turbulences on the thermal driven flows due to the additional volumes (passengers) are not considered. The following figure 4 shows the transmission on the upper level for the initial scenario and the two passengers once.

Figure 4 Simulated transmission of three scenarios with FDS 6

The additional volumes of the passengers lead to a low improvement of the transmission in the upper level during the first seconds, because of the influence of the passengers in the lower level. However, the smoke accumulates after 180 s in the upper level and the values of the transmission become a little lower as the simulation without passengers. The additional simulated quantities like, extinction and different gas concentration confirm the smoke movement similar to the transmission.

CONCLUSIONS

The simulation with FDS shows the same tendency of the transmission as in the experiment, though the measured quantities are not reproduced. FDS 5 and FDS 6 do not show significant difference but there is a tendency, that FDS 6 simulates a slower decrease in transmission in the upper level of the coach. For this, FDS 6 was used to simulate different scenarios with passengers in the train.

The influence of the smoke movement based on additional volumes, which represent the passengers is marginal for the considered scenarios. Also standing passengers located in the corridor do not significantly influence the smoke movement in the upper level compared to the initial scenario without passengers.

The critical scenario is to evacuate the passengers from the upper level which is immediately filled up with smoke, if the fire is located in the lower level. After two minutes the transmission decreases below 90 % at a height of 1.4 m. This effect influences the required behavior of the passengers, who possibly evacuate crawlingly, similar to air plane evacuation.

REFERENCES


A Rational Scrapping Method for Automotive Compressed Hydrogen Cylinders

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ABSTRACT
The present study was focused on the possibility of omitting the vacuuming step for removing residual hydrogen from cylinders to be dismantled. The test results indicated that 1) if the vacuuming step was omitted while the cylinders were simply left open to the atmosphere, it took over 80 hours before the hydrogen concentration inside cylinders declined below the explosion limit range and 2) in case the hydrogen inside a cylinder catches fire, the persons present near the cylinder opening may be injured. For these reasons it was concluded that the vacuuming step should not be omitted from cylinder scrapping work.

KEYWORDS: hydrogen safety, hydrogen cylinder, cylinder scrapping work

INTRODUCTION
A fatal explosion accident occurred during scrapping work for automotive compressed natural gas (‘CNG’) cylinders in Japan, September 2012. The main cause of this accident was attributed to the skipping of the degassing step in cylinder dismantling process. As a result, a renewed light has been cast on the importance of observing the Residual Gas Treatment and Automotive CNG Cylinder Scrapping Manual (‘CNG Cylinder Scrapping Manual’) published by an industry organization in Japan [1] and of establishing a safe cylinder scrapping method inclusive of a degassing step. Since fuel cell vehicles are expected to enter their full-scale commercialization phase from around 2015, early effort is considered necessary to prepare a scrapping manual and establish a scrapping method for automotive hydrogen cylinders. Figure 1 shows the individual work steps described in the CNG Cylinder Scrapping Manual in Japan [2]. Because these safety steps are laborious and time-consuming, there are growing demands for a more rational and safe scrapping method aimed at automotive compressed hydrogen cylinders (‘hydrogen cylinders’). Focused on the possibility of omitting the vacuuming step, the present study was conducted to measure the time-dependent hydrogen concentration and to perform ignition tests on hydrogen-containing cylinders opened up to the atmosphere.

MEASUREMENT OF TIME-DEPENDENT HYDROGEN CONCENTRATION
In the present study, the vacuuming step was omitted after the combustion step for residual gas inside cylinders. Instead of the vacuuming step, the cylinders were simply opened up to the atmosphere by removing their bosses. To more clearly determine how the hydrogen concentration would change in time...
series when the cylinders were kept open, the measurement was started with the cylinders filled up to a 100vol% hydrogen content.

**Test method**

*Table 1  Test conditions*

<table>
<thead>
<tr>
<th>Boss diameter</th>
<th>1/2inch, 1 inch, 2 inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td></td>
</tr>
<tr>
<td>A (29litter, φ280mm, Length 720mm)</td>
<td></td>
</tr>
<tr>
<td>B (33litter, φ400mm, Length 820mm)</td>
<td></td>
</tr>
<tr>
<td>Cylinder set</td>
<td>Horizontal, Upward, Downward</td>
</tr>
<tr>
<td>H2 sensor</td>
<td>TCD (Manuf.: ZIROX, Model: WMF)</td>
</tr>
<tr>
<td>H2 measurement time</td>
<td>2.5min (intake: 100m/min)</td>
</tr>
<tr>
<td>Sensor location</td>
<td>Shoulder midpoint opposite to the boss</td>
</tr>
<tr>
<td>Room temp.</td>
<td>15 ± 5°C</td>
</tr>
</tbody>
</table>

The test cylinders were filled sufficiently with hydrogen gas to ensure a 100vol% hydrogen content and were held stationary in their test positions for at least 30 minutes in order to stop gas flow inside the cylinders, before the start of hydrogen concentration measurement. Table 1 the test conditions. As test conditions, there were three different boss diameters (1/2, 1, 2 inches), three different container positions (horizontal, upward, downward in relation to boss location), and two different container sizes (cylinder A, cylinder B).

**Results and discussion**

For all the different boss diameters, in-cylinder hydrogen concentration declined with time presumably because the hydrogen gas gradually diffused out from and air moved into the cylinder. When the boss direction was same, the hydrogen concentration declined more quickly with the increase in boss diameter. As for the effect of boss direction, hydrogen concentration declined most slowly when the cylinder was set downward, irrespective of boss diameter. In the comparison of horizontally and upward set cylinders, the hydrogen concentration decline was slower with a 1/2-inch boss, while the decline speed was practically equal between 1-inch and 2-inch bosses.

*Table 2  Measured time in hours*

<table>
<thead>
<tr>
<th></th>
<th>1/2inch</th>
<th>1 inch</th>
<th>2 inch</th>
<th>1/2inch</th>
<th>1 inch</th>
<th>2 inch</th>
<th>1/2inch</th>
<th>1 inch</th>
<th>2 inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to reach 75vol%</td>
<td>2.8</td>
<td>1.2</td>
<td>9.0</td>
<td>0.15</td>
<td>0.15</td>
<td>3.9</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
</tr>
<tr>
<td>Time in explosion limit range</td>
<td>80 hours or more</td>
<td>6.6</td>
<td>5.5</td>
<td>35</td>
<td>0.60</td>
<td>0.60</td>
<td>12</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

*The number of hours calculated by extrapolation* and in cylinder A with a 1-inch boss fell into the explosion limit range respectively 6 and 9 minutes after the opening of the boss. The shortest time of hydrogen concentration entering into the safety range (i.e., below the explosion limit range) was 36 minutes, recorded by cylinder A with a 2-inch boss. Yet cylinder A with a 1/2-inch boss took more than 80 hours to reach the safe range.

**HYDROGEN IGNITION TESTS**

To investigate the effect of accidental hydrogen ignition when a cylinder is opened, the hydrogen inside test cylinders was artificially ignited and the impacts of blast on the surroundings were investigated.
Test method

Table 3  Test conditions and measuring devices

<table>
<thead>
<tr>
<th>Boss diameter</th>
<th>1inch, 2inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder set</td>
<td>Horizontal</td>
</tr>
<tr>
<td>H2 sensor</td>
<td>TCD (Manuf.: NEW COSMOS ELECTRIC, Model: XP-3140)</td>
</tr>
<tr>
<td>Sensor location</td>
<td>Cylinder midportion</td>
</tr>
<tr>
<td>Blast pressure sensor</td>
<td>Type: ICP, Manuf.: PCB Piezotronics, Inc., Model: 113B21</td>
</tr>
<tr>
<td>Noise level meter</td>
<td>Manuf.: RION CO., LTD., Model: NL-52</td>
</tr>
<tr>
<td>Ignition method</td>
<td>Spark discharge (30mJ, gap length 2~3mm)</td>
</tr>
<tr>
<td>Ignition point</td>
<td>Boss upside</td>
</tr>
<tr>
<td>Room temp.</td>
<td>8 ± 5°C</td>
</tr>
</tbody>
</table>

Table 3 the test conditions of the ignition testing. In the ignition tests, the hydrogen gas was ignited by spark discharge in the upper area of the boss while the cylinder was set horizontally. Measurement was made on hydrogen concentration at the cylinder center, on blast pressure inside the cylinder, and on noise levels at 1m away from the boss outer surface.

Results and discussion

Figure 2 shows the montage of an infrared thermal image and a photographic image of the ignition scene (Display range: 50 ~ 150°C, emissivity: 0.95) when the hydrogen concentration at the cylinder center was 40vol%. As shown in Figure 2, flames were ejected forward from the cylinder boss when the hydrogen concentration was between 15 and 60vol%. Nevertheless, when the hydrogen concentration was 80vol% or higher, combustion continued in the boss area for more than 5 minutes without generating any blasts nor leaving any blast impacts. When the hydrogen concentration was 10vol% lower, the hydrogen inside the cylinder failed to catch fire despite spark discharge in the boss area. Figure 3 shows an exemplary blast pressure waveform obtained from cylinder B with a 1-inch boss and a hydrogen concentration of 40vol%. When the hydrogen concentration was in the 15~60vol% range, blast pressure reached its peak immediately after ignition. Figure 4 shows the relationship between the measured values of peak blast pressure and hydrogen concentration. The maximum value of blast pressure was found higher in cylinder B than in cylinder A, and with a 1-inch boss than with a 2-inch boss. With a 1-inch boss, the peak blast pressure was recorded at a hydrogen concentration of 35~40vol%, thus indicating an explosion characteristics similar to those of hydrogen-air mixture gas [3]. Focusing on cylinder B with a 1-inch boss which recorded the highest maximum blast pressure in the above Figure 4. Table 4 shows the maximum blast pressure and noise levels measured for this cylinder at different hydrogen concentration levels. Table 4 indicates that where blast pressure peaked, the noise level was measured at 115 dB. In this connection, there are the widely accepted observations that a blast pressure of 100 kPa can cause 50% damage to the human eardrums [4], that the human auditory organ can be impaired by a noise of 90~120 dB, and that the malfunction of the whole body can be induced by a noise exceeding 120 dB [5].

![Fig. 2  Ignition scene (at 40vol%)](image1)

![Fig. 3 Blast pressure inside cylinder B (1-inch, 40vol%)](image2)
Consequently, the present test results suggested that in case the hydrogen inside a cylinder is ignited, persons present in the vicinity of the cylinder opening may be injured by the blast pressure and/or blast noise. For this reason, the vacuuming step should not be omitted from the cylinder scrapping process.

CONCLUSIONS

The present study was conducted to evaluate the safety of omitting the vacuuming required as one of the work steps for the cylinder scrapping process diagramed in Figure 1. Two types of tests were performed: measurement in time series of hydrogen concentration inside cylinders opened up to the atmosphere, and ignition testing on the hydrogen in cylinders. The results indicated: 1) When the vacuuming step was omitted and the cylinders were left open to allow the hydrogen escape into the atmosphere by the action of natural forces, it took 80 hours or more for the hydrogen concentration in cylinders with a 1/2-inch boss to decline below the explosion limit range or into the safety range. 2) In case the hydrogen inside the cylinder catches fire, the persons present near the cylinder opening may be injured by blast pressure or noise. Consequently, it was concluded that the vacuuming step should not be omitted.

ACKNOWLEDGEMENTS

This paper introduces one of the achievements of the “technology development project for hydrogen production, transport and storage systems” commissioned by the New Energy and Industrial Technology Development Organization (NEDO) in Japan.

REFERENCES

1. The Japanese Minister of Economy, Trade and Industry
Tunnel Fire on the Expressways of Japan
- The Wide-spread Use of Next-generation Vehicles -

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ABSTRACT
Currently, the total length of Japanese existing expressways is approximately 8,000 km long, and the total length of the tunnels on the expressways, including both inbound and outbound tubes, reaches approximately 1,600 km long. From 1990 to 2012, the number of recorded fire accidents that happened inside the tunnels ranges from 4 to 21 times per year, or on the average of one fire accident per month. Seventy percent of the fire incidents are due to vehicle defects, while thirty percent of the fires are due to traffic accidents.

Putting the tunnel fire incidents into consideration, together with the increasing need for global environment conservation and advancing technical innovations, next-generation vehicles which include hybrid vehicles (HV) and electric vehicles (EV) have become the current trend. Among other countries, Japan is leading in the usage of such vehicles. Expectedly, this trend will continue in the future. However, for these next-generation vehicles such as HV and EV, the source of electrical energy, which differs from conventional fossil energy (such as gasoline and diesel that are generally known as hazardous substances), is stored in on-board battery packs. In order to upgrade further performance, the technologies of these stored batteries are currently being developed and the studies regarding fire safety are also being worked on.

Therefore, it is essential to collect information such as the characteristic of fires, fire statistics of the tunnels on expressways, the performance of the next-generation vehicles in the future, and the fast-growing trend of the vehicle, and to discuss safety measures for road tunnels to be fulfilled.

KEYWORDS: Expressway tunnel, Next-generation vehicle, Hybrid car, Electric Vehicle, Fire characteristics, Statistical data

EXPRESSWAYS IN JAPAN
As shown in Figure 1, in the expressway networks in Japan, major highways, which connect between cities, have been mostly completed, and the maintenance and improvement have been promoted in the crossing roads which pass through the mountain area and the ring roads which is the connecting point of intercity expressways and cities. In this situation, local expressway networks were heavily damaged by Tohoku earthquake (March, 2011), yet expressways were used as the route for emergency assistance to the disaster areas. The results proved how important these routes are relied on. However, in December of 2012, concrete ceiling panels were collapsed in Sasago Tunnel on the Chuo Expressway. It exposed the problem regarding deterioration of structures due to its age. Therefore, various measures are being taken to improve the reliability and safety as civil infrastructure. Additionally, studies regarding road tunnel fires are being conducted as one of our research subjects.

ROAD TUNNEL FIRE IN EXPRESSWAYS
Road tunnel is a confined space. Once fire occurs inside the tunnel, it can be hazardous to life due to thermal air current and smoke which blocks people’s view. The direction that people evacuate can be the same direction as the one where smoke goes, which is caused by combustion. As of 2012, in Japan,
there are 9,700 road tunnels and 1,750 expressway tunnels. From 1980 to 2012, the average occurrence of tunnel fire accidents on the expressways is 12.3 times per year, that is, on the average there is about one fire accident per month. As shown in Figure 2, when the factor of tunnel fire was roughly classified, it shows that seventy percent of the fire incidents are due to vehicle defects, while thirty percent of the fires are due to traffic accidents. Fire due to traffic accidents is classified as single vehicle accident or multiple-vehicle collision, and each percentage of totals is approximately same. As shown in Figure 3, for the vehicles caused fire accidents, passenger vehicle is the most significant factor, and HGV and general goods vehicle come as second. Organizing these vehicles into three types (passenger vehicle, goods vehicle, and others); we found that the percentage of passenger vehicle and goods vehicle is approximately the same.

![Figure-2 Factor of Tunnel Fire in NEXCO Expressway](image)

![Figure-1 Major Japanese Expressway](image)

![Figure-3 Classification, the causes of the accident vehicle](image)

![Figure-4 Penetration of the Next-Generation Vehicles in Japan](image)

**PENETRATION OF THE NEXT-GENERATION VEHICLES**

As shown in Figure 4, the number of next-generation vehicles such as HV and EV is increasing rapidly due to global environmental perspective and technical renovation. As of 2012, the number of vehicles owned in Japan reached 58.14 million units for passenger vehicles, 15.14 million units for trucks, 230,000 units for buses, and 1.65 million units for special-purpose vehicles, which totals 75.16 million units. On the other hand, as of the end of 2012, the
number of next-generation vehicles reached 2.9 million units for HVs and 56,000 units for EVs as shown in Figure 4. The percentage of the total passenger vehicles is only 5% for HVs and 0.1% for EVs. However, it shows that both numbers are increasing rapidly. It is considered to be due to tax incentives and rising public awareness for environmental protection. The government forecasts that the penetration rate will be up to 20% in 2020 and up to 30% in 2030.

**FIRE CHARACTERISTICS OF THE NEXT-GENERATION VEHICLES**

The safety of lithium-ion battery is one of the issues to be considered as fire related to the next-generation vehicles. Compared to the battery that was previously used, it has higher capacity, and for the purpose of offering higher performance and lower prices to meet future demand, research development is being conducted. However, only Table-1 shows the information regarding the fire characteristics for lithium-ion battery body and EV equipped with it. There is no information regarding fire due to traffic accidents and vehicle defects; and the comparison with conventional fossil fuelled vehicles (heat release rate, generated gas, and the risk of explosion) has yet to be fully understood. Table 1 shows the characteristics which are understood by experiments presented in Japan.

<table>
<thead>
<tr>
<th>Year</th>
<th>Overview</th>
<th>Experimental outcome</th>
<th>Implementing body</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Penetration test of lithium-ion battery</td>
<td>Detected combustible gas including hydrogen, carbon monoxide, and ethane (assumed to be at risk for burning) and temperature increase.</td>
<td>Japan Automobile Research Institute (JARI) 5)</td>
</tr>
<tr>
<td>2012</td>
<td>Fire behaviour of ordinary EV 24kWh battery pack Charging rate 100%</td>
<td>Maximum burning velocity: 6.3MW Flame injection was observed from battery packs.</td>
<td>National Research Institute of Police Science et al 6)</td>
</tr>
<tr>
<td>2013</td>
<td>Fire behaviour and charging rate of ordinary EV 24kWh battery pack Charging rate 10%, 100%</td>
<td>Maximum burning velocity Charging rate (100%) : 6.3MW Charging rate (10%) : 3.4MW</td>
<td>Same as above 7)</td>
</tr>
<tr>
<td>2013</td>
<td>Fire extinguishing by ordinary EV</td>
<td>Fire can be extinguished by water-based method of hydrant (400 ℓ/min) It is important to cool battery parts (in order to prevent re-burning) Caution against thermal runaway and combustion of electrolyte.</td>
<td>National Research Institute of Fire and Disaster et al 8)</td>
</tr>
<tr>
<td>2013</td>
<td>Fire behaviour of ordinary compact EV 16kWh battery pack</td>
<td>Maximum burning velocity: 2.8MW Flame injection was observed from battery packs.</td>
<td>National Research Institute of Police Science et al 9)</td>
</tr>
</tbody>
</table>

**TUNNEL EMERGENCY FACILITY**

Road tunnels have to be prepared for accidents and fire incidents, therefore, there is the need to install the following tunnel emergency facilities: (1) Information Equipment to report to the road operator immediately; (2) Alarm Equipment to prevent succeeding disasters; (3) Fire Extinguishing Equipment to extinguish fire at an early stage; (4) Escape and Guidance Facilities to assist people’s evacuation; (5) Smoke Control System to exhaust smoke and ensure environmental sustainability; (6) Emergency Passage to guide affected people to safer area; (7) Water Spray System to control fire and reduce internal temperature. (See Table-2)

However, these facilities are to be installed according to the plan applicable for fossil fuel. Also, further confirmation is needed since there is limited experimental result regarding the effect of water-based fire extinguishing method and the characteristics of fire caused by EVs as shown in previous section.
### Table-2 Type of emergency facilities in tunnels

<table>
<thead>
<tr>
<th>Information and alarm equipment</th>
<th>Information</th>
<th>Emergency telephone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Push-button type reporting system</td>
<td>Fire detector</td>
</tr>
<tr>
<td>Alarm</td>
<td>Emergency alarm equipment</td>
<td>Fire extinguishing equipment</td>
</tr>
<tr>
<td></td>
<td>Fire extinguisher</td>
<td>Escape and guidance facilities</td>
</tr>
<tr>
<td></td>
<td>Fire hydrant</td>
<td>Guidance signboard</td>
</tr>
<tr>
<td></td>
<td>Smoke control system or emergency passage</td>
<td>Other facilities</td>
</tr>
<tr>
<td></td>
<td>Hydrant</td>
<td>Wireless communication aid facility</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio rebroadcasting system or loud speaking broadcast system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water spray system</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Monitoring system</td>
</tr>
</tbody>
</table>

### CONCLUSIONS

Regarding the growing trend of next-generation vehicles and fire characteristics, these depend on not only the vehicle type but also on the battery charging condition, and the continuous technical development that is being conducted. In this context, many uncertainties still remain. Therefore, it is difficult to understand the actual condition. However, fossil energy is running out and next-generation vehicles are continually improving. The number is expected to increase in the near future.

To address these aspects as those engaged in road management, it is important to have an updated understanding of emergency facilities. We need to understand whether the current emergency facilities are suitable and applicable through steady investigations and analysis of fire incidents and conducting experiments to understand fire characteristics.

### REFERENCES

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