HOW ELECTRIC VEHICLES CHANGE THE FIRE SAFETY DESIGN IN UNDERGROUND STRUCTURES

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ABSTRACT

Driven by climate change, the need to reduce the production of climate-wrecking gases, especially CO_2, is resulting in a diversification in the mobility sector. Therefore, the number of vehicles using so-called new energy carriers (NEC), in particular electric drive concepts, is constantly increasing. Electric vehicles itself as well as the mixture of vehicles are causing new fire risks, which are currently hardly known. Moreover, this risks are even intensified when occurring in underground facilities.These circumstances are demanding for research on those new fire risks. The German research project SUVEREN is focussing on the described deficit. Various fire tests with NECs, including different types of lithium-ion batteries, have been conducted. Furthermore, a design fire curve for modern passenger cars regardless their propulsion system was developed. This curve can be utilized for designing underground facilities when using performance-based design.

KEYWORDS: NEC, Lithium-Ion batteries, Electric vehicle, Fire tests

BACKGROUND

The global climate change has resulted in a change of the public opinion and further politic decisions towards more sustainable technologies in many countries. One important aspect is to reduce the production of CO_2 gas. This has been impacting especially the transportation and car production sectors to wide extend. It is expected that car manufacturers will face multibillion fines in 2020/2021 for not reaching ambitious CO_2 goals set by the European Union. Such political decisions have made the development of alternative technologies extremely fast to reduce the CO_2 emissions of transport. Vehicles with New Energy Carriers (NECs) meaning vehicles using alternative energies as primary or secondary drive system are one of the results of this. NECs include different kinds of technologies but the currently most common are those based on some sort of electric drive concept (e.g. fully electric, hybrid oder fuel-cell vehicles) or gaseous-fuelled combustion engines (CNG, LNG, LPG, hydrogen), see Figure 1.

There are various expectations how different technologies and markets will develop. Nowadays, electric vehicles based on Lithium-Ion batteries (LIBs) are considered the primary solution for NECs. This can be fully electric (battery electric vehicle, BEV) or hybrid vehicles combining an internal combustion engine and an electric drive. Also hydrogen fuel cell electric vehicles (FCEV) utilise batteries, typically Lithium-Ion based, as energy storage system. In addition, the development of autonomous driving is proceeding. Fully autonomous operation is relatively complex to realise with a conventional combustion engine (ICE) drive compared to the electric motor. This also supports the development of different technologies using electric drives.

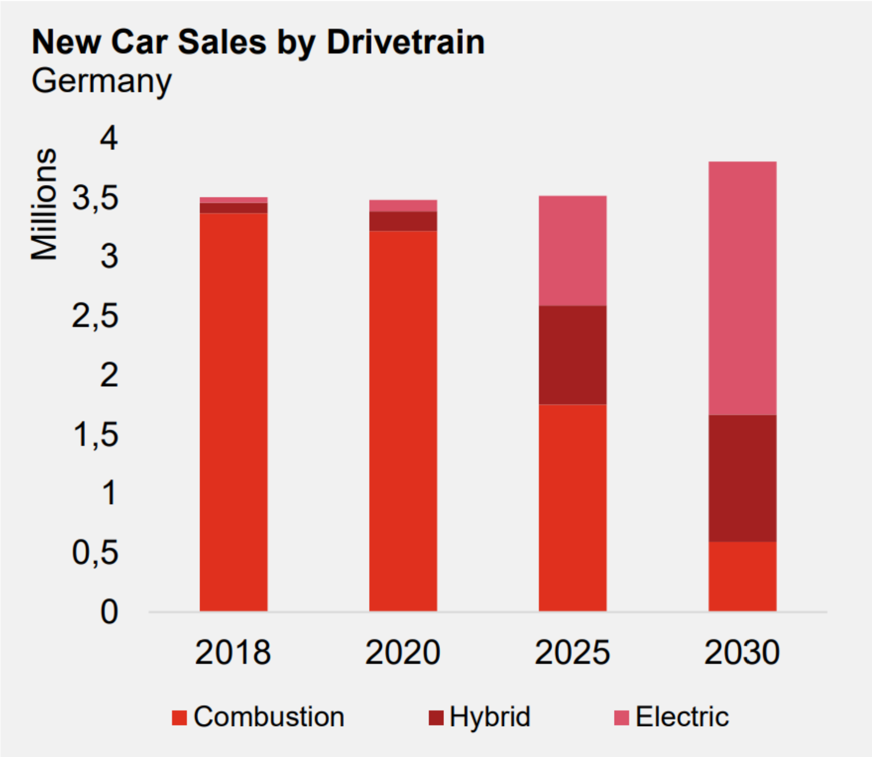


Figure 1 *Forecast of the number and the market share of combustion, hybrid and electric vehicles [1].*

As the NECs using fully or partially electric drives have become more common, their fire risks have to be evaluated. These are typically compared to the hazards of conventional ICEs, which have been the main technology for over a hundred of years. Electric vehicles have very different burning charasteristics which largely result from the Lithium-Ion batteries they are using. Vehicles with flammable gaseous fuels have also many diffrences compared to combustion engine vehicles. The fire engineering has definitely been much slower than the development of vehicles. The recent focus has also been a lot on the fuel and drive type instead of a holistic approach analysing how car size and materials have changed in general.

Current safety concepts and standards for planning and operation of different facilities, rescue concepts as well as firefighting measures are mainly based on the risks of conventional energy carriers, whereas NEC related risks are not taken into account so far. Underground facilities are especially vulnerable for fires since they form a confined space with limited volume. In that way, the effects of fire are maximising as well as challenging the fire fighting and rescue operations the most. According to the prognosis of the number of NEC vehicles increasing, a raise of fire incidents involving such vehicles needs to be considered. Up to now, some underground facilities, e.g. car parks or bus terminals in many countries, are designed following primarily prescriptive standards[1] not including additional risks of NECs or any other variables. Moreover, there is a lack of detailed knowledge concerning the NEC specific risks themselves. This all is covered by the SUVEREN research project that is presented in this paper.

RESEARCH PROJECT SUVEREN

The Federal Institute of Education and Research in Germany (BMBF) is funding the research project “Safety in Urban Underground Structures due to the Use of New Energy Carriers” – SUVEREN (Figure 2).

[1] Like the „Musterbauordnung“ and the “Muster-Garagenverordnung“ in Germany [2]

Figure 2 Logo of research project SUVEREN

The project focus is the evaluation of additional risks caused by the increasing numbers of NEC vehicles in underground facilities in Germany. The project also tries to develop experimental knowledge and design tools (also numeric) to derive suitable safety concepts that include the best practice.

SUVEREN focusses on the following underground facilities designed according to prescriptive standards and being considered as the most relevant in urban areas:

- Underground car parks/ confined parking spaces
- Bus terminals
- Bus depots
- Tunnels
- Delivery zones

In contrast to the current prescriptive design standards, especially in Germany, the research project SUVEREN develops tools and concepts for a performance-based design. In that way, the specific requirements arising by way of usage and occurring risks and hazards can be met with individual designs. The purpose is to develop design guidance reports to be used for different stakeholders like operators, designers and fire services.

The SUVEREN project has a total budget of 1.2 M€ and its duration is from 2017-2020. The project includes widespread working packages, covering literature studies about the status quo of NEC vehicles and suitable fixed firefighting systems, real world case studies, the modelling of NEC fire risks as well as the modifications of safety concepts, standards and education programs to address the NEC fire risks.

This paper focuses on two main elements that have been carried out in the project. One is a new design fire curve for passenger vehicles with all kinds of drives, ICEs and NECs. Secondly, preliminary results of the fire tests with LIBs are presented.

Passenger vehicle design fire curve

One fundamental element of performance-based design is a design fire curve. It is needed to describe the worst-credible fire risk in the specific facility being designed. The SUVEREN research project worked out a design fire curve for modern cars that can be used for designing underground or confined car parks. The design fire curve is needed for example in the evaluation of life safety aspects like evacuation as well as smoke management. The curve indicates the heat release rate (HRR) being the rate of energy released per time.

Commonly, design fire curves are used for the life safety design of road and rail tunnels where performance based design is applied. Those have been specified in various standards depending on country and legislation. Typically, heavy goods or dangerous goods vehicles are the basis for those design fire curves. Passenger vehicles have been studied and specified much less, especially in underground facilities where heavy vehicles provide much higher HRR. Facilities that only allow passenger vehicles are designed by presprective requirements and therefore the design fire curve has not been in the focus.

The main variables of the passenger vehicle design fire curve are the total energy content as well as the HRR. These are primarily influenced by the size of vehicle and the total amount of combustible materials. If the vehicle is using an internal combustion engine the material composition is different compared to, for example, the fully electric vehicle. Studies have shown that the average weight of cars has increased by more than 41 % or 400 kg between 1993 and 2007, see Figure 3. If this comparison was drawn with cars from the 80's the difference would be even higher. This is primarily caused by an increased size of the cars, but also a change in technologies. Modern cars often include safety systems and technologies that have not excisted 20 to 30 years ago. Also car materials have changed significantly in the last decades. Many light weight metallic alloys, composite materials, and plastics are used nowadays. Those are widely installed to replace metallic parts. Therefore, the passenger cars' weight should rather have been reduced than increased. However, this is compensated by the cars getting bigger in size and using more material overall. Moreover, many materials have changed from non-combustible to combustible.

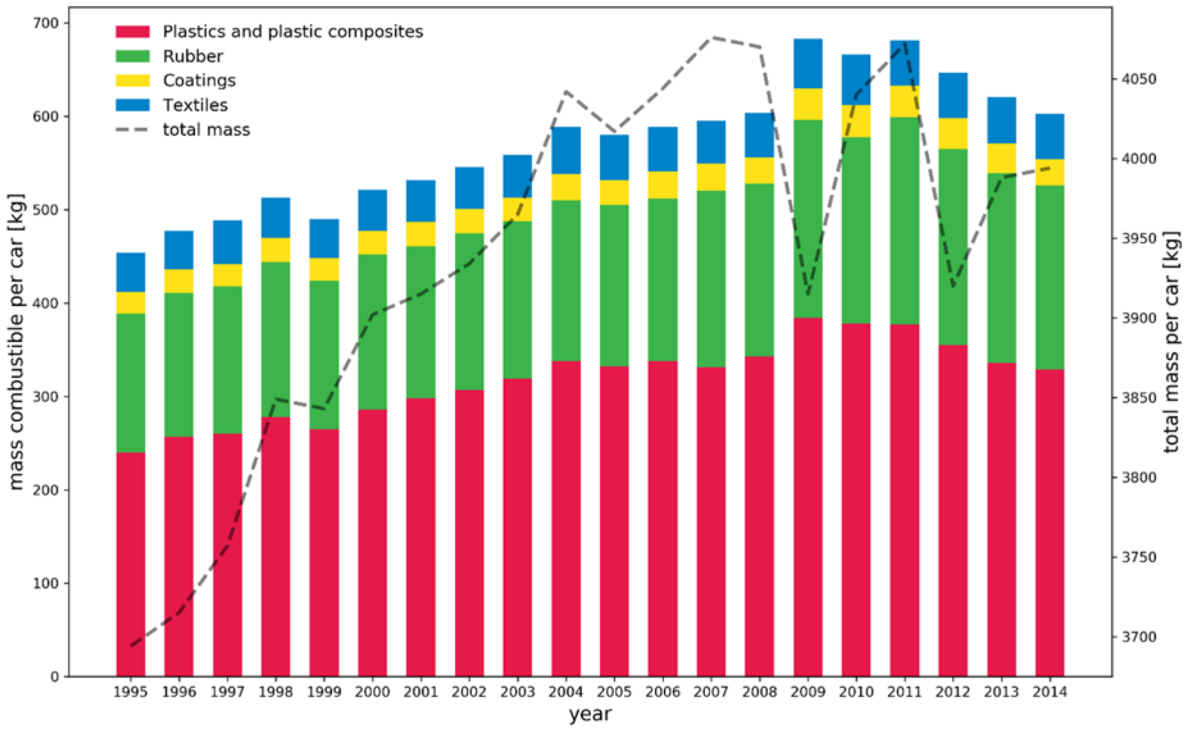


Figure 3 Development of total mass and mass of combustibles per car in the years 1995 to 2014 [3, 4]

The changed car design and material composition emphasises the importance of looking only to the fire test data of relatively modern vehicles when assessing the design fire curve. The second important fator is the car's drive type. ICEs can have different burning charasteristics than BEVs as Lithium-Ion batteries burn differently. However, there are also other parameters like ignition method, location, cause of fire (technical/external), opening of windows, battery charge level, fuel tank level, etc. that are influencing the fire development. Therefore, it is important to develop a realistic worst-case design curve that can be utilised for the performance-based design. A number of different fire test data with both ICEs and BEVs was selected as the reference data for the new design fire curve. These are shown in Figure 4. The detailed analysis revealed some differences between ICEs and BEVs but it has to be remembered that most of the combustible material in vehicles is the same. The analysis also included assessing the amount of combustible materials in modern vehicles based on [3] and [4].

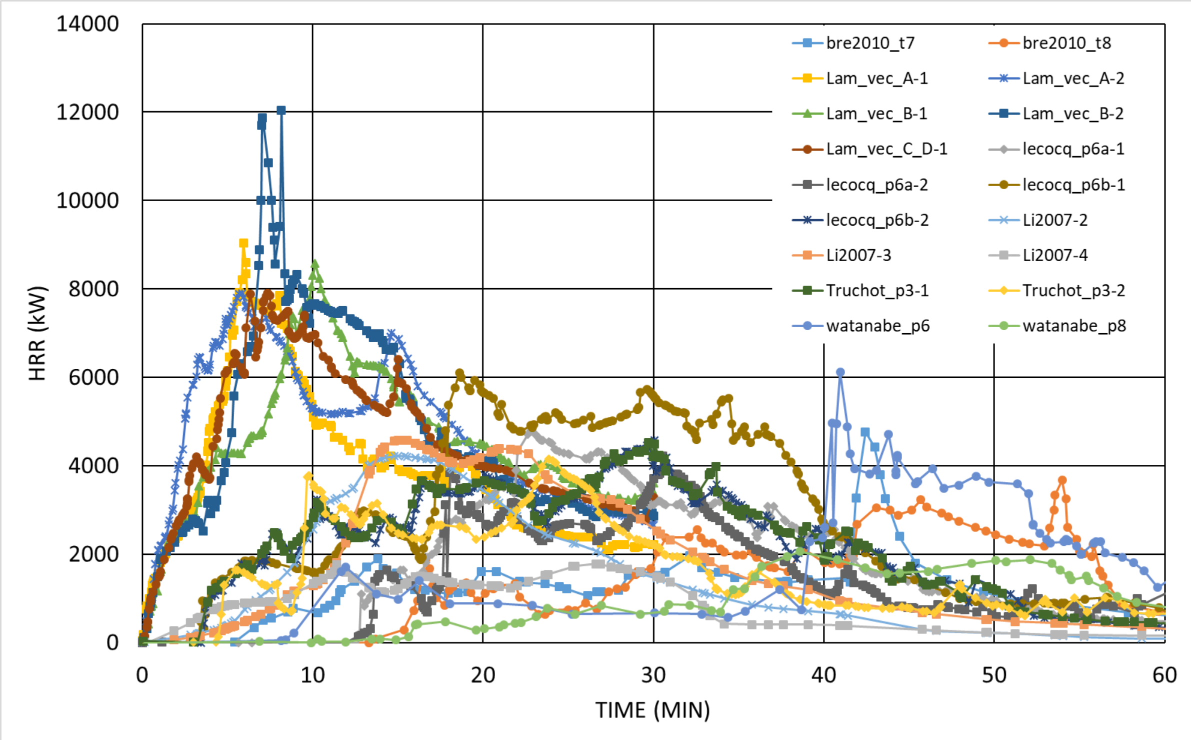


Figure 4 Collection of vehicle fire test data (HRR) with different ICE and battery vehicles based on literature studies [5, 6, 7, 8, 9, 10, 11]

Based on the fire test data as well as the combustible material analysis, the new design fire curve for passenger cars including all types (ICEs and NECs) was derived and is presented in the Figure 5. The curve is focusing to both realistic peak HRR value and fire development/duration. The basic assumption is that the vehicle should have a total energy content of 10 GJ for the design purposes. This is considered being a typical realistic passenger vehicle independent from the manufacturer, drive/fuel type or country related size preference. The fire growth rate in the beginning (marked with letter A) follows the NFPA and SFPE "fast" curve. The peak value of 7 MW is reached within 420 seconds. The peak value corresponds to a fully developed fire, lasting for 300 seconds (marked with letter B). The declining stage of the fire is a linear function (marked with letter C) and ends at 1980 seconds.

The equation describing the new design fire curve mathematically is given in Eq. (1).

$$\dot{Q}(t) = \begin{cases} 892857{,}14\ \mathrm{MW} * \left(\frac{t}{150\ \mathrm{s}}\right)^2 & ,\ \text{for } 0\ \mathrm{s} \leq t \leq 420\ \mathrm{s} \\ 7\ \mathrm{MW} & ,\ \text{for } 420\ \mathrm{s} < t \leq 720\ \mathrm{s} \\ -3535{,}354\ \frac{\mathrm{MW}}{\mathrm{s}} * t + 9545454{,}55\ \mathrm{MW} & ,\ \text{for } 720\ \mathrm{s} < t \leq 2700\ \mathrm{s} \end{cases} \quad (1)$$

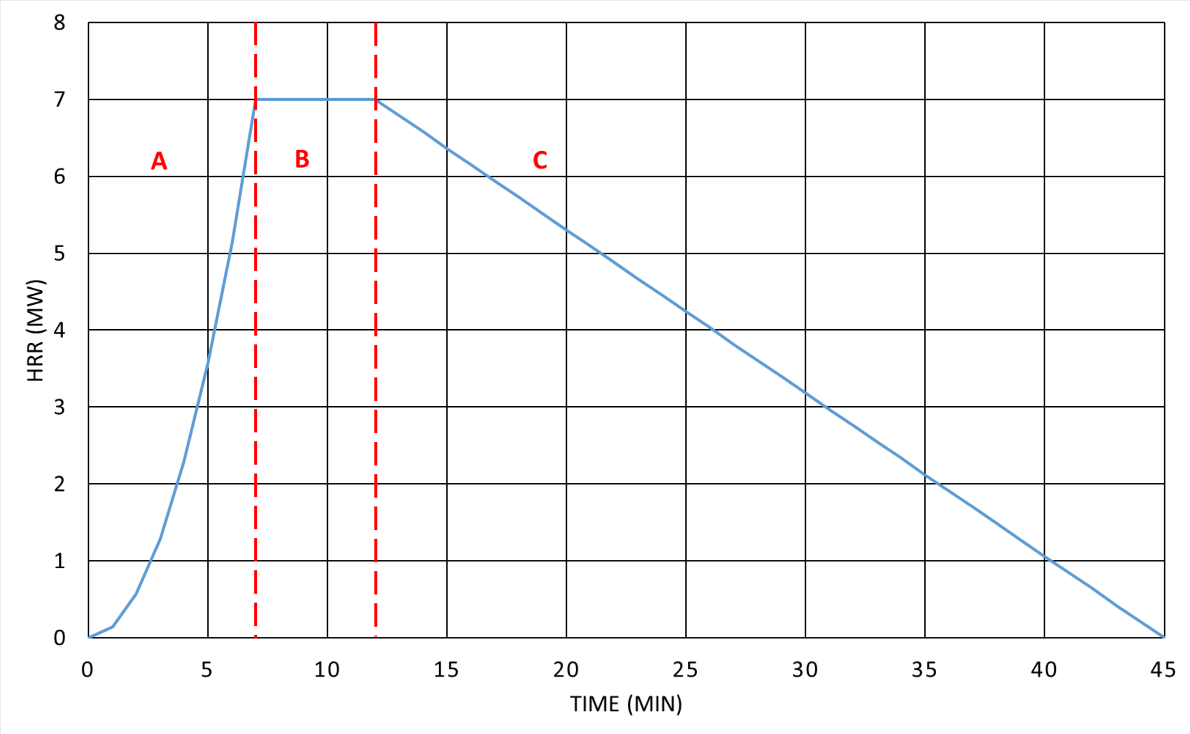


Figure 5 Design fire curve for ICE and electric vehicles

Figure 6 is displaying a comparison of the new design fire curve and the HRR data from selected reference fire tests. Over 90 % of the experimental data is covered by the new fire curve in terms of fire growth rate and maximum value. There are some peaks exceeding the chosen maximum but when considering the accuracy of HRR measurements and the duration of the peaks, the new design fire curve can be assessed as well conservative.

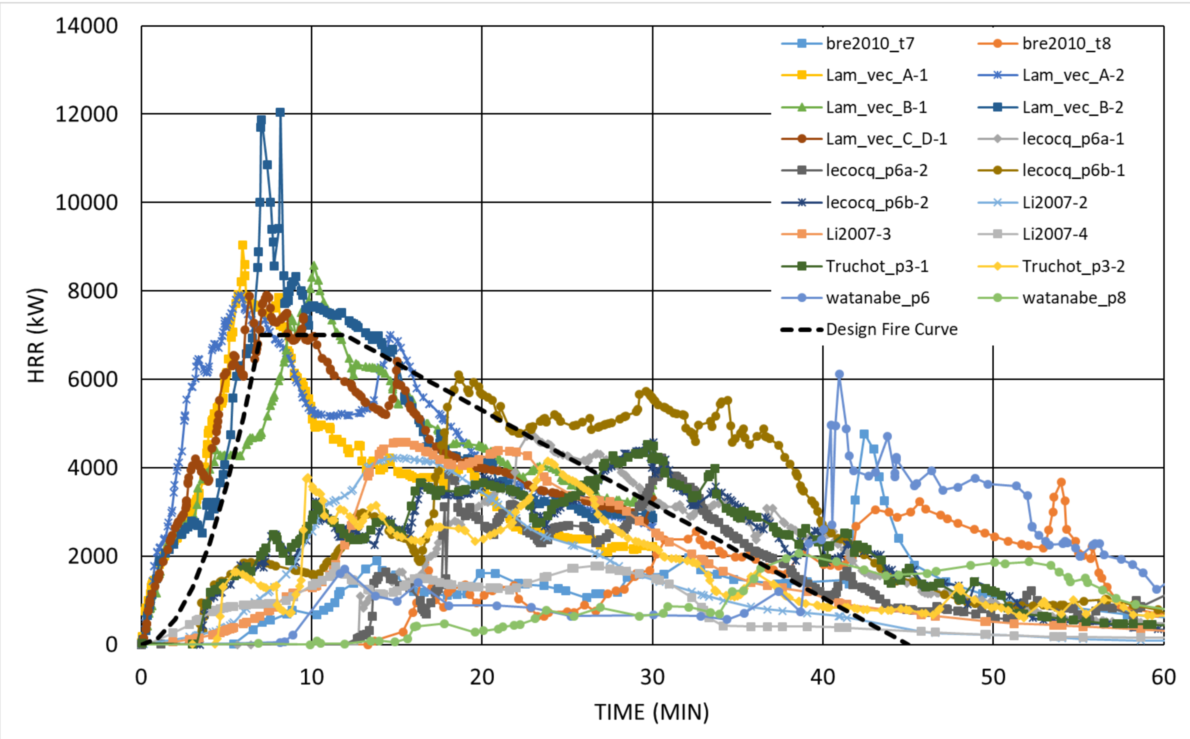


Figure 6 Comparison of new design fire curve and test data from literature

There are only very few references for design fire curves for passenger vehicles published in the literature. The most common one is NFPA502 [12]which only specifies the growth rate and the maximum value but neither the declining stage nor the duration of the fire. PIARC specifies two different generic curves for small and large vehicle fires [13]. However, these curves are rather new and not utilized within the industry as well as the scientific basis is not documented.

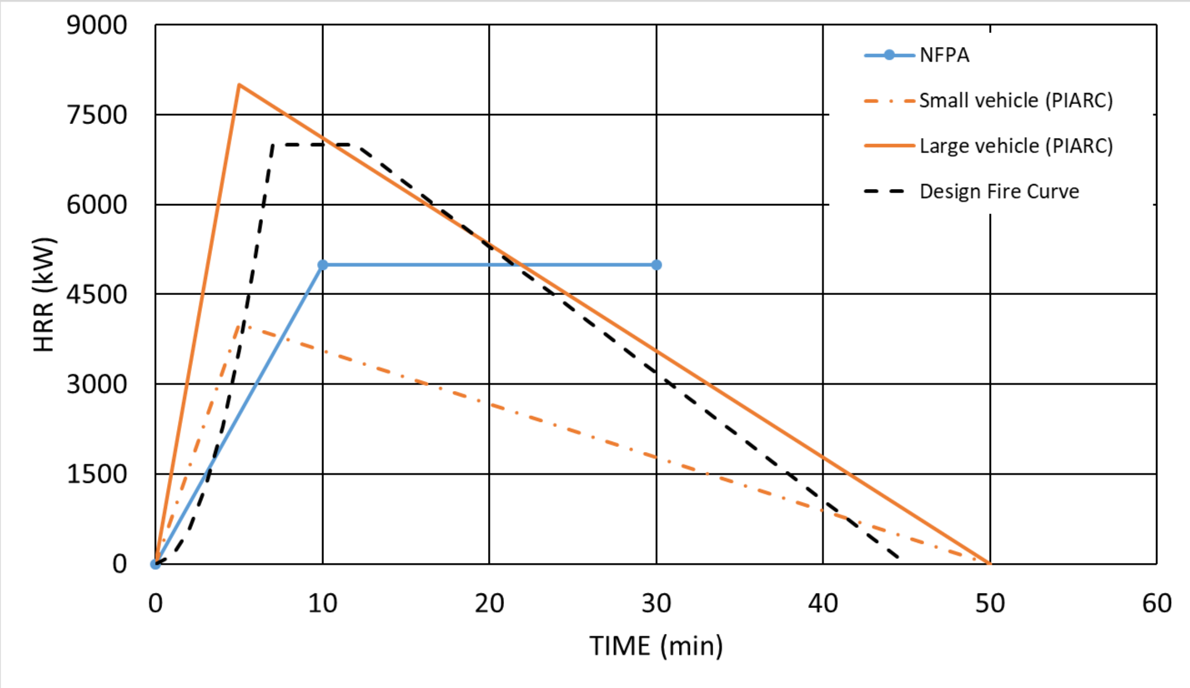


Figure 7 New design fire curve in comparison to design fires from other standards [12, 13]

Fire tests - Background

One of the major aims of the project SUVEREN were fire tests with NECs in order to gain knowledge and experience about their fire safety. Therefore, large-scale fire tests with batteries, gaseous and solid design fire loads were conducted in northern Germany between March and June 2019. Additionally, a separate fire test series comparing different detection and extinguishing technologies with LIBs was realised in December 2019 and January 2020. All fire tests were carried out by IFAB - Institute for Applied Fire Research GmbH.

Preliminary results of the first fire test series have also been published in [14].

Fire tests - Programs

The fire tests were performed in a test arrangement that was especially built for SUVEREN. The arrangement included an oxygen consumption calometry configuration (OCC), but also two other independent methods for measuring the HRR. The second one was related to scaling the mass loss of material and the third one was based on the energy balance by measuring temperature directly and indirectly inside the controlled test volume. In addition, the fire tests were recorded with two optical and two infrared cameras. Additionally to O_2, CO, CO_2 measurements, the FTIR (Fourier-transformed Infrared Spectroskopy) was applied to detect the different combustion products.

a) b)

Figure 8 Pictures a) and b) are showing impressions of measurement systems applied in the fire tests

In order to find efficient ways of fighting fires with NECs, e.g. retarding the thermal runaway within a battery, the calorimeter was equipped with a firefighting system (FFS). As fire tests in the past have shown that water mist was very efficient in cooling and reducing heat radiation in many cases, a high-pressure water mist system was used in the calorimeter during the first fire test series (later other technologies were assessed). Dependent on the test scenario, four or five single nozzles have been activated with an overall discharge rate between 40 and 80 l/min. Parts of the discharged water were collected and has been analysed chemically for dissolved elements. Moreover, linear and point-type smoke detectors as well as a smoke aspiration system were tested.

A German battery manufacturer provided two different types of LIBs for the fire tests: 30 kWh with prismatic cells and 40 kWh with cylindrical cells. Several methods of igniting the batteries were pre-tested in order to find a consistent way to get the thermal runway working. Overcharging and selective flame treatment did not ignite the battery or were not repeatable enough. The most convenient method of ignition was the mechanical penetration by a drilling machine that was used throughout the first series of fire tests.

In addition to the battery fire tests, other fire tests with a design fire load consisting of a mock-up loaded with 24 wooden pallets were conducted in order to gain reference data for the evaluation of numerical models developed within the project. The mock-up replicated a passenger car including roof and front lid with sheets of steel. The corresponding test stand (with two walls open) with the design fire load is shown in Figure 9. When examining these tests, the time of activation of the FFS was altered and the effect on the fire development was documented.

Figure 9 Calorimeter with vehicle mock-up and wooden design fire load

In gaseous-fuelled cars, the pressure vessels are equipped with pressure valves releasing overpressure to prevent the vessel from bursting. In combination with a fire, the gas emitted by the pressure valve is ignited and forms a jet flame. In order to simulate this case of fire event and to measure the effect of the FFS on the temperature distribution in the room, fire tests with a methane jet flame were conducted.

Moreover, during December 2019 and January 2020, additional fire tests with batteries have been examined. This time, various firefighting agents were tested in order to determine their performance in a battery fire. Therefore, the fire load was the same in all the tests. The agents tested include a sprinkler system, water mist (high- and low-pressure), F-500, foam, inert gases (CO_2 and N_2), NOVEC, and aerosol.

The test stand and the used measurement systems were similar to those used in the 1st test series in spring 2019. Nevertheless, there have been some modifications listed below.

1. The roof was built in a flat way in order to provide a more realistic scenario for the detection systems.
2. There was no artificial ventilation; therefore, the HRR can only be determined by mass loss rate/ energy balance
3. The walls of the calorimeter were equipped with reversible openings. In that way, the test stand could be used as a tight room as needed for gaseous firefighting agents or in an open way allowing passive ventilation.
4. Ignition was performed by overcharging. This time, the process could be optimised involving in repeatable results.

Fire tests – Preliminary results (24 kWh prismatic cells)

The results presented in the following are focussing on the battery fire tests conducted in spring 2019. Due to the tight time schedule, it was not possible to evaluate all the data from the fire tests but only give some examples. This applies also to the fire tests with different fire fighting systems in winter 2019/2020.

During the free-burn tests, the different battery cell types already showed a very different behaviour. When these different battery types were tested with FFS, the activation time was differing. In case of the cylindrical cells, the FFS was activated appx. 20 seconds after ignition. However, in the case of the prismatic cells the FFS was activated as soon as the thermal runaway was clearly propagating meaning the bursting of a second, third and fourth cell and the ignition of the emitted gases. Within this test, it was observed that the FFS extinguished the flames and interrupted the cells' reactions. A more detailed analysis of the tests including the activation of the FFS is still ongoing, but it is sure that it is not only the cell type but also the battery design and ignition location which is affecting the burning charasteristics.

The following figures show the results from one of the fire tests with the prismatic cells but without activating the FFS. The tested battery was reduced by two of the usually eight modules so that its energy content was 24 kWh with a state of charge (SOC) of 100 %. In this case, the battery was tested also with its plastic housing. Ignition was forced by mechanical penetration.

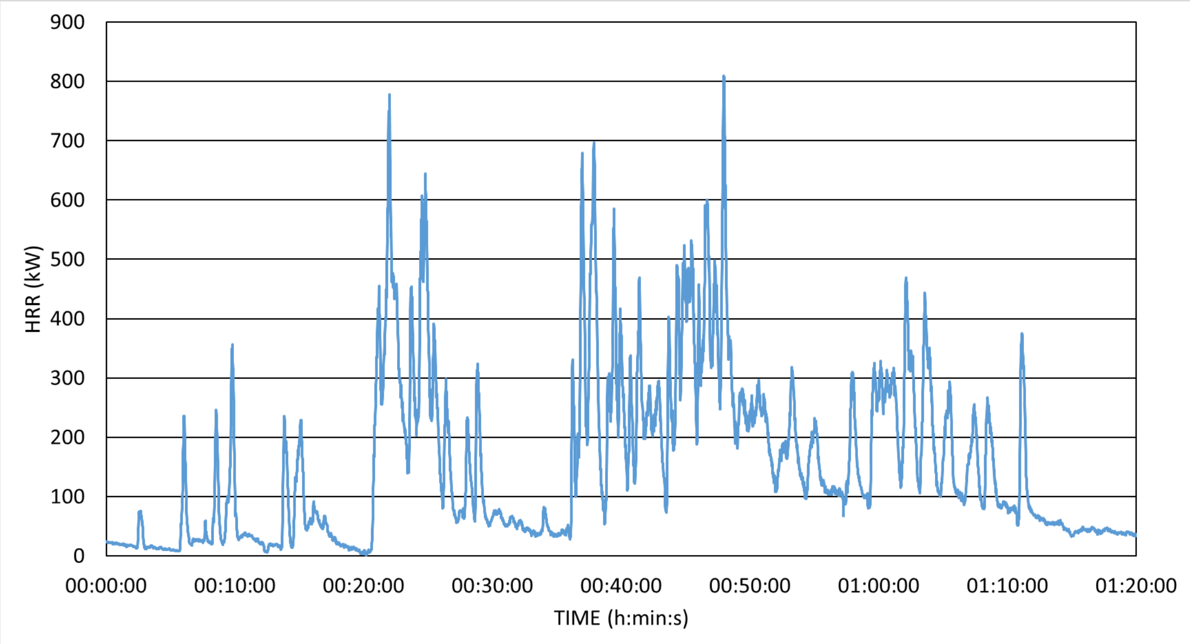


Figure 10 Heat Release Rate of 24 kWh battery pack determined by OCC

Figure 10 is showing the HRR determined by OCC after correcting it from temperature-dependent disturbance and differences in sensor latencies. Visual observations prove that the peaks in the HRR are caused by the cells bursting and releasing their gas. This gas release was seen as jet flames lasting for numerous seconds and being of appx. 30 cm in length. The duration of the whole reaction of the tested battery unit, meaning that the thermal runaway propagated to every single cell, was about 80 minutes in total. This highlights that fires with LIBs can take very long. Re-igntion was not analysed as the battery burned out completely.

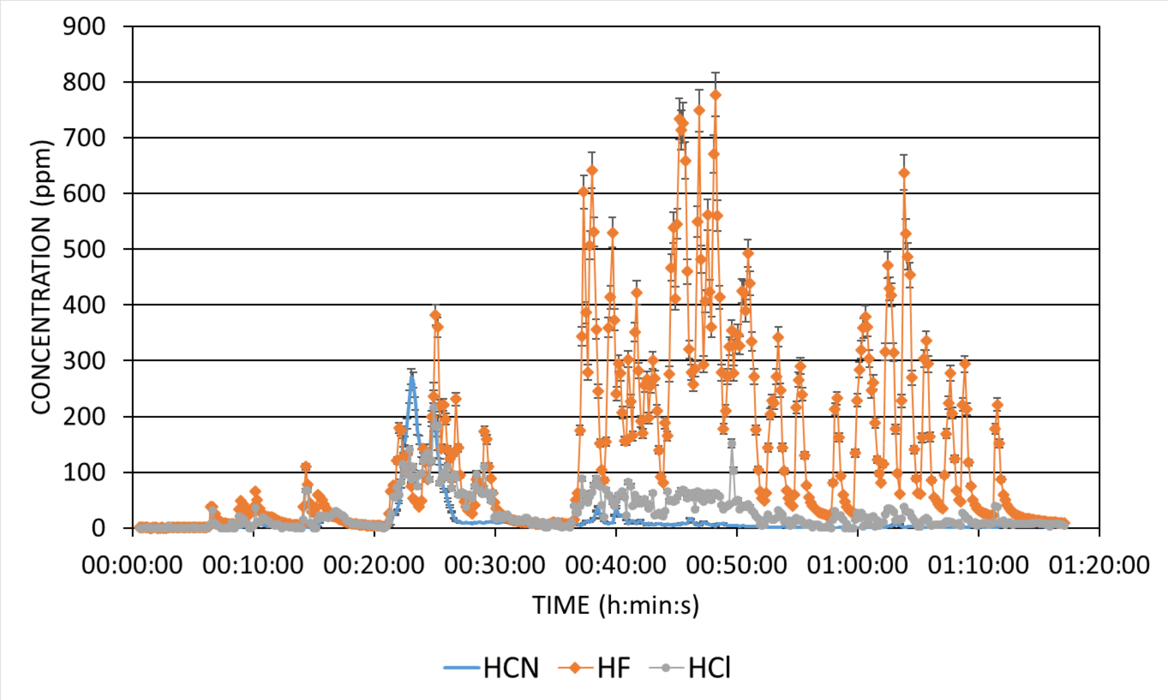


Figure 11 Gas concentrations of HCN, HF, and HCl measured during the 24 kWh battery fire test including error indicators.

Figure 11 is showing selected toxic gas concentratins (hydrogen cyanid, HCN, hydrogen fluoride, HF, and hydrogen chloride, HCl) measured with FTIR in the smoke exhaust. When evaluating the concentrations measured, it has to be considered that the calorimeter was heavily ventilated as HRR was measured. During this fire test, overall 8,325 m³ of air have passed the calorimeter. In that way, the gas concentrations were diluted. Due to this, the concentrations measured can be considered as even more critical when comparing, for example, the HF concentration measured to a threshold value of 500 ppm as given in [15]. Also for HCN and HCl, the concentrations need to be classified as critical for life safety.

Fire tests – Preliminary results (24 kWh prismatic cells with FFS)

In another fire test, the same battery set-up was tested with activated water mist. The water discharged was collected at three different places (on the scale next to battery, on the floor sidewards the battery and directly below the battery) and was analysed conforming to standards regarding dissolved substances. Table 1 gives the measured values respectively in brackets the factor with which the samples' values are deviating from the control sample. Especially for fluoride, cobalt, and manganese the values measured are heavily deviating from the control sample.

Table 1 Quantity of substances measured in the extinguishing water, in brackets factor compared to control sample meaning how many times higher it was compared to clean sample

Substance		Scale next to battery	Floor	Below battery
Fluoride	mg/l (-)	20.1 (104)	18.0 (89)	35.0 (174)
Cobalt	mg/l (-)	48.0 (639)	22.1 (294)	20.8 (276)
Nickel	mg/l (-)	47.9 (162)	26.9 (90)	24.6 (82)
Manganese	mg/l (-)	43.0 (433)	22.0 (221)	26.0 (262)

The fire tests showed that the thermal runaway of the batteries with prismatic cells was propagating more slowly and regularly than the thermal runaway of the cylindrical batteries. These differences caused by differences in the construction of the cells indicates that the passive fire safety of a battery has a major impact.
In all the fire tests involving the activation of the FFS and under the given conditions, the propagation

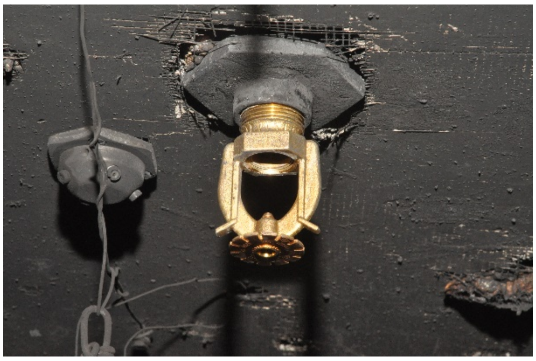
of the thermal runaway to adjacent modules could be interrupted and the surrounding was cooled effectively.

Fire tests – Comparison of different firefighting systems

In a second fire test series, different firefighting agents were compared regarding their performance in battery fires. This included the following agents:

- High-pressure water mist with different droplet sizes
- Low-pressure water mist
- Sprinkler
- F-500
- Foam
- N_2
- CO_2
- NOVEC
- Aerosol

As explained before, the fire load was the same in all the test. This time, two modules with cylindrical cells were used resulting in an electrical energy content of 5 kWh. First of all, two free-burn tests have been conducted. One in the test room being closed, the other one with the test room open. In that way, the different agents can be tested under conditions the application requires and their performance can be compared to the corresponding free-burn test.
Unfortunately, the time between this fire test series and the publication of the present paper has been too short to analyse the data. Nevertheless, Figure 12 shows pictures of the different firefighting systems tested.



a)

b)

c)

Figure 12 Photos of different parts of the systems used in the second fire test series: a) sprinkler head, b) different detection systems installed, c) nozzle for gaseous agents.

CONCLUSIONS AND PRELIMINARY ANALYSIS

All studies in mobility show that the numbers of NEC vehicles will increase within the next years. Currently, the main focus has especially been on vehicles utilizing traction batteries as energy storage system – either as primary or secondary energy storage. New vehicle types have given considerations on other fields of engineering, and fire engineering is one of those. The German research project SUVEREN studies the fire risks of NEC vehicles, particulary in underground facilities. The project’s scope is very wide; its aim is to develop knowledge, tools and guidance for designing underground structures. By March 2020, the project is still ongoing, yet a lot of research has already been done. This paper shows a newly developed design fire curve for all kinds of passenger cars that designers can use in performance-based design. Previously, the vehicles' size or traction energy type was not well assessed with old design curves. Moreover, the present paper describes some example fire tests with different batteries. Unfortunately, the results could not be analysed completely, but a final assessment and report are to come by the end of 2020. However, the research done so far within the project with experimental fire tests has shown the following preliminary findings:

- The type of cells (prismatic, pouch, or cylindrical) used has a major impact on the burning behaviour of the battery.
- The battery module casing design and construction material can enhance or limit fire propagation.
- Even without ignition of the off-gas, the energy released was high enough to propagate the thermal runaway to the whole module.
- The propagation of the thermal runaway on module level could be interrupted by fire fighting agents, e.g. water mist.
- Conventional detection systems were able to detect the failure of the battery once the first cell bursted.
- The concentrations of toxic and corrosive gases released exceeded common standard thresholds.
- HRR measurement of battery fires is challenging and three different methods were tested simultaneously in order to find the most suitable one.

According to the current state of knowledge, the life safety level in modern road tunnels can be considered as high enough even for the new risks arised by passenger cars with NECs. The transportation of LIBs or several passenger cars on a truck can imply a different scenario though. In contrast, for other underground facilities like car parks or bus terminals, the NEC specific risks can create risks that did not exist in the same extent with conventional vehicles. This refers to both life safety as well as the safety of fire services, who always have major differences when NECs are involved. Research has shown that LIBs can produce very aggressive gases in higher concentrations that may endanger the safety of fire services. The preliminary fire test results could not confirm that, nonetheless a release of corrosive gases was recorded. However, the results were not as significant as in some other previous research. The preliminary analysis of the results has confirmed that NEC vehilces, also LIB driven ones, create new risks that need to be assessed in any case.
One approach to overcome these increased risks is the application of performace-based design.

Further analysis and the final results will be published on www.suveren-nec.info.

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