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Risk minimisation of electric vehicle fires in underground traffic infrastructures

Risikominimierung von Elektrofahrzeugbränden in unterirdischen Verkehrsinfrastrukturen

Minimisation des risques d'incendie de véhicules électriques dans les infrastructures de circulation souterraine

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Legal notice

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Table of contents

Summary

Electric vehicle fires with lithium-ion batteries lead to new types of pollutant emissions. The present study shows that this changes the toxicological risks in underground traffic infrastructures because these pollutants do not occur in fires of conventional vehicles. These battery specific contaminations will not impair technical operations in underground car parks or road tunnels; but they will make a careful handling of firefighting and cooling water essential.

The experimental findings were derived using a systematic approach based on scientific principles. The experiment was carried out in the underground facilities of VersuchsStollen Hagerbach AG, which provide a real environment for fire tests related to both underground car parks and road tunnels. Since the present study is based on the experiments of a previous project from 2018, the same test material was used: The experiment focused on maximum damaging a lithium-ion battery (type NMC) used in a battery electric vehicle approved for traffic (status 2019). The analysis of fire residues and their impact on infrastructures was the main focus. Neither fire or crash tests were conducted with full electric vehicles nor were there any analyses on the probability of such damages.

The hypothesis that the emissions from electric vehicle fires in underground traffic infrastructures lead to lasting effects cannot be confirmed. The study concludes that a technical impairment of typical infrastructure components in underground car parks and road tunnels can be practically excluded. However, the battery specific emissions will lead to contamination which is of toxicological importance especially for decontamination and disposal works. Based on the findings, six risk-reducing measures can be derived, which are primarily of an organisational nature; two of them are urgent.

Firefighting and cooling water resulting from an electric vehicle fire is highly contaminated. Since the concentrations of lithium and the heavy metals cobalt, nickel and manganese exceed current thresholds for discharge into the sewerage system many times over, appropriate pre-treatment must be implemented in practice. The application of the current principles for NBC operations is sufficient for this purpose. Regarding the cooling water which is typically produced in the after-treatment of damaged batteries, a standardised handling needs to be defined. The other recommendations include additional preventive measures that allow an appropriate handling of the changing risk landscape.

Concerning electric mobility in underground infrastructures, two aspects are in the foreground that should be investigated in greater depth: (I) The effectiveness of high-pressure water mist systems, which are used internationally, especially under the argument of new energy carriers. Since these systems are hardly or not at all used in underground infrastructures in Switzerland, they should be reassessed in the course of the increasing use of lithium-ion storage systems. (II) On the other hand, the risks of fuel cell electric vehicles, especially in the case of heavy goods vehicles in underground infrastructures, are still not clear. A risk assessment with experimental methods seems to be recommendable.

Lithium-ion storage systems lead to changed risks, not only in mobile applications. Stationary storage systems of buildings are based on the same technology and are increasingly installed in basements where the operational and safety situation is similar. The specific risks, particularly the potential severity, are largely unclear and should also be investigated experimentally.

1 Introduction

1.1 Changed fire hazards due to electric vehicles

In 2018, the research project ‘Electric mobility and road tunnel safety – hazards of electric vehicle fires’ ([59]) furnished experimental proof that burning electric vehicle batteries change the chemical hazard situation in underground traffic infrastructures.

Several experiments showed that severe mechanical and thermal damage to the lithium-ion batteries of an electric vehicle instantly lead to uncontrollable fires with high energy expenditure, strong smoke generation and new pollutant emissions. The study concluded that the thermal fire hazards of electric vehicles are comparable to those of conventional vehicles. However, given an immediate vicinity to the fire and unfavourable ventilation conditions, electric vehicle fires lead to new, potentially more severe chemical hazards. The pollutant analyses indicated critical concentrations of the heavy metals cobalt, nickel and manganese as well as lithium in the form of aerosols. The emitted metal dust exceeded maximum concentration values above which an exposed person will suffer severe or permanent damage after 30 minutes (*immediately dangerous to life or health*, IDLH). These pollutants do not occur at the same high levels in conventional vehicle fires and are toxic both to humans and the environment ([10]).

By contrast, the blanket hypothesis that high-capacity traction batteries in electric vehicles would increase fire hazards in road tunnels overall was not confirmed. The experimental findings suggested the conclusion that the chemical energy storage of typical electric vehicles in the form of lithium-ion batteries does not result in an escalation per se, but instead in a changed hazard situation inside road tunnels. To facilitate classification, the state of knowledge to date can be summarised according to the essential questions in Table1.

***Table1** Changes due to electric vehicle fires: findings to date ([59])*

Aspect	**Conclusion**
Does this result in changed thermal hazards inside the road tunnel?	No.
Do the chemical hazards change with potential effects on humans?	Yes, in the immediate vicinity of the fire or in unfavourable ventilation conditions.
Do the chemical hazards change with potential effects on the environment?	Yes, with regard to possible contaminants.
Does this result in a need for technical adaptation in road tunnels?	No.
Does this change the incident response with regard to firefighting?	No, regarding the selection of extinguishing agents or tactical approaches. Yes, regarding new potential dangers when firefighting.
Does this change the incident response with regard to safety measures and protective equipment for emergency personnel?	No, provided that they correspond to the current state of the art.

1.2 Project hypothesis and objectives

As it can be assumed that the existing safety and safety operating equipment in road tunnels is sufficient to combat these changed hazards (in terms of detection, ventilation, water supply, etc.), no technical adaptations were recommended. However, no conclusive answers have been found to date regarding the possible effects and long-term consequences of the emissions of electric vehicle fires in road tunnels, and particularly in small underground traffic infrastructures.

After being emitted, the metal dust that is toxic to humans and the environment spreads in the surrounding area and will not react to exhaustion after deposition. It therefore had to be assumed that, in unfavourable cases, this new type of pollutant could lead to large-scale contamination and thus to long-term adverse effects on operation, infrastructure safety and the environment. Current studies from Germany also indicate this problem (cf. [49]), but there are currently no recommendations of suitable measures for preventing and minimising such damage.

Questions and hypothesis

Taking this current state of knowledge into consideration, the following questions can be discussed with regard to pollution caused by electric vehicle fires in tunnels, multi-storey car parks or garages:

- To what extent do emissions caused by electric vehicle fires in underground infrastructures result in contamination that differs from that of conventional vehicle fires?
- Are special measures necessary to handle contaminated components, technical facilities and firefighting water after electric vehicle fires?
- Does this result in long-term effects on the operation and safety of underground infrastructures?

To fill these knowledge gaps, subsequent tests were initiated with the support of FEDRO and the French Centre d’études des tunnels (CETU). The present research project investigated whether the specific hazards of electric vehicle fires have a long-term effect on the operation and safety of underground traffic infrastructures. Experiments conducted together with the Swiss Federal Laboratories for Materials Science and Technology (Empa) and VersuchsStollen Hagerbach AG (VSH) aimed to derive measures that contribute to minimising risks in the event of electric vehicle fires (i.e. to prevent and minimise potential damage). The project was based on the following hypothesis, which was to be conclusively proven or disproven through specific experiments.

> **‘Electric vehicle fire emissions in underground traffic infrastructures cause contamination with long-term effects on operation and safety’**

The research project focused exclusively on passenger vehicles powered purely by electric battery (*battery electric vehicles*, BEV); the effects of fires caused by electrically powered commercial vehicles or hybrid vehicles were not investigated.

Availability and safety of underground traffic infrastructures

Available and safe underground infrastructures are becoming ever more important in view of increasing electric mobility and the trend towards relocating traffic in urbanised areas underground. A large part of future individual traffic in cities will be electrified and take place underground, either by driving through tunnels or parking and charging in car parks. As long as the potential effects of electric vehicle fires on the operation of these traffic infrastructures remain unknown, they present a risk for operators that is difficult to predict. Unavailabilities due to complex decontamination measures or improper handling of residues after a fire can significantly impact both the operation and the safety of infrastructures.

Therefore, the above hypothesis was formulated to focus on this problem across infrastructures, and it illustrates that this research project covers not only road tunnels but all underground traffic infrastructures within the sphere of electric mobility. To conclusively verify the hypothesis, the research approach needed to be accordingly comprehensive and to take central aspects of underground infrastructure operating safety into consideration.

State-of-the-art technology and worst-case approach

Although decades of development have produced several technologies and variants, automobile manufacturers currently use mainly lithium-ion batteries as rechargeable electrochemical storage devices for electric vehicles – and will likely continue to do so in future (cf. [19]; [22]; [23]; [50]; [93]). Essentially, the aim was to experimentally analyse the battery-specific pollutant contamination of a typical electric vehicle (as of 2019) with a high-capacity lithium-ion battery and to derive suitable measures to minimise risk in underground traffic infrastructures. The project's main focus was on the already measured heavy metal aerosols cobalt, nickel and manganese, as well as on lithium and fluoride compounds. The project aimed to reach the following objectives:

1. **Experimental analysis** of possible pollutant contamination due to electric vehicle fires using significant fire tests and measurements

2. Deduction of the **effects on underground traffic infrastructures** in the sphere of electric mobility (tunnels, multi-storey car parks, garages, etc.)

3. Formulation of appropriate technical and organisational **measures for damage prevention and mitigation**

1.3 Report structure

The following report is divided into five consecutive parts that also act as the framework for the entire project. Section 2 initially covers the theoretical fundamentals of battery-specific fire emissions as well as the risks in underground traffic infrastructures so that the considerations of the following chapters can be better understood. These fundamentals also give a theoretical overview of the potential hazards arising from electric vehicle fires as well as the applicable standards and directives for safety equipment in underground traffic infrastructures.

Section 3 is the methodical part that covers the approach during the experiment. It gives a detailed explanation of the necessary preparations and concepts, as well as differentiations, in order to create a comprehensible basis for the later description and discussion of the results.

Section 4 documents the results of all tests carried out during the experiment. It describes each test individually, ending with a short assessment, but no interpretation.

Section 5 correlates the experiment's various findings and reflects on them in the overall context of increasing electric mobility in underground traffic infrastructures. To facilitate classification, the most important findings are discussed on the basis of several essential questions and the validity of the underlying hypothesis is examined.

To conclude, Section 6 is an outlook on the need for further research.

2 Fundamentals

All vehicles powered by electricity are considered electric vehicles [42] irrespective of the degree of electrification: hybrid and fuel cell electric vehicles are also, per definition, electric vehicles ([42]; [83]). However, when the general term ‘electric vehicle’ is used in the present project, this refers only to passenger vehicles for road traffic, even though the term actually covers all electrified vehicles, including rail vehicles and bicycles powered by electricity.

Electric vehicles that use only a rechargeable battery (or ‘traction battery’) for energy storage are called battery electric vehicles (BEVs); internal combustion engine vehicles (ICEVs) are all referred to as ‘conventional vehicles’ for the sake of convenience. The central comparisons made in this report are between BEVs and ICEVs.

Table 2 *Definition of various vehicle types (acc. to [7] and [43])*

Vehicle type	Abbreviation	Definition
‘Conventional’ internal combustion engine vehicle	ICEV	Vehicle powered by internal combustion engine
Battery electric vehicle	BEV	Vehicle powered by electric motor; battery can be charged from the mains
Fuel cell hybrid electric vehicle	FCHEV	Vehicle powered by electric motor plus fuel cell to generate power
Range extended electric vehicle	REEV	Electric vehicle with additional internal combustion engine or fuel cell for mobile charging of the battery (actually a hybrid, as it has 2 energy converters and 2 power sources)
Hybrid electric vehicle	HEV	Vehicle powered by internal combustion engine plus electric motor; battery cannot be charged from the mains
Plug-in hybrid electric vehicle	PHEV	Combination of electric power system and internal combustion engine, battery can be charged from the mains

2.1 Energy storage for electric vehicles

To best ensure the availability of electric power as needed, energy is stored in electric vehicles with rechargeable batteries ([84]). Major vehicle characteristics such as performance or range depend directly on the battery, which is why it takes on the role of a central component and is often described as the key technology for electric mobility ([41]; [46]). Therefore, there have always been numerous requirements that the traction battery of an electric vehicle must fulfil in particular ([51]).

Despite decades of developments and technological optimisation, lithium-ion batteries are practically the only type of rechargeable electro-chemical storage method in use ([60]; also cf. Figure 1). The reason for this is the whole range of positive characteristics that these batteries offer, ranging from high cell voltage, performance and energy density, as well as low susceptibility to temperature and self-discharge, to high cycle stability. These characteristics provide fundamental benefits particularly for the field of electric mobility ([13]; [43]). As few comparable storage technologies are market-ready to date, lithium-ion batteries will continue to play an important role in the future of electric mobility in the medium term ([19]; [22]; [23]; [93]).

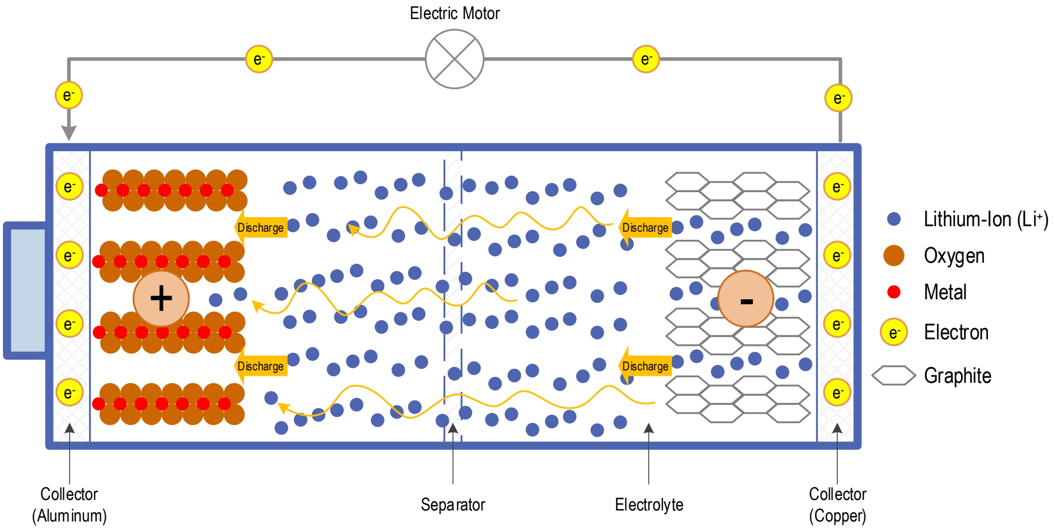


Figure 1 Schematic construction of a lithium-ion battery (own depiction based on [20]; [22]; [43]; [94])

This storage technology has been tried and tested over many years and has undergone rapid developments since its commercial market launch in 1991, also with regard to safety. Lithium-ion batteries are systematically tested for function and safety during production, before they are approved as traction batteries ([17]; [61]; [62]). During battery use, safety is additionally ensured by further chemical, mechanical and electrical protective measures and is functionally monitored by a superordinate battery management system ([18]; [33]; [44]; [87]). Lithium-ion batteries can therefore be regarded as very reliable ([45]).

Battery research focuses primarily on the optimisation of cell chemistry in order to continuously improve energy density and service life as well as safety. A wide range of promising materials can be used for this purpose. As all of them have their own chemical or economic disadvantages, the aim is to achieve the best possible variant with suitable material combinations and substitutions. Several types of lithium-ion batteries are currently available on the market. These differ mainly in the chemical composition of their active cathode material ([37]; [56]). The most common variants of the required lithium metal oxide at the positive electrode are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP) ([64]). It is important to emphasise that all variants are ultimately compromises that include economic and performance-specific, but also safety-related considerations ([89]).

However, the NMC type is currently mainly used in the concrete application of electric vehicles, as batteries with this cathode material ideally combine the advantages of other technologies and are considered to be very reliable. With NMC batteries, high energy densities, good high-current capabilities, overcharge stability and price advantages can thus be combined into the best possible overall solution. They also offer a high average discharge voltage and can be charged relatively quickly ([81]; [89]).

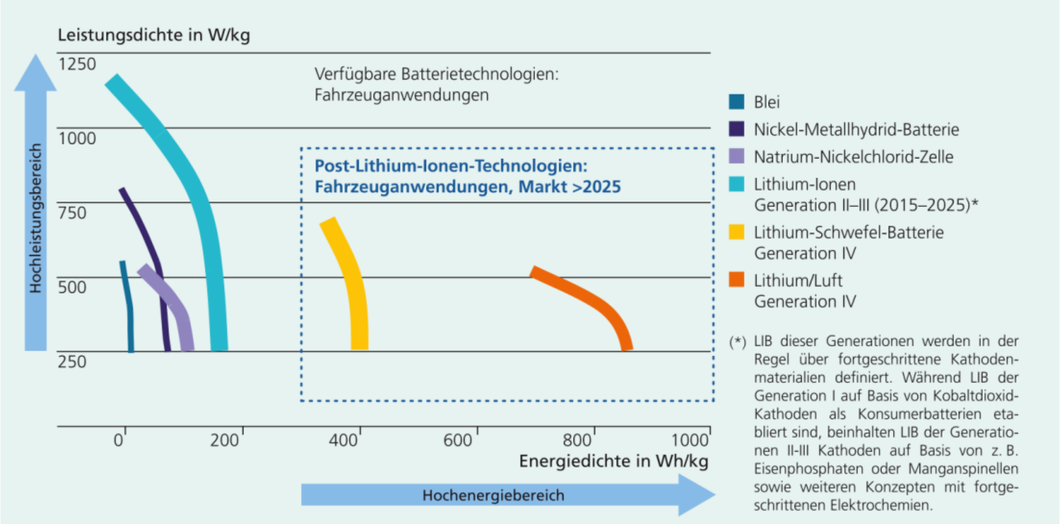


Figure 2 Energy and power density of current and future battery technologies ([80])

2.2 Specific fire emissions

Battery fires

Under normal operating conditions and provided that the system has no manufacturing defects, lithium-ion battery systems are designed to be adequately protected against spontaneous combustion (cf. [72]; [73]). As a rule, the batteries of an electric vehicle will not combust without a previous stress event.

However, due to their high energy content, high voltages and, above all, highly reactive components, lithium-ion batteries nevertheless pose potential fire hazards with adverse health effects, which have been very well researched. For example, it is known that the non-aqueous, organic electrolyte solution and the graphite in the active anode material are combustible ([14]; [22]). When exposed to a mechanical, thermal or electrical event, a battery can suddenly be overstressed and a self-amplifying reaction can be triggered ([68]). During this thermal runaway, the battery independently heats up through chemical processes, i.e. without external thermal influence, and also very quickly (>10°C/min, [94]). In doing so, it leaves its stable operating range and the materials begin to decompose exothermically, resulting in a battery fire with a very high energy release. Such battery fires cannot be extinguished in the conventional sense ([34]) for reasons of battery chemistry (the required oxygen is released by the burning cathode material itself), and instead can only be cooled.

Potential fire emissions and hazards

A material analysis of current battery systems shows that fluorine and organic components occur in the electrolyte in addition to lithium and the heavy metals in the cathode material ([39]). These substances can pose a significant risk to humans and the environment if they are released as dust or in gaseous form in the event of fire. Studies to date show that, apart from conventional fire emissions (e.g. CO, CO_2, cf. [16]; [55]), particular attention should be paid to these additional toxic and in part carcinogenic substances, for example the fluorine phosphate salts in the electrolyte, which are non-combustible but are hazardous to health ([53]; [54]; [63]). Pollutant emissions of a lithium-ion battery fire that differ from those of a petrol or diesel fire are listed in Table 3.

***Table 3** Decomposition products occurring during a lithium-ion battery fire*

Substance	**Formula**	**Description (acc. to [25] inter alia)**
Hydrogen fluoride	HF	colourless gas with a biting odour, highly toxic
Phosphoryl fluoride	POF_3	colourless gas with a biting odour, toxicity not defined ([53])
Phosphoric acid	H_3PO_4	colourless, odourless solid or liquid, toxic
Volatile organic compounds	VOC	carbonic substances, typically gaseous
Phosphine	PH_3	flammable, toxic, colourless and odourless gas, highly toxic
Heavy metal aerosols	Co, Ni, Mn	Dusty residue in the air, highly toxic

As a rule, lithium-ion batteries are sealed in a gas-tight manner, preventing the egress of constituents from and ingress of outside materials into the batteries during normal operation. This precautionary measure is especially important with regard to water, as the batteries contain elementary lithium which exhibits a strong exothermal reaction to form hydrogen and lithium hydroxide when it comes into contact with water. The resulting hydrogen H_2 is explosive under atmospheric pressure given a percentage by volume between 4 and 77% (oxyhydrogen). This very wide range of flammable mixture ratios is what makes hydrogen so dangerous, particularly in underground infrastructures. Fire brigades must take this problem into account in particular, as water is still recommended as the best firefighting measure for non-extinguishable lithium-ion battery fires ([27]; [74]). These potential emissions, as well as hazards posed by lithium-ion batteries in underground infrastructures, can be derived from the chemical constituents of the batteries and are now sufficiently known to the emergency personnel concerned.

Some studies have determined the composition and volume of the partly flammable gases produced by the thermal runaway of commercial battery cell types (e.g. NMC, LCO, LFP, LMO) ([85]; [36]; [71]). These studies found concentrations of 5-30% of H_2, 5-30% of CO, 20-50% of CO_2 and 0.1-9% of various hydrocarbons (methane, ethene, propene, ethane, butene, propane, butane). The comprehensive report of the Research Centre for Fire Protection Technology of the Karlsruhe Institute of Technology (*Karlsruher Institut für Technologie,* KIT, [48]) describes the various compositions of lithium-ion batteries and theoretically possible chemical reactions during thermal runaway. A fire test with a lithium-ion vehicle battery (not further specified) found irritant, toxic, polycyclic aromatic hydrocarbons (PAHs) which are environmental and water pollutants, as well as, in part, toxic concentrations of heavy metals. Dioxins, furans and phosgene were not detected. A substantial proportion of the literature only refers to the analysis of the chemical decomposition during the combustion of the electrolyte, the conducting salt $LiPF_6$ or a combination thereof ([15]; [24]; [47]; [58]). In [24], a quantity of 18 to 60 mg of HF per gram of electrolyte mixture is specified for the combustion of electrolyte mixtures with conducting salts consisting of $LiPF_6$ and LiFSI. During the combustion of complete lithium-ion battery systems of the types LCO, LFP and NCA, quantities of 10 to 200 g of HF per Wh of battery capacity were determined in [52]; [70] specifies 36 to 68 mg of HF per Wh for an LMO pouch cell of 2.9Ah/11Wh. [78] shows a relative comparison of the quantities of HF and POx during the combustion of commercial 18650 cells (LMO, NMC, LFP) and finds a large number of acutely toxic substances, although no quantities are given.

We can therefore conclude that the potential fire emissions of lithium-ion battery fires are generally known. However, due to the wide variance of findings, it is currently unclear whether electric vehicle fires in underground infrastructures represent a long-term impairment of operational safety. This is also the reason why there are no uniform recommendations to date regarding technical or organisational measures to prevent and mitigate the damage caused by such events.

2.3 Risks in underground traffic infrastructures

Due to the changing drive types and the increased use of high-capacity lithium-ion batteries in road vehicles, the safety risk will presumably also change over time. Here, a particular focus is placed on closed and underground traffic infrastructures, which are often characterised by limited options for ventilation and rescue. The reactive and, in part, highly toxic substances primarily cause the chemical hazards to change in closed infrastructures, which can result in various changed risks ([59]). However, the possible effects and long-term consequences of a traction battery fire have still not been conclusively determined.

Under certain circumstances, the pollutants emitted can, on the one hand, still concentrate in the ambient air during the fire event and exceed critical threshold values for humans faster than outdoors, where the smoke gases are rapidly diluted. On the other hand, due to the persistent nature of certain battery-typical emissions, these could possibly be displaced during and even after firefighting and thus contaminate other, event-independent locations. The changes in risk to be expected in underground traffic infrastructures can hardly be quantified at the present time, but they can be categorised according to certain aspects. The possible changes in risk listed in Table 4 are based on the assumption of a worst-case scenario in which, among other things, incident response is not carried out in accordance with the current state of the art or based on experience.

Table 4 *Potential changes in risk in underground traffic infrastructures*

Aspect	**Change in risk**	**Effects**
Availability	Long-term closures of the infrastructure due to complex decontamination activities.	Operational failures
Personal safety	Impairment of personal safety through deposition and displacement of toxic pollutants, e.g. via ventilation ducts or contaminated protective equipment.	Health risk
Protection of components and technical facilities	Additional corrosion damage of operating and safety equipment caused by new pollutant emissions that are atypical to date.	Safety impairment
Incident response	Improper incident response due to a lack of knowledge about specific fire emissions of lithium-ion batteries and inconsistent practice recommendations.	Uncoordinated process changes
Environmental protection	Damage to the environment due to deposition and displacement of toxic pollutants, e.g. in the event of uncontrolled draining of contaminated firefighting water or in the discharge area of ventilation systems.	Environmental risk

2.4 Directives and standards

Road tunnels

A basic principle for the planning of operational and safety equipment (OSE) in road tunnels is the assumption of an expected traffic composition in the tunnel concerned (proportion of heavy traffic, transport of dangerous goods, etc.). In the context of changing mobility, however, this aspect is currently undergoing a gradual shift: In future, traffic composition will be characterised less and less by pure petrol and diesel vehicles and more by battery-powered and other alternatively-powered vehicles (cf. [79]; [80]; [81]).

Although electric mobility is being actively promoted through policy (cf. [4]; [8]), the Swiss directives and standards currently do not cover the potential effects of electric mobility on tunnel safety. For example, the recommendations for assessing OSE are currently based on vehicle fires with fossil fuels – new types of energy storage have not been included to date. Although the transport of dangerous goods is taken into account in the considerations, the definitions in standard SIA 197/2 are based exclusively on fire events involving conventional drive systems (cf. [75]). However, the increasing use of alternative fuels, i.e. not only electrochemical storage but also gaseous fuels, has a significant potential for damage ([1]).

New types of damage scenarios caused by the accumulation of flammable gas-air mixtures after an accident, possible limit loads for firefighters due to the changed chemical hazards or the danger of hydrogen formation through the use of water as an extinguishing agent are therefore not examined. The FEDRO specifications for the ventilation and detection systems in road tunnels (cf. [2] and [3]) also do not take into account the effects of the increasing proportion of electric vehicles and thus do not provide for any risk-reducing measures. Even if the findings of the previous project did not reveal any fundamental need for change ([59]), an update of the existing FEDRO specifications with regard to new drive technologies is still considered worthwhile.

Smaller underground infrastructures

The applicable Swiss directives do also not yet comprehensively cover the shift in mobility with a view to safety in smaller traffic infrastructures. As a result, the development of fire protection measures is still based on a traffic composition that consists exclusively of vehicles with conventional drive systems. Specific hazards that may emanate from alternative drive types, as well as more extensive operational or organisational protective measures, are thus overlooked for the time being.

At present, there are no uniform guidelines for Switzerland for dealing with specific fire hazards posed by electric vehicles in multi-storey car parks, underground car parks or garages. Since the risk of fire during the charging process of a battery at a charging station is fundamentally increased due to potential overcharging ([94]), the following normative documents of the Swiss Association of Road and Transportation Experts (VSS) and the Swiss Society of Engineers and Architects (SIA) make more concrete recommendations in this regard:

Table 5 *Current state of standards concerning smaller traffic infrastructures*

Standard	Specifications concerning
VSS 40 294 ‘Parkfelder mit Ladestationen für Elektrofahrzeuge in Parkhäusern – Sicherheitsmassnahmen’ (Parking areas with charging stations for electric vehicles in car parks – safety measures) (cf. [88])	Site selection for charging stations from a safety perspective
	Technical safety measures
	Organisational safety measures
SIA 2060 ‘Infrastruktur für Elektrofahrzeuge in Gebäuden’ (Infrastructure for electric vehicles in buildings) (cf. [76])	General fire protection

Various information brochures by charging station operators or power supply companies regularly give an overview of important topics regarding electric mobility in infrastructures for various actors in Switzerland (e.g. charging stations and charging management in residential area construction). However, these brochures mainly deal only with risks posed by electricity; other safety aspects, such as the thermal and chemical hazards in closed spaces in particular, are not emphasised. Owners and operators of smaller infrastructures therefore have only sparse guidelines to fall back on and often have to fend for themselves when selecting specific safety precautions.

3 Methodology

The contamination tests in the present project examined the worst-case scenario with the largest possible battery-specific effects of an electric vehicle fire. Only risks posed by chemical hazards were considered, and thermal and electric risks were disregarded.

The experimental situation had to be prepared in such a way that the characteristics to be examined (dependent variables) could be measured without restriction. To exclude further influencing factors such as electronic or mechanical protections for the battery systems, the tests analysed individual modules of a battery system without a monitoring battery management system and detached from a typical overall vehicle structure. The test results were subsequently scaled to the vehicle level (cf. Figure 3), checked for plausibility and put in relation to real events in underground traffic infrastructures.

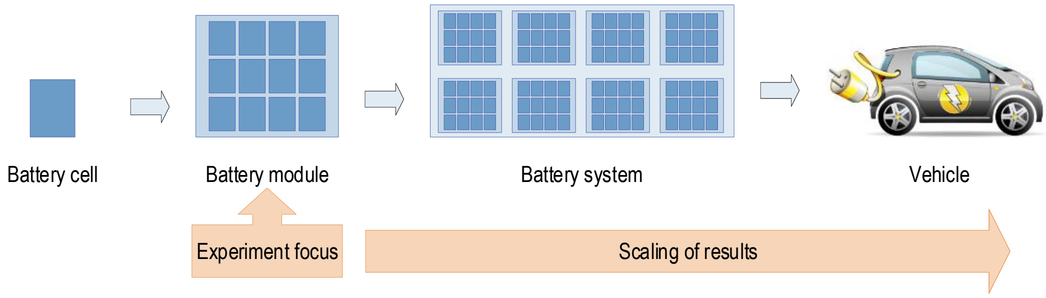


Figure 3 Modular structure of a battery system and focus of the tests

3.1 Test material

The tests focused on high-capacity batteries for popular mid-range battery electric passenger vehicles (as of 2019), i.e. not hybrid or commercial vehicles. So that the analyses could build directly on the findings of the previous project (cf. [59]), these tests examined the same vehicle battery system (cf. Figure 4 and Table 6).

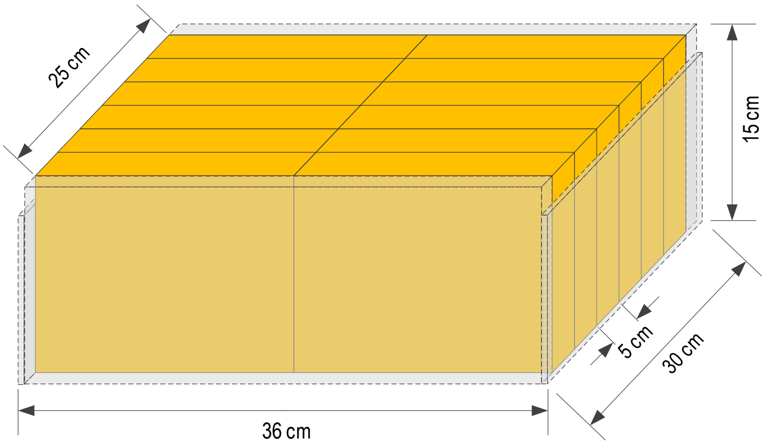


Figure 4 Schematic representation of the examined battery module with 12 battery cells (orange) and stabilising aluminium frame (transparent grey)

The battery modules used in the experiment were new (produced in 2018) and fully serviceable components of a registered BEV. For safety reasons, the vehicle brand representative delivered them with a nominal voltage of 3.6 V per battery cell (state of charge <60%) and they were stored in suitable premises at the VSH until the test date, i.e. with few flammable materials and access exclusively for authorised persons. At the test date, the battery cells were charged to the recommended end-of-charge voltage (cf. Table 6).

***Table 6** Characteristics of the examined battery system for BEVs (as of 2019)*

	Description	
Characteristic	**Battery module**	**Battery system**
Number of cells	12	96
Cell type	Prismatic cells	
Electrode active mass	Anode: graphite; cathode: lithium nickel manganese cobalt oxide (NMC)	
Conducting salt	Lithium hexafluorophosphate $LiPF_6$	
Nominal voltage	44.4 V (3.7 V per battery cell)	355 V
End-of-charge voltage	49.2 V (4.1 V per battery cell)	394 V
Power	4.15 kWh	33.2 kWh
Specific energy	0.14 kWh/kg	
Thermal runaway	Typical from 210°C. High charges are advantageous.	

Damage concept

A realistic course of events leading to battery damage (crash, fire, electric damage) was not relevant for the present worst-case scenario analysis and was therefore not further elaborated for the tests. The objective of all test scenarios was the simultaneous damaging of all battery cells in order to cause an overall thermal runaway in a controlled environment. The damage concept of the previous project was adopted for this purpose, as it is well-established for research of this kind. Accordingly, all battery cells of the battery modules were damaged mechanically at the same time using blasting technology for the required forces. The battery modules themselves were not blasted.

A steel plate (38 cm x 27 cm x 2 cm) with two 8-cm-long steel wedges (8 cm x 25 cm x 0.8 cm) running the entire length of its underside was loosely placed atop each of the battery modules, which were affixed to the ground using screws (cf. Figure 5). Two 100 g bundles of detonating fuse (Detonex, 40 g/m) were affixed to the upper side of the steel plate. Through the simultaneous detonation of both blasting charges, the steel plate was accelerated in the direction of the battery module. The objective was for the wedges affixed to the underside to penetrate the two battery cell rows of the battery modules, remaining there and causing short circuiting.

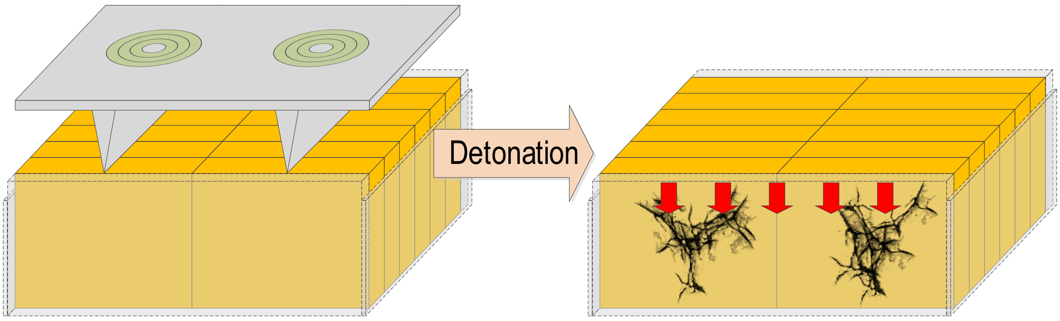


Figure 5 Battery module (orange) and overlying steel plate with wedges (grey) with detonating fuse (green) before and after application of force (red)

3.2 Test space and locations

Testing was carried out in the tunnel system of VSH. This system had already proven adequate for experiments of this kind in the past and was also suitable for investigating the present, more far-reaching questions.

For a target-oriented, safe and environmentally sound execution of the tests, two different environmental profiles were required (cf. Figure 6): on the one hand, a test site with a clearly delimitable spatial volume (tunnel ‘A’) for the analysis of contaminations in a closed environment without air circulation, and on the other, a test site with a long measuring section to examine the transport and deposition behaviour of the battery-specific fire emissions (tunnel ‘B’).

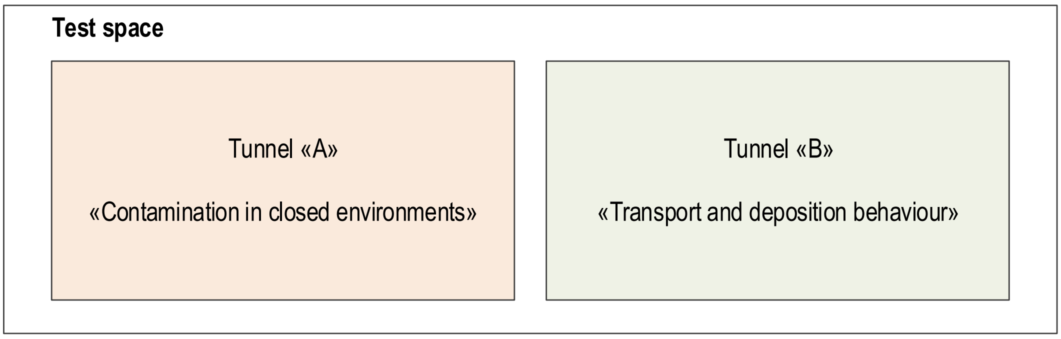


Figure 6Structuring of the test space based on different analysis objectives

Tunnel ‘A’
This site hosted the tests examining fire residue in a clearly delimited spatial volume without air circulation, i.e. without mechanical ventilation. To allow scaling of the concentration measurements to the vehicle level, the experimental spatial volume was chosen proportional to the energy capacity of the battery modules: 1/8 of a battery system → 1/8 of a parking floor with approx. 2,000 m^3 (28 x 28 x 2.5 m) ≈ 250 m^3. Tunnel ‘A’ was characterised by the following parameters (cf. Figure 7):

- Clearly delimitable room volume (≈ 250 m^3) without mechanical ventilation: The volume was delimited on both sides by means of a nonwoven geotextile for construction, which was suspended with a hanging lower edge (possibility of expansion) and moistened with water (fire protection).
- Environment similar to a tunnel or car park
- Explosion-proof and smoke-insensitive environment
- Chemically inert surfaces
- Mechanical air purification and smoke ventilation into the open air were possible at any time

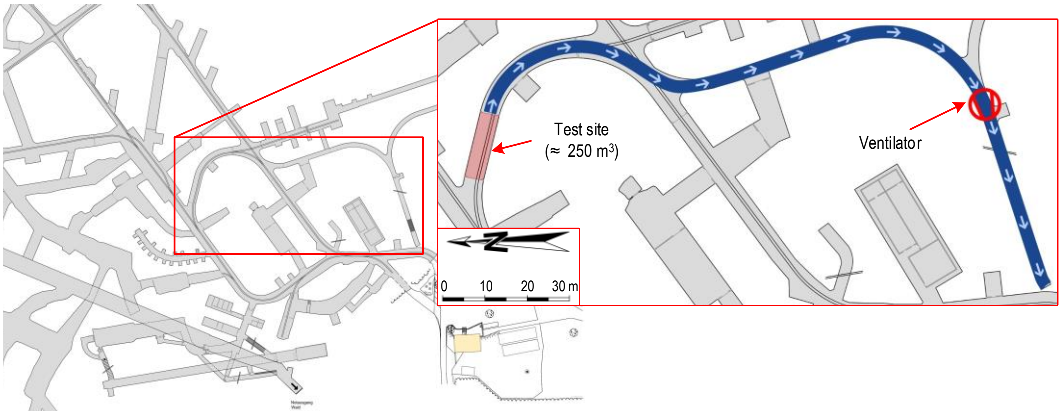


Figure 7 Position of tunnel ‘A’ with ventilation section (blue)

Figure 8 Testing site tunnel ‘A’ (left) with exhaust air purification equipment (right)

Tunnel ‘B’

This site hosted the test examining fire residue over a longer transport distance. To make the distance-dependent deposition behaviour of battery-specific fire emissions visible, the measuring section was deliberately chosen to be as long as possible. Tunnel ‘B’ was characterised by the following parameters (cf. Figure 9):

- Environment similar to a tunnel or car park with a long measuring section (approx. 160 m)
- Explosion-proof and smoke-insensitive environment
- Chemically inert surfaces
- Constant airflow of approx. 1.5 m/s
- Ventilation control and smoke ventilation into the open air were possible at any time

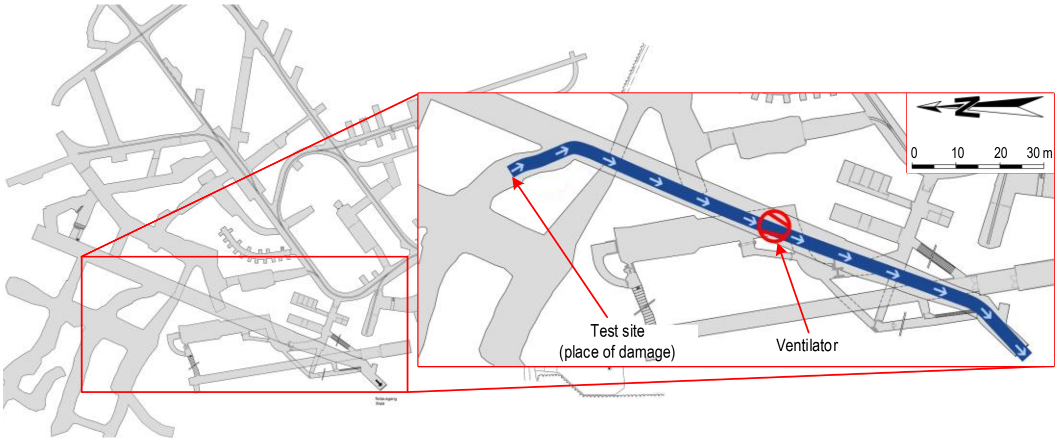


Figure 9 Position of tunnel 'B' with ventilation section (blue)

Figure 10 Testing site tunnel 'B' (left) and adjoining measuring section (right)

3.3 Measurement concept

Measurands and methods

The present project focused on the so-called 'cold fire area', which is why only analyses of fire residue were carried out instead of gas analyses during the fires. The latter are the focus of the previous project and are documented in the corresponding final report (cf. [59]). The measurements at that time and initial practical experience gathered by Empa indicated that BEV fires resulted in changed chemical hazards and contaminations in comparison to conventional vehicle fires. Therefore, these needed to be analysed in greater depth in the present research project using suitable measurands and appropriate methods.

Only inspected measuring equipment and devices that were within the calibration cycle specified by the manufacturer were used during the tests. The ambient conditions on site were recorded and documented with suitable measuring equipment before and during each test. The measurement techniques and methods used for the individual parameters are shown in Table 7 and Figure 11.

***Table 7** Measurands during the experiment*

Measurand	Description	Method/measuring technology
Temperature (°C)	Temperature in the direct vicinity and inside the damaged battery module	Direct, with type K thermocouple
F^-, Cl^-, Br^-	Contamination with halogens (particularly hydrofluoric acid HF)	Surface swipe samples; anion analysis in aqueous extract through capillary electrophoresis (CE)
$HCOO^-$, CH_3COO^-	Contamination with formic and acetic acid	
SO_4^{2-}, NO_3^-, PO_4^{3-}	Contamination with sulphuric, nitric and phosphoric acid	

***Table 7** Measurands during the experiment*

Measurand	Description	Method/measuring technology
Li	Contamination with lithium compounds	Surface swipe samples; cation analysis in nitric acid extract through inductively coupled plasma optical emission spectrometry (ICP-OES)
Ni, Co, Mn	Contamination with nickel, cobalt and manganese compounds	
PAH, PCB, PCDD/F	Contamination with polycyclic aromatic hydrocarbons, polychlorinated biphenyls and polychlorinated dibenzodioxins/furans	Surface swipe samples; PAH, PCB and PCDD/F analysis in cyclohexane or toluene extract through gas chromatography and high-resolution mass spectrometry (GC-MS)
Element screening	Analysis of the overall chemical composition of the fire soot samples	Semiquantitative element analysis using REM/EDX and ED-XRF
Smoke generation	Intensity and chronological sequence of smoke generation	Direct, with video (high-resolution recordings [1080p] with normal frame rate [30 fps]).
Thermal effects	e.g. deflagration, explosion, etc.	Direct, with video (high-resolution recordings [1080p] with normal frame rate [30 fps]).
Corrosiveness of smoke gases	Analysis of corrosion damage to various typical infrastructure metals (zinc, steel, copper, aluminium, stainless steel, etc.)	Gravimetric analysis of corrosion-induced material abrasion on exposed test plates: • Directly after exposure of the test plates to smoke gases (and decontamination) • After exposure of the contaminated test plates at 90% relative humidity (for a period of 3 months)

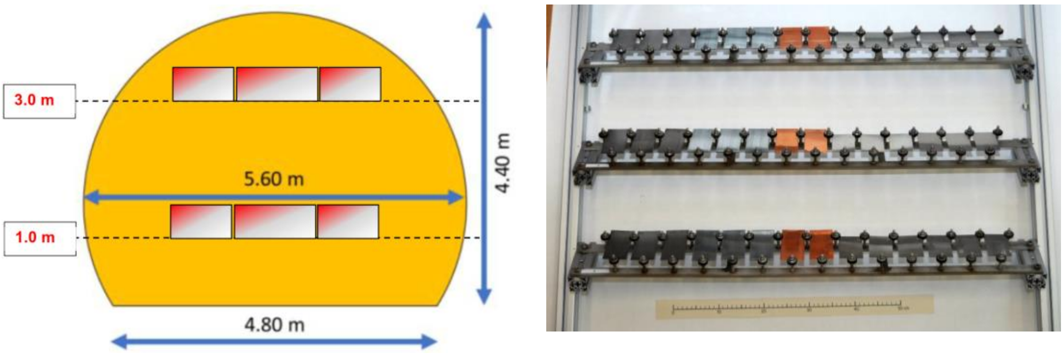
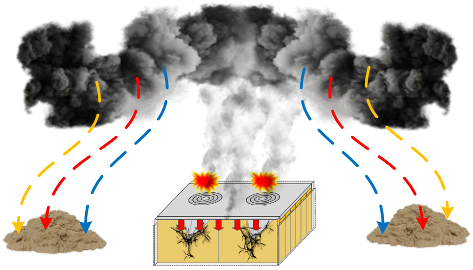
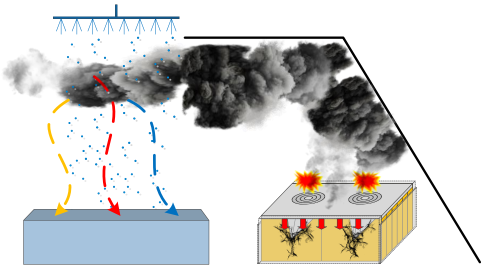
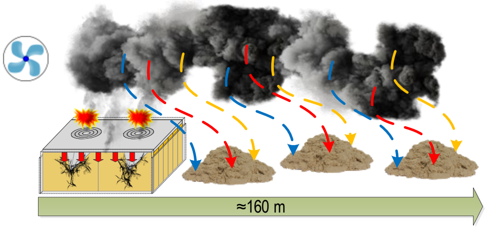
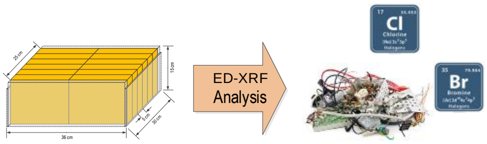


Figure 11 Sample collector assembly diagram (left, e.g. tunnel A) and rack for corrosion monitoring (right)

3.4 Test scenarios

To examine potential secondary damage caused by fire in underground traffic infrastructures, a total of four battery modules were tested in three test scenarios and underwent a material analysis (cf. Table 8).

__Table 8__ Test scenarios with battery modules 1, 2, 3 and 4

#	Scenario	Illustration
1	**‘Infrastructure and protective equipment’**: mechanical damage to the battery module using blasting technology in a closed space without mechanical ventilation. Objective: analysis of fire residue on surfaces and protective textiles as well as corrosiveness to typical metals. →Tunnel ‘A’	
2	**‘Firefighting water’**: mechanical damage to the battery module using blasting technology in a closed space without mechanical ventilation and with continuous water influx to fire emissions (not to battery module, without pressure conditioning). Objective: analysis of firefighting water contamination →Tunnel ‘A’	
3	**‘Transport and deposition behaviour’**: mechanical damage to the battery module using blasting technology in an open space with a constant airflow of approx. 1.5 m/s. Objective: analysis of spatial deposition behaviour → Tunnel ‘B’	
4	**‘Material analysis’**: examination of the battery module without destroying the battery cells to analyse the materials of all module components (battery cells, cables, electronics, insulation, housing, etc.). Objective: Differentiation between ‘cell-chemical’ and ‘other’ secondary products of the fire → Empa laboratory	

3.4.1 Infrastructure and protective equipment

__Table 9__ Test scenario with battery module 1

Aspect	Description
Objectives	Quantitative analysis of the contaminations which are toxicologically relevant and relevant in terms of chemical corrosion
	Quantitative analysis of the corrosiveness of the fire emissions to various typical infrastructure metals
	Findings regarding the contamination of protective equipment through toxicologically relevant substances (especially heavy metals and HF) and consequences for humans and the environment in the event of displacement.
Setup and procedure	1 NMC battery module (with approx. 4 kWh)
	Clearly delimited, not mechanically ventilated test space with approx. 250 m^3 of volume and chemically inert surfaces (tunnel ‘A’)
	Assembly of several sample collector plates (stainless steel 1.4401) exposed by tilting (45° towards experiment) within the test space at heights of 1.5 and 3.0 m

***Table 9** Test scenario with battery module 1*

Aspect	Description
	Assembly of corrosion monitoring racks in the test space at a height of 1.5 m
	Placement and exposure of a firefighter's textile protective suit typically used in such operations (93% aramid (Nomex), 5% p-aramid (Kevlar), 2% P140 (carbon))
	Installation of various instruments for continuous measurements (e.g. temperature, voltage variation within the battery module, film recordings)
	Mechanical damage to all battery cells using blasting method (cf. Figure 5)
	Complete burn-up of the battery module without mechanical ventilation of the test space and without extinguishing attempts (→ free deposition of fire emissions on surfaces)
	Controlled ventilation of the test space after the end of the test via air purification system in compliance with the safety and environmental requirements
	Immersion of the damaged battery module in a water tank in order to analyse the contamination potential of a burnt-up and subsequently flooded battery (→current practice recommendation)
Sampling	Swipe samples: sampling of decontaminated collectors on surface areas of 200 m^2 (samples for analysis of anions and cations) and 1,000 cm^2 (samples for analysis of PAH, PCB and PCDD/F) with de-ionised water or n-hexane
	Fire soot samples: dry sampling of decontaminated collectors on a surface area of 8,000 cm^2 (samples for chemical analysis of anions, cations, PAH, PCB and PCDD/F and for element screening)
	Textile samples: swipe sampling (see above) in contaminated and cleaned states
Analysis methods	Capillary electrophoresis (CE): anion analysis in aqueous extract
	Plasma optical emission spectrometry (ICP-OES): cation analysis in nitric acid extract
	Isotope dilution analysis (GC-HRMS): PAH, PCB and PCDD/F analysis in cyclohexane or toluene extract
	X-ray fluorescence spectrometry (ED-XRF, REM/EDX): semiquantitative analysis of the elements in dry samples
Corrosion monitoring	Test metals: carbon steel, zinc, copper, aluminium alloy AlMgSi1 and stainless steel 1.4404 (cf. Figure 11)
	Exposure to combustion gases: tilted (45° towards experiment)
	Exposure to moisture: at 90% relative humidity (for a period 1 month and 3 months)
	Analysis of material abrasion: gravimetric

3.4.2 Firefighting water

***Table 10** Test scenario with battery module 2*

Aspect	Description
Objectives	Findings regarding the contamination of firefighting water by toxicologically relevant substances (especially heavy metals and HF) and consequences for humans and the environment in the event of uncontrolled draining.
Setup and procedure	1 NMC battery module (approx. 4 kWh)
	Clearly delimited, not mechanically ventilated test space with 250 m^3 of volume and chemically inert surfaces (tunnel 'A')
	Installation of various instruments for continuous measurements (e.g. temperature, voltage variation within the battery module, film recordings)
	Mechanical damage to all battery cells using blasting method (cf. Figure 5)

Table 10 *Test scenario with battery module 2*

Aspect	Description
	Complete burn-up of the battery module without mechanical ventilation of the test space (→ free deposition of fire emissions in firefighting water)
	Transfer of the smoke escaping from the battery module to an ‘irrigation zone’ using suitable baffle plates
	Irrigation of the fire smoke[1] using a sprinkler (400 mm x 400 mm) with 324 nozzles at a height of 2.5 m using conventional tap water with a continuous volume flow rate of approx. 20 l/min, without additional pressure conditioning (no extinguishing attempt)
	Collection of all firefighting water in the irrigation zone using an adjacent, chemically inert plastic container with a volume of ≈ 200 l.
	Collection of the occurring sediment as a sample. Documentation of the total water volume collected. Forwarding of the aliquots of the collected fluid in laboratory glass bottles to the Empa laboratory for analysis.
	Controlled ventilation of the test space via air purification system and, where applicable, separate disposal of the collected firefighting water after the end of the test in compliance with the safety and environmental requirements
Firefighting water analysis methods	Capillary electrophoresis (CE): anion analysis (direct analysis)
	Plasma optical emission spectrometry (ICP-OES): cation analysis (direct analysis)
	Isotope dilution analysis (GC-HRMS): PAH, PCB and PCDD/F analysis (n-hexane extract from C18 phase or polymer cartridge)
Analysis methods for solids (sediment, suspended particles)	according to battery module 1 (dry samples), cf. Table 9

3.4.3 Transport and deposition behaviour

Table 11 *Test scenario with battery module 3*

Aspect	Description
Objectives	Quantitative analysis of the contaminations which are toxicologically relevant and relevant in terms of chemical corrosion over a longer transport distance.
	Findings regarding the transport and deposition behaviour of heavy metal aerosols over a longer distance.
Setup and procedure	1 NMC battery module (approx. 4 kWh)
	Execution at the testing site of the previous project (tunnel ‘B’ and fire tunnel) with clearly defined airflow (1-2 m/s) and predetermined ventilation section from the fire tunnel into the open air
	Assembly of several sample collector plates (stainless steel 1.4401) exposed by tilting (45° towards experiment) in the smoke removal tunnel at a height of 3.0 m and at distances of approx. 50, 100 and 150 m to the experiment.
	Installation of various instruments for continuous measurements (e.g. temperature, voltage variation within the battery module, film recordings)
	Mechanical damage to all battery cells using blasting method (cf. Figure 5)
	Complete burn-up of the battery module without extinguishing attempts (→ free movement and deposition of fire emissions along the measuring section)
	Thermal imaging camera (TIC) recordings by a firefighting expert from the Zurich rescue organisation Schutz & Rettung Zürich (SRZ)
	Ventilation of the test space after the end of the test in compliance with the safety and environmental requirements

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[1] It was not permitted to wet the battery module directly with water, as otherwise the formation of hydrogen could have led to an explosion hazard.

Table 11 *Test scenario with battery module 3*

Aspect	**Description**
Sampling and analysis methods	according to battery module 1 (swipe samples and fire soot samples), cf. Table 9

3.4.4 Material analysis

Table 12 *Test scenario with battery module 4*

Aspect	**Description**
Objectives	Material characterisation of the individual components of an NMC battery module (battery cells, cables, electronics, insulation, housing, etc.)
	Differentiation between 'cell-chemical' and 'other' secondary products of the fire (e.g. Cl, Br)
Setup and procedure	1 NMC battery module (approx. 4 kWh)
	Examination of a battery module without destroying the battery cells
	Non-destructive material analysis of the other module components using ED-XRF

3.5 Safety and environment

The experiment was carried out in compliance with the applicable safety and environmental regulations and in accordance with relevant international standards (e.g. ISO 45001). All tests at the VSH were also discussed in advance with the responsible Environmental Office of the Canton of St. Gallen. The resulting kinetic, thermal and chemical hazards to test personnel were eliminated by way of appropriate safety precautions.

Explosion protection regarding pyrolysis gases
It had to be assumed that flammable gas mixtures would escape at the beginning of the thermal runaway of the battery modules, but that a permanent, effective ignition of the gases would not take place initially. In this phase, the possible accumulation of flammable gas mixtures would have led to a deflagration in the event of a subsequent ignition. To effectively prevent this event, a spark gap was operated in the immediate vicinity of the battery module during the tests in order to ignite any escaping flammable gas mixtures continuously, thus burning the gas off before a critical accumulation could take place. In addition, burning battery modules in the unventilated and closed test space were not allowed to be cooled with water, as this would have favoured the escape of pyrolysis gases that did not burn directly.

Explosion protection regarding hydrogen (oxyhydrogen)
If battery modules that have not been reacted to exhaustion are exposed to water, the remaining lithium therein can react with the water to form gaseous hydrogen.

$$2\,Li_{(s)} + 2\,H_2O_{(l)} \rightarrow 2\,Li^+_{(aq)} + 2\,OH^-_{(aq)} + H_{2(g)}$$

Gaseous hydrogen (H_2) poses a high risk of explosion[2], which is why an accumulation in closed spaces without mechanical ventilation had to be absolutely excluded for safety reasons. For this reason, no burning battery modules were allowed to be exposed directly to water inside the VSH tunnel system.

Exhaust air purification

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[2] Hydrogen is explosive under atmospheric pressure given a percentage by volume between 4 and 77%. This very wide range of mixture ratios is what makes accumulations of hydrogen so dangerous, particularly in underground infrastructures.

Large quantities of pollutants were emitted into the ambient air of the test space during the experiment. For the tests in tunnel ‘A’, the ambient air was not exchanged while burning the battery modules for experimental reasons. After the tests had been carried out, the contaminated air was extracted by means of a fan and air duct, purified by a suitable filter system and finally discharged into the open air (cf. Figure 7). The fan had a nominal capacity of 4,000 m^3h^{-1} and a four-stage filter system. The first three stages remove particles (solid, liquid) and the downstream activated carbon filter also removes gaseous substances. With the exception of low-boiling contaminants such as CO or CO_2, all pollutants were thus reliably removed from the exhaust air.

After the tests in tunnel ‘A’ had been carried out, the test space was flushed with fresh air (see scenario descriptions in Table 9 and Table 10). As soon as no more smoke clouds were visible in the test area, an HF measurement (Dräger Tubes) was carried out by a firefighting expert from Schutz & Rettung Zürich with protective equipment suitable for such operations (air-independent respiratory protection, gloves, etc.). For the test space to be released, the HF concentration must not exceed the maximum occupational exposure value (8-hour exposure) of 1 mlm^{-3} or 0.83 mgm^{-3} or the short-term exposure value (maximum 4 x 15 minutes per day with at least 1 hour of interruption) of 2 mlm^{-3} or 1.66 mgm^{-3}.The measurement results were then evaluated by an expert chemical consultant. After a positive evaluation, the test space was released for sampling.

During the test in tunnel ‘B’, the test space was continuously mechanically ventilated with a constant airflow of approx. 1.5 m/s. Due to the very high volume flow rate and the fact that it caused strong attenuation effects in the tunnel itself, exhaust air purification was not considered to be necessary at this location.

Deposition contamination (HF)

Significant emissions of hydrogen fluoride in combination with moisture were expected to result in HF-contaminated precipitates on the surrounding surfaces. If the precipitates were not fully chemically converted (e.g. through existing bases), a continuous emission of HF to the ambient air would be possible even after the elimination of gaseous contamination in the test space. Even chemically bound HF (in the form of fluoride salt) can emit free HF to the ambient air under certain conditions (e.g. in an acid environment). These safety-relevant effects are particularly important in the event of large affected areas, which is why they were a necessary part of the considerations. If the workplace exposure limit (WEL) or the short-term exposure limit (STEL) had been exceeded due to such an effect, the fallback plan was to clean the test space with water (by spraying down the walls).

Water contamination

Large quantities of contaminated water were accumulated during the experiment, either due to tests or to cleaning work (cf. scenario description in Table 10). After completion of the tests, battery modules that had been reacted to exhaustion were additionally flooded with water for safety reasons and further analyses. All of the contaminated water was collected in one central plastic tank and later handed over to a certified disposal firm.

Decontamination of test space (soot and other emissions)

Particularly tunnel ‘A’ was heavily contaminated with depositions (soot, fluorides, metal aerosols, etc.) after completion of the tests. The test space was cleaned by a specialised fire damage restoration firm with professional equipment within a few days after test completion. Finally, the effectiveness of the cleaning method (the same as for fire damage restoration in road tunnels) was verified with comparative measurements.

Safety zones

During the tests, four different safety zones were defined in line with the zone formation of emergency personnel for special events (cf. Table 13). All persons in the areas of operations permanently had to wear suitable work clothing in signal colours, safety shoes (at least S3) and a helmet. Protective goggles, safety gloves and hearing protection had to be carried at all times and had to be worn when indicated.

Table 13 *Safety zones during the experiment*

Zone	Description
0	Areas that may be hit by splinters either directly or indirectly, that may be exposed to high temperatures or fire or that may contain highly concentrated emissions (smoke) from the test. No persons may be in these areas for the duration of the test. Only authorised blasting personnel is permitted to access to zone 0 while there is an explosive substance in zone 0. Any exceptions must be accompanied directly by the responsible blasting officer.
1	Until final release by the testing manager, areas that may contain emissions (smoke) from the tests can only be accessed wearing a respirator (ABEK-P), a protective suit and gloves.
2	Areas that may be affected by sound pressure from the tests but that are otherwise not exposed to any hazards. During the test, only persons authorised and accordingly instructed by the testing manager are allowed to remain in these areas. These persons must wear earmuffs.
Decontamination zone	Clearly defined area directly adjacent to the test space, in which all contaminated or potentially contaminated protective equipment and devices can be deposited and clothing can be changed.

Disposal of damaged battery modules

After completion of the test, battery modules that had been reacted to exhaustion were checked for remaining reactive material. This check was carried out with heavy protective equipment (respirator, helmet, heavy splash guard suit [taped shut], heavy gloves). During the check, the battery modules could only be viewed from the side (danger of activating the overpressure releases affixed to the top). If no remaining reactive material could be determined in the battery modules, they were locked in a plastic box, which was then filled with water. After at least two days unattended under water, the remains of the battery modules were drained and disposed of at a regular incineration facility. If reactive material had been found in a battery module, it would have had to be neutralized, with the testing manager deciding the appropriate measures on a case-by-case basis (e.g. penetration with a spike, bombardment, reaction with water, incineration). A proven expert was a permanent member of the testing team in order to eliminate hazards in advance by rendering them harmless with the appropriate measures.

4 Results

4.1 Pre-analyses

Initial situation and objectives
On 11 July 2019, almost two years after the previous experiment in the autumn of 2017, the former test space was examined for possible pollutant contamination caused by the previous battery tests. The aim of these analyses was to prove the presence of certain pollutants that could be causally attributed to the experiment even two years after their emission. Sampling points were selected based on their exposure to the previous battery tests: all material and swipe samples (MS and SS) were taken from locations on the ceiling of the test tunnel or on the housing of the smoke exhaust ventilator, all of which were directly exposed to the smoke (cf. Figure 12).

The examined tunnel section was not decontaminated after the previous tests. It should be noted here that within the relatively long period of almost two years between emission and measurement, the test site was used for normal VSH operation, but no other events involving heavy metal emissions occurred.

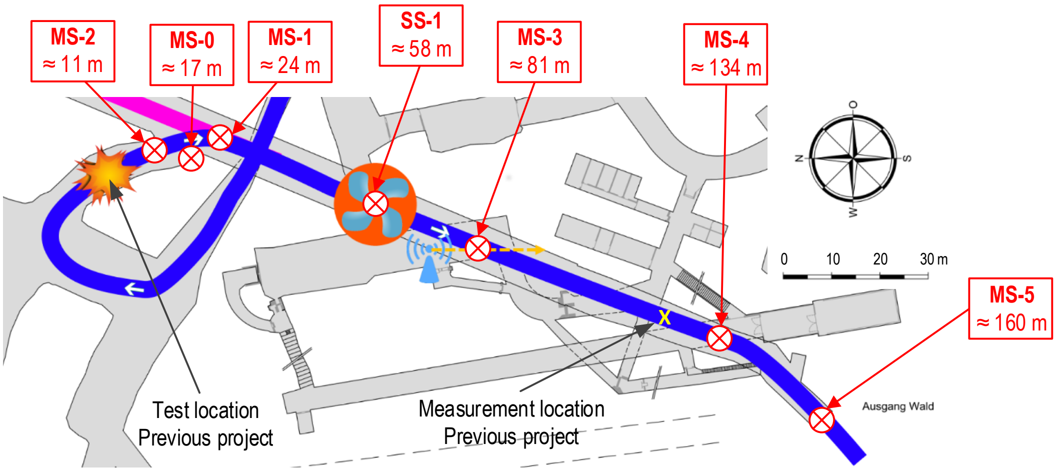

Figure 12 Empa sampling plan as of 11 July 2019

Concept and methods
On the one hand, preliminary examinations were carried out using a measurement method to determine the preliminary, semi-quantitative proof of the heavy metals Co, Ni and Mn (X-ray fluorescence spectrometry) which could be used both on site and in the lab. On the other hand, suitable samples were taken to determine the presence of water-soluble lithium and fluoride compounds in a quantitative laboratory analysis using capillary electrophoresis (CE). After sampling at the locations as per Figure 12, the following analytic methods were used (also cf. Annex I):

- X-ray fluorescence spectrometry (ED-XRF): preliminary, semi-quantitative analysis of dry samples (fire soot residue) to determine levels of Ni, Co and Mn (as well as other heavy metals). The analyses take place in the laboratory after preparation of the sample material.
- Capillary electrophoresis (CE): quantitative laboratory analysis of the dry and swipe samples in aqueous extract to determine the water-soluble anion and cation concentrations (lithium and fluoride, inter alia).

Figure 13 Former test site with black fire soot residue (left) and sampling location SS-1 on the smoke exhaust ventilator housing (right)

Results

Table 14 Anion exposure (aqueous extract, surface swipe samples) in µg/cm²

Sample no.	Chloride Cl^-	Bromide Br^-	Fluoride F^-	Sulphate SO_4^{2-}	Nitrate NO_3^-	Formate $HCOO^-$	Acetate CH_3COO^-
SS-1	0.7	n.v.	n.v.	420	n.v.	n.v.	n.v.

n.v. = not verifiable (<0.1 µg/cm²) specifications in () = levels in the detection limit range

Table 15 Cation exposure (aqueous extract, surface swipe samples) in µg/cm²

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
SS-1	n.v.	7.9	4.5	(0.1)	12	150

n.v. = not verifiable (<0.1 µg/cm²) specifications in () = levels in the detection limit range

Table 16 Anion levels in % by mass (in relation to the dry solid)

Sample no.	Chloride Cl^-	Bromide Br^-	Fluoride F^-	Sulphate SO_4^{2-}	Nitrate NO_3^-	Formate $HCOO^-$	Acetate CH_3COO^-
MS-1	n.v.	n.v.	(0.01)	4.6	0.07	n.v.	n.v.
MS-2	n.v.	n.v.	(0.01)	0.72	0.05	n.v.	n.v.
MS-3	n.v.	n.v.	n.v.	4.4	n.v.	n.v.	n.v.
MS-4	0.02	n.v.	n.v.	5.3	0.09	n.v.	n.v.
MS-5	0.02	n.v.	n.v.	3.0	0.06	n.v.	n.v.
MS-0	n.v.	n.v.	n.v.	2.4	0.12	n.v.	n.v.

n.v. = not verifiable (<0.01 – 0.001% by mass); specifications in () = levels in the detection limit range

Table 17 Cation levels in % by mass (in relation to the dry solid)

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
MS-1	n.v.	0.07	0.15	(0.001)	0.07	1.2
MS-2	n.v.	0.50	0.18	(0.001)	(0.002)	(0.01)
MS-3	0.02	0.86	0.03	n.v.	0.04	1.1
MS-4	n.v.	0.19	0.05	n.v.	0.51	1.2

Table 17 Cation levels in % by mass (in relation to the dry solid)

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
MS-5	n.v.	0.33	0.06	n.v.	0.02	1.0
MS-0	n.v.	0.15	0.04	n.v.	0.01	1.0

n.v. = not verifiable (<0.01 – 0.001% by mass); specifications in () = levels in the detection limit range

Table 18 Preliminary chemical analysis (analysis of solids ED-XRF, fire soot samples) *levels specified in % by mass (triple measurement of mean values ± standard deviation)*

Element	MS-1	MS-2	MS-3	MS-4	MS-5	MS-0	SS-1
Al	0.9 ± 0.1	1.3 ± 0.1	0.8 ± 0.1	0.9 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	0.8 ± 0.1
Ca	17 ± 2	21 ± 2	25 ± 2	15 ± 2	21 ± 2	29 ± 2	14 ± 2
Cl	n.v.	n.v.	(0.04)	(0.04)	(0.04)	n.v.	n.v.
Co	0.08 ± 0.01	0.11 ± 0.01	0.22 ± 0.01	n.v.	(0.01)	n.v.	0.15 ± 0.01
Cu	(0.01)	(0.03)	n.v.	(0.01)	(0.01)	(0.01)	(0.02)
Fe	0.7 ± 0.1	1.4 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	1.5 ± 0.1	1.5 ± 0.1	0.9 ± 0.1
K	1.7 ± 0.1	2.8 ± 0.1	2.0 ± 0.1	1.0 ± 0.1	1.8 ± 0.1	1.1 ± 0.1	0.5 ± 0.1
Mn	0.11± 0.01	0.19 ± 0.01	0.26 ± 0.01	(0.01)	0.03 ± 0.01	0.06 ± 0.01	0.17± 0.01
Ni	0.08± 0.01	0.11 ± 0.01	0.22 ± 0.01	(0.01)	(0.01)	(0.01)	0.15± 0.01
P	0.12 ± 0.03	0.24 ± 0.03	0.49 ± 0.03	0.09 ± 0.03	0.51 ± 0.03	0.28 ± 0.03	(0.04)
Pb	(0.01)	(0.01)	(0.01)	(0.02)	0.05 ± 0.01	(0.01)	0.08 ± 0.01
S	10.4 ± 0.2	0.7 ± 0.1	6.4 ± 0.2	12.0 ± 0.2	3.1 ± 0.2	2.5 ± 0.2	1.1 ± 0.2
Si	3.3 ± 0.2	5.8 ± 0.2	4.0 ± 0.2	3.5 ± 0.2	5.2 ± 0.2	4.8 ± 0.2	2.5 ± 0.2
Zn	(0.02)	0.05 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	0.10 ± 0.01	(0.02)	(0.02)

n.v. = not verifiable (<0.01 – 0.001% by mass); specifications in () = levels in the detection limit range

Overall assessment

The substances cobalt, nickel and manganese, which were measured in high concentrations in the previous experiment by means of aerosol analyses, were still detectable in significant quantities at some sampling locations (cf. MS-1, MS-2 and MS-3 as well as SS-1 in Table 18). The locations of these samples were closest to the actual test location and were therefore exposed to the highest levels of smoke gas emissions during the battery tests. In the material samples MS-0 (blank), MS-4 and MS-5, whose sampling locations were exposed to the lowest level of smoke gas emissions during the experiment (side wall and discharge area), the above-mentioned substances were not detected (cf. Figure 12).

The correlation of the mass fractions of the above-mentioned substances and the fact that the substances could not be detected at less exposed sites suggests two conclusions: (I) that the residues originate from the same event and (II) that they can be traced back to the November 2017 test series. Since then, further activities and fire tests have taken place in this tunnel section, but no heavy metal emissions have been released. The fact that the residues are still clearly detectable after 19 months in the affected tunnel section highlights the persistence of these specific emissions from a BEV fire.

4.2 Infrastructure and protective equipment (battery module 1)

Pollutant analyses

The following analyses are based on the measurements carried out on 10 December 2019 at the test site of Versuchsstollen Hagerbach AG using the defined test scenario of Section 3.4.1 and in accordance with the analysis concept documented in Annex II. The full list of samples with explanations is given in Annex III.1.

Table 19 Anion exposure (aqueous extract, surface swipe samples) in µg/cm²

Sample no.	Chloride Cl^-	Bromide Br^-	Fluoride F^-	Sulphate SO_4^{2-}	Nitrate NO_3^-	Phosphate PO_4^{3-}	Formate $HCOO^-$	Acetate CH_3COO^-
Stainless steel collector plates								
A-11	5.2	n.v.	40	4.6	n.v.	2.1	n.v.	n.v.
B-11	6.4	n.v.	52	6.0	n.v.	2.2	n.v.	n.v.
Textile samples								
T-11	5.3	n.v.	46	6.0	n.v.	0.8	n.v.	n.v.
TR-11	1.5	n.v.	n.v.	1.3	n.v.	n.v.	n.v.	n.v.
Blanks								
0W-K	0.1	n.v.	n.v.	6.7	0.4	n.v.	0.1	n.v.
0T-K	1.5	n.v.	n.v.	1.2	n.v.	n.v.	n.v.	n.v.

n.v. = not verifiable (<0.1 µg/cm²)

Table 20 Cation exposure (aqueous extract, surface swipe samples) in µg/cm²

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
Stainless steel collector plates						
A-11	n.v.	n.v.	3.2	17	n.v.	n.v.
B-11	n.v.	n.v.	3.6	23	n.v.	n.v.
Textile samples						
T-11	n.v.	n.v.	1.1	9.0	n.v.	n.v.
TR-11	n.v.	n.v.	0.9	n.v.	5.9	35
Blanks						
0W-K	n.v.	n.v.	1.2	n.v.	n.v.	n.v.
0T-K	n.v.	n.v.	3.0	n.v.	0.2	0.3

n.v. = not verifiable (<0.1 µg/cm²)

Table 21 Co, Ni, Mn and Li exposure (nitric acid extract, surface swipe samples) in µg/cm²

Sample no.	Cobalt Co	Nickel Ni	Manganese Mn	Lithium Li
Stainless steel collector plates				
A-12	233	234	221	42
B-12	155	156	148	30
Textile samples				

Table 21 Co, Ni, Mn and Li exposure (nitric acid extract, surface swipe samples) in µg/cm^2

Sample no.	**Cobalt Co**	**Nickel Ni**	**Manganese Mn**	**Lithium Li**
T-12	400	400	380	70
TR-12	<0.2	<0.3	<0.4	<0.5
Blanks				
0W-A	<0.2	<0.3	<0.4	<0.5
0T-A	0.5	0.5	0.5	<0.5

Table 22 Exposure to organic pollutants (n-hexane extract, surface swipe samples)

Sample no.	**PAH Σ 16 EPA-PAH µg/m2**	**PCB Σ 6 cong. Ballschmiter x 5 µg/m2**	**PCDD/PCDF Σ I-TEQ ng/m^2**
Stainless steel collector plates			
A-13	269	--	--
B-13	304	--	--
A-14	--	0.22	6.3
B-14	--	9.6	8.4
Textile samples			
T-13	120	--	--
TR-13	5.6	--	--
T-14	--	0.26	3.4
TR-14	--	0.17	0.3
Blanks			
0W-O1	6.0	--	--
0T-O1	6.0	--	--
0W-O2	--	0.36	0.2
0T-O2	--	0.80	0.2

Table 23 Fire soot contamination (exposure quantities and analysis of solids, fire soot samples)

Sample no.	**Quantity**	**Composition***
A-2b Tunnel A Stainless steel collector plates Height = 3.5 m	17 g/m2	Principal constituents: • Co, Ni, Mn (each 18-20% w/w) • (20-25% w/w) Minor constituents: • Al, C, F, P (each 1-5% w/w) • Si, Ca, S, Cl (<1% w/w)
B-2b Tunnel A Stainless steel collector plates Height = 1.5 m	20 g/m2	Principal constituents: • Co, Ni, Mn (each 18-20% w/w) • O (20-25% w/w) Minor constituents: • Al, C, F, P (each 1-5% w/w) • Si, Ca, S, Cl (<1% w/w)

**Results of REM-EDX analyses*

Figure 14 Arrangement of protective equipment (left) and collector plates (right)

Table 24 Preliminary chemical analysis (analysis of solids ED-XRF, fire soot samples) *levels specified in % by mass (triple measurement of mean values ± rounded-up standard deviation)*

Substance	A-2b	B-2b	Substance	A-2b	B-2b
Ag	<0.01	<0.01	Ni	18.1 ± 0.5	18.6 ± 0.5
Al	1.4 ± 0.2	1.2 ± 0.2	P	0.8 ± 0.1	0.8 ± 0.1
As	<0.01	<0.01	Pb	<0.01	<0.01
Au	<0.01	<0.01	Pd	<0.01	<0.01
Ba	<0.05	<0.05	Rb	<0.01	<0.01
Bi	<0.01	<0.01	Re	<0.01	<0.01
Ca	0.5 ± 0.1	0.5 ± 0.1	S	0.2 ± 0.1	0.2 ± 0.1
Cd	<0.01	<0.01	Sb	<0.01	<0.01
Cl	0.4 ± 0.1	0.3 ± 0.1	Se	<0.01	<0.01
Co	18.2 ± 0.5	18.6 ± 0.5	Si	<0.5	<0.5
Cr	<0.05	<0.05	Sn	<0.01	<0.01
Cu	<0.05	<0.05	Sr	<0.01	<0.01
Fe	0.3 ± 0.1	0.3 ± 0.1	Ta	<0.01	<0.01
Hf	<0.01	<0.01	Th	<0.01	<0.01
Hg	<0.1	<0.1	Ti	<0.1	<0.1
K	<0.1	<0.1	U	<0.01	<0.01
Mg	<1	<1	V	<0.1	<0.1
Mn	19.6 ± 0.5	19.9 ± 0.5	W	<0.05	<0.05
Mo	<0.01	<0.01	Zn	<0.1	<0.1
Nb	<0.01	<0.01	Zr	<0.1	<0.1

Table 25 Co, Ni, Mn and Li levels (nitric acid extract, fire soot samples) in % by mass

Sample no.	Cobalt Co	Nickel Ni	Manganese Mn	Lithium Li
Stainless steel collector plates				
A-2b	17.7	17.4	17.1	3.2

Table 25 Co, Ni, Mn and Li levels (nitric acid extract, fire soot samples) in % by mass

Sample no.	Cobalt Co	Nickel Ni	Manganese Mn	Lithium Li
B-2b	17.7	17.3	17.1	3.2

Corrosion monitoring
For the purpose of analysing the corrosion-induced material abrasion, the various materials were examined for the first time after three days under ambient conditions and for the second time after one or three months of storage at 90% relative humidity.

Table 26 Corrosion-induced material abrasion

	Loss of mass in g/m^2		
Material	**after 3 days (Storage in tunnel A)**	**after 1 month (Storage at 90% relative humidity)**	**after 3 months (Storage at 90% relative humidity)**
Unalloyed steel	4.3	23	37
Zinc	1.8	4.4	7.3
Copper	0.3	0.4	0.4
Aluminium	0.2	0.2	0.2
Stainless steel	0.1	0.1	0.1

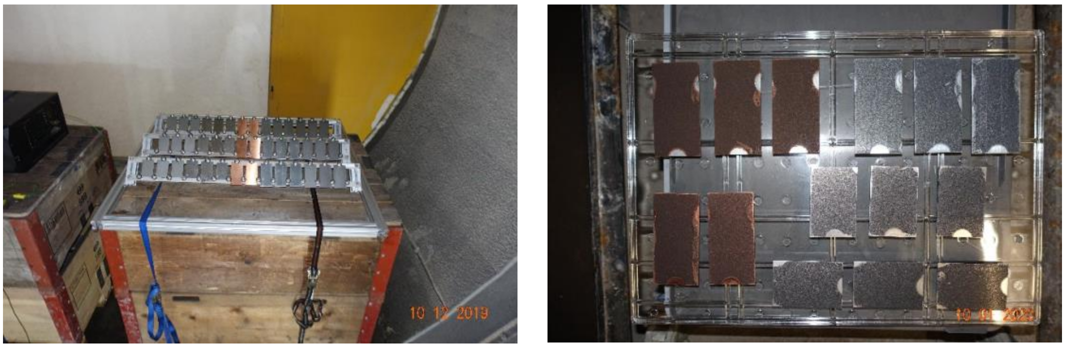

Figure 15 Corrosion monitoring in tunnel ‘A’

Measuring the fire temperatures
The highest measured temperatures occurred at the measuring points T4 (>900°C, 0.4 m above the cell stack) and T7 (>700°C, 0.6 m to the side of the cell stack, on the ground). At a height of 1.5 m above the cell stack, the highest value was 163°C (T8). The highest temperatures at a good distance from the cell stack were 59°C (T5, wooden pallet with PC housing) and 65°C (T6, sample plate). The cables of thermocouples T1, T2 and T3 were damaged by the flames escaping from the side.

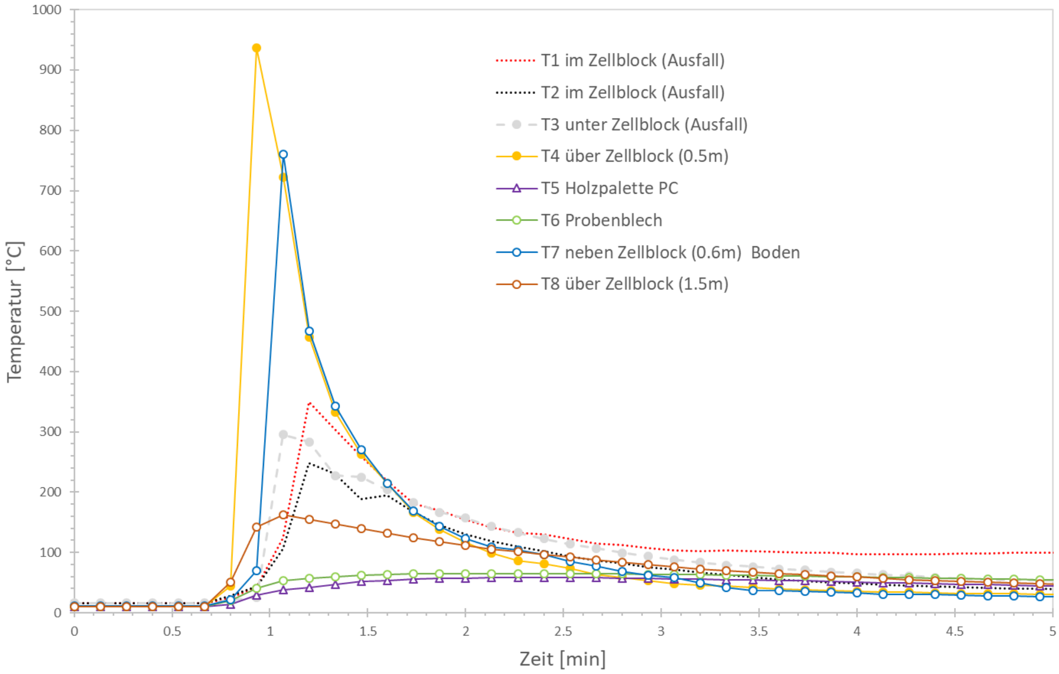

Figure 16 Trend for the fire temperatures in the 'infrastructure and protective equipment' scenario

Findings on electronic test device

All circuit boards and the SIR single measuring comb were covered with a thick layer of fire soot after the fire test (cf. Figure 17, Figure 18 and Figure 19). However, the insulation measurements were in order, i.e. the fire soot did not result in conductive paths between the fingers of the measuring combs. The analysis with SEM/EDX (Hitachi TM3030 plus) primarily showed the heavy metals nickel, cobalt and manganese at the cathode of the battery cells, as well as larger quantities of carbon and oxygen.

Figure 17 PC housing (left) and circuit boards (right) after fire test

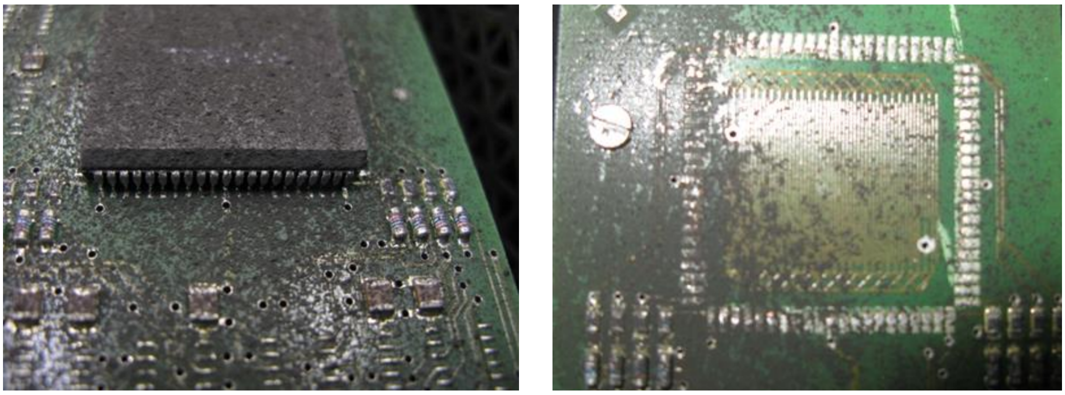

Figure 18 IC on circuit board (left) and exposed SIR single measuring comb (right) after fire test

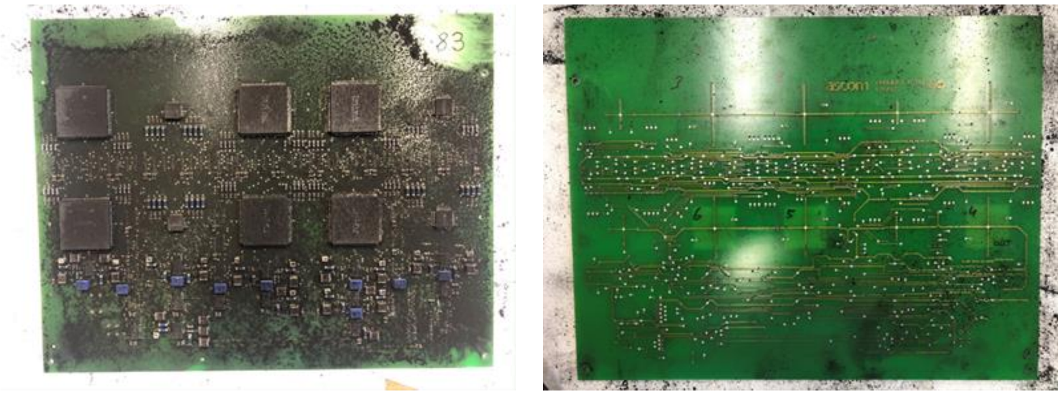

Figure 19 Upper side (left) and underside (right) of circuit board after fire test

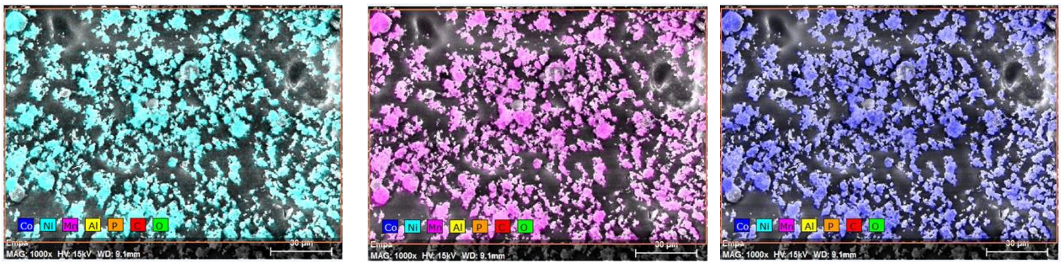

Figure 20 SEM pictures of depositions on the circuit boards; EDX element analysis nickel (left), manganese (centre) and cobalt (right)

Overall assessment

Fire soot – exposure quantities and composition
The fire soot exposure quantities in the test tunnel are at around 20 g/m^2, and the fire soot depositions consist of around 18-20% by mass of the elements Co, Ni, Mn and O, respectively, as well as around 1-5% by mass of the elements Al, C, F and P. In the nitric acid extract of the fire soot depositions, around 17-18 % by mass of each of the elements Co, Ni and Mn, as well as around 3% by mass of the element Li were detected.

Infrastructure – contamination
With a view to anorganic pollutants which are toxicologically relevant and relevant in terms of chemical corrosion, very high exposure quantities of the elements Co, Ni and Mn, each amounting to approximately 150-250 µg/cm^2, of the element Li amounting to around 30-40 µg/cm^2, and of water-soluble fluorides amounting to around 40-50 µg/cm^2 were proven on the collector plates (surfaces tilted by 45°), which exceeded the usual background levels for non-contaminated surfaces by factors up to approx. 2,000 (Co, Ni), 500 (Mn), 400 (Li)

and 50 (fluorides) (cf. Table 42). Only very small amounts (≤5 µg/cm^2) of water-soluble chlorides and bromides were detected, which were negligible from a chemical corrosion standpoint.

Textiles – contamination before and after cleaning
With regard to toxicologically relevant organic pollutants, slightly elevated PAH exposure quantities of approximately 250-300 µg/m^2 were detected, which exceeded the usual background levels for non-contaminated surfaces by factors up to approx. 3 and 30, respectively (cf. Table 43). The PCB and PCDD/F exposure quantities of ≤10 µg/m^2 (PCB) and ≤10 ng/m^2 (PCDD/F) are within the normal range for background levels of non-contaminated surfaces.

With a view to toxicologically relevant anorganic pollutants, very high exposure rates of the elements Co, Ni and Mn amounting to approximately 400 µg/cm^2 for each element, of the element Li amounting to around 70 µg/cm^2 and of water-soluble fluorides amounting to around 50 µg/cm^2 were measured on the *contaminated* textiles (horizontal surfaces), which exceeded the usual background levels for non-contaminated surfaces by factors up to around 4,000 (Co, Ni), 700 (Mn), 700 (Li) and 50 (fluorides) respectively (cf. Table 44). Only very small amounts (≤5 µg/cm^2) of water-soluble chlorides and bromides were detected, which were negligible from a chemical corrosion standpoint.

With regard to toxicologically relevant organic pollutants, slightly elevated PAH exposure quantities of approximately 300 µg/m^2 were detected on the *contaminated* textiles, which slightly exceeded the usual background levels for non-contaminated surfaces by a factor of 1.2 (cf. Table 45). The PCB and PCDD/F exposure quantities of ≤10 µg/m^2 (PCB) and ≤10 ng/m^2 (PCDD/F) are within the normal range for background levels of non-contaminated surfaces.

The above-mentioned toxicologically relevant anorganic and organic pollutants could no longer be detected on the *cleaned* textile surfaces, or only negligible amounts of these substances could be detected.

Infrastructure – corrosion damage
The corrosiveness of the fire gas condensates produced during the battery fire test can be assessed as insignificant overall (cf. [85]) and can be summarised as follows:

- The test metals ‘steel, unalloyed’ and ‘zinc’ show only very weak material abrasion after 3 months of exposure to 90% relative humidity, which is comparable to the abrasion of metals contaminated by a chloride exposure of 5 µg/cm^2 and exposed to 90% relative humidity for 3 months (cf. Figure 21).
- No corrosion-induced material abrasion was detected on the test metals ‘copper’, ‘aluminium’ and ‘stainless steel’ after 3 months of exposure at 90% relative humidity.

Damage to electronics
All the circuit boards in the PC housing were covered with a thick, soot-like layer. All 42 SIR measuring combs and the SIR single measuring comb showed a high insulation resistance (∞) when measured at 500 VDC. The analysis of the depositions using SEM/EDX found considerable amounts of nickel, manganese, cobalt and oxygen as well as small amounts of aluminium. The high insulation resistance is an indication that the heavy metals are present in the form of poorly conducting oxides.

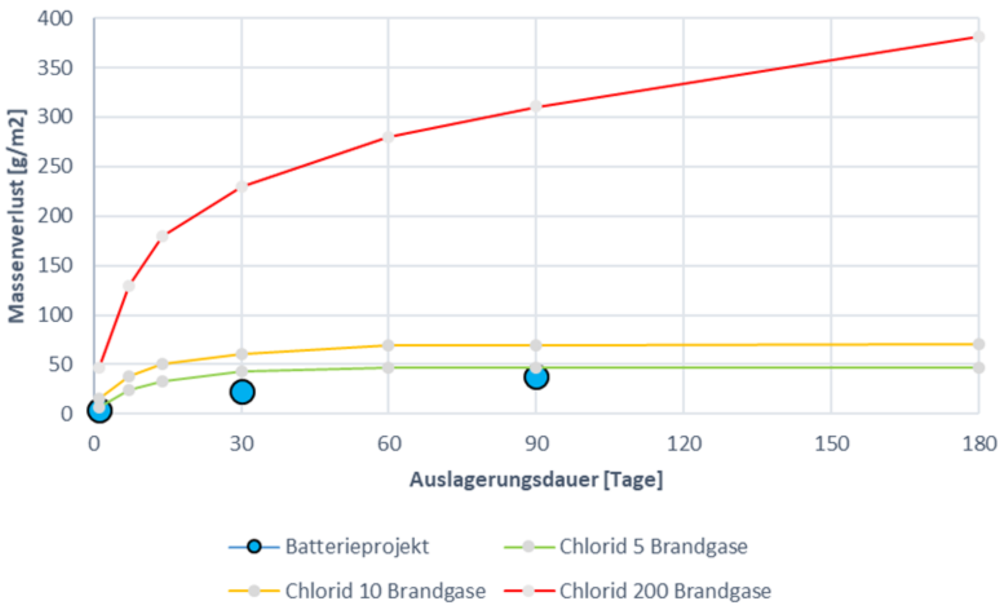

Figure 21 Corrosion-induced material abrasion of unalloyed steel at 90% relative humidity – Comparison of the test results with Empa's test results under exposure to combustion gases containing chloride (chloride exposure quantities of 5, 10 and 200 µg/cm² [85])

4.3 Firefighting water (battery module 2)

Pollutant analyses

The following analyses are based on the measurements carried out on 9 December 2019 at the test site of Versuchsstollen Hagerbach AG using the defined test scenario of Section 3.4.2 and in accordance with the analysis concept documented in Annex II. The full list of samples with explanations is given in Annex III.2.

Table27 Anion levels (water samples) in mg/l

Sample no.	Chloride Cl^-	Bromide Br^-	Fluoride F^-	Sulphate SO_4^{2-}	Nitrate NO_3^-	Phosphate PO_4^{3-}	Formate $HCOO^-$	Acetate CH_3COO^-
Firefighting water								
W-41	2	n.v.	8	34	2	n.v.	n.v.	n.v.
Cooling water								
CW-41	22	n.v.	330	98	n.v.	n.v.	n.v.	n.v.
Blank (process water)								
0W-K	3	n.v.	n.v.	2	n.v.	n.v.	n.v.	n.v.

n.v. = not verifiable (<1 mg/l)

Table 28 Cation levels (water samples) in mg/l

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
Firefighting water						
W-41	n.v.	n.v.	n.v.	4	11	67
Cooling water						
CW-41	16	59	52	1,600	n.v.	n.v.

Table 28 Cation levels (water samples) in mg/l

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
Blank (process water)						
0W-K	n.v.	n.v.	5	n.v.	n.v.	n.v.
n.v. = not verifiable (<1 mg/l)						

Table 29 Co, Ni, Mn and Li levels (water samples, acidulated) in mg/l

Sample no.	Cobalt Co	Nickel Ni	Manganese Mn	Lithium Li
Firefighting water				
W-42	36	36	36	7
Cooling water				
CW-42	50	55	53	1,460
Blank (process water)				
0W-A	<0.4	<0.7	<1.3	<1.3

Table 30 Organic pollutant levels (water samples)

Sample no.	PAH Σ 16 EPA-PAH µg/l	PCB Σ 6 cong. Ballschmiter x 5 ng/l	PCDD/PCDF Σ I-TEQ ng/l
Firefighting water			
W-43	1.9	0.2	0.013
Cooling water			
CW-43	0.11	2.9	n.d.
Blank (process water)			
0W-O	0.06	0.2	0.018
n.d. = not determinable			

Table 31 Co, Ni, Mn and Li levels (suspended particles in water samples) in % by mass

	Cobalt Co		Nickel Ni		Manganese Mn		Lithium Li	
Sample no.	**% by mass**	**mg/l**	**% by mass**	**mg/l**	**% by mass**	**mg/l**	**% by mass**	**mg/l**
Firefighting water								
W-45	21	46	22	48	20	44	1.4	3.1
Cooling water								
CW-45	10	181	10	181	11	199	1.7	31
Proportions of suspended particles: W-45 = 0.22 g/l; CW-45 = 1.81 g/l								

Table 32 Organic pollutant levels (suspended particles in water samples)

	PAH **Σ 16 EPA-PAH**		**PCB** **Σ 6 cong. Ballschmiter x 5**		**PCDD/PCDF** **Σ I-TEQ**	
Sample no.	**mg/kg**	**µg/l**	**µg/kg**	**ng/l**	**µg/kg**	**ng/l**
Firefighting water						
W-43	11	1.8	4.1	0.67	0.20	0.032
Cooling water						
CW-43	3.2	3.4	0.9	0.91	0.92	1.0

Proportions of suspended particles: W-43 = 0.16 g/l; CW-43 = 1.15 g/l

Measuring the fire temperatures

The highest measured temperatures occurred at measuring points T8 (>1,300°C, 2.3 m above the cell stack) and T7 (>1,100°C, next to the cell stack, on the ground). These measurements may have been impaired by the thermal effects of the explosion. At a height of 0.4 m above the cell stack, the highest value was 788°C (T4). The temperatures measured within the cell stack (T1, T2) increased to over 600°C within 143 seconds after detonation, corresponding to a rate of around 4 K/s. The maximum value in the cell stack was 678°C and was achieved after 9.2 minutes (T2). The temperatures in the cell stack dropped slowly from their highest values and only passed below 200°C after approx. 95 minutes. The highest temperatures at a good distance from the cell stack were 69°C (T5, wooden pallet with PC housing) and 74°C (T6, sample plate). The water temperature in the basin rose from 12°C to a maximum of 30°C.

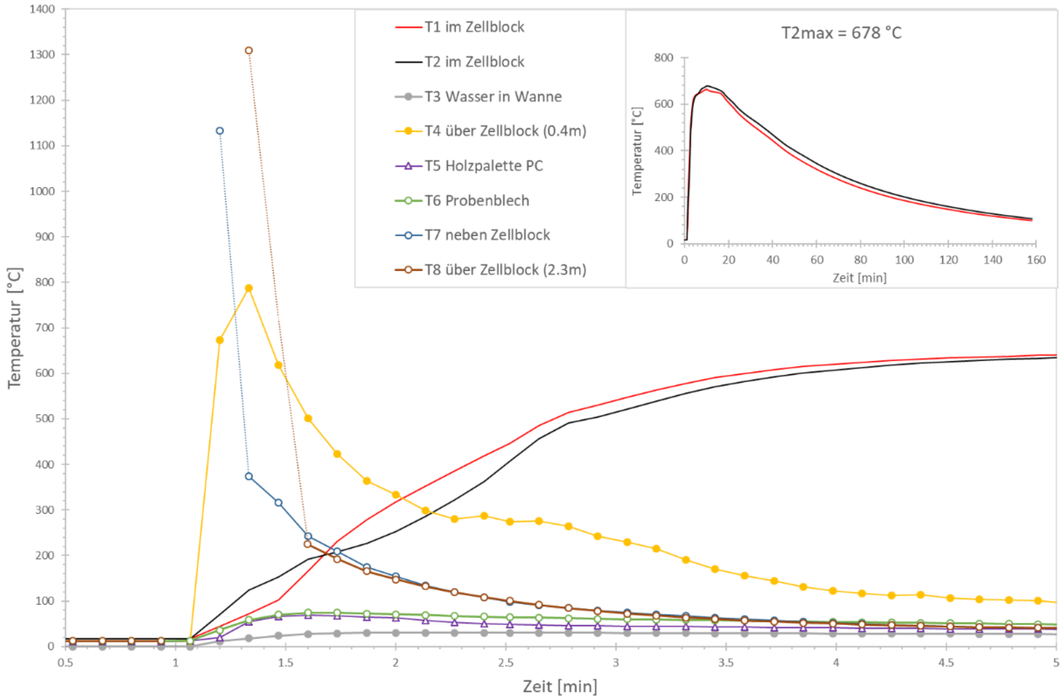

Figure 22 Trend for the fire temperatures in the ‘firefighting water’ scenario

Overall assessment

Firefighting water – contamination

In the firefighting water, which is chemically almost neutral (pH value 8) and has a moderate electrical conductivity of almost 500 µS/cm, only low levels of water-soluble sulphates (34 mg/l), fluorides (8 mg/l), chlorides and nitrates (2 mg/l each) and lithium ions (4 mg/l) were detected by the analysis. The analysed anion and cation levels of sulphates, chlorides and nitrates were well below the limit values for drinking water in Switzerland (cf. Table 48). The analysed fluoride levels exceeded the limit value by a factor of 5. The analysed lithium levels exceeded the typical levels of drinking water in Germany (<0.05 mg/l) by a factor of >80 (a limit value does not exist).

Dissolved organic secondary substances caused by the fire (PAH, PCB, PCDD/F) were detected only in extremely low concentrations of 2 µg/l (PAH; Σ 16 EPA-PAH), 0.2 ng/l (PCB; Σ 6 cong. Ballschmiter x 5) and 0.01 ng/l (PCDD/F; Σ I-TEQ). In the case of PCBs and PCDD/Fs, the concentrations were in the range of the process water used in the extinguishing attempt. In the case of PAHs, the dissolved levels were 30 times higher than those found in process water. The applicable limit values for drinking water were not exceeded in the case of PAHs (dissolved fractions) or were exceeded by a factor of 4 to 7 (particle-bound fractions) (cf. Table 48). PCB concentrations were in the range of typical levels found in Swiss watercourses (dissolved and particle-bound fractions).

The heavy metals Co, Ni and Mn were detected in very high acid-soluble concentrations of 36 mg/l each. The analysed Co, Ni and Mn levels exceed the limit values for drinking water in Switzerland (where they are defined) by factors of 700 to 1,800 (cf. Table 48). The values for introducing fluids into the sewage system for industrial effluent in Switzerland are exceeded by factors of 20 to 70.

Battery cooling water – contamination
In the cooling water of the battery, which has a highly alkaline chemical reaction (pH 12) and very high electrical conductivity of about 35,000 µS/cm, the analysis found very high concentrations of water-soluble fluorides (330 mg/l) and lithium ions (1,600 mg/l) in addition to low levels of water-soluble sulphates (98 mg/l), chlorides (2 mg/l) and nitrates (<1 mg/l). The analysed fluoride levels exceeded the limit value for drinking water in Switzerland by a factor of 220 (cf. Table 48). The analysed lithium levels exceeded the typical levels of drinking water in Germany (<0.05 mg/l) by a factor of >30,000 (a limit value does not exist).

Organic secondary substances caused by the fire (PAH, PCB, PCDD/F) were detected only in extremely low dissolved concentrations of 0.1 µg/l (PAH; Σ 16 EPA-PAH) and 2.9 ng/l (PCB; Σ 6 cong. Ballschmiter x 5) (PCDD/F could not be determined). In the case of PAHs, the dissolved levels were in the range of the process water used in the extinguishing attempt. In the case of PCBs, the dissolved levels are 15 times higher than those found in process water (cf. Table 48). The applicable limit values for drinking water were not exceeded in the case of PAHs (dissolved and particle-bound fractions). The PCB levels exceeded the typical levels of Swiss watercourses (dissolved and particle-bound fractions) by a factor of 5 to 15.

The heavy metals Co, Ni and Mn were detected in very high acid-soluble concentrations of 50 to 55 mg/l each. The analysed Co, Ni and Mn levels exceed the limit values for drinking water in Switzerland (where they are defined) by factors of 1,000 to 2,800. The values for introducing fluids into the sewage system for industrial effluent in Switzerland are exceeded by factors of 30 to 100.

4.4 Transport and deposition behaviour (battery module 3)

Pollutant analyses
The following analyses are based on the measurements carried out on 11 December 2019 at the test site of Versuchsstollen Hagerbach AG using the defined test scenario of Section 3.4.3 and in accordance with the analysis concept documented in Annex II. The full list of samples with explanations is given in Annex III.3.

Table 33 Anion exposure (aqueous extract, surface swipe samples) in µg/cm^2

Sample no.	Chloride Cl^-	Bromide Br^-	Fluoride F^-	Sulphate SO_4^{2-}	Nitrate NO_3^-	Phosphate PO_4^{3-}	Formate $HCOO^-$	Acetate CH_3COO^-
Stainless steel collector plates								
C-11	0.7	n.v.	0.5	1.5	n.v.	n.v.	n.v.	n.v.
D-11	0.6	n.v.	0.3	1.3	n.v.	n.v.	n.v.	n.v.
E-11	0.6	n.v.	0.2	0.9	n.v.	n.v.	n.v.	n.v.
Ventilator surface								
V-11	1.8	n.v.	1.4	3.5	n.v.	n.v.	n.v.	n.v.
n.v. = not verifiable (<0.1 µg/cm^2)								

Table 34 Cation exposure (aqueous extract, surface swipe samples) in µg/cm^2

Sample no.	Ammonium NH_4^+	Potassium K^+	Sodium Na^+	Lithium Li^+	Magnesium Mg^{2+}	Calcium Ca^{2+}
Stainless steel collector plates						
C-11	n.v.	n.v.	1.5	0.3	0.1	0.8
D-11	n.v.	n.v.	1.4	0.2	0.1	0.9
E-11	n.v.	n.v.	1.3	0.1	0.1	0.7
Ventilator surface						
V-11	n.v.	n.v.	3.2	0.9	0.3	3.9
n.v. = not verifiable (<0.1 µg/cm^2)						

Table 35 Co, Ni, Mn and Li exposure (nitric acid extract, surface swipe samples) in µg/cm^2

Sample no.	Cobalt Co	Nickel Ni	Manganese Mn	Lithium Li
Stainless steel collector plates				
C-12	4.5	4.6	4.3	0.8
D-12	4.3	4.3	4.1	0.6
E-12	2.3	2.3	2.2	0.3
Ventilator surface				
V-12	18	19	17	2.6

Table 36 Exposure to organic pollutants (Soxhlet extract, surface swipe samples)

Sample no.	PAH Σ 16 EPA-PAH µg/m2	PCB Σ 6 cong. Ballschmiter x 5 µg/m2	PCDD/PCDF Σ I-TEQ ng/m^2
Stainless steel collector plates			
C-13	8.8	--	--
D-13	7.6	--	--
E-13	5.9	--	--
C-14	--	0.20	0.2

Table 36 Exposure to organic pollutants (Soxhlet extract, surface swipe samples)

Sample no.	**PAH** **Σ 16 EPA-PAH** **µg/m2**	**PCB** **Σ 6 cong. Ballschmiter x 5** **µg/m2**	**PCDD/PCDF** **Σ I-TEQ** **ng/m^2**
D-14	--	1.1	0.2
E-14	--	0.18	0.2
Ventilator surface			
V-13	17	--	--
V-14	--	0.66	0.4

Table 37Fire soot contamination (exposure quantities and analysis of solids, fire soot samples)

Sample no.	**Quantity**	**Composition**
C Tunnel B Stainless steel collector plates Height = 3.5 m Distance 50 metres	0.4 g/m2	Principal constituents: • Co, Ni, Mn (each 7-9% w/w) • O (20-25% w/w), • C and Ca (each 10-15% w/w) Minor constituents: • Si, Al, F (each 1-5% w/w) • Mg, K, P, S, Cl (<1% w/w)
D Tunnel B Stainless steel collector plates Height = 3.5 m Distance 100 metres	0.4 g/m^2	Principal constituents: • Co, Ni, Mn (each 7-9% w/w) • O (20-25% w/w), • C and Ca (each 10-15% w/w) Minor constituents: • Si, Al, Mg, S, F (each 1-5% w/w) • P, Cl (<1% w/w)
E Tunnel B Stainless steel collector plates Height = 3.5 m Distance 150 metres	0.1 g/m2	Principal constituents: • Co, Ni, Mn (each 7-9% w/w) • O (20-25% w/w), • C and Ca (each 10-15% w/w) Minor constituents: • Si, Al, Mg, S, F (each 1-5% w/w) • P, Cl (<1% w/w)

***Table 38 Preliminary chemical analysis (analysis of solids ED-XRF, fire soot samples)** levels specified in % by mass (triple measurement of mean values ± rounded-up standard deviation)*

Substance	**C**	**D**	**E**	**Substance**	**C**	**D**	**E**
Ag	<0.01	<0.01	<0.01	Ni	7.4 ± 0.5	7.4 ± 0.5	7.5 ± 0.5
Al	3.1 ± 0.2	1.9 ± 0.2	2.0 ± 0.2	P	0.4 ± 0.1	0.4 ± 0.1	0.4 ± 0.1
As	<0.01	<0.01	<0.01	Pb	<0.01	<0.01	<0.01
Au	<0.01	<0.01	<0.01	Pd	<0.01	<0.01	<0.01
Ba	<0.05	<0.05	<0.05	Rb	<0.01	<0.01	<0.01
Bi	<0.01	<0.01	<0.01	Re	<0.01	<0.01	<0.01
Ca	14.4 ± 0.5	15.9 ± 0.5	17.2 ± 0.5	S	1.2 ± 0.1	1.1 ± 0.1	1.4 ± 0.1
Cd	<0.01	<0.01	<0.01	Sb	<0.01	<0.01	<0.01

Table 38 Preliminary chemical analysis (analysis of solids ED-XRF, fire soot samples) *levels specified in % by mass (triple measurement of mean values ± rounded-up standard deviation)*

Substance	C	D	E	Substance	C	D	E
Cl	0.2 ± 0.1	<0.2	<0.2	Se	<0.01	<0.01	<0.01
Co	7.5 ± 0.5	7.5 ± 0.5	7.5 ± 0.5	Si	2.8 ± 0.2	3.1 ± 0.2	3.7 ± 0.2
Cr	<0.05	<0.05	<0.05	Sn	<0.01	<0.01	<0.01
Cu	0.2 ± 0.1	<0.2	<0.2	Sr	<0.01	<0.01	<0.01
Fe	1.2 ± 0.1	1.5 ± 0.1	1.6 ± 0.1	Ta	<0.01	<0.01	<0.01
Hf	<0.01	<0.01	<0.01	Th	<0.01	<0.01	<0.01
Hg	<0.1	<0.1	<0.1	Ti	<0.1	<0.1	<0.1
K	0.5 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	U	<0.01	<0.01	<0.01
Mg	<1	<1	<1	V	<0.1	<0.1	<0.1
Mn	8.3 ± 0.5	8.1 ± 0.5	8.0 ± 0.5	W	<0.05	<0.05	<0.05
Mo	<0.01	<0.01	<0.01	Zn	<0.1	<0.1	<0.1
Nb	<0.01	<0.01	<0.01	Zr	<0.1	<0.1	<0.1

Measuring the fire temperatures

The highest temperature measured occurred at measuring point T5 (approx. 850°C, near the cell stack, in the fire cone). From this maximum value, the temperature dropped below 200°C within less than 30 seconds and was under 100°C within around 100 seconds. The temperatures measured within the cell stack (T1, T2) increased to over 600°C within 173 seconds after detonation, corresponding to a rate of around 3.4 K/s. The maximum value in the cell stack was 661°C and was achieved after 10.3 minutes (T2). The temperatures in the cell stack dropped slowly from their highest values and only passed below 200°C after approx. 92 minutes. The highest temperature in the side wall of the cell stack was attained after 240 seconds and was 617°C (T3), although the initial temperature increase in the first 5 seconds was at a rate of 43.6 K/s. A maximum temperature of 395°C was registered under the cell stack after 12 minutes.

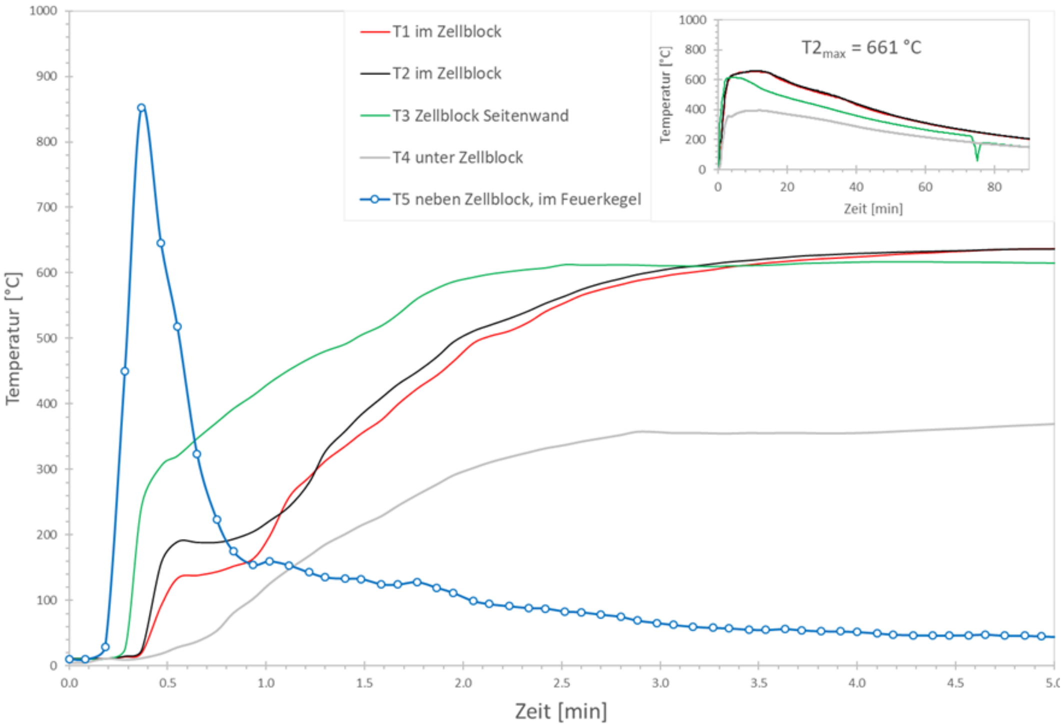

Figure 23 Trend for the fire temperatures in the 'Transport and deposition behaviour' scenario

Overall assessment

Fire soot – exposure quantities and composition

The exposure quantities for fire soot and builder's dust that has been stirred up are <1 g/m² at all sampling points in the test tunnel. The fire soot and builder's dust deposits each consist of around 7-9 % by mass of the elements Co, Ni and Mn, around 10-15 % by mass of the elements Ca and C, around 20-25 % by mass of the element O and are each around 1-5 % by mass of the elements Si, Al, Mg, S and F.

Infrastructure (collector plates) – contamination

With a view to anorganic pollutants which are toxicologically relevant and relevant in terms of chemical corrosion, slightly increased exposure to the elements Co, Ni and Mn amounting to approximately 2-5 µg/cm² each and to the element Li amounting to around 0.3-0.8 µg/cm² were found and analysed on the collector plates (surface tilted by 45°). These exceed the usual background levels for non-contaminated surfaces by factors of around 50 (Co, Ni), 5 (Mn) and 10 (Li) (cf. Table 42). Only very small amounts of water-soluble chloride, bromide and fluoride could be detected which were negligible from a chemical corrosion standpoint: ≤5 µg/cm² (chloride, bromide) and <1 µg/cm² (fluoride).

The PAH, PCB and PCDD/F exposures of ≤10 µg/m² (PAH), ≤1 µg/m² (PCB) and <1 ng/m² (PCDD/F) are within the normal range for background levels of non-contaminated surfaces (cf. Table 43).

Infrastructure (ventilator housing) – contamination

With a view to anorganic pollutants which are toxicologically relevant and relevant in terms of chemical corrosion, high exposure to the elements Co, Ni and Mn amounting to approximately 20 µg/cm² for each element and to the element Li amounting to around 3 µg/cm² were found and analysed on the ventilator housing (horizontal surface). These exceeded the usual background levels for non-contaminated surfaces by factors of around 200 (Co, Ni), 20 (Mn) and 30 (Li) respectively (cf. Table 42). Only very small amounts of water-soluble chloride, bromide and fluoride could be detected, which were negligible from a chemical corrosion standpoint: ≤5 µg/cm² (chloride, bromide) and around 1 µg/cm² (fluoride).

The PAH, PCB and PCDD/F exposures of <20 µg/m^2 (PAH), 0.7 µg/m^2 (PCB) and 0.4 ng/m^2 (PCDD/F) are within the normal range for background levels of non-contaminated surfaces (cf. Table 43).

4.5 Material analysis (battery module 4)

The metallic components in the battery module (battery housing, cell housing) consist of various aluminium alloys. The majority of the plastic components in the battery module (housing, insulation films and cell films) consist of chlorine and bromine-free plastics. Only the cable casings for the battery and cell cables consist of a plastic containing chlorine (PVC). The material characterisation is executed using energy dispersive X-ray fluorescence (ED-XRF).

Table 39 Preliminary material characterisation: plastic components

	Chemical composition expressed in % by mass				
Components	**Cl**	**Br**	**Co**	**Ni**	**Mn**
Housing, black	<0.5	<0.01	<0.05	<0.05	<0.05
Cover, black	<0.5	<0.01	<0.05	<0.05	<0.05
Connector, black	<0.5	<0.01	<0.05	<0.05	<0.05
Battery insulation, white	<0.5	<0.01	<0.05	<0.05	<0.05
Cell film, transparent	<0.5	<0.01	<0.05	<0.05	<0.05
Terminal cover, beige	<0.5	<0.01	<0.05	<0.05	<0.05
Thick cable, orange	28	<0.01	<0.05	<0.05	<0.05
Thin cable, orange	35	<0.01	<0.05	<0.05	<0.05

Table 40 Preliminary material characterisation: metallic components

	Chemical composition expressed in % by mass						
Components	**Al**	**Si**	**Mg**	**Fe**	**Co**	**Ni**	**Mn**
Housing base plate	95	0.2	3.6	0.2	<0.05	<0.05	0.4
Housing front plate	98	0.5	0.6	0.2	<0.05	<0.05	<0.05
Housing side plate	98	1.2	0.6	0.1	<0.05	<0.05	0.05
Housing partition plate	98	1.2	0.4	0.1	<0.05	<0.05	0.06
Battery baffle plate	99	0.2	<0.2	0.2	<0.05	<0.05	<0.05
Battery cell housing	98	0.2	0.5	0.5	<0.05	<0.05	1.1
Battery pole	98	0.9	<0.2	0.3	<0.05	<0.05	1.0

Figure 24 Setup of battery module with investigated components made of plastic and metal

5 Discussion

This experiment has proven that BEV fires involving lithium-ion batteries (NMC type) lead to new forms of pollutant emissions. These change the toxicological risks in underground traffic infrastructures as they do not occur for usual ICEV fires. The thermal effects (>700°C) observed during the experiment also suggest that a fire in a lithium-ion battery would spread to the surrounding bodywork components and, in general, lead to a total vehicle fire. However, once a total BEV fire has occurred, it is not particularly different from an ICEV fire in terms of its thermal characteristics: Experimental studies have shown that fires in comparable electric vehicles and traditional vehicles have a similar thermal power output (approx. 5 MW) and are not influenced by a high-capacity traction battery (cf. [16]; [55]).

The hypothesis that the specific emissions from electric vehicle fires in underground traffic infrastructures can have long-term effects on operation and safety cannot be proven globally as such, and instead must be responded to in a more differentiated manner. The central findings make it clear that fire incidents like these in small or not actively ventilated infrastructures have a different effect as compared to large or mechanically ventilated infrastructures and also contain an object-independent risk:

- In multi-storey car parks, underground car parks or garages, BEV fires increase the safety and operating risks under certain conditions. In terms of toxicology, these fires have an impact on decontamination and disposal work in particular; technical impairments due to corrosive damage are unlikely.

- In road tunnels, it can practically be excluded that critical contamination, technical impairments due to corrosive damage or atypical reductions in safety or operations would occur following a BEV fire incident. In terms of toxicology, the decontamination and disposal work can however be influenced by this (e.g. personal safety, detention and correct disposal of the wash water).

- BEV fires lead to lithium and heavy metal concentrations in firefighting and cooling water which exceed, many times over, the applicable and/or currently available limit values for introducing it into the sewage system. This fact makes the relevant treatment process of both the firefighting and cooling water absolutely imperative before introducing them into sewage fluids in practice.

The findings from the experiment are discussed in the following chapters using essential questions in order to better classify the findings. Unless otherwise mentioned, it must be assumed that the incident response on the one hand and the subsequent decontamination on the other have always been performed professionally and in accordance with current state-of-the-art techniques.

5.1 Impact on safety and operations

Do the measured pollutants also occur in conventional vehicle fires?
No. The heavy metals cobalt, nickel, manganese and lithium are substances that do not occur in conventional vehicles with combustion engines, or, if they do occur, they do not occur in great quantities, neither in the vehicle's superstructure nor within the drive system. Therefore, they are not emitted in this case, even in the event of a total fire.

A recent fire incident in Switzerland really drove this point home (cf. Table 41): After a depot fire in February 2020 which involved seven completely burned-out delivery vans with conventional combustion engine drive systems, no noteworthy concentrations of heavy metals could be detected in the fire residue. In this incident, the measurements were taken using identical methods and by the same person executing this present project. The measured concentrations of pollutants were many times smaller than they were in this current experiment, which is based on just one lithium-ion battery (cf. Table 41).

Table 41 *Specific comparison of pollutants present in a BEV fire and an ICEV fire*

	Pollutant concentrations following a	
Substance	**BEV fire in μg/cm^2 (experiment)**	**ICEV fire in μg/cm^2 (real fire)**
Cobalt	155 – 400	0.2
Nickel	156 – 400	0.3
Manganese	148 – 380	3
Lithium	30 – 70	1.2
Fluoride	40 – 52	0.5

The heavy metals cobalt, nickel and manganese as well as fluoride and lithium emissions which have already been described in the previous project ([59]) and which have been reconfirmed in this one can thus be designated BEV-specific pollutants, as they did not have to be considered within the context of ICEV fires up until this point. Naturally, this statement is dependent upon the chemical composition of the traction battery and is particularly relevant for the NMC battery type. However, it is still admissible as currently the batteries in most BEVs worldwide utilise these substances in their active cathode materials in comparable ratios to those stated here.

Are the measured quantities of pollutants even relevant?

Yes, the concentrations of pollutants must be noted because they do not occur in conventional ICEV fires and thus present an additional hazard. They are also relevant because they exceed the background levels for non-contaminated surfaces, particularly those in smaller infrastructures, multiple times over (cf. Table 42). At this juncture, fluoride, lithium and PAH contamination in particular, along with the heavy metals cobalt, nickel and manganese, must be observed (cf. Table 43). These BEV-specific substance groups are hazardous for humans from a toxicological point of view and can thus lead to aggravation of the risks in underground infrastructures. The established contaminations can be considered to be representative for the situation which occurs following a BEV fire on the parking floor of an underground car park with a volume of approximately 2,000 m^3 (approx. 28 x 28 x 2.5 m).

Table 42 *Potential contamination in an underground infrastructure (≈ 2,000 m^3) without mechanical ventilation and background values for non-contaminated surfaces (Empa empirical values)*

Elements	**Measured values for tunnel A in μg/cm^2**	**WEL values in mg/m^3**	**Background levels in μg/cm^2**	**Quotient (measured values/background levels)**
Co	155 – 400	0.05	<0.1	≈ 1,500 – 4,000
Ni	156 – 400	0.05	<0.1	≈ 1,500 – 4,000
Mn	148 – 380	0.5	<1	≈ 150 – 400
F	40 – 52	1	<1	≈ 40 – 50
Li	30 – 70	0.2	<0.1	≈ 300 – 700

Table 43 *Potential contamination in underground infrastructure (≈ 2,000 m^3) without mechanical ventilation and PAH, PCB and PCDD/F exposure on non-contaminated surfaces (in accordance with VdS 2357, [35])*

Compounds	Measured values for tunnel A	Background levels for industry	Residential /office background levels	Quotient (Measured values/background levels for industry)
PAH Σ 16 EPA-PAH	269 – 304 µg/m2	<100 µg/m2	<10 µg/m2	≈ 2.7 – 3
PCB Σ 6 cong. Ballschmiter x 5	0.22 – 9.6 µg/m2	<<100 µg/m2	<<100 µg/m2	<<1
PCDD/F Σ I-TEQ	6.3 – 8.4 ng/m2	<50 ng/m2	<10 ng/m2	<1

However, these statements can be relativised. The measurements in the present experiment were in fact executed in a space where the traction battery was exposed, meaning that it was not installed in a vehicle. The cover of the battery, which was missing due test-related reasons, provided favourable conditions for the pollutants to spread immediately and without hindrance within the space. In a real fire incident with a BEV in which a traction battery would typically be solidly installed in the vehicle due to safety reasons, we can assume that the pollutants would not be able to disperse so easily in the environment. We can assume that notable portions of the pollutants would be deposited inside the vehicle superstructure, which would reduce widespread contamination within the infrastructure. A trial using a mock-up vehicle would have to be executed to verify this assumption.

Is personal safety impaired?
In terms of people directly affected by the fire incident – no. The pollutant emissions from a vehicle fire have always been hazardous and, under certain circumstances, can even be lethal. Regardless of the drive type or energy storage technology in the vehicle, the top-priority objective will always be to ensure that people leave the hazardous zone and reach safety as quickly as possible. In a real fire incident involving a BEV, it can therefore be assumed that vehicle occupants escaping the hazardous situation, either unaided or with the aid of other parties, must take place as quickly as possible, just as it must for conventional vehicle fires. Basic personal safety of those directly affected should thus not be further impaired by the additional chemical hazards. The typical tolerance and resuscitation limits for the fire brigade (the standard for content of combustion gases in a fire room [30]) continue to be valid and shall be applied, as previously, as guideline times for fire brigades.

The safety of indirectly affected persons can, however, be impaired – the operating, decontamination and disposal personnel constitute a focal group here. The persistent heavy metal emissions can be carried via ventilation channels or firefighting water and be deposited in other locations over long periods of time and, in the worst case, can accumulate (cf. Section 4.1). If this remains undetected and untreated, this potentially displaced contamination can impair personal safety in the long term, namely when people come into contact with locations that have been polluted by the contaminants at a later point in time, without prior knowledge or without implementing suitable protective precautions (e.g. operating personnel could experience this when cleaning ventilation channels). Here, however, the extent of the problem is perceived as smaller in large underground traffic infrastructures such as tunnels or car parks, with professional organisation and regular operating procedures; it is suspected that small areas will experience greater issues here, such as underground car parks or private garages, which are often operated with less resources and effort and which may not always be decontaminated correctly and in line with the latest state-of-the-art techniques after an incident.

The second issue in conjunction with this are, as ever, the widespread and contradictory recommendations for fighting a lithium-ion battery fire. When fighting the fire and decontamination work is executed with insufficient or even entirely without protective precautions, not being aware of the additional chemical hazards can significantly impair personal safety.

Table 44 and Table 45 illustrate that firemen's protective suits can become heavily contaminated by battery-specific pollutants during a fire incident. It is evident that exceeding concentrations of these pollutants, which can be absorbed by people via their respiratory tracts, mucous membranes and even skin contact, to this extent would result in long-term damage in unprotected cases. Cobalt and nickel oxides are also designated 'sensitisers': They can (even when exposure to them is brief) elicit immune reactions (type IV hypersensitivity) via the skin. Some studies further indicate that they can also produce this reaction via the respiratory tract.

***Table 44** Potential contamination of textile protective equipment and background values for non-contaminated surfaces (Empa empirical values)*

Elements	Measured values for in µg/cm^2	WEL values in mg/m^3	Background levels in µg/cm^2	Quotient (measured values/background levels)
Co	400	0.05	<0.1	≈ 4,000
Ni	400	0.05	<0.1	≈ 4,000
Mn	380	0.5	<1	≈ 700
F^-	46	1	<1	≈ 50
Li	70	0.2	<0.1	≈ 700

***Table 45** Potential contamination of textile protective equipment and background levels of PAH, PCB and PCDD/F exposure on non-contaminated surfaces (in accordance with VdS 2357, [35])*

Compounds	Measured values for	Background levels for industry	Residential /office background levels	Quotient (Measured values/background levels for industry)
PAH Σ 16 EPA-PAH	120 µg/m2	<100 µg/m2	<10 µg/m2	≈ 1.2
PCB Σ 6 cong. Ballschmiter x 5	0.26 µg/m2	<<100 µg/m2	<<100 µg/m2	<< 1
PCDD/F Σ I-TEQ	3.4 ng/m2	<50 ng/m2	<10 ng/m2	< 1

However, it must be stressed that, in principle, both the Swiss emergency personnel and the professional fire damage restoration and decontamination companies and the disposal companies have appropriate protective equipment and the specialist knowledge required to undertake these tasks. It is also true that the established cleaning processes for contaminated textile protective equipment following a fire incident are also sufficient for BEV-specific contamination: The anorganic and organic pollutants could no longer be detected on the cleaned textile surfaces, or only negligible amounts of these substances could be detected. Therefore, no new recommendations or measures must be established for BEV fire incidents. The current recommendations and measures are sufficient but must be viewed as mandatory and implemented as such.

Do air pollutants pose new hazards to the environment?

No. In the event of a total BEV fire, many more toxic combustion gases will be emitted in quantities which exceed the additional battery-specific pollutants by far. In addition, significant attenuation effects occur in large or mechanically ventilated infrastructures while the fire incident is taking place, meaning that it is unlikely that the ambient air is filled with critical concentrations of new types of substances. The test of battery module no. 3 further illustrates this fact (cf. Table 46): Only a fraction of the heavy metal concentration in the unventilated, smaller test space could be proven when the experiment was executed in a ventilated test space with dimensions that were similar to those of road tunnels. As soon as these emissions reach the open air, they are rarefied further, meaning that they can no longer be designated relevant in terms of causing harm to the environment.

Table 46 *Volume-dependent and ventilation-dependent rarefication effects during a BEV fire in underground infrastructures*

	Measured values in μg/cm² within		
Elements	**unventilated space (tunnel A)**	**ventilated space (tunnel B)**	**Quotient (Tunnel A/B)**
Co	155 – 400	2.3 – 18	≈ 9 – 174
Ni	156 – 400	2.3 – 19	≈ 8 – 171
Mn	148 – 380	2.2 – 17	≈ 9 – 173
Li	30 – 70	0.3 – 2.6	≈ 11 – 233

Are new environmental hazards posed by the uncontrolled draining of firefighting water?

Yes. The water that is used by the fire brigade when fighting a BEV fire incident will be very heavily contaminated with battery-specific substances, including heavy metals in particular. The high measured concentrations of cobalt, nickel and manganese exceed the limit values for drinking water in Switzerland (where they are defined) by factors of 700 to 1,800; the limit values for discharging fluids into the sewage system for industrial effluent in Switzerland are exceeded by factors of 20 to 70 (cf. Table 48). These findings underscore the importance of appropriate firefighting water treatment during and after handling an incident. As retention and control of firefighting water are already part of the regular incident procedure for the Swiss fire brigade ([31]; [32]), it should be possible to mitigate the environmental risk posed by draining water after a BEV fire. The objective is always to comply with the legally stipulated water contamination prevention measures.

On federal roads, this environmental hazard is also minimised by road surface water treatment plants (SABAs), which are becoming more and more ubiquitous. Under the Water Protection Act provisions as issued by the Swiss Federal Council, these special purification plants must be set up on roads that experience heavy traffic and are also capable of purifying water contaminated with heavy metals and PAHs via transportation and retention methods and by implementing efficient filter systems ([5]). As implementing SABAs is also intended for managing vehicle accidents and hazardous incidents involving chemical pollutants, the risk of the uncontrolled draining of firefighting water during a BEV fire incident is categorised as low; current knowledge states that in the event of a BEV incident, it is recommended that the SABA be set to emergency mode as a preventive measure. On sections of national roads in which drainage takes place in a decentralised manner via the hard shoulder (cf. Figure25), i.e. without a SABA, appropriate measures for treating firefighting water must always be implemented in the event of an incident due to the battery-specific substances which could be present.

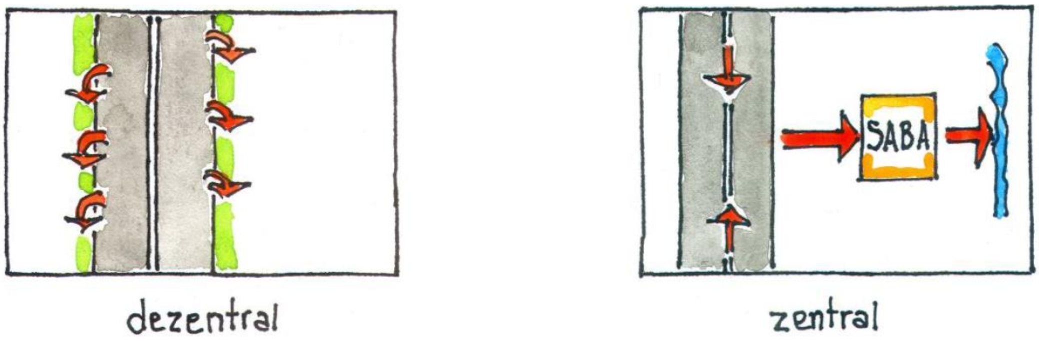

Figure25 Decentralised elimination via bank (left) and centralised elimination of surface water by SABA (right) ([5])

A check must be carried out in each individual case to see whether special secondary treatment of banks and grass verges along a road that has been affected by a BEV incident. Special secondary treatment is not necessarily mandatory based on the risks present: These surfaces are, in principle, already heavily contaminated by splashing and scattering of other pollutants due to traffic (including heavy metals and PAHs). Contaminated firefighting water that flows off via the bank after a BEV fire would thus lead to an increase in pollutants in areas of the road systems that were already pre-contaminated anyway [3] (cf. [5]).

What happens to the cooling water for an accident-damaged lithium-ion battery?
Yes, the cooling water can pose potential risks to the environment. The current practice recommendation for damaged traction batteries states that complete flooding should be carried out in a dip tank and this should be monitored over several days. The objective here is to slow down the chemical reactions and, in particular, to prevent overheating of cells that are still intact – in ideal cases, the chain reaction can be interrupted. Cells that have already been damaged will react to exhaustion and burn out despite water cooling (non-extinguishable lithium-ion battery fires, cf. Section 2.2). If a damaged or completely burned out traction battery is stored using this method for a few days, then the cooling water will penetrate the entire battery and come into contact with all of the substances contained within it. Due to this, numerous substances are dissolved in the water, changing its almost neutral pH value (pH ≈ 8) to an extremely basic solution (pH > 12) (cf. Table 47).

Table 47 Electrochemical characteristics (water samples)

Sample no.	pH value (23°C) (DIN 19268)	Electrical conductivity µS/cm (25 °C) (DIN EN 27 888)
Firefighting water (W-41)	8.2	488
Cooling water (CW-41)	12.3	35,200
Blank (process water) (0W-K)	8.0	421

The established fluoride, lithium and heavy metal contents in the cooling water exceed the limit values or typical contents for drinking water in Switzerland and/or Germany several times over: fluoride >220, lithium >30,000, cobalt, nickel and manganese >1,000-2,800 (cf. Table 48). The values for introducing fluids into the sewage system for industrial effluent in Switzerland are exceeded by factors of 30 to 100.

Due to the fact that no standardised information has been created for transferring and post-treatment processes for accident-damaged traction batteries at present, they are currently stored in very different locations. From professionally operated accident management facilities to unmonitored skips on gravel areas close to a protected area, anything is possible. Therefore, we must assume that disposing heavily contaminated cooling water will also be handled in very different ways and, in a worst-case scenario, will be undertaken without any protective precautions. Based on the current state of knowledge, we must assume that simply discharging cooling water contaminated in this way into the environment can have consequences that cannot yet be estimated and which in turn are dependent on the relevant location (e.g. urban or rural locations, protected areas, etc.). Here, it must be noted in particular that some materials are carcinogenic, are present in their elementary form, are not degradable and can accumulate in the environment. The importance of appropriate disposal cannot be emphasised enough in this situation also.

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[3] Surface water is, in principle, considered very polluted when it experiences average daily traffic of > 14,000 vehicles ([5]).

***Table 48** Comparison of measured test values with limit, guideline and background values for water*

	Test values				
Criterion	**Firefighting water**	**Cooling water**	**Process water**	**Drinking water limit values (1)**	**Discharge limit values for industrial effluent (2)**
pH value	8.2	12.3	8.0	6.8 – 8.2	6.5 – 9.0
Chloride (mg/l)	2	22	3	250	not specified
Sulphate (mg/l)	34	98	2	250	not specified
Nitrate (mg/l)	2	<1	<1	40	not specified
Phosphate (mg/l)	<1	<1	<1	1	not specified
Fluoride (mg/l)	8	330	<1	1.5	not specified
PAH(c) (µg/l)	0.001 (a) 0.36 (b)	0.02 (a) 0.02 (b)	0.001 (a) <0.001 (b)	0.1	not specified
Benzo[a]pyrene (µg/l)	<0.001 (a) 0.07 (b)	0.004 (a) 0.01 (b)	<0.001 (a) <0.001 (b)	0.01	not specified
Cobalt (µg/l)	36,000 (a) 46,000 (b)	50,000 (a) 181,000 (b)	<400	not specified (≤70)	500
Manganese (µg/l)	36,000 (a) 44,000 (b)	53,000 (a) 199,000 (b)	<1,300	50	not specified
Nickel (µg/l)	36,000 (a) 48,400 (b)	55,000 (a) 181,000 (b)	<700	20	2,000
Lithium (µg/l)	7,000 (a) 2,200 (b)	1,460,000 (a) 31,000 (b)	<1,300	not specified (≤40)	not specified

(a) Content, dissolved/ (b) Content, particle-bound/ (c) Sum of Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[ghi]perylene, Indeno[1,2,3-cd]pyrene

(1) Limit values for drinking water in Switzerland in accordance with the Decree of the Swiss Federal Department of Home Affairs (EDI) regarding the water and drinking water in baths and shower facilities that are accessible to the public (TBDV) (2016)

(2) Discharge limit values for industrial effluent into Swiss sewage system in accordance with the Swiss Waters Protection Ordinance (GSchV) (2014)

Colour code key for the table:

- *green = lower than limit value for drinking water*
- *yellow = up to 10x over the limit value for drinking water*
- *orange = 50x to 200x over the limit value for drinking water*
- *red = >500x over the limit value for drinking water*

Does the decontamination work mean that areas/facilities need to be blocked off for longer?

No. Professionally operated underground traffic infrastructures are, in any case, comprehensively sanitised after a fire incident. As every fire in a road tunnel or a car park could potentially impair operations on a long-term basis, the commissioned fire damage sanitisation officers will decide on the appropriate measures and the sequence in which they are implemented in each individual case on-site and based on the incident. The objective of each sanitisation process is to ensure correct removal of fire residue such as soot, fire condensates or contaminated wash water and thus to minimise the potential secondary damage following a fire incident.

In the present project, a very heavily contaminated trial area (tunnel A) was comprehensively cleaned with a typical procedure for spaces such as these. Samples of points on the tunnel walls that were heavily contaminated prior to the test have now confirmed that the BEV-specific emissions can also be sufficiently removed with conventional sanitation methods and that the amount of resources and effort involved remain the same as usual. Following cleaning, all concentrations, particularly those for heavy metals and fluoride and lithium, were under the empirical background levels that are drawn on by the entire industry as actual target values.

Naturally, with an increase in BEV traffic and the observable trend towards taking traffic underground, new risks result for infrastructure operators. Simultaneously, they are exposed to increasing pressure to keep their infrastructures available and to open them again quickly following any hazardous incidents. Long downtimes and additional costs due to decontamination work that needs to be more thorough following a BEV fire are consequences that operators of city infrastructures with typically high traffic volumes and a relatively high amount of BEVs in particular definitely need to avoid. Due to the confirmed efficacy of the conventional sanitation measures, the all-clear can be given here. We do not need to assume that more extensive decontamination work needs to be carried out for a fire incident with BEV involvement as compared to the previously required standards. Therefore, longer periods during which the infrastructures are blocked off due to this and extended interruptions in operations or even periods of complete unavailability are unlikely, as long as the sanitation measures are implemented appropriately, systematically and using state-of-the-art techniques.

Are asset values of components and technical facilities decreased to an excessive extent?
No. The investigations into corrosive damage of different metallic materials did not supply any significant findings. No atypical material abrasion was noted, neither directly after exposure nor after three months of storage at different air humidities (cf. Table 26). Due to the established contaminations, technical impairment (corrosion damage of metallic components, damage to electronics) of typical infrastructure components in underground car parks or road tunnels can be practically excluded. Thus, we can assume that BEV fire incidents that occur in road tunnels and multi-storey car parks do not increase corrosive environments in any case and thus that the asset values of components and technical facilities are not decreased to an excessive extent.

5.2 Effects on incident response

Do processes within incident response need to be adapted?
No. Incident response in road tunnels or car parks by emergency personnel and subsequent fire damage sanitation units do not need to be fundamentally altered. If implemented in accordance with current state-of-the-art practice, techniques and technology, the guide times and recommendations that have applied up until now shall continue to suffice in order to ensure safe, secure responses to the thermal and, specifically, the chemical risks of BEV fires. The importance of appropriate sanitation has not changed at all due to the change in the risk landscape for underground traffic infrastructures: By implementing suitable measures in an ordered sequence, it will also be possible to cushion the impact of subsequent risks and thus minimise the long-term effects of BEV fires in the future.

At this juncture, we must however restate the importance of a continuous transfer of knowledge between all those involved in incident response. Various circles at home and abroad emphasise again and again that the high amount of confusion in the professional handling of battery-powered vehicles involved in accidents means that the exchange of knowledge must be rendered more intensive and supported more broadly: Currently, particularly for towing services or normal scrap dealers, there is often insecurity, meaning that smooth and, most importantly, standardised operating processes are not always assured (cf. [77]). This results in the risk that transportation, storage and disposal of wrecked battery-powered vehicles are not executed correctly and that additional risks could result from this (see sections on personal safety and environmental hazards in Section 5.1).

Due to the few incidents that have occurred as of now, practical experience in handling BEV fires in underground infrastructures has not yet had the chance to broadly mature.

Nevertheless, it is important that prior knowledge that has been collected, even if it is sparse, is prepared and shared with the relevant interested parties as best-practice guidelines. On an international level, some recommendations and codes of practice for fire services are available, but they do not place the focus on the potential long-term consequences of a fire event and do not examine the risks in underground infrastructures specifically (cf. [27]; [29]; [48]; [90]). This means that it is of great importance that scientific findings from applied research projects are united with experience from practice and are formulated into practical recommendations for measures.

Does the use of water as a means to fight fires in closed infrastructures need to be reviewed?

No – water remains the best means to fight a BEV fire. Due to their chemical properties, burning lithium-ion batteries cannot be extinguished as such. During a thermal runaway, the oxygen that is required for a combustion reaction is created by the active cathode material of the battery cells themselves, which means that the fire will keep itself going as long as active cathode material is present. Suppression of the oxygen supply by applying water, even complete soaking of the entire battery, therefore does not lead to extinguishing of the fire (cf. also [34]) – cells that are already damaged will react to exhaustion.

Burning traction batteries can only be 'cooled down', and water is still the best coolant for lithium-ion battery fires. Fighting such fires with water has the objective of cooling the undamaged cells of a battery effectively and preventing them from undergoing a delayed thermal runaway. In any case, the issue standing in the way of efficient cooling with water is that a traction battery in a typical electric vehicle is difficult to access. A potential solution is found in special, usually closed ports on the vehicle which can be opened and enable the fire brigade to feed the water supply directly into the battery space. As far as is currently known, the only average BEV for road traffic with flooding fixtures such as these is the Renault Zoe 50 (cf. Figure 26).

Figure 26 Rescue data sheet for the Renault Zoe 50 stating the specific fire service access point and the recommendation to use water to fight the fire ([69])

In theory, there are two main hazards for fighting fires stemming from burning lithium-ion batteries in closed spaces: One is the potential accumulation of hydrogen. In the present experiment, however, no critical H2 concentrations were measured during the test with water ingress in a non-ventilated test space (cf. Section 3.4.2). Despite this, the possibility that this could be attributed to the precautionary measures for the test (cf. Section 3.5) means that it cannot be concluded that hydrogen accumulation would be a risk that could be neglected. It is a chemical fact that lithium and water react to form gaseous hydrogen as soon as they come into direct contact with each other. The extent to which flammable ratios of this mixture then occur within a room is dependent on many factors and cannot be predicted. Due to the huge potential for damage, when responding to a BEV fire in underground infrastructures, it must be assumed that H_2 has accumulated and the relevant prevention measures (e.g. mobile fans) must be taken as always. For this reason, the implementation of piercing nozzles is not recommended, at least not in closed spaces: When this extinguishing technique is implemented, the piercing tip of the nozzle is plunged into the battery cells and the extinguisher water enters into direct contact with the cell chemical reaction, which can lead to the formation of critical gas mixtures under certain circumstances.

On the other hand, different investigations, including experimental ones, have indicated the potential hazard posed by hydrogen fluoride (HF) in conjunction with using water to fight fires from batteries (cf. [16]; [34]; [55]; [82]). The conducting salt lithium hexafluorophosphate $LiPF_6$ which is often contained in electrolytes reacts with water to form hydrofluoric acid, which is very toxic to people and to the environment. The formation of hydrofluoric acid could, however, not be proven in critical quantities in the preceding project of the present experiment: The analyses from the first experiment showed formation of just under 40 g HF/kWh ([59]). These results are backed up by the information gleaned from other studies as described in Section 2.2 but cannot be designated as critical and also cannot be stated as valid under the current state of knowledge. The extent to which they can be attributed to the specific test layout (e.g. measurement sequence, air ratios in test space) is currently unknown and would have to be investigated further. However, due to the toxicity and the incumbent potential for damage to people and the environment, appropriate precautionary measures continue to be indicated for the fire brigade in the event of an incident, as they are for hydrogen accumulation (e.g. firefighting water, ventilation).

5.3 Recommendations for measures

Different recommendations for action can be derived based on the above assessments of impact. These primarily affect organisational measures and can be structured as follows, according to the influence that they have on the risk, in descending order:

***Table 49** Measures for minimising the risks of electric vehicle fires in underground traffic infrastructures*

#	Measure	Type	Influence on risk
1	Mandatory retention and environmentally correct and professional disposal of firefighting water in accordance with the applicable provisions	Organisational / technical	Minimises damage
2	Definition of a safe process for handling cooling water and immediate implementation in practice	Organisational	Minimises damage
3	Standardisation of the handover process for accident-damaged traction batteries	Organisational	Minimises damage
4	Risk-based siting of charging stations in multi-storey car parks	Organisational	Preventative
5	Consideration of further fire protection measures in smaller infrastructures	Technical	Preventative / minimises damage
6	Integration of new drive technology into risk models	Technical	Preventative

Mandatory retention and correct environmentally friendly and professional disposal of firefighting water in accordance with the applicable provisions
Firefighting water used during a BEV fire is heavily contaminated. As the concentrations of lithium and the heavy metals cobalt, nickel and manganese in the firefighting water and cooling water for the battery module will exceed the applicable and/or currently available limit value concentrations for discharging water into the sewage system multiple times over, appropriate pre-treatment of the firefighting and cooling water must be implemented in practice before it is discharged into other sewage fluids. Therefore, it is urgently recommended that the standard implementation regulations and principles for CBRN defence are applied and that waste such as effluent are disposed of in an environmentally friendly and professionally correct manner in accordance with the provisions (cf. also [31]; [32]). On national roads with SABAs present, accident damage operations and incident response in

accordance with the applicable accident damage management concept are recommended following a BEV incident (cf. [5]).

Definition of a safe process for handling cooling water and urgent implementation in practice

In many European countries, the current practice recommendation following a BEV fire incident is as follows: 'Recover, submerge in water, cool and observe'. Sometimes, specially manufactured containers for the fire services are used for this[4], sometimes more pragmatic solutions are implemented [5] (cf. Figure 27). In any case, a considerable amount of cooling water (up to 20 m^3) must be reckoned with, and this can be heavily contaminated with pollutants, as stated above (cf. Section 4.3). It is true that the methods are not currently standardised and that a safe procedure for the resulting cooling water is not currently defined. This must change.

Figure 27 Solutions in current practice for cooling accident-damaged BEV wrecks (for sources see footnotes4 and [5])

Currently, it cannot be predicted where and by whom vehicles that have been cooled in this way following an accident will be stored. Due to risk considerations, it must be assumed that the cooling water will not be disposed of in a standardised manner and will not always be disposed of professionally and correctly. Due to the potential hazards posed to humans and the environment, it is therefore recommended that a standardised procedure be defined for handling water-cooled BEV wrecks. The processes for transportation and storage and, in particular, the disposal must be described in the form of a guideline and the responsibilities must be clearly assigned. It is recommended that all potential participants, i.e. fire services, towing services, vehicle recyclers, scrap dealers, etc. are integrated in the drafting process for recommendations at an early stage. This ensures that the definition of a safe process for handling contaminated cooling water is observed and also implemented once it has been created.

Standardisation of the handover process for accident-damaged traction batteries

In contrast to the test material for the present research project, in the majority of cases, traction batteries are not completely reacted to exhaustion and chemically inert following a real mechanical or thermal damage incident. If traction batteries are, for example, cooled by emergency personnel using water in the event of a vehicle fire, the battery cells may be in a temporarily supressed state. Earlier attempts have illustrated that this state cannot be reliably verified when it is observed externally (cf. [59]). Studies have also proven that even when the battery state is apparently stable, the exothermic reactions can lead to significant local heating hours or even days after undergoing stress and thus to another transition into an uncontrollable state.

This means that damaged cells or cells not completely reacted to exhaustion in a lithium-ion battery can repeatedly and without any warning signs emit substances that are hazardous to health or could even burst into flames again. Furthermore, after an accident incident

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[4] https://www.blubox.ch/download/firebox-flyer.pdf

[5] https://www.moto.ch/gefaehrliche-elektrofahrzeuge/

involving an electric vehicle, there is the latent hazard of an electrical voltage being present. Battery cells not completely reacted to exhaustion can absolutely still have relevant cell voltages which can accumulate to produce fatal direct-current voltages, particularly in combination with other battery cells that could still be intact. This direct-current voltage can be transferred to vehicle components by the damaged battery and thus put persons who come into contact with the affected vehicle components at risk.

From the point of view of emergency personnel, it is therefore eminently important that we can assume that damaged traction batteries no longer pose chemical or electrical hazards (cf. [21]). Currently, there are no standardised procedures for limiting risks here. Emergency personnel and also towing services and vehicle recyclers are currently called upon to exercise general caution with accident-damaged traction batteries and car wrecks (cf. [13]; [20]; [26]; [28]; [57]). Due to a lack of experience and specifications, there are currently different concepts in use for the correct manner in which to handle damaged chemical energy storage carriers, and there is also a certain level of uncertainty.

In terms of the handover and further treatment of accident-damaged traction batteries and electric vehicles, more clarity and legal certainty must be created. This is a necessity for all persons involved. The Swiss trade association for road assistance (ASS) has launched a recommendation for handling BEV vehicles and a handover report in cooperation with the fire brigade, police, insurers, recyclers and disposal services. Recommendations for correct handling, even during disposal, have also been formulated in a current study from the Bern University of Applied Sciences for estimation of the technological impact assessment of batteries containing lithium ([94]). In any case, these are generalised and require further clarifications for each specific usage case. Thus, generally accepted, practical action instructions for emergency personnel in the form of documented process sequences are still lacking. The following measures can make a contribution to minimising damage following an event and are recommended for implementation:

- Formulation of solid, scenario-based process sequences for safe transport from the incident location and correct disposal by emergency personnel
- Definition of the skills of all parties involved which are required for this

A standardised procedure for ultimately rendering traction batteries harmless would fundamentally increase safety. This also has the potential to reduce operation times, make it easier to release the damaged location faster and thus to make impaired sections of the road accessible again within shorter time periods.

Risk-based siting of charging stations in multi-storey car parks

During the charging process – and the discharging process – a lithium-ion battery is in constant motion from a chemical point of view: Lithium ions move from the active material of the cathode to the anode and are deposited in the graphite there ([91]). Heat is released in this process, meaning that the battery must be constantly thermally monitored and regulated by the superordinate battery management system ([92]). In comparison to a dormant battery, several risks are involved in this process in particular, which may provoke a thermal runaway (according to [7]):

- Charging a battery which has already been damaged
- Too-high currents when charging or discharging (regardless of charging performance)
- Overcharging, exhaustive discharge (regardless of charging performance)
- Unbalanced electrical cell charging distribution
- Charging in cold environments (<0 °C) and at high currents
- Mechanical impacts (vibrations, shocks)
- Overheating, cold, moisture
- Short-circuiting

As the charging process for BEV, particularly in underground infrastructures, is marked by specific risks, appropriate measures for preventing damage should be undertaken. The most important of these is to take the safety aspect into consideration when selecting where to site charging stations in multi-storey car parks. Ideal locations for parking spaces with charging stations are generally characterised by having an option for extracting smoke quickly in the event of a fire, so that contamination via the new heavy metal emissions can be curbed early on. Parking spaces with charging stations should therefore be sited near extraction facilities if the area has a smoke and heat extractor. If no machine-based smoke extraction is planned, charging stations must be placed around a location in which air exits the infrastructure. Taking this safety aspect into account, siting near escape routes and lift shafts and generally in deeper levels of car parks is fundamentally not recommended (cf. Figure 28).

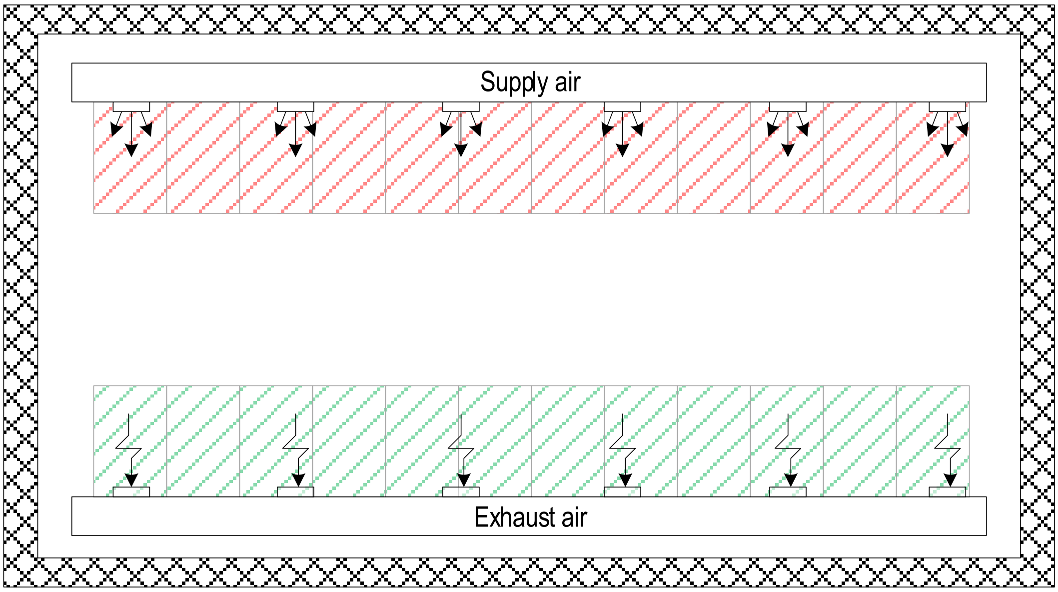

Figure 28 Suitable (green) and unsuitable (red) siting locations for parking spaces with charging stations ([88])

Experience and observations from day-to-day routine show that these simple principles are often not implemented. The reason for this is frequently due to the fact that car parks are equipped with charging stations at a later date (after they are built) and the deciding economic criteria that are linked with this. Often, charging stations are placed where the shortest cable routes to a pre-existing current distributor can be used. However, this purely financial consideration neglects to pay attention to the fact that these siting locations are not necessarily ideal from a risk assessment point of view. Therefore, it is recommended that, in addition to economical aims, safety aspects should be considered authoritative when contemplating to which parking spaces charging stations should be allotted. In the event that a conflict of aims arises between the economic, user-friendliness and safety aspects, careful weighing up of the interests must always be executed by the infrastructure operator ([88]).

Consideration of further fire protection measures in smaller infrastructures

Underground traffic infrastructures do not necessarily have to be refitted due to the increase in electromobility, whether they be large or small. The thermal effects of a BEV fire are comparable with those of an ICEV fire. The additional chemical risks can also be managed with the technical facilities and practices already available.

However, based on the present findings, operators of smaller infrastructures should scrutinise their current fire protection measures with a critical eye. Indeed, the legally stipulated measures always assume that the composition of traffic is ‘conventional’. They do not take new drive technology or energy storage system technology into account at all (cf. Section 2.4). Indeed, specifically for car parks in urban areas where the proportion of BEVs is potentially high, strictly following the legally stipulated measures can fall short under some circumstances. It is therefore recommended that infrastructure operators also integrate fire protection measures that extend beyond the applicable cantonal and federal specifications into their considerations if need be, always basing these on their specific property, in order to elicit improved management of the risks. Taking the economic significance of a car park into account, the following preventative and damage-reducing measures could be considered expedient, in particular:

- Fire alarms over parking spaces for electric vehicles so that the situation can be assessed more rapidly in the event of an incident (charging stations are also typically located here).
- Automatic start-up of a smoke and heat extractor system via local fire alarms over parking spaces with charging stations in order to prevent the spread of battery-specific emissions as early as possible.
- Implementation of BEV-specific operating processes to ensure early detection of risks (e.g. inspection of charging stations, on-site inspections of operations, making operational personnel aware of the specific fire hazards posed by electric vehicles, informing charging station users how to handle the charging stations correctly)
- Thermal control facilities on entrances for early detection of overheated traction batteries (similar to the thermal portal on the Gotthard road tunnel[6])

Integration of new drive technology into risk models

Systemic risk analysis for road tunnels is well-established internationally and is also applied with broadly supported input parameters in Switzerland (cf. [3]; [6]). However, for historical reasons, only incidents involving conventional vehicles which use fossil fuels and transportation of dangerous goods have been taken into account here. The specific risks which will occur in the future due to the increasing proportion of BEVs and also due to alternative drive and storage technology (e.g. hydrogen vehicles, natural gas vehicles) remain unobserved for the time being. The focus here are the toxic emissions that have been proven in this present project, but also potential gas emissions without fires or gas explosions. In order for risk analyses to remain up to date, they must take current the state of the art in mobility development into account. If this is not done, changes in the risk landscape can no longer be mapped. The international road association PIARC[7] therefore recommends that the following aspects are researched in-depth and implemented in the existing risk analysis models in its research strategy (cf. [66]):

- Definition of new scenarios including new drive and storage technology
- Taking new input parameters for new substances into account, particularly heavy metals (Co, Ni, Mn), hydrogen fluoride (HF) and phosphine (PH_3)
- Probability determination for new scenarios
- Impact assessment for new scenarios

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[6] https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-60226.html

[7] https://www.piarc.org/en/

6 Need for further research

In the present research project, various aspects within the stress field of electromobility and infrastructural safety could be investigated using a systematic procedure that is based on scientific principles. These findings make operators of traffic infrastructures aware of the potential changes to the hazardous situation and also support emergency personnel in responding to the incident. Although the original hypothesis on long-term safety and operational impact could not be confirmed, new subject areas were uncovered during the course of the experiment that should be researched in-depth in further steps.

6.1 Efficacy of high-pressure water mist systems

Experiences with incidents on sea-going ferries have shown that the implementation of high-pressure water mist systems appears to be particularly appropriate for electric vehicle fires. This means of fighting fires spreads well throughout the space and, more importantly, penetrates into covered spaces and places ([74]). The traction battery is difficult to access due to safety reasons, which makes it difficult to contain thermal runaway because the coolant cannot be applied directly to the source of the fire ([34]). Now, it is suspected that high-pressure water mist systems could contain flash-over and thus spreading of a lithium-ion battery fire and potential contaminations resulting from it as the water mist has a small droplet size and a locally inertising and cooling effect. Considering the increasing ubiquity of lithium-ion storage carriers in both mobile and stationary applications and due to the fact that high-pressure water mist systems could be an effective piece of safety equipment for fighting lithium-ion battery fires, an in-depth investigation is recommended.

High-pressure water mist systems are not yet widespread within Swiss underground infrastructures; in essence, they are currently not planned at all for road tunnels. In an international context, high-pressure water mist systems are integrated into safety considerations individually, as a potential equipment feature for structural protection of specific tunnels ([40]; [66]). Examples from bordering foreign countries include the Arlberg Road Tunnel, the Mona Lisa Tunnel and the Felbertauern Tunnel in Austria as well as the Virgolo Tunnel in Italy. The risk-based efficacy of high-pressure water mist systems remains a matter of debate in professional circles as they need to be custom-integrated into the existing system landscape and they have not yet been investigated in detail in underground infrastructures (e.g. road tunnels, multi-storey car parks). It thus remains unclear whether and to what extent these systems can impact the course of a fire originating from battery-powered vehicles.

Therefore, in terms of safety in underground infrastructures, specific vehicle fire tests will be used to check whether the stated efficacy of high-pressure water mist systems against electric vehicle fires justifies their installation in certain infrastructures from a risk-based point of view and whether they are at least recommendable as a safety device for specific properties (e.g. urban road tunnels with a high volume of traffic, significant multi-storey car parks, stationary storage systems).

6.2 Risk assessment of hydrogen mobility for road infrastructures

The present results illustrate that the risk landscape in underground infrastructures will change due to increasing electromobility. In addition to the purely battery-powered electric vehicles investigated here, electric vehicles with fuel cells – which are also fitted with traction batteries – in particular are said to proffer excellent prerequisites for the future ([65]). Even if the market penetration of fuel cell vehicles is not particularly developed at the moment, their technical maturity in terms of their performance, function and safety too is now very advanced. In addition, the ranges of vehicles that store their energy in the form of hydrogen and convert it into electric drive energy via fuel cells are constantly being optimised and are greater in comparison to those of battery-electrical vehicles. The reason for this is that fuel cell systems have a far higher energy density, which is why we generally expect to see an increase in this form of drive ([1]).

Due to these technical advantages and other environmental aspects, we must assume that hydrogen mobility will also increase in Switzerland, at least in specific application areas ([9]), even if setting up the required fuelling infrastructure throughout the country still remains to be done. The potential for this sustainable form of mobility is thought to be particularly effective for heavy-duty commercial vehicles and heavy goods vehicles. These types of vehicles can exploit the long ranges and the very high energy densities of hydrogen. As fuel cell vehicles do not emit any emissions locally, it also stands to reason that such vehicles will be used for applications in closed spaces, such as in logistics sectors or in large underground infrastructures. Under these assumptions and against the backdrop of the current developments in mobility worldwide (increasing displacement of traffic into underground infrastructures, [11]), a risk assessment must definitely be executed in addition to the assessment of the potential in order to elicit an overall socio-political evaluation.

This is exactly what is stated in the current policy document from the Swiss Federal Office of Energy (BFE) ([9]): Hydrogen mobility has not been sufficiently considered in the various scenarios for the 2050 federal energy strategy and, in addition, the data foundation for common economic cost assessments is currently not present. It is also mentioned that '...no clear visions of the role that this technology could play in the national energy scenarios...' ([9]) are yet available and that the mid-term and long-term potential of this technology has not yet been fully clarified. In the arguments for implementing hydrogen in mobility, no statements are made on the potential risk consequences. Although significant potential for damage is theoretically possible with hydrogen when flammable mixtures accumulate in closed spaces ([34]; [38]), no robust appraisals or even potential practical measures for this are yet available. From the perspective of road infrastructure operators, the following queries in this regard are up for discussion today:

- Which road-infrastructure-related risk scenarios result from increasing hydrogen mobility?
- Which specific risks and potential damage can we expect to see in underground or closed traffic infrastructures which experience heavy traffic or higher amounts of people?
- Which preventative or damage mitigation measures appear to be expedient for operators of road infrastructures?
- Will infrastructural adaptation measures be required if hydrogen mobility increases?

As long as the potential safety effects of increasing hydrogen mobility remain unknown for operating these traffic infrastructures, they present a risk that is difficult to calculate for operators. Thus, the above queries are also covered by research focal point no. 9 from the 'Bridges, Engineering Geology and Tunnels' working group from FEDRO, the Swiss Federal Roads Office[8] and are furthermore taken into consideration in the research strategy of the PIARC international road association[9]. The aspects that remain unanswered should be clarified with appropriate investigations and with reference to mobility conditions in Switzerland so that they can be used to derive specific recommendations for measures for the Swiss traffic infrastructure. To create a reliable data foundation, it is recommended that experimental and scenario-based investigations be carried out.

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[8] https://www.astra.admin.ch/dam/astra/de/dokumente/forschung_im_strassenwesen/forschungsschwerpunkte.pdf.download.pdf/Forschungsschwerpunkte%202020-2024.pdf

[9] https://www.piarc.org/ressources/documents/Technical-Committees-2016-2020-Terms-of-Reference/8b6e056-32562-Terms-of-Reference-TC-4.4-TUNNELS.pdf

6.3 Risks caused by stationary storage systems

Fires caused by electric vehicle batteries cannot be extinguished. This is also the case with stationary lithium-ion storage systems, which are increasingly used as energy buffer solutions for solar power systems in buildings and are typically placed on underground floors. As they are often installed during the course of retrofitting projects, they are often placed in a room that is not ideal in terms of safety. Both the technology implemented and the surroundings of these stationary storage systems are thus comparable with the present research project in terms of risk. Due to the test results, it thus appears evident that the subject of safety should be allotted greater attention, not only in conjunction with increasing electromobility but also generally for chemical storage systems in closed or sub-optimally ventilated infrastructures (cf. also [12]).

This subject area is to be explored with a robust experiment. Taking current storage technology into account, we must explore the following questions in particular by carrying out specific trials in a realistic environment:

- What are the risks for building users and building operators?
- Do appropriate detection options exist?
- Which technical options for fighting fires could be considered for this (efficacy of high-pressure water mist systems, cf. Section 6.1)?
- What are the actual recommendations for responding to the incident?

Annexes

I Pre-analyses concept

I.1 Applied sampling and analysis methods

Swipe samples (SS-1)
A representative surface with defined dimensions was thoroughly cleaned with two cotton pads that were dampened with deionised water. The cotton pads were stored in a closed plastic bag until analysis in a lab.

The preliminary semi-quantitative element screening was executed directly on the cotton pad, using energy dispersive X-ray fluorescence spectrometry (see below).

The samples were extracted in the laboratory using deionised water. Determination of the anion and cation concentrations is executed via capillary electrophoresis (Empa SOP No. 03’043).

Material samples (MS-1 to MS-5; blank MS-0)
A collective sample of the surface contamination (in the present case: fire soot residue and a blank sample of operational dust deposits) was taken dry from a representative surface with an appropriate, clean tool (a steel brush in the present case). The collective sample was stored in a closed plastic bag until analysis in a lab. Sample preparation: Reduction/homogenisation and extraction of the fraction <0.125 mm (sieving).

The preliminary semi-quantitative element screening is carried out on the prepared material samples using energy dispersive X-ray fluorescence spectrometry (ED-XRF), according to Empa SOP No. 03’850. The analyses were executed using a ‘NITON XL5’ (Thermo Fisher Scientific) type device in the ‘MINING’ measuring mode (filter configuration / measuring interval= Main-Low-High-Light / 45-45-45-45 s).

The samples were extracted in the laboratory using deionised water. Determination of the anion and cation concentrations is executed via capillary electrophoresis (Empa SOP No. 03’043).

II Experiment analysis concept

II.1 Investigation and sampling concept

II.1.1 Swipe samples and fire soot collective samples (modules 1 and 3)

Type and number of sample collectors

- Stainless steel plates 1.4401 (mill finish; plate thickness: 1.5 mm)
- 1 piece (50 x 120 cm) and 2 pieces (50 x 90 cm) per sampling position

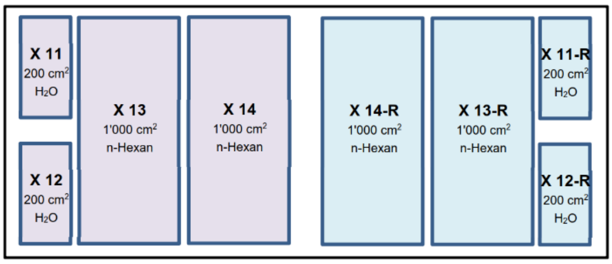
Positioning of sample collectors for module 1:

- Positioning in tunnel A: collectors made from substructure steel plates approx. 1.0 and 3.0 metres above the ground (on the steel gate side)
- Alignment: inclined at 45° (towards experiment)
- Fitted on horizontal timber beams that are anchored in the arch (2 pieces on each beam)

Positioning of sample collectors for module 3:

- Positioning in tunnel B: collectors made from substructure steel plates approx. 3.0 metres above the ground / 3 positions: exit for tunnel A, height of ventilator for tunnel B, exit for tunnel B
- Alignment: inclined at 45° (towards experiment)
- Fitted e.g. on horizontal timber beams that are anchored in the arch (2 pieces on each beam), for example
- cf. Figure 11

Kollektor Xa (Inox 1.4401; 50 x 120 cm):



[R-Proben = Rückstellmuster]

Kollektoren Xb und Xc (Inox 1.4401; je 50 x 90 cm):

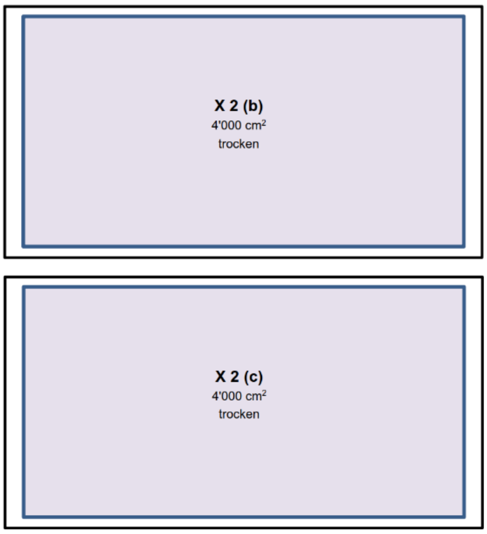


Figure 29 Sampling diagram for swipe samples and fire soot collective samples (collectors)

Designation of collectors

- Module 1: Aa/Ab/Ac (h = 3.0 m) and Ba/Bb/Bc (h = 1.0 m)
- Module 3: Ca/Cb/Cc (d = 50 m), Da/Db/Dc (d = 100 m) and Ea/Eb/Ec (d = 150 m)

Additional swipe samples from ventilator

- Module 3: A complete additional swipe sample set was taken in the ventilator housing, which had been cleaned before sampling (d = 55 m)

II.1.2 Textile specimens (module 1)

Type and quantity of specimens

- Firefighter jackets (2 pieces)
- Cleaned material: 93% m-aramid (Nomex), 5% p-aramid (Kevlar), 2% P140 (carbon)

Positioning of textile samples

- Positioning in tunnel A: distance > 5m from battery, at approx. 0.8 – 1 m in height (steel gate side)
- Alignment: horizontal (back of the jacket faced upwards)
- Fitted: on wood pallet

Sampling

- Swipe samples, taken in contaminated and cleaned (standard cleaning by Zurich Emergency Services [*Schutz & Rettung Zürich*]), state as described in Section 2.1

II.1.3 Firefighting water samples (module 2)

Type and quantity of collecting containers

- Plastic collecting containers (>200 litres)

Positioning of collecting containers

- Positioning: underneath fire extinguisher nozzle
- Fitted: on tunnel floor

Auxiliary tools for taking samples

- Power drill
- Large paint mixer drill attachment

II.1.4 Cooling water samples (module 2)

Battery cooling reservoir

- Plastic box with lid
- Storage of the burned-out battery module (including steel plate) from 09 December 2019 to 10 January 2020 in type 0W water (total water volume: approx. 56 x 37 x 20 cm = approx. 42,000 cm^3)

Auxiliary tools for taking samples

- Power drill
- Large paint mixer drill attachment

II.1.5 Corrosion monitoring (module 1)

In order to characterise the corrosive influence of combustion gases on different metallic materials, an exposure test was executed on various metal samples. Following exposure to combustion gases, the metal samples were stored at 90% relative humidity for periods of 1 month and 3 months. Then, the metal samples were inspected visually and in terms of corrosion chemistry. The erosion rate due to corrosion is determined via gravimetric measurements.

Table 50 **Fitting of monitoring racks**

Sample no.	Material	Sample type	Material no.	Dimensions (mm)
1	Plain carbon steel	Plates	1.0660	100 x 50 x 1
2	99.9% zinc	Plates	-	100 x 50 x 1
3	99.9% copper	Plates	-	100 x 50 x 1
4	Aluminium alloy AlMgSi1 (Anticorodal-100)	Plates	3.2315	100 x 50 x 1
5	Stainless steel	Plates	1.4404	100 x 50 x 1

Positioning of corrosion monitoring for module 1

- Positioning in tunnel A: substructure aluminium frames (1x1 metres) approx. 1 m above the ground (on the steel gate side)
- Alignment: aluminium frames are horizontal / metal samples are tilted by 45° (towards experiment)
- Fitted on wood pallet
- cf. Figure 11

II.1.6 Electronic test equipment (module 1)

Type and quantity of test equipment

- 7 test circuit boards from Topline (ascom L54927) in Pur Base 500 PC housing with 2 fans (Pure Wings 2, 140 mm, 104m^3/h per fan)
- Optical inspection and electrical characterisation (SIR Surface Insulation Resistance) before and after fire test
- METRISO 1000V insulation measurement instrument (Metrawatt GmbH, Empa M21434)
- Execution of initial measurements:
  - Cleaning of PCBs with compressed air
  - Measurement of resistance of the 6 SIR measuring combs per circuit board at 500 VDC
  - Laboratory conditions, temperature 23°C

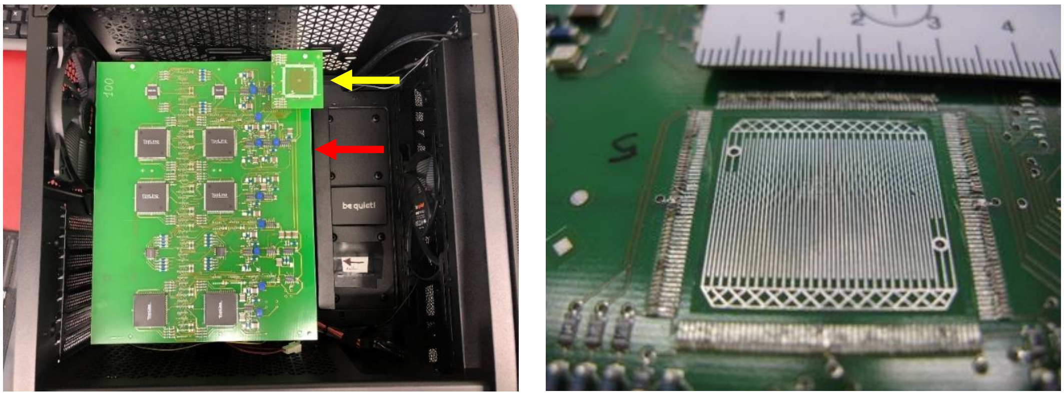


Figure 30 Electronic test equipment for module 1: test circuit board in PC housing, red arrow shows flow direction, yellow arrow shows individual exposed SIR measuring combs (left) and SIR measuring combs under chips, distance to the measuring probe is 0.2 mm (right)

Positioning of the equipment

- Positioning in tunnel A: 1m above the floor, 5m distance from cell stack (on side of steel gate)
- Fitted on wood pallet
- During the fire test, both fans in the PC housing are running

II.1.7 Measuring the fire temperatures (modules 1 to 3)

Temperatures in and around the battery were measured using robust 4.5 mm type K sheathed thermocouples and a Keithley 2700 multiplexer data acquisition system. Positioning of the thermocouples was adapted to the relevant test conditions. The sampling rate for measurements is dependent on the number of channels recorded. For modules 1 and 2, the sampling rate was 8 measurements / minute, for module 3 the sampling rate was 10 measurements / minute.

Equipment

- Keithley 2700 multichannel data acquisition system
- Labview data acquisition software, program TDL, V1.3.6
- HP Probook 6570b laptop, Empa Inv. No. 4674

Figure 31 Two sheathed thermocouples with measuring tips in the centre of the battery module

II.1.8 Climate monitoring (modules 1 to 3)

Location of climate monitoring
Supporting structure for collector plates (top)

Recording period
9 December (12:00 noon) to 12 December (08:15 a.m.) 2019

Method
The iButton type temperature/humidity logger from the Thermochron company was used:

- Programmed data sampling rate: 1 minute
- Recording period: 3 days

II.1.9 Preliminary material characterisation for battery module (module 4)

The chemical compositions of the materials implemented in the battery module (metals and plastics) underwent preliminary analysis using non-destructive energy dispersive X-ray fluorescence spectrometry (ED-XRF) as far as was possible without taking apart the module.

A ‘NITON XL2’ type device (Thermo Fisher Scientific, Billerica, MA 01821) was used. The element contents were analysed using the ALLOYS and PLASTICS measuring modes.

II.2 Applied sampling methods

II.2.1 Swipe sampling

Swipe sampling 1 (inorganic analytics)
An **area of 200 cm^2** on the collector plate and/or textile surface was thoroughly cleaned with two cotton pads that were dampened with deionised water. The cotton pads were stored in a closed plastic bag until analysis in a lab.

Swipe sampling 2 (organic analytics)
An **area of 1,000 cm^2** on the collector plate and/or textile surface was thoroughly cleaned with several cotton pads that were dampened with n-hexane and pre-extracted. The cotton pads are stored in a closed glass container (glass bottle with screw lid) up until analysis in the laboratory.

Blanks
Blank samples (‘0’ samples) are taken of all sample sets before the trials.

II.2.2 Sampling of solids

Fire soot sampling
A dry fire soot collective sample is taken from a **total area of 8,000 cm^2** the two collector plate surfaces using an appropriate, clean implement (e.g. a spatula). The fire soot collective sample is stored in a closed glass vessel until subsamples have been created from it and analysed in a lab.

II.2.3 Firefighting water sampling

Water sampling 1 (heavy metal analytics)
An **aliquot of 2 x 2 litres** is taken during constant agitation via the stirring rod driven by the drill and is placed into PE bottles to which 10 mL HNO_3 65% p.a. is added (pH= <1). The samples are stored in a fridge at 4-5°C until they are analysed.

Water sampling 2 (inorganic and organic analytics)
An **aliquot of 2 x 2 litres** (inorganic analytics) and an **aliquot of 5x 2 litres in glass bottles** (organic analytics) is taken during constant agitation via the paint mixer drill attachment and is placed into glass bottles. The samples are stored in a fridge at 4-5°C until they are analysed.

Suspended particle sampling
After decanting and membrane filtration of the samples (<0.45 µm for heavy metal analytics or <1 µm for organic analytics), the filters are stored in a desiccator in order to determine the proportion that is undissolved.

Retention specimen ‘R’
Blank samples ('0’ samples) are taken of process water before the tests.

II.3 Applied analysis methods

II.3.1 Anion analytics (solids and water samples)

The swipe samples and the fire soot and textile samples are extracted using deionised water. The water samples are analysed directly in an undiluted state following filtration at <0.45 µm. Analysis of the chloride, bromide, fluoride, sulphate, nitrate, phosphate, formate and acetate concentrations is executed using capillary electrophoresis.

II.3.2 Cation analytics (solids and water samples)

The swipe samples and the fire soot and textile samples are extracted using concentrated nitric acid (swipe and textile samples: reflux extraction; fire soot samples: microwave pressure digestion). An aliquot from the water samples is analysed after filtration at <0.45 µm and after being acidulated to pH 1 using HNO_3 65%.

Analysis of cobalt, lithium, manganese and nickel concentrations is executed via inductively-coupled plasma optical emission spectrometry (ICP-OES).

II.3.3 PAH analytics (solids)

The swipe samples and the fire soot and textile samples are extracted over the course of 16 hours using cyclohexane in a Soxhlet extractor. The extract is then diluted to 250 ml using cyclohexane and an aliquot of 50 ml is used for analysis. After adding a mixture of 16 deuterated PAH (as an internal standard), the solvent is concentrated to approx. 1 ml at 50°C and approx. 300 mbar using the rotavap. Then, chromatographic purification is carried out using silica gel.

The purified extract is concentrated down to 0.3 ml and, after adding the recovery standard (deuterated perylene), the PAH concentrations are determined using GC-HRMS (isotope dilution analysis).

II.3.4 PCDD/F and PCB analytics (solids)

The swipe samples and the fire soot and textile samples are extracted over the course of 16 hours using toluene in a Soxhlet extractor. The extract is then diluted to 250 ml using toluene and an aliquot of 50 ml is used for analysis. After adding a mixture of 17 $^{13}C_{12}$ isotope-labelled PCDD/F and 18 $^{13}C_{12}$ isotope-labelled PCB (6 iPCBs and 12 dl-PCBs) as internal standards, the solvent is concentrated to approx. 1 ml at 50°C and approx. 70 mbar using the rotavap. Then, chromatographic sample purification is carried out on three different solid phases (acid, base, neutral silica gel, aluminium oxide and activated carbon).

The purified extract is then separated into two fractions which are both concentrated down to 0.025 ml and, after adding the recovery standard ($^{13}C_{12}$ 1,2,7,8-TCDF and $^{13}C_{12}$ PCB-70), the PCDD/F and PAH concentrations are determined using GC-HRMS (isotope dilution analysis).

II.3.5 PAH, PCDD/F and PCB analytics (water samples)

The isotope-labelled internal standard mixtures (16 deuterated EPA PAH, 17 $^{13}C_{12}$ labelled PCDD/F und 18 $^{13}C_{12}$ labelled PCB) are added to the water samples (approx. 2 litres) once they have been filtered at <1.0 µm. The sample is thoroughly agitated in order to ensure that the standards are homogeneously integrated into the solution. Following this, the sample is pumped onto a C_{18} phase or a polymer cartridge with an adsorbency of approx. 500 mg at light pressure. The flow rate is approx. 3 ml/minute. The cartridges are then dried under a vacuum for exactly 30 seconds and the PAH, PCDD/F and PCB are then eluted from the cartridge using 6-8 ml of n-hexane.

The volume is reduced to approx. 0.05 ml using nitrogen flushing, and after addition of the recovery standard ($^{13}C_{12}$-1,2,7,8-TCDF, $^{13}C_{12}$-PCB-70, deuterated perylene), the PAH, PCDD/F und PCB concentrations are determined using GC-HRMS (isotope dilution analysis).

II.3.6 Semiquantitative element analytics (solids)

The fire soot samples are directly analysed in powder state.

Using energy dispersive X-ray fluorescence spectrometry (ED-XRF), the concentrations of the *chemical elements* are semiquantitatively analysed using a procedure which does not involve standards.

II.3.7 Preliminary material analytics (battery module)

The materials integrated into the battery module are analysed directly, as far as is possible without destroying the module.

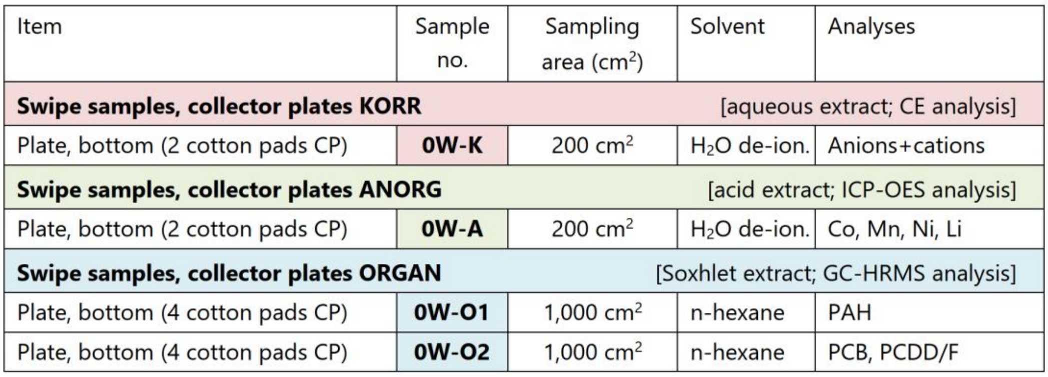
The chemical compositions of the metallic materials in the module (metals and plastics) are characterised using energy dispersive X-ray fluorescence spectrometry (ED-XRF).

III Sample tables

III.1 Battery module 1

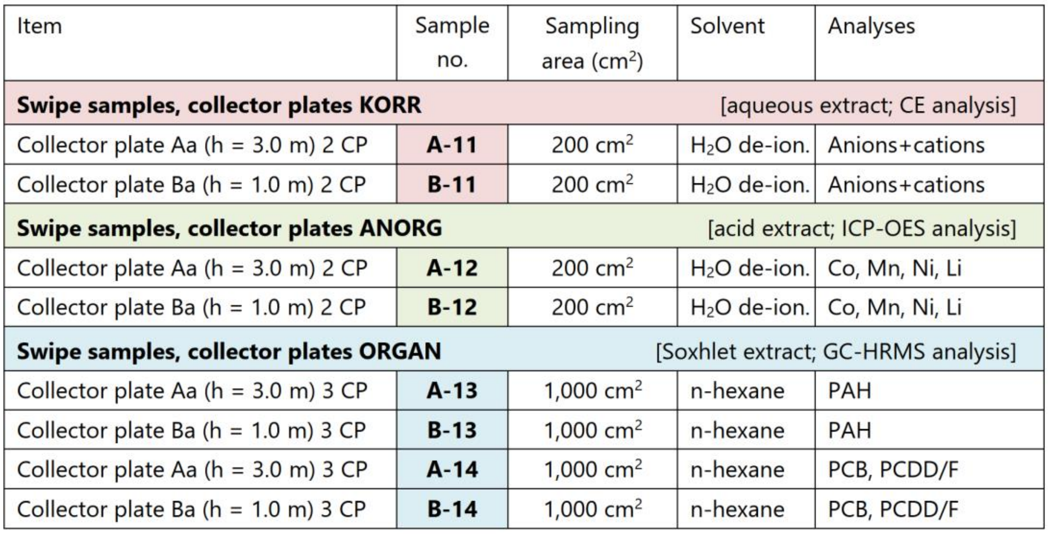
Sample table of 10 December 2019

BLANKS ‘plate’:

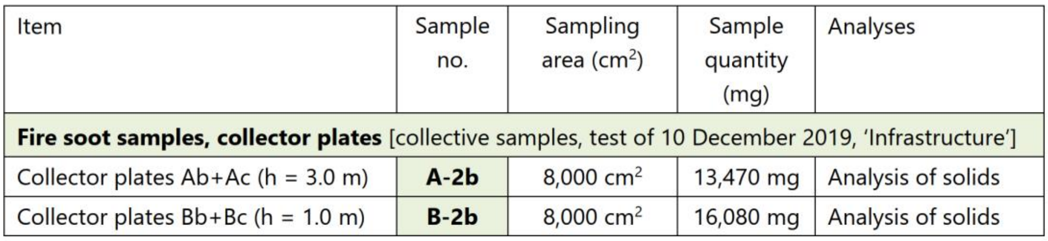


Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, collector plates KORR				[aqueous extract; CE analysis]
Plate, bottom (2 cotton pads CP)	**0W-K**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, collector plates ANORG				[acid extract; ICP-OES analysis]
Plate, bottom (2 cotton pads CP)	**0W-A**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, collector plates ORGAN				[Soxhlet extract; GC-HRMS analysis]
Plate, bottom (4 cotton pads CP)	**0W-O1**	1,000 cm^2	n-hexane	PAH
Plate, bottom (4 cotton pads CP)	**0W-O2**	1,000 cm^2	n-hexane	PCB, PCDD/F

MAIN SAMPLES ‘plate’:



Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, collector plates KORR				[aqueous extract; CE analysis]
Collector plate Aa (h = 3.0 m) 2 CP	**A-11**	200 cm^2	H_2O de-ion.	Anions+cations
Collector plate Ba (h = 1.0 m) 2 CP	**B-11**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, collector plates ANORG				[acid extract; ICP-OES analysis]
Collector plate Aa (h = 3.0 m) 2 CP	**A-12**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Collector plate Ba (h = 1.0 m) 2 CP	**B-12**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, collector plates ORGAN				[Soxhlet extract; GC-HRMS analysis]
Collector plate Aa (h = 3.0 m) 3 CP	**A-13**	1,000 cm^2	n-hexane	PAH
Collector plate Ba (h = 1.0 m) 3 CP	**B-13**	1,000 cm^2	n-hexane	PAH
Collector plate Aa (h = 3.0 m) 3 CP	**A-14**	1,000 cm^2	n-hexane	PCB, PCDD/F
Collector plate Ba (h = 1.0 m) 3 CP	**B-14**	1,000 cm^2	n-hexane	PCB, PCDD/F



Item	Sample no.	Sampling area (cm^2)	Sample quantity (mg)	Analyses
Fire soot samples, collector plates [collective samples, test of 10 December 2019, ‘Infrastructure’]				
Collector plates Ab+Ac (h = 3.0 m)	**A-2b**	8,000 cm^2	13,470 mg	Analysis of solids
Collector plates Bb+Bc (h = 1.0 m)	**B-2b**	8,000 cm^2	16,080 mg	Analysis of solids

BLANKS ‘textile’:

Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, textile specimens KORR				[aqueous extract; CE analysis]
Suit 1 (2 cotton pads)	**0T-K**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, textile specimens ANORG				[acid extract; ICP-OES analysis]
Suit 2 (2 cotton pads)	**0T-A**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, textile specimens ORGAN				[Soxhlet extract; GC-HRMS analysis]
Suit 1 (2 cotton pads)	**0T-O1**	1,000 cm^2	n-hexane	PAH
Suit 2 (2 cotton pads)	**0T-O2**	1,000 cm^2	n-hexane	PCB, PCDD/F

MAIN SAMPLES ‘contaminated textile’:

Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, contam. textile specimens KORR				[aqueous extract; CE analysis]
Suit 1 (2 cotton pads)	**T-11**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, contam. textile specimens ANORG				[acid extract; ICP-OES analysis]
Suit 2 (2 cotton pads)	**T-12**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, contam. textile specimens ORGAN				[Soxhlet extract; GC-HRMS analysis]
Suit 1 (4 cotton pads)	**T-13**	990 cm^2	n-hexane	PAH
Suit 2 (4 cotton pads)	**T-14**	990 cm^2	n-hexane	PCB, PCDD/F

MAIN SAMPLES ‘cleaned textile’:

Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, cleaned textile specimens KORR				[aqueous extract; CE analysis]
Suit 1 (2 cotton pads)	**TR-11**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, cleaned textile specimens ANORG				[acid extract; ICP-OES analysis]
Suit 2 (2 cotton pads)	**TR-12**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, cleaned textile specimens ORGAN				[Soxhlet extract; GC-HRMS analysis]
Suit 1 (4 cotton pads)	**TR-13**	990 cm^2	n-hexane	PAH
Suit 2 (4 cotton pads)	**TR-14**	990 cm^2	n-hexane	PCB, PCDD/F

III.2 Battery module 2

Sample table of 09 December 2019

BLANKS 'firefighting water':

Item	Sample no.	Sample quantity (mg)	Dilution	Analyses
Water samples KORR				[CE analysis]
Water sample, uncontaminated	**0W-K**	2,000 ml	none	Anions+cations
Water samples ANORG				[acidulated, ICP-OES analysis ME]
Water sample, uncontaminated	**0W-A**	2,000 ml	none	Co, Mn, Ni, Li
Water samples ORGAN				[Extraction; GC-HRMS analysis]
Water sample, uncontaminated	**0W-O**	2,000 ml	none	PAH, PCB, PCDD/F

MAIN SAMPLES 'firefighting water':

Item	Sample no.	Sample quantity (mg)	Dilution	Analyses
Water samples KORR				[CE analysis]
Firefighting water, homogenised	**W-41**	2 x 2,000 ml	none	Anions+cations
Water samples ANORG 1				[acidulated, ICP-OES analysis ME]
Firefighting water, homogenised	**W-42**	2 x 2,000 ml	none	Co, Mn, Ni, Li
Water samples ANORG 2				[ICP-OES analysis NM + analysis of solids in filtrate]
Firefighting water, homogenised	**W-45**	2 x 2,000 ml	none	... + Co, Mn, Ni, Li
Water samples ORGAN				[Extraction; GC-HRMS analysis]
Firefighting water, homogenised	**W-43**	5 x 2,000 ml	none	PAH, PCB, PCDD/F

MAIN SAMPLES 'cooling water':

Item	Sample no.	Sample quantity (mg)	Dilution	Analyses
Water samples KORR				[CE analysis]
Cooling water, homogenised	**CW-41**	2 x 2,000 ml	none	Anions+cations
Water samples ANORG 1				[acidulated, ICP-OES analysis ME]
Cooling water, homogenised	**CW-42**	2 x 2,000 ml	none	Co, Mn, Ni, Li
Water samples ANORG 2				[ICP-OES analysis NM + analysis of solids in filtrate]
Cooling water, homogenised	**CW-45**	2 x 2,000 ml	none	... + Co, Mn, Ni, Li
Water samples ORGAN				[Extraction; GC-HRMS analysis]
Cooling water, homogenised	**CW-43**	1 x 2,000 ml	none	PAH, PCB, PCDD/F

Sampling of battery 'cooling water'

- Storage of the burned-out battery module (including steel plate) from 9 December 2019 to 10 January 2020 in a plastic box filled with type '0W' water
- Total water volume: approx. 56 x 37 x 20 cm = approx. 42,000 cm^3
- Sampling of cooling water: 10 January 2020

III.3 Battery module 3

Sample table (test of 11 December 2019)

MAIN SAMPLES 'plate':

Item	Sample no.	Sampling area (cm^2)	Solvent	Analyses
Swipe samples, collector plates KORR				[aqueous extract; CE analysis]
Collector plate Ca (d = 50 m) 2 CP	**C-11**	480 cm^2	H_2O de-ion.	Anions+cations
Collector plate Da (d = 100 m) 2 CP	**D-11**	480 cm^2	H_2O de-ion.	Anions+cations
Collector plate Ea (d = 150 m) 2 CP	**E-11**	480 cm^2	H_2O de-ion.	Anions+cations
Ventilator V (d = 55 m) 2 CP	**V-11**	200 cm^2	H_2O de-ion.	Anions+cations
Swipe samples, collector plates ANORG				[acid extract; ICP-OES analysis]
Collector plate Ca (d = 50 m) 2 CP	**C-12**	480 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Collector plate Da (d = 100 m) 2 CP	**D-12**	480 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Collector plate Ea (d = 150 m) 2 CP	**E-12**	480 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Ventilator V (d = 55 m) 2 CP	**V-12**	200 cm^2	H_2O de-ion.	Co, Mn, Ni, Li
Swipe samples, collector plates ORGAN				[Soxhlet extract; GC-HRMS analysis]
Collector plate Ca (d = 50 m) 3 CP	**C-13**	1,000 cm^2	n-hexane	PAH
Collector plate Da (d = 100 m) 3 CP	**D-13**	1,000 cm^2	n-hexane	PAH
Collector plate Ea (d = 150 m) 3 CP	**E-13**	1,000 cm^2	n-hexane	PAH
Ventilator V (d = 55 m) 3 CP	**V-13**	1,000 cm^2	n-hexane	PAH
Collector plate Ca (d = 50 m) 3 CP	**C-14**	1,000 cm^2	n-hexane	PCB, PCDD/F
Collector plate Da (d = 100 m) 3 CP	**D-14**	1,000 cm^2	n-hexane	PCB, PCDD/F
Collector plate Ea (d = 150 m) 3 CP	**E-14**	1,000 cm^2	n-hexane	PCB, PCDD/F
Ventilator V (d = 55 m) 3 CP	**V-14**	1,000 cm^2	n-hexane	PCB, PCDD/F

Item	Sample no.	Sampling area (cm^2)	Sample quantity (mg)	Analyses
Fire soot samples, collector plates				[collective samples]
Collector plates Cb+Cc (d = 50 m)	**C-2**	8,000 cm^2	338 mg	ED-XRF
Collector plates Db+Dc (d = 100 m)	**D-2**	8,000 cm^2	309 mg	ED-XRF
Collector plates Eb+Ec (d = 150 m)	**E-2**	8,000 cm^2	106 mg	ED-XRF

IV Climate monitoring

Table 51 *Information on climate monitoring*

Location	Date	Height	Distance to test area
Tunnel ‘A’	09 – 10 December 2020	Approx. 4 m	Approx. 4 m
Tunnel B	11 December 2020	Approx. 4 m	Approx. 50 m

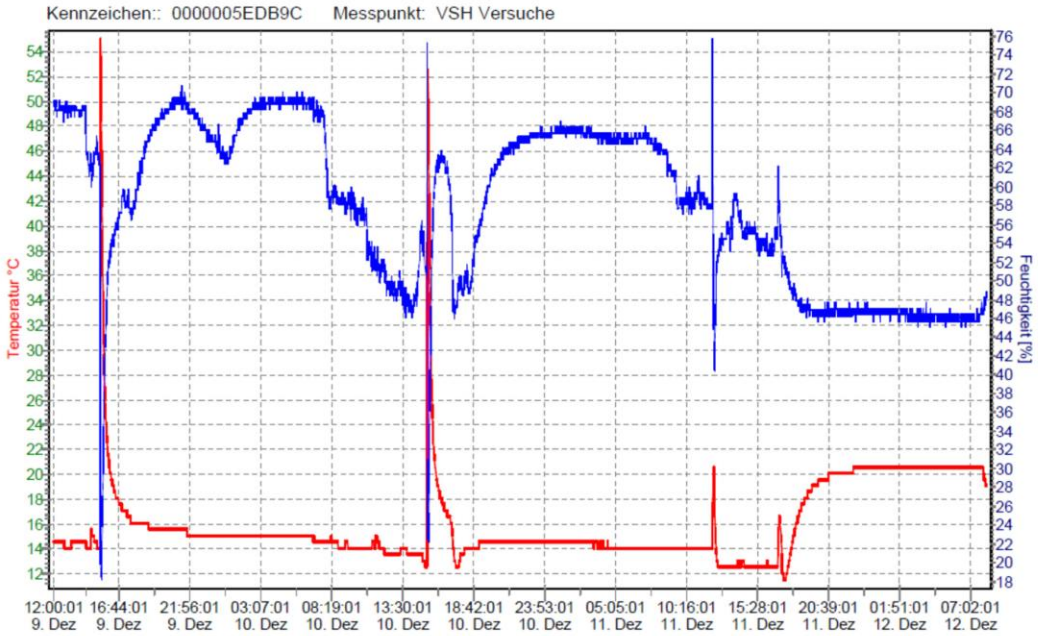


Figure 32 Trends for temperature and relative humidity throughout the entire experiment

Figure 33 Climate monitoring in tunnels A (left) and B (right)

Glossary

Term	Meaning
FEDRO	Swiss Federal Roads Office
Battery electric vehicle (BEV)	Electric vehicles wherein the energy is exclusively stored in the form of a rechargeable battery (also called an accumulator).
Battery management system (BMS)	Electronic monitoring and control unit of a battery for preventing critical events (e.g. overcharging) and for data communication.
Battery module	A battery module is a group of several battery cells connected in series, in parallel or in a combination of both.
Battery system (also called a battery)	A battery system consists of one or more battery cells or battery modules. It has a superordinate BMS and, under certain conditions, also a heating and cooling system.
Battery cell	A battery cell constitutes the actual energy storage system via the electrochemical setup of anode, cathode, separator and electrolyte.
BEV	Battery Electric Vehicle →
Fuel cell hybrid electric vehicle	Electric vehicle that is driven by an electric motor and whose energy is produced by a fuel cell.
OSE	Operating and safety equipment
Electric vehicle	Vehicle that is driven with an electric motor.
Electric vehicle with range extender	Electric vehicle that is driven with an electric motor and has an additional internal combustion engine or fuel cell for mobile charging of the battery (actually a hybrid, as it has 2 energy converters and 2 power sources).
Electromobility	Person and goods traffic using vehicles that are driven with electric energy.
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
Hybrid vehicle (HEV)	Electric vehicle that has two energy converters (electric motor and internal combustion engine) as well as two different energy storage systems (e.g. battery and fuel). The battery cannot be charged via the mains.
IDLH	Immediately Dangerous to Life or Health
ISO	International Organization for Standardization
WEL values	Workplace exposure limits – maximum permissible concentrations of hazardous substances within the workplace.
NMC	A type of battery cell whose cathode material is made out of a layered metal compound of a lithium-nickel-manganese-cobalt oxide.
PAH	Polycyclic aromatic hydrocarbons
PHEV	Plug-in Hybrid Electric Vehicle
Plug-in hybrid electric vehicle (PHEV)	Electric vehicle that has two energy converters (electric motor and internal combustion engine) as well as two different energy storage systems (battery and fuel). The battery can be charged via the mains.
SABA	Road surface water treatment plant
Thermal runaway	An exothermic reaction which fuels itself. During thermal runaway, a battery heats up independently and quickly (>10°C/min) due to chemical processes, meaning that it exceeds its stable operating range. The result is a battery fire that releases a great amount of energy.

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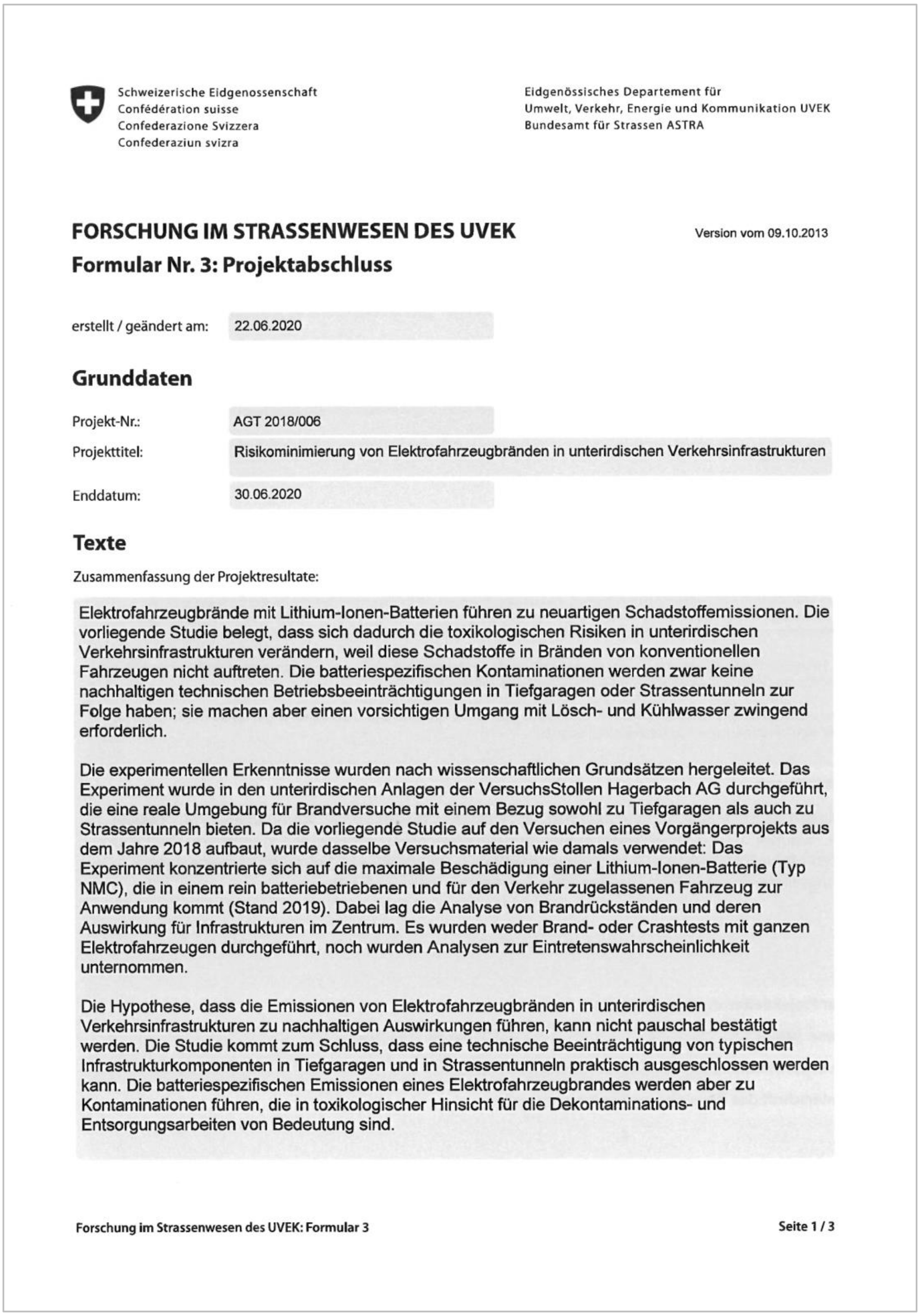
Project conclusion



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Version vom 09.10.2013

Formular Nr. 3: Projektabschluss

erstellt / geändert am: 22.06.2020

Grunddaten

Projekt-Nr.: AGT 2018/006

Projekttitel: Risikominimierung von Elektrofahrzeugbränden in unterirdischen Verkehrsinfrastrukturen

Enddatum: 30.06.2020

Texte

Zusammenfassung der Projektresultate:

Elektrofahrzeugbrände mit Lithium-Ionen-Batterien führen zu neuartigen Schadstoffemissionen. Die vorliegende Studie belegt, dass sich dadurch die toxikologischen Risiken in unterirdischen Verkehrsinfrastrukturen verändern, weil diese Schadstoffe in Bränden von konventionellen Fahrzeugen nicht auftreten. Die batteriespezifischen Kontaminationen werden zwar keine nachhaltigen technischen Betriebsbeeinträchtigungen in Tiefgaragen oder Strassentunneln zur Folge haben; sie machen aber einen vorsichtigen Umgang mit Lösch- und Kühlwasser zwingend erforderlich.

Die experimentellen Erkenntnisse wurden nach wissenschaftlichen Grundsätzen hergeleitet. Das Experiment wurde in den unterirdischen Anlagen der VersuchsStollen Hagerbach AG durchgeführt, die eine reale Umgebung für Brandversuche mit einem Bezug sowohl zu Tiefgaragen als auch zu Strassentunneln bieten. Da die vorliegende Studie auf den Versuchen eines Vorgängerprojekts aus dem Jahre 2018 aufbaut, wurde dasselbe Versuchsmaterial wie damals verwendet: Das Experiment konzentrierte sich auf die maximale Beschädigung einer Lithium-Ionen-Batterie (Typ NMC), die in einem rein batteriebetriebenen und für den Verkehr zugelassenen Fahrzeug zur Anwendung kommt (Stand 2019). Dabei lag die Analyse von Brandrückständen und deren Auswirkung für Infrastrukturen im Zentrum. Es wurden weder Brand- oder Crashtests mit ganzen Elektrofahrzeugen durchgeführt, noch wurden Analysen zur Eintretenswahrscheinlichkeit unternommen.

Die Hypothese, dass die Emissionen von Elektrofahrzeugbränden in unterirdischen Verkehrsinfrastrukturen zu nachhaltigen Auswirkungen führen, kann nicht pauschal bestätigt werden. Die Studie kommt zum Schluss, dass eine technische Beeinträchtigung von typischen Infrastrukturkomponenten in Tiefgaragen und in Strassentunneln praktisch ausgeschlossen werden kann. Die batteriespezifischen Emissionen eines Elektrofahrzeugbrandes werden aber zu Kontaminationen führen, die in toxikologischer Hinsicht für die Dekontaminations- und Entsorgungsarbeiten von Bedeutung sind.

Forschung im Strassenwesen des UVEK: Formular 3 **Seite 1 / 3**

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Zielerreichung:

Die aufgeworfenen Fragestellungen wuden mit diesem Foschungsprojekt systematisch und mit einer wissenschaftlichen Vorgehensweise beantwortet. Die folgenden Projektziele wurden dabei erreicht:

1. Wissenschaftliche Analyse mittels aussagekräftiger Brandversuche und Messungen

2. Deduktion der Auswirkungen auf unterirdische Verkehrsinfrastrukturen im Einflussbereich der Elektromobilität

3. Formulierung von angemessenen technischen und organisatorischen Massnahmen zur Schadensprävention und -minderung

Folgerungen und Empfehlungen:

Aufgrund der Erkenntnisse können sechs risikomindernde Massnahmen abgeleitet werden, die primär organisatorischer Natur sind; zwei davon werden als dringend erachtet.

1. Bei einem Elektrofahrzeugbrand anfallendes Lösch- und Kühlwasser ist stark kontaminiert. Da die Konzentrationen von Lithium und der Schwermetalle Kobalt, Nickel und Mangan derzeitige Grenzwerte für die Einleitung in die Kanalisation um ein Vielfaches überschreiten, muss eine entsprechende Vorbehandlung in der Praxis zwingend umgesetzt werden. Die Anwendung der aktuellen Grundsätze für ABC-Einsätze sind hierfür ausreichend.

2. Hinsichtlich des Kühlwassers, das typischerweise in der Nachbehandlung von ausgebrannten Batterien anfällt, ist zudem die Definition eines standardisierten Umgangs erforderlich.

Die weiteren Empfehlungen umfassen zusätzliche präventive Massnahmen, die einen angemessenen Umgang mit der sich verändernden Risikolandschaft erlauben.

Publikationen:

Mellert, L. D., Welte, U., Tuchschmid, M., Held, M., Hermann, M., Kompatscher, M., Tesson, M., Nachef, L. (2020): Risikominimierung von Elektrofahrzeugbränden in unterirdischen Verkehrsinfrastrukturen. Forschungsprojekt AGT 2018/006 auf Antrag der Arbeitsgruppe Tunnelforschung (AGT), Bundesamt für Strassen ASTRA, Bern.

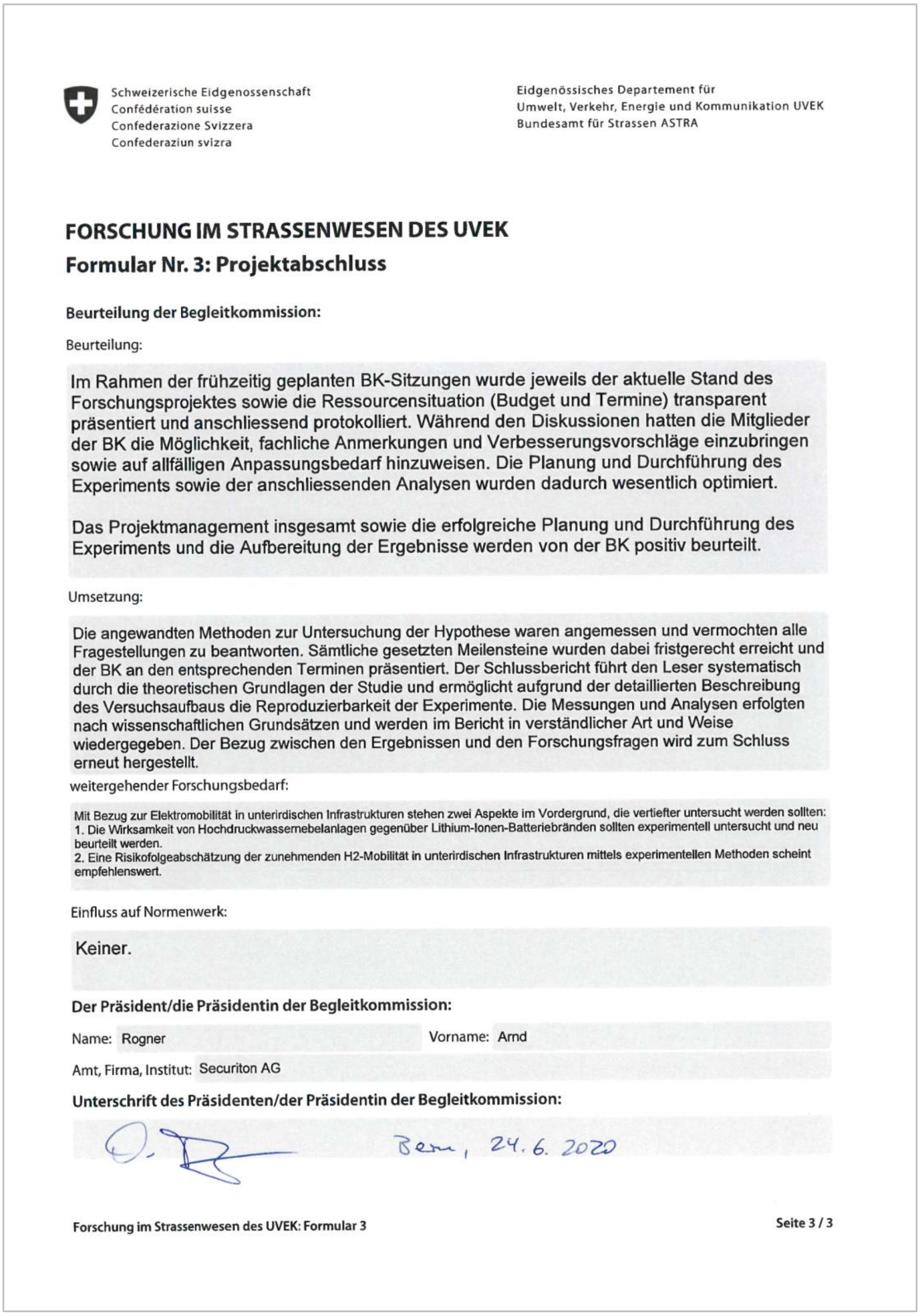
Der Projektleiter/die Projektleiterin:

Name: Mellert Vorname: Lars Derek

Amt, Firma, Institut: Amstein + Walthert Progress AG

Unterschrift des Projektleiters/der Projektleiterin:

Forschung im Strassenwesen des UVEK: Formular 3 **Seite 2 / 3**



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Formular Nr. 3: Projektabschluss

Beurteilung der Begleitkommission:

Beurteilung:

Im Rahmen der frühzeitig geplanten BK-Sitzungen wurde jeweils der aktuelle Stand des Forschungsprojektes sowie die Ressourcensituation (Budget und Termine) transparent präsentiert und anschliessend protokolliert. Während den Diskussionen hatten die Mitglieder der BK die Möglichkeit, fachliche Anmerkungen und Verbesserungsvorschläge einzubringen sowie auf allfälligen Anpassungsbedarf hinzuweisen. Die Planung und Durchführung des Experiments sowie der anschliessenden Analysen wurden dadurch wesentlich optimiert.

Das Projektmanagement insgesamt sowie die erfolgreiche Planung und Durchführung des Experiments und die Aufbereitung der Ergebnisse werden von der BK positiv beurteilt.

Umsetzung:

Die angewandten Methoden zur Untersuchung der Hypothese waren angemessen und vermochten alle Fragestellungen zu beantworten. Sämtliche gesetzten Meilensteine wurden dabei fristgerecht erreicht und der BK an den entsprechenden Terminen präsentiert. Der Schlussbericht führt den Leser systematisch durch die theoretischen Grundlagen der Studie und ermöglicht aufgrund der detaillierten Beschreibung des Versuchsaufbaus die Reproduzierbarkeit der Experimente. Die Messungen und Analysen erfolgten nach wissenschaftlichen Grundsätzen und werden im Bericht in verständlicher Art und Weise wiedergegeben. Der Bezug zwischen den Ergebnissen und den Forschungsfragen wird zum Schluss erneut hergestellt.

weitergehender Forschungsbedarf:

Mit Bezug zur Elektromobilität in unterirdischen Infrastrukturen stehen zwei Aspekte im Vordergrund, die vertiefter untersucht werden sollten:
1. Die Wirksamkeit von Hochdruckwassernebelanlagen gegenüber Lithium-Ionen-Batteriebränden sollten experimentell untersucht und neu beurteilt werden.
2. Eine Risikofolgeabschätzung der zunehmenden H2-Mobilität in unterirdischen Infrastrukturen mittels experimentellen Methoden scheint empfehlenswert.

Einfluss auf Normenwerk:

Keiner.

Der Präsident/die Präsidentin der Begleitkommission:

Name: Rogner
Vorname: Arnd
Amt, Firma, Institut: Securiton AG

Unterschrift des Präsidenten/der Präsidentin der Begleitkommission:

Bern, 24.6.2020

Index for reports on research in road transport

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