Toxic Gases from Electric Vehicle Fires

Ola Willstrand, Roeland Bisschop, Per Blomqvist, Alastair Temple, Johan Anderson
RISE Research Institutes of Sweden, Division Safety & Transport
Borås, Sweden

ABSTRACT
The ongoing shift to electromobility has identified new risk areas. Fires involving electric vehicles have attracted considerable media attention and a strong concern related to burning electric vehicles containing lithium-ion batteries is the release of toxic gas. In this study, full-scale tests on two electrical and one conventional vehicle have been performed to gather data on gas and heat release during fire. One electrical vehicle and one conventional vehicle were of the same model from the same manufacturer which enable a good comparison between the powertrains. Peak heat release rate and total heat release are affected by the fire scenario and vehicle model, but not significantly on the powertrain. Regarding toxic gases, hydrogen fluoride represents the largest difference between electric vehicles and conventional vehicles, but when smoke from vehicle fire is inhaled there are several acute toxic gases present regardless of the type of vehicle burning. Except hydrogen fluoride, there are also some specific metals present in the smoke that constitutes a large difference between the powertrains.

KEYWORDS: toxic gases, heat release, electric vehicles, fire tests, simulations

INTRODUCTION

The number of electric vehicles (EVs) that are released onto our roads each year continues to increase. The look and design of these vehicles can vary, but they are all (except some non plug-in hybrids) using lithium-ion batteries today and will continue to do so for many years to come [1]. China is housing approximately 47 % of the world's passenger car EVs and in second and third place are the USA and the EU with 20 % and 16 % of the cars in 2019, respectively [2, 3]. The introduction of EVs, and fire incidents involving them, have attracted considerable media attention [4, 5]. Fire risks related to the on-board lithium-ion battery are often mentioned, despite the fact that most fire incidents have other origins and that EV fires are less probable than conventional vehicle fires [4, 6, 7, 8]. However, it is true that abuse due to unexpected mechanical or thermal loading or internal failures can turn the Li-ion battery into a fire hazard [4]. In addition, arson fires are likely to affect EVs in the same extent as other vehicles.

A strong concern related to burning electric vehicles containing Li-ion batteries is the release of toxic gas. Toxic gases are however released in all fires, but some materials and products are of more concern for toxic emissions. All modern vehicles contain a large amount of plastics which could be a source of a variety of toxic combustion products. These include carbon monoxide, hydrogen cyanide, organic irritants and carcinogenic organic compounds, further can some plastics be the source of e.g. hydrogen chloride (HCl) and hydrogen fluoride (HF). The combustion of the AC-gas in the vehicle could additionally release a substantial amount of HF. In electric vehicles, Li-ion batteries release toxic gases during fire primarily from combustion of the electrolyte. The electrolyte contains lithium hexafluorophosphate ($LiPF_6$) and can also include other fluorine containing compounds which provide the potential for emission of HF during heating and combustion.

Few full-scale fire tests on electric vehicles are available in literature to date. A total of 4 studies [9, 10, 11, 12] were performed in recent years where electric vehicles were considered and those are summarized in Table 1. Gaseous products from the combustion are however not often captured in detail. Except for CO and CO_2, information on the production of asphyxiant or irritant gases, such as HCl or HF, is hard to find. It is only in the French study [9] that measurements and analysis of the toxic compounds were performed in detail. Other studies have attempted to find out how much toxic gases are generated from li-ion batteries and in some cases also tried to extrapolate the results to be valid for larger battery systems or electric vehicles [13, 14, 15, 16, 17, 18].

Toxic gases are of great concern, but without external combustion the composition of gases released by batteries during thermal runaway is primarily made up of CO, CO_2, H_2 and different hydrocarbons [19] [20]. Except CO_2, this is flammable gases which could be of a larger and more immediate threat than the toxic gases due to the risk of gas explosion.

Table 1. Full-scale fire tests that included EVs. Note that BEV and PHEV refer to abbreviations for battery electric vehicles (pure electric) and plug-in hybrid electric vehicles, respectively. Internal combustion engine vehicles (ICEV) are conventional vehicles without electric powertrain.

Study	Vehicle	Ignition source	Ignition point	Measurement	Environment
Lecocq et al. [9], Truchot et al. [21]	ICEV, BEV	6 kW propane burner	Inside the passenger compartment (lacerated driver seat, open windows)	HRR, heat flux, mass loss, temperature, gas flow, gas composition	Confined area (Tunnel, 3.5 m high and 50 m long)
Lam et al. [10]	ICEV, PHEV, BEV	2 MW propane burner, 2.4 m x 1.2 m	Simulated pool fire underneath the vehicle (Centred, 0.2 m underneath the vehicle)	Temperature, heat flux, HRR, gas composition, voltage, crane scale (mass loss)	Free burn (Full-scale test facility, burn hood 6 m x 6 m)
Watanabe et al. [11]	ICEV, BEV	80 g alcohol gel-fuel	Behind rear wheel well	Weighing platform (mass loss and mass loss rate), heat flux	Free burn (15 m x 15 m x 15 m fire test room)
NHTSA [12]	BEV	1.55 W/cm^2 film heater	Single battery cell	Voltage, smoke detector, gas composition, temperature	Free burn (Outdoors)

Toxicity

To give an idea of the gases and compounds worth focusing on a comparison have been done between listed health exposure limits and total quantities measured in mentioned studies, including EV fire tests [9] and battery tests [13, 14, 15, 16, 17, 18] as well as two conventional vehicle (ICEV) fire tests [21, 22]. Health exposure limit values used in this study include "Immediately Dangerous to Life or Health" (IDLH) values published by the National Institute for Occupational Safety and Health (NIOSH) in the USA [23], "Acute Exposure Guideline Level" (AEGL) values published by the Environmental Protection Agency (EPA) in the USA [24], and legislative requirements for exposure limits in work environments published by the Swedish Work Environment Authority [25]. Based on the maximum levels measured in any of the studies (per vehicle or per Wh) the substances with the highest measured quantities in relation to listed health exposure limits were CO, HF, HCl, SO_2, Co, Li and polycyclic aromatic hydrocarbons (PAH). PAHs are persistent and cancerogenic and are a known health issue for firefighters [26]. CO_2, HCN and NO were also measured in relatively high quantities compared to their health exposure limits, while most individual organic compounds and metals where measured in lower quantities in comparison. Note that not all substances have listed health exposure limits, especially not among organic compounds and metals. In addition, this initial analysis does not consider combined effects due to exposure of several substances at the same time.

Asphyxiant gases cause unconsciousness or death by suffocation. Sometimes only nontoxic or minimally toxic gases with no other major health effects than displacement of oxygen in breathing air is meant, e.g. H_2, N_2, CO_2 and methane. These are also referred to as simple asphyxiants. Symptoms such as dizziness and nausea can occur when oxygen levels are less than approximately 19.5% and oxygen levels under 10% can cause unconsciousness in short time [27]. Other asphyxiants that will cause suffocation of body cells are carbon monoxide (CO) and hydrogen cyanide (HCN). Poisoning by carbon monoxide is estimated to causing half of all deaths related to fire [28].

All fire gases contribute to suffocation of body cells by displacement of oxygen. However, some gases also have a toxic and irritating effect that could be significant already at low concentrations, these include e.g. hydrogen fluoride (HF), hydrogen chloride (HCl), sulphur dioxide (SO_2) and nitrogen oxides (NO_x). A recent study [29] analyzing toxic gases from Li-ion batteries (LFP cathode) conclude that the effects of irritant gases are much more significant than those of asphyxiant gases. As for other irritant gases HF is severely irritating and can cause severe injury to e.g. respiratory tract if inhaled. In contact with moisture hydrofluoric acid is formed, which is more corrosive than hydrochloride acid [30]. However, the major difference between HF and other irritant gases is that the fluoride ion is able to penetrate skin and other tissues and is causing systemic poisoning effect by changing the levels of calcium, potassium and magnesium in the blood [31]. Other fluorine-based compounds, such as POF_3 and COF_2, are also very toxic but have not been reported from fire tests with batteries in significant quantities. Particulate fluoride is not considered as toxic as some of the decomposition products since health exposure limits have focus on the irritating effect at inhalation.

Metal residues associated to particulates in the air from fire in electric vehicles have not been studied in detail but one previous study show alarmingly high levels of cobalt (Co), lithium (Li) and manganese (Mn) from battery fire tests [14]. Heavy metals can be very toxic [32] and the composition is expected to be different with the contribution from the batteries in electric vehicles. From an ICE car [22] the highest metal levels detected were for zinc (Zn), lead (Pb) and copper (Cu) and very low levels were detected for metals such as lithium (Li), cobalt (Co), manganese (Mn) and nickel (Ni). Cobalt has a very low IDLH value (20 mg/m^3), while e.g. manganese has a quite high value (500 mg/m^3). There are efforts made to lower the cobalt in batteries due to scarce supply and debated mining, but the replacing nickel has however an even lower IDLH value (10 mg/m^3). Lithium is not expected to bioaccumulate and its human as well as environmental toxicity is considered low [33]. Nor does lithium have an occupational exposure limit, but as for all particulate matter the analyses do not consider chemical state or possible compounds. For example, lithium hydride (LiH) has a very low IDLH value (0.5 mg/m^3).

The ability of HF to penetrate skin and the fact that higher levels of HF are expected from electrical vehicles compared to conventional vehicles is a concern for the rescue service. It can be seen in guidelines used by the rescue services in Sweden, which focus a lot on the toxic gases and specifically on hydrogen fluoride [34, 35, 36]. Tests that have been performed in Sweden with two combinations of combined base layer and turnout gear materials to evaluate protection capacity against gases and particulates resulting from EV fires [37]. Results show good protection against HF for very high concentrations. Still, the concern regarding toxic gases may contribute to greater hesitation in their firefighting and response strategy regarding EVs. In addition, a delayed response entails a greater risk of fire spread as well as reduced recycling potential and higher insurance costs. This may have a critical impact to personal safety, the environment, the vehicle industry, and society’s shift towards electromobility.

VEHICLE FIRE TESTS

Three full-scale vehicle fire tests have been performed. The vehicles comprised of two battery electric vehicles (BEVs) and one conventional internal combustion engine vehicle (ICEV), see Table 2. The ICEV and one of the BEVs were of the same vehicle model from the same manufacturer which enable a good comparison between the powertrains.

Table 2. Specifications of the vehicles tested.

Test	Type	Propulsion energy	SOC	Cell type	Model	Year	Manufacturer
1	ICEV	Diesel, 44 l	-	-	Full-size van	2011	A
2	BEV	40 kWh	80 %	Pouch, NMC	Full-size van	2019	A
3	BEV	24 kWh	80 %	Prismatic, NMC	Small family car	2016	B

The vehicle fire tests have been performed inside a fire hall with a large calorimeter hood above to collect smoke and gas emissions. An overview of the test setup is seen in Figure 1. A fire scenario was selected to primarily give a worst-case scenario with regards to toxic gas release, which means a scenario where the batteries of the electric vehicles are involved and consumed close to when the vehicle fire is at peak heat release rate. The ICEV was set on fire by a small diesel pool fire located directly underneath its fuel tank. The total amount of diesel was 44 l including both the pool underneath and the fuel inside the tank. 44 l was 80% of full tank capacity. For the electric vehicles, a gas burner with a defined output of 30 kW was considered and located underneath the battery pack. The burner was active for the complete test duration and contribution to the heat release measured were removed from the results. A large steel tray (4.7 m × 2.0 m) was positioned under the vehicles to collect liquids and to avoid too large pool fire from the fuel tank of the ICE vehicle.

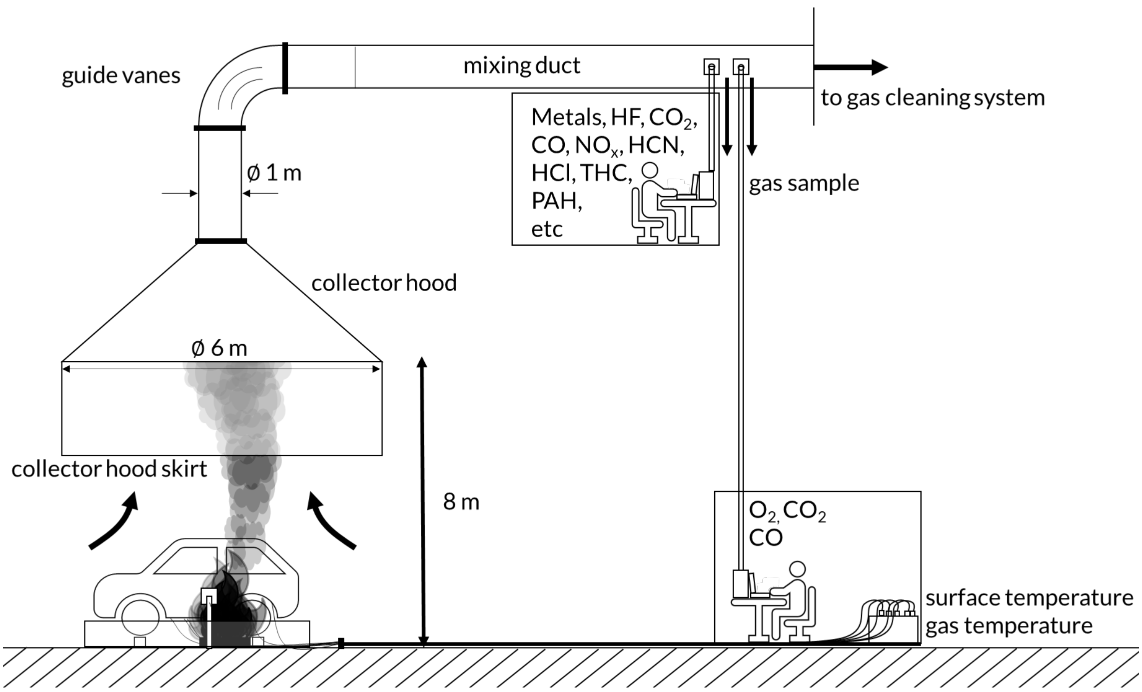


Figure 1. An overview of the test facility, test setup and measured data.

In addition to the full-scale vehicle tests a battery pack from a plug-in hybrid electric SUV from 2014 was used for battery tests. The purpose with the battery fire tests were to compare heat release and gas emissions from small-, medium- and large-scale tests with the same type of battery to analyze the scalability of the measured quantities. Three out of ten battery modules were removed from the battery pack from the PHEV before the large-scale test with the remaining of the battery pack. The three modules were used both for cell-level tests and for module-level tests. The prismatic battery cells had a capacity rating of 40 Ah.

Measurements

Oxygen, carbon monoxide and carbon dioxide concentration as well as mass flow of the extracted combustion gases were measured. Thereby, the heat release rate could be calculated by oxygen consumption calorimetry. Convective heat release rate was also calculated based on temperature measurements to see that oxygen produced from the battery had no significant effect on the calorimetry-based measurements. The difference between convective and total heat release rate was not significantly changed when the battery got involved in the fire.

Type-K thermocouples were positioned at various locations on each vehicle to monitor how the fire developed. To capture the risk for fire spread to neighboring objects, or vehicles, temperatures were also measured next to the vehicle. This was done with plate-thermometers at a 1 m distance from the side of each vehicle. However, note that temperature data is not presented in this paper.

Gas and soot sampling was done from the exhaust duct to measure the composition of combustion products, as seen in Figure 1. An overview of the equipment used, and their purpose is shown in Table 3. Isokinetic extractive sampling of soot contents in the exhaust duct was performed with quartz filters.

Table 3. Overview of equipment used, and measured gases/metals/anions.

Measurement method	**Compounds measured**	**Chemical formula**
FTIR spectroscopy	Hydrogen Fluoride	HF
	Hydrogen Chloride	HCl
	Hydrogen Bromide	HBr
	Carbon Dioxide	CO_2
	Carbon Monoxide	CO
	Hydrogen Cyanide	HCN
	Sulphur Dioxide	SO_2
	Nitrogen Dioxide	NO_2
	Nitric Oxide	NO
Flame Ionization Detector (FID)	Total Hydrocarbons (THCs)	-
Gas washing bottles	Fluoride	F^-
	Chloride	Cl^-
	Bromide	Br^-
XAD-2 adsorbent (gas) and GC-MS analysis (soot)	Polycyclic Aromatic Hydrocarbons (PAHs)	-
ICP-MS and ICP-OES (soot analysis)	Aluminum	Al
	Cadmium	Cd
	Lead	Pb
	Cobalt	Co
	Chromium	Cr
	Copper	Cu
	Lithium	Li
	Manganese	Mn
	Nickel	Ni
	Zinc	Zn
Ion chromatography (soot analysis)	Fluoride	F^-
	Chloride	Cl^-
	Bromide	Br^-

RESULTS

Gases measured from the three vehicles are presented in Table 4. In addition to total amounts, presented in parentheses are amounts normalized to the mass loss from the vehicle. Total amounts of HCN for ICEV A and BEV A are not presented since the maximum levels did not reach up to defined detection limit. For presented gases, HF constitutes (in percentage) the largest difference between the ICEV and the BEVs. The HF graphs show for the BEVs an initial peak of HF production before battery ventilation probably due to combustion of the gas from the air conditioning system. No such HF production was however seen from ICEV A, despite that pressure of the AC-system was checked before tests. Both AC-gases expected from these vehicles (R134a and R1234yf) contain almost the same amount of fluorine. By integration of the second HF peak for the BEVs an estimated contribution from the batteries from these tests are 450 g and 610 g for BEV A and BEV B, respectively.

Table 4. Gas compounds measured from the exhaust duct.

Gas measurements	ICEV A	BEV A	BEV B
CO_2, **[kg]** / [g/lost g]	**344** / (1.4)	**335** / (1.4)	**438** / (1.1)
CO, **[g]** / [mg/lost g]	**6 420** / (25.5)	**7 790** / (31.5)	**9 510** / (23.8)
THC, **[g]** / [mg/lost g]	**2 370** / (9.4)	**3 130** / (12.7)	**2750** / (6.9)
HF, **[g]** / [mg/lost g]	**11** / (0.04)	**573** / (2.3)	**859** / (2.1)
HCl, **[g]** / [mg/lost g]	**1100** / (4.4)	**1590** / (6.4)	**1800** / (4.5)
HBr, **[g]** / [mg/lost g]	**18** / (0.1)	**115** / (0.5)	**88** / (0.2)
HCN, **[g]** / [mg/lost g]	-	-	**155** / (0.4)
SO_2, **[g]** / [mg/lost g]	**479** / (1.9)	**575** / (2.3)	**645** / (1.6)
NO, **[g]** / [mg/lost g]	**452** / (1.8)	**371** / (1.5)	**617** / (1.5)
NO_2, **[g]** / [mg/lost g]	**44** / (0.2)	**25** / (0.1)	**76** / (0.2)
PAH, **[g]** / [mg/lost g]	**112** / (0.4)	**29** / (0.1)	**334** / (0.8)

In addition, Figure 2 shows total amounts of HF, HCl and HBr measured by the FTIR (including analysis of sampling filters) compared with total amounts of fluoride, chloride and bromide captured by the gas washing bottles, recalculated to HF, HCl and HBr. The correlation between these two independent measurement techniques is good. The gas-washing sampling method is very sensitive, and losses can be avoided to a higher degree compared to FTIR. It is expected that the gas-washing bottle values would most often be higher, as these possibly contain other water-soluble fluorides, chlorides and bromides in addition to HF, HCl and HBr.

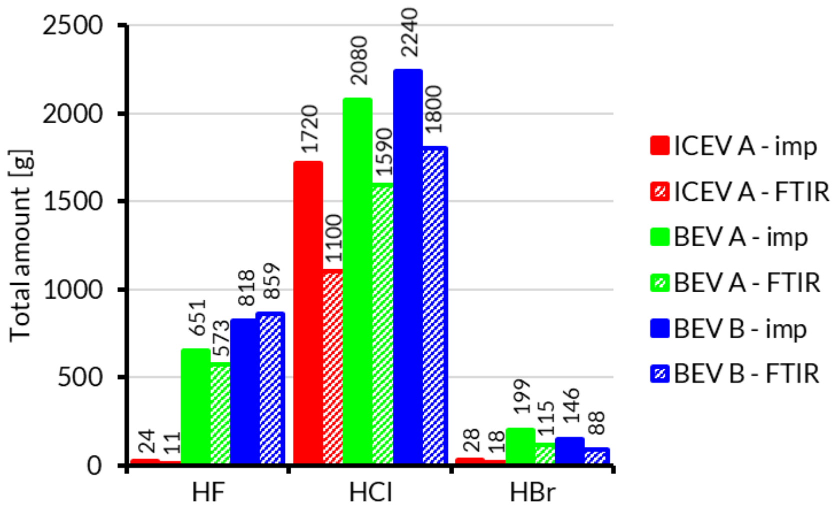


Figure 2. Total amounts of anions (HF/HCl/HBr equivalents) sampled by the washing bottles (impingers) and compared with total amounts measured by the FTIR.

Total amounts of metals and anions from the soot analysis of the exhaust gases are visualized in Figure 3. As seen, the metal content on soot particles are dramatically higher for the BEVs compared to the ICEV, particularly for metal elements typically found in Li-ion batteries: nickel, cobalt, manganese, lithium, aluminum and copper.

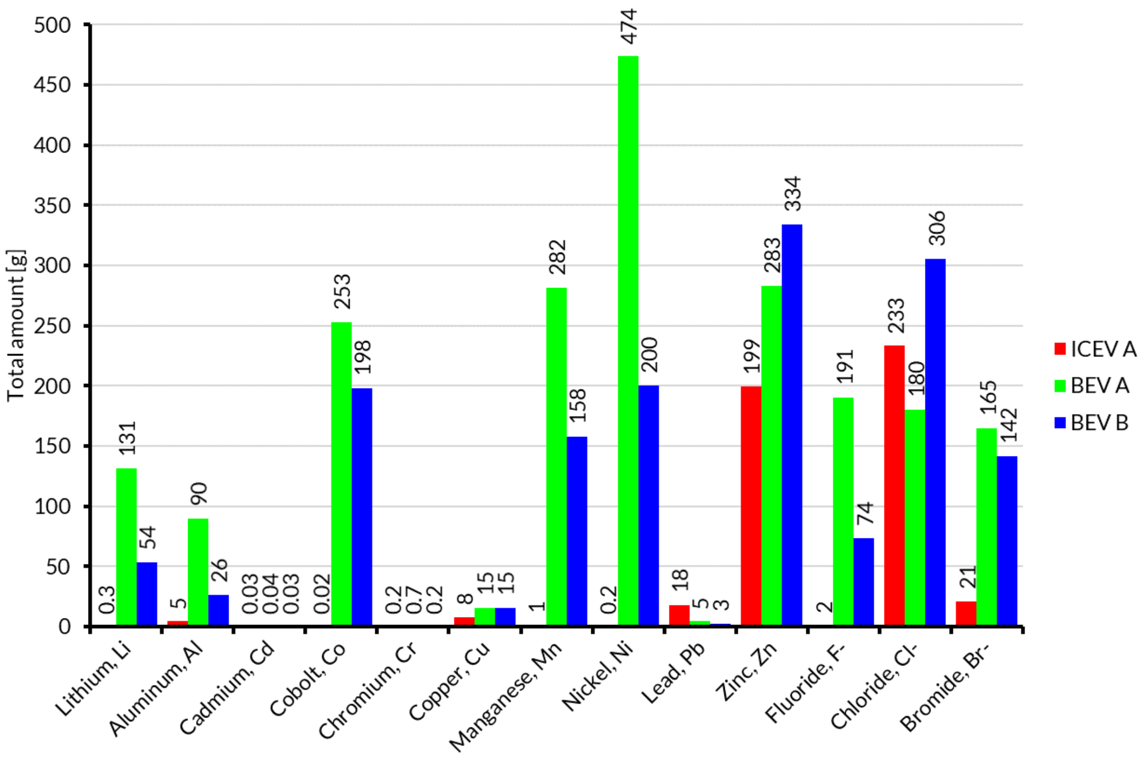


Figure 3. Total amounts of metals and anions on soot particles.

Heat Release

The heat release rates measured by oxygen consumption calorimetry in the three tests are presented in Figure 4. The test procedure was the same for all tests, with ignition of the external fire at t = 5 min.

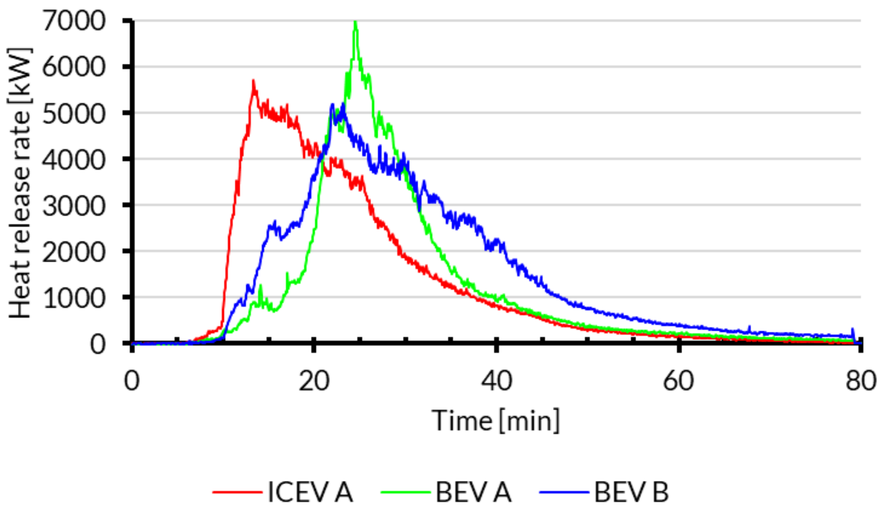


Figure 4. Heat release rate (oxygen consumption calorimetry) for the three vehicles.

As seen, after the fuel tank ruptured for ICEV A there was much faster fire development compared to the BEVs. The subsequent diesel pool fire burned out before fire development of the engine and passenger compartments reached its maximum why a higher peak heat release rate was achieved by BEV A where battery ventilation and maximum fire development happened at approximately the same time. The difference in battery configuration and especially cell type between BEV A and BEV B is causing a large difference in the heat release rate curves. When the pouch cells in BEV A started to ventilate, very large amounts of gas were released in relatively short time. This contributed significantly to the high peak heat release rate from BEV A. In comparison, the prismatic cells in BEV B started to ventilate later and continued release gas for a longer time. The gas release was irregular with a slower thermal runaway propagation between cells, resulting in a less apparent contribution to the overall heat release rate as seen in the graph.

The total heat releases from the three vehicles are presented in Table 5. The THR and mass loss is much greater for the family car compared to the vans which is expected due to the much larger amounts of combustible material available, primarily in the passenger compartment.

Table 5. Total heat release.

	ICEV A	BEV A	BEV B
Total heat release (THR), [GJ]	5.9	5.2	6.7

Total heat release (THR) data from the separate battery tests performed are presented in Figure 5 (denoted "E-TOX") together with test data on battery tests found in the literature [38, 39, 40, 41, 42, 16, 43, 44, 45, 46, 47, 48, 49, 50, 51]. There appears to be a linear correlation between the nominal electrical energy of the battery and the total amount of heat it may release during a fire, as shown by the trendline for all data. It may be useful for conservatively estimating the total contribution from an EV battery pack.

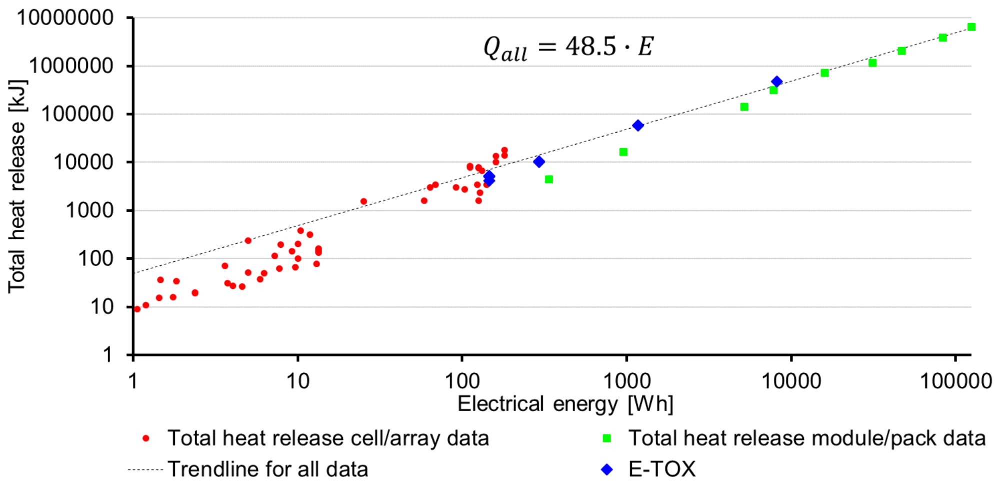


Figure 5. Total heat release data plotted with respect to the nominal electrical energy of the test objects.

DISCUSSION

The test results obtained, both from vehicle tests and battery tests, are in consistency with previous data both with regard to heat release and gas production. Concerning heat release, one of the BEVs burned in this project resulted in the highest peak heat release rate measured for EVs. This is not surprising since a fire scenario was chosen where the batteries of the electric vehicles were expected to be involved close to when the vehicle fire was fully developed. In addition, the battery configuration with pouch cells contributed to the high peak for one of the BEVs. The diesel van had a higher total heat release compared to the corresponding electric van, which should not be the case based on theoretical assumptions for the chemical energy available in the diesel and the battery, respectively. The calorific value for diesel gives that 44 l contain approximately 1.6 GJ, while based on the equation in Figure 5 a free burning 40 kWh battery would contain approximately 1.9 GJ. However, taken into account that a diesel pool fire on the ground burn more efficient compared to a vehicle integrated battery pack, one realize that the trendline shown in Figure 5 give a conservative estimate.

Concerning gas production, the total quantity of different gases measured from the vehicles are all in the lower part or slightly below quantities from previous tests, especially for NO_x, HF and HCl. Differences between ICEVs and BEVs are however similar, with the largest difference for HF. For HCl there was higher quantities for the BEVs in current study, however, in previous comparative study [9] it was the opposite with lower quantities for the BEVs compared to ICEVs. Except hydrogen fluoride, there are also some specific metals present in the smoke that constitutes a large difference between the powertrains. A previous study [14] reported high levels of cobalt, lithium and manganese from battery fire tests, but the largest quantities measured in this study was of nickel. Nickel has a lower IDLH value compared to e.g. cobalt, and there is a trend in battery development to use more nickel. The effect of the metals could be studied in more detail, but it is expected that this is more of an environmental issue rather than a health issue.

Hydrogen fluoride is of certain interest both due to its characteristics and that it constitutes one of the largest differences between electric vehicles (EVs) and conventional vehicles (ICEVs). Figure 6 summarize and visualize data from vehicle tests together with some interesting trendlines. The circular blue dots and corresponding black trendline is from the battery tests in current study, which showed a good linear relationship between HF production and nominal electrical energy. The green and red lines are based on the lowest and highest amount of HF measured in previous battery cell tests at RISE [45] (the interval corresponds to 12-200 mg/Wh). The square dots are from full-scale vehicle tests, blue dots from current study (E-TOX) and yellow dots from previous study [9]. Light square dots are the actual measurements while dark square dots are estimated contribution from the battery packs. For the E-TOX tests this estimation was explained earlier and is the integration of the second HF peak in the time-resolved graph from the FTIR, while for the INERIS tests the estimation is the difference between total amounts from the BEVs and corresponding ICEVs. As seen, the full-scale tests on EVs with toxic gas measurements are all in the lower part of potentially expected HF quantity. We know that on battery cell level the variation is large and based only on four tests with different vehicles (and different batteries) one should be careful with conclusions. However, HF readily reacts upon contact with most materials and “wall losses” can be significant. The difference between a pool fire with battery electrolyte and when the electrolyte is within a battery casing is large [16] and this could also potentially explain more losses when the battery is placed within a vehicle.

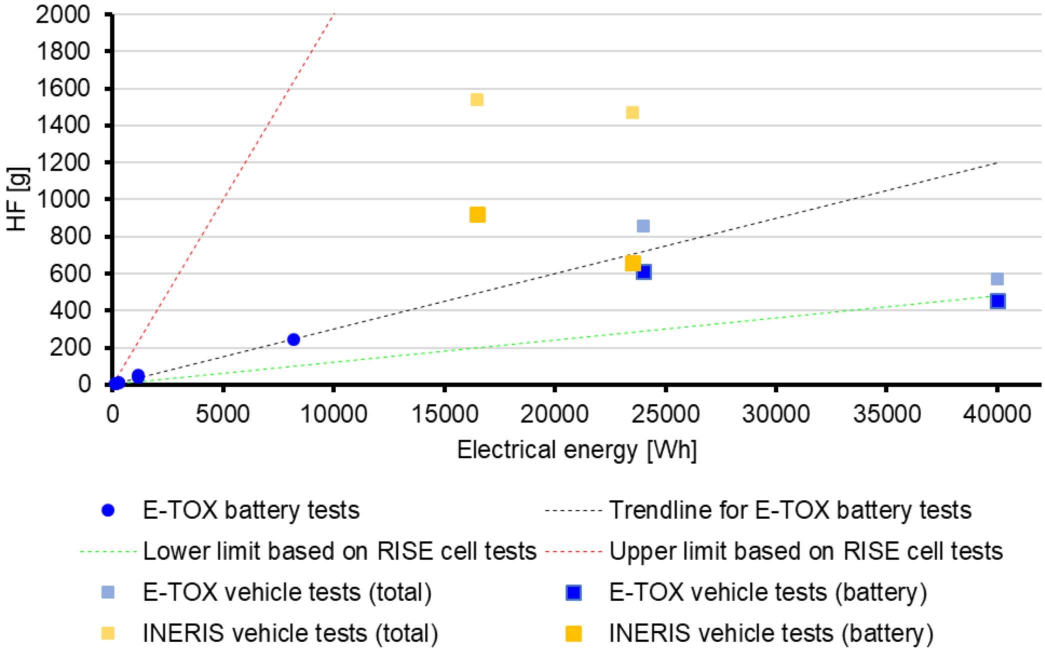


Figure 6. Total amounts of HF from EV fire tests as well as battery tests with corresponding trendlines.

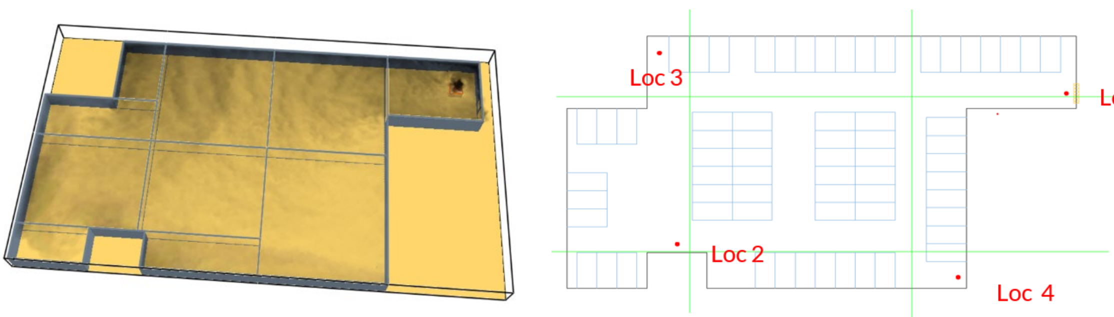
SIMULATIONS

The objective with the simulation and modelling efforts in this project was to assess risks attributed to spreading of toxic gases in confined spaces with limited natural or mechanical ventilation such as garages. Given the nature of the problem being studied, a fire starting in an electric vehicle within a garage, there is a very large range of variables which could have an impact on the fire growth and spread of smoke and combustion products throughout the space. The garage itself may vary from a small space for only a handful of cars, to a multi-storey space for dozens, if not more, vehicles. It could be a simple rectangular space, or a space with many different angles and internal walls which will all affect smoke movement. Likewise, the fire itself could vary significantly depending upon the exact situation and ventilation. Different vehicles will have fires which grow at different rates and give off different amounts of different species and finally the number of other vehicles in close proximity to the initial fire source will also vary. It is not therefore possible to conduct detailed simulations covering this full range of scenarios which is reasonable. Scenarios which can be considered a reasonable "worst case" should therefore be prioritised yet cover as many variations as possible while being computationally feasible.

To choose a base geometry for the simulations the following considerations were made:

- The smaller the garage, the less volume there is for mixing of combustion products with air, and therefore higher concentrations should be expected.
- The smaller the garage, the easier it is for the fire service to vent out gases upon arrival, and for very small garages it may even be possible to fight a fire from outside the garage.
- Very large garages provide a large volume for the mixing, and therefore diluting, of combustion gases with air, and therefore lower concentrations should be expected.
- Larger garages are also more likely to either be provided with large areas of natural ventilation, or provided with dedicated smoke extraction systems, which would also reduce the likelihood of high concentrations of combustion products within the garage.
- The minimum requirement for natural ventilation to an underground garage in Sweden is an opening of 0.5% of the floor area which can wholly or in part be made from the garage entrance door.

It was concluded that a reasonable "worst case" scenario would be a garage on the limit between what can be achieved with natural ventilation primarily by an open garage door, see Figure 7. This means that the ventilation remains limited while the space is too large for fires to be often fought from outside or to easily ventilate by the fire service upon arrival. The modelling was done with Fire Dynamics Simulator (FDS) (Version 6.7.0). FDS is a 'large eddy' based fluid dynamics for the study of the movement and behaviour of fire and smoke in 3D spaces. To assist with the modelling the PyroSim FDS interface by Thunderhead Engineering has been used.



(a) *(b)*

Figure 7. (a) Plan view of the garage geometry showing the spreading of smoke in the garage during the early stage of the fire. (b) Sampling locations in a plan view of the garage.

Two fire locations, fire adjacent to garage door and in the far corner, and three ventilation scenarios have been evaluated. In the different ventilation scenarios, the garage door is either open entire duration or opened after 20 or 35 minutes from start of the fire. At the time of writing this paper, due to the extensive running times of the models (several weeks on multiple cores), the simulations are ongoing and it is too early to draw any full conclusions from their results. However some early processing of the results to date have been completed and some FEC values (fraction effective does of irritants), as calculated to ISO 13571:2012 [52], and HF concentrations at 4 sampling locations (showed in Figure 7 (b)), can be seen in Figure 8. Scenario 1 here is fire location adjacent to garage door, as also seen in Figure 7 (a), and a-c are the different ventilation scenarios. Test 3 (small family car) is used as basis for fire and note that the graphs in Figure 8 start at the start of the fire. As seen, the HF concentration strongly affect the FEC, but critical FEC values (at head height) are reached before the battery gets involved. Note also that these HF concentrations are conservative since HF readily reacts upon contact with surfaces and solid particles. In a small enclosed space (15 m^3) the half-life of HF concentration could be as low as about 10 minutes [53].

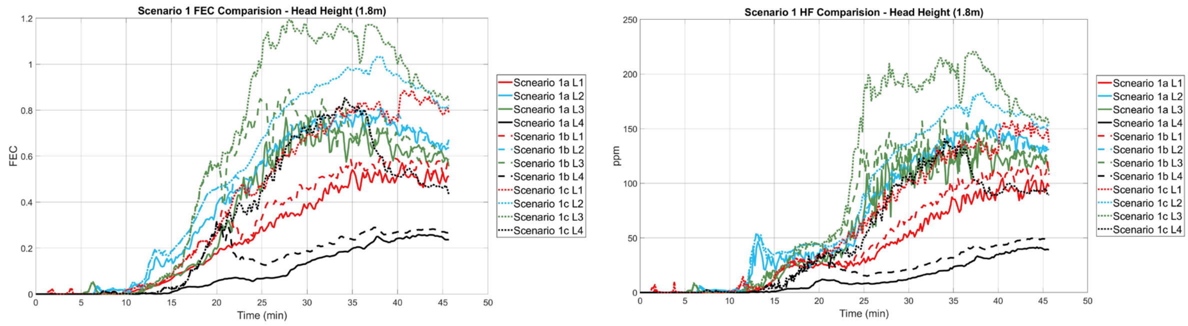


Figure 8. Extract of results to date showing FEC values calculated to ISO 13571 and HF concentrations at 4 sample locations.

CONCLUSIONS

New data from three full-scale vehicle fire tests confirm previous studies on EVs and Li-ion batteries that HF together with some specific metals, e.g. Ni, Co, Li and Mn (depending on the battery cell chemistry), in the smoke exhaust constitute a large difference between electrical and conventional vehicles. When smoke from a vehicle fire is inhaled however there are several acute toxic gases present regardless of the type of vehicle burning, e.g. CO, HF, HCl and SO_2, based on total quantities of different substances compared to health exposure limit values. For the rescue services HF is of certain interest due to that it can be absorbed through the skin, but the total quantities might be lower than potentially expected as was elaborated on in the discussion of the test results and the simulations of a potentially worst case scenario in a parking garage also show relatively low maximum concentrations. Much higher concentrations were used when firefighting turnout gear materials were evaluated and still showed good protection against HF. Peak heat release rate and total heat release are affected by the fire scenario and vehicle model, but not significantly on the powertrain.

ACKNOWLEDGEMENTS

This work is part of the project E-TOX (Toxic gases from fire in electric vehicles) financed by the Swedish Energy Agency. Partners within the project comprise of RISE Research Institutes of Sweden, the Swedish Civil Contingencies Agency (MSB), three insurance companies (If, Länsförsäkringar Älvsborg and Länsförsäkringar Göteborg & Bohuslän), six rescue services (RSG, SÄRF, SSBF, SBFF, RTJ Luleå, RSYD) and a dismantling/scrap yard (Borås Bildemontering).

REFERENCES

[1] Y. E. Durmus, H. Zhang, F. Baakes, G. Desmaizieres, H. Hayun, L. Yang, M. Kolek, V. Küpers, J. Janek, D. Mandler, S. Passerini och Y. Ein-Eli, ”Side by Side Battery Technologies with Lithium-Ion Based Batteries,” *Advanced Energy Materials,* vol. 2000089, pp. 1-21, 2020.

[2] International Energy Agency, ”Global EV Outlook 2018,” International Energy Agency, 2018.

[3] European Alternative Fuels Observatory, ”Total Number Alternative Fuels Passenger Cars: AF Fleet (Electricity) (2019),” 29 October 2018. [Online]. Available: https://tinyurl.com/y9g45w6p. [Använd 1 February 2019].

[4] R. Bisschop, O. Willstrand, F. Amon och M. Rosengren, ”Fire Safety of Lithium-Ion Batteries in Road Vehicles,” RISE Research Institutes of Sweden, RISE Report 2019:50, 2019.

[5] P. Sun, R. Bisschop, X. Huang och H. Niu, ”A Review of Battery Fires in Electric Vehicles,” *Fire Technology,* 2020.

[6] U. Bergholm, ”Sammanställning av bränder i eltransportmedel 2018-2019,” MSB - Swedish Civil Contingencies Agency, Sweden, 2020.

[7] A. W. Brandt and K. Glansberg, “Lading av elbil i parkeringsgarasje,” RISE Fire Research AS, RISE Report 2019:123, Trondheim, Norway, 2019.

[8] “Tesla Vehicle Safety Report,” [Online]. Available: https://www.tesla.com/sv_SE/VehicleSafetyReport. [Accessed 2 March 2020].

[9] A. Lecocq, M. Bertana, B. Truchot och G. Marlair, ”Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle,” Proceedings of 2nd International Conference on Fires In Vehicles - FIVE 2012, pp.183-194, Chicago, United States, 2012.

[10] C. Lam, D. MacNeil, R. Kroeker, G. Lougheed och G. Lalime, ”Full-Scale Fire Testing of Electric Vehicles and Internal Combustion Engine Vehicles,” i *Fourth International Conference on Fire in Vehicles*, Baltimore, USA, 2016.

[11] N. Watanabe, O. Sugawa, T. Suwa, Y. Ogawa, M. Hiramatsu, H. Tomonori, H. Miyamoto, K. Okamoto och M. Honma, ”Comparison of Fire Behaviours of an Electric-Battery-Powered Vehicle and Gasoline-Powered Vehicle in a Real-Scale Fire Test,” i *Second International Conference on Fires in Vehicles (FIVE)*, Chicago, USA, 2012.

[12] International, SAE, ”Single Cell Thermal Runaway Initiation (SCTRI),” NHTSA.

[13] F. Larsson, Lithium-ion Battery Safety - Assessment by Abuse Testing, Fluoride Gas Emissions and Fire Propagation, Göteborg, Sweden: Department of Physics, Chalmers University of Technology, 2017.

[14] L. D. Mellert, U. Welte, M. Hermann, M. Kompatscher, X. Ponticq, M. Tesson and J. Beckbissinger, “Electric mobility and road tunnel safety – hazards of electric vehicle fires,” VSS 2016/221, Switzerland, 2018.

[15] DNV GL AS Maritime, “Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression,” Report No.: 2019-1025, Rev. 4, Norway, 2019.

[16] P. Ribière, S. Grugeon, M. Morcrette, S. Boyanov, S. Laruelle och G. Marlair, ”Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry,” *Energy Environ. Sci.,* vol. 5, pp. 5271-5280, 2012.

[17] U. Bergström, Å. Gustafsson, L. Hägglund, C. Lejon, D. Sturk and T. Tengel, “Vented Gases and Aerosol of Automotive Li-ion LFP and NMC Batteries in Humified Nitrogen under Thermal Load,” FOI-R--4166--SE, Sweden, 2015.

[18] D. Sturk, L. Rosell, P. Blomqvist and A. Ahlberg Tidblad, “Analysis of Li-Ion Battery Gases Vented in an Inert Atmosphere Thermal Test Chamber,” *Batteries,* vol. 5, no. 61, 2019.

[19] N. Ponchaut, K. Marr, F. Colella, V. Somandepalli och Q. Horn, ”Thermal Runaway and Safety of Large Lithium-Ion Battery Systems,” Exponent Inc., Natick, USA.

[20] A. R. Baird, ”A Framework for Characterizing the Safety of Li-BESS using Performance Based Code Analysis and Testing,” The University of Texas at Austin, Austin, 2019.

[21] B. Truchot, F. Fouillen and S. Collet, “An experimental evaluation of the toxic gas emission in case of vehicle fires,” Proceedings of 7th International Symposium on Tunnel Safety and Security (ISTSS), pp.419-429, Montreal, Canada, 2016.

[22] A. Lönnermark and P. Blomqvist, “Emissions from an automobile fire,” *Chemosphere,* no. 62, pp. 1043-1056, 2006.

[23] The National Institute for Occupational Safety and Health (NIOSH) , “Immediately Dangerous To Life or Health (IDLH) Values,” [Online]. Available: Immediately Dangerous to Life or Health (IDLH) values. [Accessed 6 December 2019].

[24] United States Environmental Protection Agency (EPA), “About Acute Exposure Guideline Levels (AEGLs),” [Online]. Available: https://www.epa.gov/aegl/about-acute-exposure-guideline-levels-aegls. [Accessed 6 December 2019].

[25] The Swedish Work Environment Authority, “Hygieniska gränsvärden - Arbetsmiljöverkets föreskrifter och allmänna råd om hygieniska gränsvärden,” AFS 2018:1, Sweden, 2018.

[26] K. W. Fent, C. Toennis, D. Sammons, S. Robertson, S. Bertke, A. M. Calafat, J. D. Pleil, M. A. G. Wallace, S. Kerber, D. Smith and G. P. Horn, “Firefighters’ absorption of PAHs and VOCs during controlled residential fires by job assignment and fire attack tactic,” *Journal of Exposure Science & Environmental Epidemiology,* 2019.

[27] D. Stephens, P. Shawcross, G. Stout, E. Sullivan, J. Saunders, S. Risser and J. Sayre, “Lithium-ion battery safety issues for electric and plug-in hybrid vehicles,” National Highway Traffic Safety Administration (NHTSA), Report No. DOT HS 812 418, USA, 2017.

[28] U. Björnstig, L. Hoffmann and K. Palmkvist, “Brand i moderna bilar - Speciella faktorer att beakta i relation till olika drivsystem, Råd till räddningstjänst- och ambulanspersonal,” Swedish Civil Contingencies Agency (MSB), 2017.

[29] Y. Peng, L. Yang, X. Ju, B. Liao, K. Ye, L. Li, B. Cao och Y. Ni, ”A comprehensive investigation on the thermal and toxic hazards of large format lithium-ion batteries with LiFePO4 cathode,” *Journal of Hazardous Materials,* nr 381, 2020.

[30] U. Björnstig, Presentation at "Arlandamötet 2018", 2018.

[31] ATSDR - Agency for Toxic Substances and Disease Registry, “Medical Management Guidelines for Hydrogen Fluoride,” [Online]. Available: https://www.atsdr.cdc.gov/mmg/mmg.asp?id=1194&tid=38. [Accessed 7 February 2019].

[32] P. B. Tchounwou, C. G. Yedjou, A. K. Patlolla and D. J. Sutton, “Heavy Metals Toxicity and the Environment,” *Exp Suppl.,* vol. 101, pp. 133-164, 2012.

[33] H. Aral and A. Vecchio-Sadus, “Toxicity of lithium to humans and the environment—A literature review,” *Ecotoxicology and Environmental Safety,* vol. 70, pp. 349-356, 2008.

[34] Räddningstjänsten Storgöteborg, ”Intern riktlinje vid batteribrand,” Sweden, 2018.

[35] Södertörns brandförsvarsförbund, ”Instruktion - Särskilda rutiner vid batteribrand (litiumjon),” I 733, Sweden, 2019.

[36] Räddningstjänsten syd, ”Metodbeskrivning för brand eller annan påverkan av batteri,” Sweden, 2019.

[37] H. Wingfors, A. Fredman and M. Thunell, “Brandskyddskläders skyddskapacitet-materialtester med kemikalier som bildas vid bränder och termisk rusning i Li-jon batterier i e-fordon.,” FOI - Swedish Defence Research Agency, by request of MSB (the Swedish Civil Contingencies Agency), Sweden, 2019.

[38] R. E. Lyon och R. N. Walters, ”Energetics of lithium ion battery failure,” *Journal of Hazardous Materials,* vol. 318, pp. 164-172, 2016.

[39] A. O. Said, C. Lee, X. Liu, Z. Wu och S. I. Stoliarov, ”Simultaneous measurement of multiple thermal hazards associated with a failure of prismatic lithium ion battery,” *Proceedings of the Combustion Institute,* vol. 37, nr 3, pp. 4173-4180, 2019.

[40] M. Chen, D. Zhou, X. Chen, W. Zhang, J. Liu, R. Yuen och J. Wang, ”Investigation on the thermal hazards of 18650 lithium ion batteries by fire calorimeter,” *Journal of Thermal Analysis*

and Calorimetry, vol. 122, pp. 755-763, 2015.

[41] X. Liu, S. I. Stoliarov, M. Denlinger, A. Masias och K. Snyder, ”Comprehensive calorimetry of the thermally induced failure of lithium ion battery,” *Journal of Power Sources,* vol. 280, pp. 516-525, 2015.

[42] Y. Fy, S. Lu, K. Li, C. Liu, X. Cheng och H. Zhang, ”An experimental study on burning behaviors of 18650 lithium ion batteries using a cone calorimeter,” *Journal of Power Sources,* vol. 273, pp. 216-222, 2015.

[43] P. Ping, D. Kong, J. Zhang, R. Wen och J. Wen, ”Characterization of behaviour and hazards of fire and deflagration for high-energy Li-ion cells by over-heating,” *Journal of Power Sources,* vol. 398, pp. 55-66, 2018.

[44] D. Sturk, L. Hoffmann och A. Ahlberg Tidblad, ”Fire Tests on E-vehicle Battery Cells and Packs,” *Traffic Injury Prevention,* pp. 159-164, 2015.

[45] F. Larsson, P. Andersson, P. Blomqvist och B.-E. Mellander, ”Toxic fluoride gas emissions from lithium-ion battery fires,” *Scientific Reports,* vol. 7, nr 10018, pp. 1-13, 2017.

[46] F. Larsson, P. Andersson, P. Blomqvist, A. Lorén and B.-E. Mellander, “Characteristics of lithium-ion batteries during fire tests,” *Journal of Power Sources,* no. 271, pp. 414-420, 2014.

[47] F. Larsson, P. Andersson och B.-E. Mellander, ”Lithium-Ion Aspects on Fires in Electrified Vehicles on the Basis of Experimental Abuse Tests,” *Batteries,* vol. 2, nr 9, 2016.

[48] P. Ping, Q. Wang, P. Huang, K. Li, J. Sun, D. Kong och C. Chen, ”Study of the fire behaviour of high-energy lithium-ion batteries with full-scale burning test,” *Journal of Power Sources,* vol. 285, pp. 80-89, 2015.

[49] Z. Wang, H. Yang, Y. Li, G. Wang och J. Wang, ”Thermal runaway and fire behaviors of large-scale lithium ion batteries with different heating methods,” *Journal of Hazardous Materials,* vol. 379, 2019.

[50] R. T. J. Long, A. F. Blum, T. J. Bress och B. R. Cotts, ”Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results,” The Fire Protection Research Foundation, Quincy, Massachusetts, USA, 2013.

[51] R. T. Long och A. M. Misera, ”Sprinkler Protection Guidance for Lithium-Ion Based Energy Systems,” Fire Protection Research Foundation, Quincy, MA, USA, 2019.

[52] International Organization for Standardization, *Life-threatening components of fire — Guidelines for the estimation of time to compromised tenability in fires,* Geneva: International Organization for Standardization, 2012.

[53] M. Rahm and A. Leandersson, “Electrical cabinet fire extinguishment testing,” SP Technical Research Institute of Sweden, Borås, Sweden, 2014.