# Risk Assessment for Battery Electric Vehicles' Occupants during Fire Accident

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**Abstract**

*The battery electric vehicle (BEV) is a promising technology for decarbonizing cities and reducing reliance on fossil fuels. However, the main barrier to its widespread adoption is the issue of safety. This study evaluates the risk of BEV occupants after exposure to hydrogen fluoride (HF) gas and thermal stress caused by a fire accident. The HF data of exploded cylindrical, pouch, and prismatic Li-ion batteries (LIBs) published in the literature were extrapolated to vehicle levels. Six commercial off-the-shelf BEV models were used, with the assumption that their entire battery packs would ignite at the same time. The risk was deemed acceptable if there was only one fatality per million incidents of HF exposure per year. The maximum tolerable rectal temperature of 38ºC and total water loss of 2500 g were used to evaluate thermal stress. The results show that, the higher the number of cell in the pack, the higher is the HF concentration in the cabin. Moreover, the selected BEV models exceeded the immediate dangerous to life or health (IDLH) level, making them prone to risk the occupant. With the battery fire of 100ºC the rectal temperatures can be adverse after 7 minutes and unacceptable dehydration after 122 minutes, posing an acute thermal risk to occupants when battery fire goes beyond 100ºC.*

***Keywords:*** Battery electric vehicle, Toxicity, Risk assessment, Occupant.

## Introduction

Recently, energy and global warming have been identified as the world's twin crises. Fossil fuel has played and continues to play a dominant role as a primary fuel (Greyson *et al.,* 2021a), meeting 40% of global energy demand (Bloomberg, 2020). However, fossil fuels will be depleted in the near future (Kuo, 2019). The transportation sector is cited as a major contributor, accounting for 24% of global emissions (IEA, 2020) that endanger the environment. To avoid the negative effects of tailpipe emissions and reach a peak by 2020, transitioning to zero-emission mobility is a critical step (Wang & Ge, 2019; Greyson *et al.,* 2021b). Vehicle electrification is a prominent solution toward greener transportation because of the low and stable electricity price, which is generated domestically and is unaffected by the global market. Among the outstanding characteristics of battery electric vehicles (BEVs) are higher energy efficiency over 77 percent (Lovell, 2020) and the ability to recover regenerative energy. Notably, the battery technology strongly assists the revolution in BEVs.

To date, Li-ion battery technology is utmost accepted for the propulsion of BEVs due to higher energy density and long cycle life(Chombo & Laoonual, 2020a). Nonetheless, the safety and dependability of Li-ion batteries are critical factors for BEV owners (Chombo & Laoonual, 2020b). In the midst of increasing global BEV sales, battery fire incidents have frequently been reported (Feng *et al.,* 2018; Chombo, Laoonual & Wongwises, 2021). For example, a BYD e6 taxi cab caught fire and killed all occupants (ChinaAutoWeb, 2012). In California, a Tesla Model X car caught fire and killed the driver (Levin & Beene, 2018); Tesla's driver in Malibu, California, died after fatal impacts and a massive battery eruption (Wilcox, 2015). Despite the increase in demand and production, the risk of toxic fumes and heat released after a BEV explosion has received little attention.

A few studies have focused on studying the flammability of the Li-ion battery materials (Yaakov *et al.,* 2010; Liu *et al.,* 2018), the toxicity of ejected gases (Lecocq *et al.,* 2012; Larsson *et al.,* 2016) and heat released during Li-ion battery failure (Ribie`re *et al.,* 2012; Ouyang *et al.,* 2017). The hydrogen fluoride (HF) has been extensively studied due to its huge quantity of toxicity (Larsson *et al.,* 2017). It's worth noting that the battery pack in a BEV contains hundreds or thousands of Lithium-ion cells. Unfortunately, the preceding studies concentrated on cell or small array levels, whereas real-world accidents stress the entire battery pack. As a result, there is a need to comprehend the occupants' risk as a result of the entire vehicle explosion.

This study assesses the risk of BEVs' occupants exacerbated by HF gas and intense heat released inside the cabin during the explosion of the whole battery pack. HF exposure in pack level of six auto-makers commercial off-shelf BEV models from giant automakers in the U.S., Europe and Asia which are available in the global market are studied. The risk of the BEV occupant being exposed for a short period of time to the common battery toxic gas – hydrogen fluoride (HF) and the temperature from the burning battery pack is evaluated. Estimated quantities and globally acceptable levels (standards) of HF toxicity and thermal risk are evaluated.

## Materials and methods

### BEV Models, vehicle cabin volume and occupant

Six commercial off-shelf BEV models made by giant automakers having different passengers' cabin volume ($m^3$), battery pack energy (kWh), battery chemistry, battery shape (cylindrical, pouch and prismatic), and battery pack configuration (underfloor, T-shaped, rear); were chosen for studying their related risk to occupant. Tesla model S100D and Mitsubishi i-MiEV based on the U.S.; BYD e6 and LEXUS UX300e based on Asia; and BMW i3s and Renault Zoe Z50 based on Europe were chosen for the study. Tesla model S100D, a sophisticated model and a representative of a pure BEV carrying huge electrical energy than any model in the market, is chosen to mimic a worst-case scenario of the fire accident.

The purpose of comparing different models is to see how the energy content of the battery pack affects the risk of passengers in the cabin. Table 1 lists the technical specifications of the selected BEV models. All commercial off-the-shelf models have internal materials such as plastic, rubber, and leather, which amplify gases and heat when burned. Furthermore, one adult male passenger is assumed to be in the cabin at the time of the occurrence.

**Table 1: Technical specifications of the selected BEV models**

| BEV Model | Cabin volume ($m^3$) | Battery pack capacity (kWh) | Number of cells | Battery shape | Battery chemistry | Ref |
|---|---|---|---|---|---|---|
| Tesla S100D | 2.66 | 100 | 7104 | Cylindrical | NCA | Hawley (2017) |
| i-MieV | 2.40 | 16 | 88 | Prismatic | - | Auto123.com (2020) |
| BYD e6 | 2.50 | 54.30 | 288 | Prismatic | LFP | Auto-data.net. (2017) |
| LEXUS UX300e | 2.83 | 54.30 | 288 | Prismatic | - | Wilde Lexus Sarasota. (2021) |
| BMW i3S | 2.38 | 42 | 320 | Prismatic | NCM622 | Caranddriver.com (2021) |
| Renault Zoe Z50 | 2.66 | 52 | 192 | Pouch | NMC172 | insideevs.com. (2019) |

**Battery chemistry and pack configuration**

According to Table 1, the Tesla Model S100D's battery pack is the only one with cylindrical cells. The main chemical in the cathode electrode is Li(NiCoAl)O2, (NCA), and the entire pack is positioned beneath the cabin floor. Table 1 contains information on the cell type, shape, chemistry, number of cells, and pack arrangement for additional types.

**HF generation during battery explosion and occupant's inhaled quantity**

During the increasing of battery temperature beyond its materials' melting point, electrolyte, made up of Li-salt e.g., LiPF6 and non-aqueous organic solvents, e.g., EC, DEC, DMC, or PC, starts to decompose, see eqn. (1) (Larsson *et al.,* 2017; Feng *et al.,* 2017). Eqn. (2) to (5) is the complete oxidation of the above organic solvents yielding to $CO_2$ and water whereas eqn. (6) to (9) is an incomplete oxidation of the organic solvents yielding to CO (Feng *et al.,* 2018).

$$LiPF_6 \rightarrow LiF + PF_5 \quad \text{.....(1)}$$

In the presence of water, the products in eqn. (1) further decompose as shown in eqn. (10) to produce significant amount of HF gas. The measurement of HF gas is conducted using a Fourier Transform Infrared (FTIR) technique incorporated into some measuring equipment. Therefore, the HF data from cylindrical, pouch and prismatic battery types were collected from the currently published literature of Andersson *et al.,* 2013, Larsson *et al.,* 2016 and Lecocq *et al.,* 2012 respectively, and are summarized in Table 2. This study assumed the same cell samples and experimental condition in all literature.

$$2.5O_2 + C_3H_4O_3(EC) \rightarrow 3CO_2 + 2H_2O \quad \text{..(2)}$$

$$6O_2 + C_5H_{10}O_3(DEC) \rightarrow 5CO_2 + 5H_2O \quad \text{..(3)}$$

$$3O_2 + C_3H_6O_3(DMC) \rightarrow 3CO_2 + 3H_2O \quad \text{..(4)}$$

$$4O_2 + C_4H_6O_3(PC) \rightarrow 4CO_2 + 3H_2O \quad \text{...(5)}$$

$$O_2 + C_3H_4O_3(EC) \rightarrow 3CO + 2H_2O \quad \text{.....(6)}$$

$$3.5O_2 + C_5H_{10}O_3(DEC) \rightarrow 5CO + 5H_2O \quad \text{.....(7)}$$

$$1.5O_2 + C_3H_6O_3(DMC) \rightarrow 3CO + 3H_2O \quad \text{.....(8)}$$

$$2O_2 + C_4H_6O_3(PC) \rightarrow 4CO + 3H_2O \quad \text{.....(9)}$$

$$PF_5 + H_2O \rightarrow POF_3 + 2HF \quad \text{.....(10)}$$

$$PF_5 + HF \rightarrow HPF_6 \quad \text{.....(11)}$$

To estimate the total HF gas to a large battery pack typically employed in BEV, the results in cell levels are then extrapolated into a vehicle level. The primary parameters are extrapolation factor, the total HF gas, HF concentration, HF generation rate, and time taken for outgassing, and are computed as given in eqn. (12) to (16).

$$Extrapolation\ factor = \frac{Cells_{pack}}{Cells_{\exp}} \quad \text{.....(12)}$$

$$HF_{total\_ext} = HF_{total\_\exp} \times Extrapolation\ factor \quad \text{...(13)}$$

$$HF_{conc\_ext} = \frac{HF_{total\_ext}}{Cabin\ volume} \quad \text{.....(14)}$$

$$HF_{gen-rate\_ext} = \frac{Cells_{pack} \times HF_{gen-rate\_\exp} \times HF_{total\_ext}}{Cells_{\exp} \times HF_{total\_\exp}} \quad \text{..(15)}$$

$$t_{gen\_ext} = \frac{HF_{total\_ext}}{HF_{\mathrm{gen-rate\_ext}}} \quad \text{.....(16)}$$

where $Cells_{pack}$ is the total number of cells in the battery pack; $Cells_{exp}$ is the total number of cells tested in the experiment; $HF_{total\_ext}$ is the total HF extrapolated (g); $HF_{total\_exp}$ is the total HF obtained in the experiment (g); $HF_{conc\_ext}$ is an extrapolated HF concetration (g/m$^3$); $HF_{total\_exp}$ is the HF concetration obtained from the experiment (g/m$^3$); $HF_{gen\text{-}rate\_ext}$ is an extrapolated HF generation rate (kg/s); $HF_{gen\text{-}rate\_exp}$ is the HF generation rate obtained from the experiment (kg/s); and $t_{gen\_ext}$ is an extrapolated HF generation time (s).

Consider a male occupant, adult, 50 years old, with an inhaling rate of 20 m$^3$/day or 0.0023 m$^3$/sec. Then, the total amount of inhaled HF can

**Table 2: Summary of the HF gas of BEV cells from published literature**

| Battery type | Weight (kg) | Voltage (V) | Capacity (Ah) | Energy (Wh) | SOC (%) | Rate of HF (mg/s) | Total HF (g) | Total HF (g/Wh) | Total HF(g/Ah) | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cylindrical** | 0.7348[c] | 3.7 | 28.80 | 106.56 | 100 | 2.9 | 2.2 | 0.021 | 0.076 | Andersson *et al.,* 2013 |
| Pouch | 1.180[a] | 4.1 | 7.00 | 5.740 | 100 | - | 184080 | 32070 | 26.297 | Sturk *et al.,* 2019 |
| | 1.925[a] | 3.3 | 14.00 | 46.20 | 100 | - | 80850 | 1750 | 5.775 | Sturk *et al.,* 2019 |
| | 0.0424[a] | 3.6 | 7.000 | 8.640 | 100 | 8.3 | 4.9-13.9 | 0.044-0.124 | 0.7-1.94 | Larsson *et al.,* 2016 |
| | - | 4.1 | 2.90 | 11.00 | 100 | - | - | - | | Ribie`re *et al.,* 2012 |
| Prismatic | 250[d] | 330 | 50.00 | 16,500 | 100 | - | 1540 | 0.093 | 30.8 | Lecocq *et al.,* 2012 |
| | 300[d] | 350 | 66.60 | 23,500 | 100 | - | 1470 | 0.063 | 22.07 | Lecocq *et al.,* 2012 |

[a] *Weight of 5 cells*
[b] *Two cells were tested*
[c] *Weight of 9 energy optimized batteries with 26650 cylindrical format (26mm outer diameter 65mm height)*
[d] *Number of cells are not known.*

be obtained ($HF_{conc\_ext}\times$ inhalation rate$\times t_{gen_ext}$). The associated health risk is quantified in the next section.

**Risk due to HF gas**

The studies of Vimmerstedt *et al.,* (1995) and Nedjalkov *et al.,* (2016) described HF gas as a non-carcinogenic gas, then, the associated short-time exposure risk is given by eqn. (17) (Ioven, 2020).

$$Risk = \frac{I_{non-carcinogen}}{R_f D} \qquad (17)$$

with $$I_{non-carcinogen} = \frac{C_o \times CR \times EF \times ED}{BW \times AT}$$

where, $I_{non\text{-}carcinogen}$ is non carcinogenic, $R_fD$ is the reference dose for HF, on which based on ATSDR, (2020), it is given as 0.06 mg/kg-day or $694.4\times10^{-12}$ g/kg-sec. Co is HF concentration in g/m$^3$, CR is the contact rate in m$^3$/sec, EF is exposure frequency in days per year, ED is exposure duration in years, BW is the body weight in kg, AT is the period over which the exposure is averaged (days).

By using CR=0.023 m$^3$/s, EF=1 day/year, ED=1 year, BW=50 kg, AT=1 day, and C in g/m$^3$ depending on the BEV model given in Table 1, and risk on each BEV model can be found.

**Estimating the risk of thermal stress**

During the eruption and fire ingress in the cabin, the interior air temperature spikes which in turn exposes the occupant into the extremely hot environment. The aggravated air poses heavy strain that eventually leads the occupant's body to undergo mechanisms such as perspiration and vasodilation to circumvent build-up of body temperature. Unfortunately, under elevated temperature, these mechanisms may fail to maintain the right body's homoeothermic condition and lead into heat stroke, syncope, burning and later occupant's demise. To evaluate the thermal risk on occupant's body, predicted heat strain (PHS) model, described in the ISO 7933 (ISO, 2004a) is employed to explore the initial indication of the possible risk. The PHS model is based on the energy balance of the human body which is a function of heat produced through metabolic heat (M); heat gained from the surrounding environment (W), see in eqn. (18) (NIOSH, 2016).

$$S=M-W\pm C\pm R\pm K\pm E \qquad (18)$$

where S is the body heat content (kcal.h$^{-1}$), M is the metabolism rate, W is the external mechanical work performed, C is the convective heat exchange ($kcal.h^{-1}$), R is the radiative heat exchange ($kcal.h^{-1}$), K is the conductive heat exchange ($kcal.h^{-1}$), E is the evaporative heat loss ($kcal.h^{-1}$). The definition of each term is given in NIOSH (2016).

Due to complexity on performing the evaluation, software developed in the FAME Lab, University of Thessaly, Greece, was employed to execute the model. The software is available in: http://www.famelab.gr/research/downloads/ and is published by Ioannou (2019). The input parameters for this study are: $t_a$ = 100ºC from the battery fire; $t_r$ = 100ºC radiated to the human body; $V_w$ = 0.3 m/s interior wind speed; $M$=450 W/m$^2$ fast metabolic rate due to increased ambient temperature; $I_{cl}$ = 0.155m$^2$/kW to reflect normal long sleeve pant and shirt; exposure time of 3 hours; body weight of 50 kg; stature of 1.80 m; and sit standstill in the vehicle's cabin.

**Results and Discussion**

Table 3 shows the results of the extrapolated HF gas and the risk due to HF exposure. It can be observed that $HF_{total\_ext}$ depends on the $Cells_{pack}$ while $HF_{conc\_ext}$ depends on the $HF_{total\_ext}$ and cabin volume. This means that, the higher the $Cells_{pack}$ the higher is the $HF_{total\_ext}$ and $HF_{conc\_ext}$ in the cabin. Table 4 shows the permissible exposure limits (PELs) of HF and other species based on the 8 working hours, 40 hours work week (Vimmerstedt *et al.,* 1995: Archuleta *et al.,* 2012; Bergstrom *et al.,* 2015: Nedjalkov *et al.,* 2016). By comparing the standard limit of HF of 2.5 mg/m$^3$ and extrapolated $HF_{conc\_ext}$ in Table 3 it can be seen that all BEV models exceed the standard limit when their whole battery pack are exploded.

Fig. 1a compares $HF_{total\_ext}$ resulted by burning of the whole battery pack of the selected BEV models. It can be shown that Tesla S100D produces more HF gas despite the small shape and size of the single cell. The reasons could be the highest energy stored in the battery pack and the large number of cells in the pack. However, this study did not relate the total amount of HF and cell chemistry. Hence, no correlation can be elucidated between the amount HF and cell chemistry. When comparing the $HF_{conc\_ext}$ among the BEV models, still Tesla S100D seems to contain the highest HF concentration (see Fig. 1b). Due to the danger of HF concentration, another parameter known as immediate dangerous to life or health (IDLH) level was employed for safety comparison. As shown in Fig. 1b, the red line indicates the IDLH level for HF (about 25 mg/m$^3$). Note: the value of IDLH has been multiplied by 1000 from the original value to get visibility on the graph. However, all BEV models are seen to surpass the IDLH level, making them prone to risk the occupant. For example, Tesla S100D has surpassed the IDLH level by 26,000 times compared to 4,000 of i-MieV. In that fact, Tesla S100D produces almost 7 times more than i-MieV. On the other side, in Fig. 1c and d, i-MieV model is seen to slowly producing the HF gas and spends the longest time to fully produce and occupy the cabin. This could rather be good hope for the occupant to use this model. On the contrary, the shortest generation time of Tesla S100D (about 1 second) could be a one way to frighten the end-users. Besides, the largest number of cells in the pack and the highest energy content could be factors aggravating the safety of Tesla S100D.

Table 3 and Fig. 1e show the estimated risk due HF inhalation inside the cabins. It should be noted that, this study considers a risk of 1 fatality per 1 million incidents of HF exposure in a year as an acceptable risk (WHO, 2001). In another way, a risk of 1.0×10-6 is considered acceptable. From Table 3 and Fig. 1e it can be seen the highest risk was estimated in Tesla S100D (423.7×106 fatalities) while the lowest was estimated in i-MiEV (68.1×106 fatalities). In terms of safety all models are seen to have high risk to occupants which is unacceptable. Even making the risk of one digit (e.g. 4 fatalities for Tesla S100D or 6 fatalities for Renault i-MiEV) yet the risk remains significant and unacceptable and raise concerns for improvement. To sum up, the risk was seen to depend on HF concentration while number of cells in the battery pack and cabin volume influenced the HF concentration. Hence, this makes risk as a multi-dimensional factor.

Figure 2 shows the results of thermal stress

**Table 3: Summary of the extrapolated HF results and estimated risk due to HF exposure**

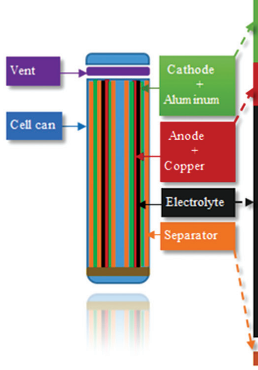
| Cell type | BEV Models | Cabin volume $m^3$ | $Cells_{pack}$ | Extrapolation factor | $HF_{total\_ext}$ (g) | $HF_{conc\_ext}$ ($g/m^3$) | $HF_{gen\text{-}rate\_ext}$ (kg/s) | $t_{gen\_ext}$ (s) | Risk due to HF $\times10^{-6}$ |
|---|---|---|---|---|---|---|---|---|---|
| Cylindrical | Tesla S100D | 2.66 | 7104 | 789.3 | 1736.5 | 652.83 | 1.8 | 1 | 432.7 |
| Pouch | Renault Zoe Z50 | 2.66 | 192 | 38.4 | 215 - 538 | 80.83-202.26 | 0.012 - 0.024 | 12 | 93.8 |
| Prismatic | i-MiEV | 2.40 | 88 | 17.6 | 246.4 | 102.67 | 0.005 | 49 | 68.1 |
| | BYD e6 | 2.50 | 288 | 57.6 | 806.4 | 322.56 | 0.053 | 15 | 212.8 |
| | Lexus UX300e | 2.83 | 288 | 57.6 | 806.4 | 284.95 | 0.053 | 15 | 188.9 |
| | BMW i3s | 2.38 | 320 | 64 | 896 | 376.5 | 0.066 | 14 | 249.6 |

simulated on the PHS software at an ambient temperature of 100ºC. It should be noted that, the model capability is to simulate moderate thermal environment. As such, the occupant was exposed for 3 hours and main focal parameters such as mean skin and rectal temperatures, and total water loss were evaluated. From Fig. 2, it is observed that $t_{re}$, $t_{sk}$, and total water loss are 75.19ºC, 59.28ºC, and 3410 g, respectively. After 7 minutes and 122 minutes of exposure, the maximum tolerable $t_{re}$ and total water loss of 38.0ºC and 2500 g, respectively, were recorded. Meaning that, with the battery fire of 100ºC the $t_{re}$ can be adverse after 7 minutes and unacceptable dehydration after 122 minutes. Notably, the battery fire mostly goes beyond 100ºC which may pose an acute thermal risk to the occupant within a short time. Moreover, the long burning time and uneasy suppression are further making the thermal risk exacerbated.

## Conclusion

The risk to BEV occupants from HF inhalation and thermal risk during a fire accident was assessed in this study. From the analysis conducted, it hve been observed that BEVs can expose passengers to high levels of HF and thermal stress, which can result in serious health problems, the extrapolated HF generation time ranges from 1 to 49s, depending on the

**Table 4: Short-time exposure limit for HF gas and other toxic gases from the exploding battery**




| Arrangement of cell layers | Cell component | Species | Standard Limit, $mg/m^3$ | Hazards | Ref |
|---|---|---|---|---|---|
| | Cathode | Nickel | 1.0 | Carcinogen | Vimmerstedt et al, 1995 |
| | | Cobalt | 0.1 | Carcinogen, cough, asthma, wheezing | Vimmerstedt et al, 1995; Bergstrom et al,2015 |
| | | Manganese | 1.0 | Neurotoxic chemical | Vimmerstedt et al, 1995; Bergstrom et al,2015 |
| | | Aluminum[1] | 5.0 | lung damage when inhaled | Vimmerstedt et al, 1995 |
| | | $V_2O_5$[3] | 0.05 | Air path irritant, liver, kidney toxin | Bergstrom et al,2015 |
| | | $MnO_2$[3] | 1.0 | Severe air path irritant, neurotoxin | Archuleta et al, 2012 |
| | | $CuO$[3] | 1.0 | Gastrointestinal irritant | Archuleta et al, 2012 |
| | | $Co_2O_3$[3] | 0.05 | Air path irritant, liver, kidney toxin | Archuleta et al, 2012 |
| | | $MoS_2$[3] | 5.0 | Upper respiratory tract irritant | Archuleta et al, 2012 |
| | Anode | Graphite | 2.0 | | Vimmerstedt et al, 1995 |
| | | Tin | 2.0 | Irritation to eyes, skin and in air path | Bergstrom et al,2015 |
| | | Copper[2] | 0.1 | Carcinogen, causes nausea | Vimmerstedt et al, 1995 |
| | Lithium salt | $LiPF_6$ | 2.5 | Upper Respiratory tract irritant | Vimmerstedt et al, 1995 |
| | | $LiAsF_6$ | 0.01 | Neurotoxin, carcinogen | Vimmerstedt et al, 1995; Archuleta et al, 2012 |
| | | $LiBF_4$ | 2.5 | Upper Respiratory tract irritant | Vimmerstedt et al, 1995 |
| | | $LiClO_4$ | - | Nervous system, thyroid, kidney toxin | Archuleta et al, 2012 |
| | Solvent | EC | | Eye, skin irritation | Nedjalkov et al, 2016 |
| | | EMC | | Eye, skin irritation, flammable liquid | Nedjalkov et al, 2016 |
| | | DEC | | Air path, skin, eyes irritation, nausea, vomiting | Vimmerstedt et al, 1995; Nedjalkov et al, 2016 |
| | | DEM | | | Vimmerstedt et al, 1995 |
| | | DMC | 14 | Eyes, skin, air path irritation, weakness | Vimmerstedt et al, 1995; Bergstrom et al,2015 |
| | | Benzene | | Aspiration hazard, carcinogenicity, eye irritation | Nedjalkov et al, 2016 |
| | | Toluene | | Aspiration hazard, flammable liquid, reproductive toxicity | Nedjalkov et al, 2016 |
| | | Styrene | | Acute toxicity, eye, skin irritation, flammable liquid | Nedjalkov et al, 2016 |
| | | Biphenyl | | Aquatic acute toxicity, aquatic chronic toxicity, eye irritation | Nedjalkov et al, 2016 |
| | | Acrolein | | Acute toxicity, aquatic acute toxicity, aquatic chronic toxicit carcinogenicity, eye damage, corrosive to respiratory tract | Nedjalkov et al, 2016 |
| | | CO | | Acute toxicity, flammable gas, reproductive toxicity | Nedjalkov et al, 2016 |
| | | COS | | Acute toxicity, eyes irritation, flammable gas | Nedjalkov et al, 2016 |
| | Binder | PVDF | | Highly toxic when inhaled | Vimmerstedt et al, 1995 |
| | Separator | Polypropylene | | Carcinogen, skin irritation | Vimmerstedt et al, 1995 |
| | | HF | 2.5 | Acute toxicity, corrosive to respiratory tract, skin corrosion | Vimmerstedt et al, 1995; Nedjalkov et al, 2016 |

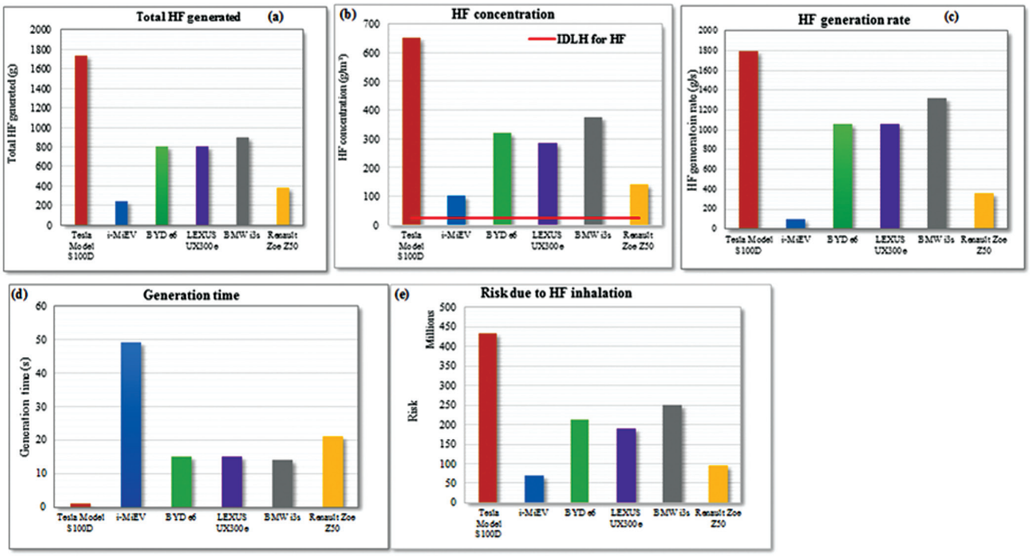



**Figure 1: Extrapolations of (a) Total HF generated form each BEV model (b) HF concentration in the cabin (c) the rate of HF generation (d) time taken to generate the total HF and (e) estimated risk due to HF inhalation**

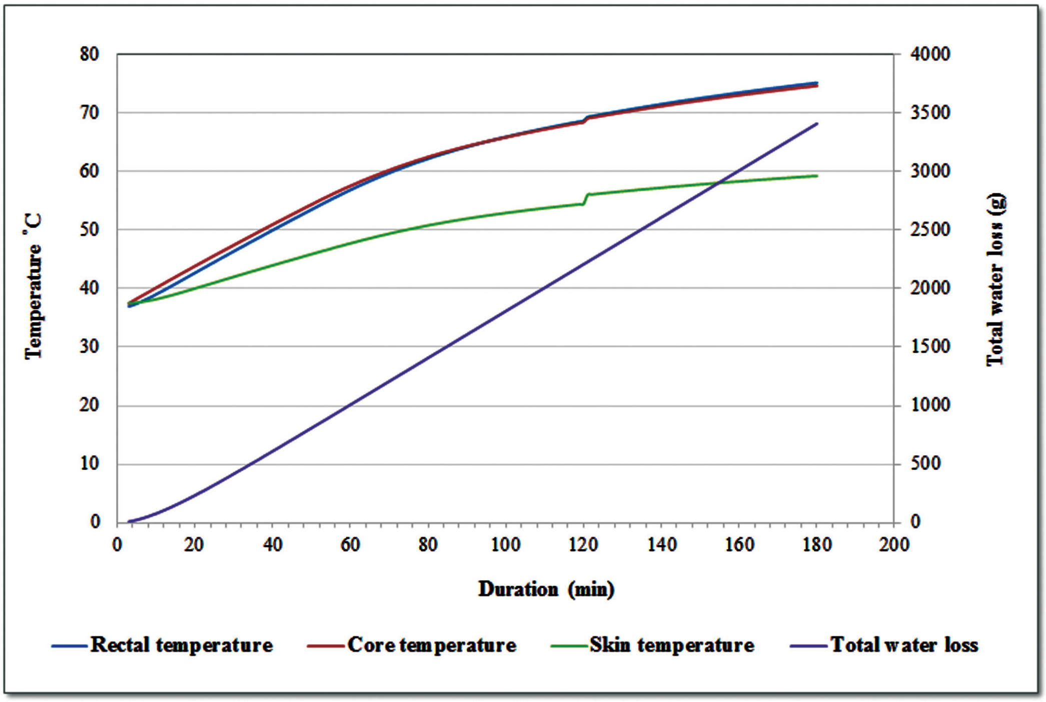



**Figure 2: Thermal stress simulated on the PHS software at an ambient temperature of 100 °C.**

energy content of the battery pack. The higher the energy content, the shorter the time required to generate HF , the total HF generated varies greatly depending on the number of cells in the battery pack, ranging from 215 to 1736.5 g for battery packs containing 88 to 7104 cells, the risk of HF is proportional to the energy content of the battery pack and exposure to temperatures and water losses of 38.0°C and 2500g, respectively, is harmful to the health of exposed occupants and should be avoided.

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**References**

Andersson, P., Blomqvist, P., Lorén, A., & Larsson, F. (2013). Investigation of fire emissions from Li-ion batteries. SP Technical Research Institute of Sweden: Borås, Sweden,

Archuleta, M.M. (2012). Toxicity of materials used in the manufacture. Sandia National Laboratories, USA. Report No. SAND94-0265C. https://prod.sandia.gov/techlib/access-control.cgi/2012/121541.pdf (accessed 24 September 2020)

ATSDR. (2020). Fluorides, Hydrogen Fluoride, and Fluorine: Regulations and advisories. https://www.atsdr.cdc.gov/toxprofiles/tp11-c8.pdf (accessed 26 September 2020)

Auto123.com (2020). Technical Specifications: 2013 Mitsubishi I-Miev Es https://www.auto123.com/en/new-cars/technical-specs/mitsubishi/i-miev/2013/base/es (accessed 30 July 2020).

Auto-data.net. (2017). https://www.auto-data.net/en/byd-e6-80-kwh-122hp-4wd-electric-34731(accessed July 2020)

Bergstrom, U., Gustafsson, A., Hagglund, L., Lejon, C., Sturk, D., & Tengel, T. (2015). Vented gases and aerosol of automotive Li-ion LFP and NMC batteries in humidified Nitrogen under thermal load.https://www.msb.se/siteassets/dokument/publikationer/english/publications/vented-gases-and-aerosol-of-automotive-li-ion-lfp-and-nmc-batte ries-in-hum idified-nitrogen-under-thermal-load.pdf (accessed 24 September 2020)

Bloomberg NEF. (2020). Oil Demand from Road Transport: Covid-19 and Beyond. https://about.bnef.com/blog/oil-demand-from-road-transport-covid-19-and-beyond/ (accessed 12 September 2020)

Caranddriver.com. (2021). Features and Specs. https://www.caranddri ver.com/bmw/i3/specs (accessed 12 September 2020)

ChinaAutoWeb. (2012). Three BYD e6 passengers killed in fiery crash, spurring EV safety concern. http://chinaautoweb.com/2012/05/three-byd-e6-passengers-killed-in-fiery-cra sh-sp urring-ev-safety-concern/ (accessed 12 September 2020)

Chombo, P.V. & Laoonual, Y. (2020a). International Conference and Utility Exhibition on Energy, Environment and Climate Change (ICUE), Pattaya, Thailand, (2020), 10.1109/ICUE49301.2020.9307122.

Chombo, P.V. & Laoonual, Y. (2020b). A review of safety strategies of Lithium-ion battery. *Journal of Power Sources.* 478( 2020): 228649-228668.

Chombo, P.V., Laoonual, Y. & Wongwises, S. (2021). Lessons from the Electric Vehicle Crashworthiness Leading to Battery Fire. Energies, 14(16), 4802.

Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y., & He, X. (2018). Thermal runaway mechanism of Lithium-ion battery for electric vehicles: a review. Energy Storage Materials. 10, 2018, pp. 246-267.

Greyson, K.A., Gerutu, G.B., Bobi, S. & Chombo, P.V. (2021a). Exploring the potential of compressed natural gas as a sustainable fuel for rickshaw: A case study of Dar es Salaam. *Journal of Natural Gas Science and Engineering*, 96, 104273.

Greyson, K.A., Gerutu, G.B., Mohamed, C.H. & Chombo, P.V. (2021b). Exploring the adoption of e-bicycle for student mobility in rural and urban areas of Tanzania. Sustainable Energy Technologies and Assessments, 45, 101206.

Hawley, G. (2017) "Understanding Tesla's lithium ion batteries" [Online] Available: https://evannex.com/blogs/news/understanding-teslas-lithium-ion-batteries.

IEA. (2020). Transport: Improving the sustainability of passenger and freight transport. https://www.iea.org/topics/transport (accessed 19 September 2020)

Insideevs.com. (2019). Meet The New 2019

Renault ZOE With 52 kWh Battery And 100 kW Motor. https://insideevs.com/news/355173/2019-renault-zoe-52-kwh-pack.( (accessed30 July 2020).

Ioannou, L.G., Tsoutsoubi, L., Mantzios, K., & Flouris, A.D. (2019). A free software to predict heat strain according to the ISO 7933:2019. Industrial Health. 57(6), 2019, pp. 711-720

Ioven, D.A. (nd). (2020). Baseline risk assessment overview. http://docplayer.net/21164133-What-is-risk-definition-probability-of-harm-or-loss-risk-hazard-exposure-risk-can-be-voluntary-or-involuntary-interpretation-of-risk-differs-for.html (accessed 24 September 2020)

ISO. 2004a. ISO 7933: (2004). Ergonomics of the thermal environment: Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. Geneva, Switzerland: International Organization for Standardization.

Kuo, G. (2019). When Fossil Fuels Run Out, What Then? MAHB. https://mahb.stanford.edu/library-item/fossil-fuels-run/ (accessed 24 September 2020)

Larsson, F., Andersson, P., & Mellander, B.E. (2016). Battery aspects on fires in electrified vehicles. Batteries 2016, 2(2), 9; https://doi.org/10.3390/batteries2020009

Larsson, F., Andersson, P., Blomqvist, P., & Mellander, B.E. (2017). Toxic fluoride gas emissions from lithium-ion battery fires. Scientific Report. 7(1), pp. 10018. https://doi.org/10.1038/s41598-017-09784-z

Lecocq, A., Bertana, M., Truchot, B., & Marlair. G. (2012). Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. International Conference on Fires in Vehicles - FIVE 2012, Sep 2012, Chicago, United States. SP Technical Research Institute of Sweden. Boras, pp.183-194, 2012.

Levin, A. & Beene, R. (2018). Tesla Model X in California crash sped up prior to impact. https://www.bloomberg.com/news/articles/2018-06-07/tesla-model-x-in california-crash-sp ed-up-seconds-before-impact (accessed 24 September 2020).

Liu, K., Liu, Y., Lin, D., Pei, A., & Cui, Y. (2018). Materials for Lithium-ion battery safety. Science Advances. Vol. 4, 9820.

Lovell, J. (2020). EVs: Are they really more efficient? Australian Energy Council. https://www.energycouncil.com.au/analysis/evs-are-they-really-more-efficient/ (accessed 24 September 2020)

Nedjalkov, A., Meyer, J., Kohring, M., Doering, A., Angelmahr, M., Dahle, S., Sander, A., Fischer, A., & Schade, W. (2016). Toxic gas emissions from damaged Li-ion batteries-Analysis and safety enhancement solution.

NIOSH. (2016). NIOSH criteria for a recommended standard: occupational exposure to heat and hot environments. By Jacklitsch B, Williams WJ, Musolin K, Coca A, Kim J-H, Turner N. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication 2016-106.

Ouyang, D., Liu, J., Chen, M., & Wang, J. (2017). Investigation into fire hazards of lithium-ion batteries under overcharging. Applied Science. 7(12), 2017, 1314; 10.3390/app7121314.

Ribie`re, P., Grugeon, S., Morcrette, M., Boyanov, S., Laruelle, S., & Marlair, G. (2012). Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry. *Energy and Environmental Science.* 5(1), pp. 5271–5280.

Sturk, D., Rosell, L., Blomqvist, P., & Tidblad, A.A. (2019). Analysis of Li-ion battery gas vented in an inert atmosphere thermal test chamber. Batteries. Vol. 5, 61: 10.3390/batteries5030061.

Vimmerstedt, L.J., Ring, S., & Hammel, C.J. (2020). Current Status Environmental, Health, and Issues of Lithium ion Vehicle Batteries, National Renewable Energy Laboratory, U.S. 1995. https://www.nrel.gov/docs/legosti/old/7673.pdf (accessed 24 September 2020)

Wang, S., & Ge, M. (2019). Everything You Need to Know About the Fastest-Growing

Source of Global Emissions: Transport. World Researches Institute. https://www.wri.org/blog/2019/10/everything-you-need-know-about-fastest-growing-source-global-emission transport.

WHO (2001). Water Quality: Guidelines, Standards and Health. Eds. Lorna Fewtrell and Jamie Bartram. Published by IWA Publishing, London, UK: https://www.who.int/water-sanitation-health/dwq/iwachap10.pdf?ua=1 (accessed 24 September 2020).

Wilcox, G. (2015). Man who died in fiery Malibu Canyon crash of Tesla is 53-year-old from Calabasas. https://www.dailynews.com/2015/06/23/man-who-died-in-fiery-malibu-canyon-crash-of-tesla-is-53-year-old-from-calabasas/ (accessed 24 September 2020).

Wilde Lexus Sarasota (2021). How to use the Navigation in the Rx 350. https://www.lexusofsarasota.com/new-vehicles/rx/how-to-use-the-navigation-in-the-rx-350. (accessed 30 July 2020).

Yaakov, D., Gofer, Y., Aurbach, D., & Halalay, I.C.(2010). On the study of electrolyte solutions for Li-ion batteries that can work over a wide temperature range. *Journal of Electrochemical Society.* 157(12), 2010, A1383-A1391.

## Nomenclature

| | | | |
|---|---|---|---|
| $Cells_{exp}$ | total number of cells used in the experiment | $M$ | metabolic rate (W/m$^2$) |
| $Cells_{pack}$ | total number of cells in the pack | $PEL$ | permissible exposure limit |
| $HF_{conc\_exp}$ | HF obtained in the experiment (g/m$^3$) | $R$ | radiative heat exchange (W/m$^2$) |
| $HF_{conc\_ext}$ | extrapolated HF concetration (g/m$^3$) | $RfD$ | reference dose for HF |
| $HF_{gen\text{-}rate\_ext}$ | HF generation rate from the experiment (kg/s) | $S$ | body heat content (kcal.h-1) |
| $HF_{gen\text{-}rate\_exp}$ | extrapolated HF generation rate (kg/s) | $t$ | temperature (ºC) |
| $HF_{total\_exp}$ | total HF obtained in the experiment (g) | $W$ | external mechanical work (W/m$^2$) |
| $HF_{total\_ext}$ | total HF extrapolated (g) | | |
| $t_{gen\_ext}$ | extrapolated HF generation time (s) | **Subscripts** | |
| $AT$ | averaged exposure period (days) | $a$ | ambient |
| $BEV$ | battery electric vehicle | $cl$ | clothing |
| $BW$ | body weight (kg) | $cr$ | core |
| $C$ | convective heat exchange (kcal.h-1) | *non-carcinogen* | non-carcinogenic |
| $Co$ | HF concentration (g/m$^3$) | $r$ | radiative temperature |
| $CR$ | contact rate (m$^3$/s) | $conc$ | Concentration |
| $E$ | evaporative heat loss (W/m$^2$) | $ext$ | extrapolation |
| $ED$ | exposure duration (years) | $exp$ | experiment |
| $EF$ | exposure frequency (days/year) | $total$ | total |
| $HF$ | hydrogen fluoride | $re$ | rectal |
| *Inon-carcinogen* | non carcinogenic | $sk$ | skin |
| $K$ | conductive heat exchange (kcal.h$^{-1}$) | $w$ | wind |