Design rules for battery fire safety in dwellings

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This report constitutes a final working manuscript for the headlined project. The official project report, to which reference should be made, can be found on the Luleå University of Technology´s website.

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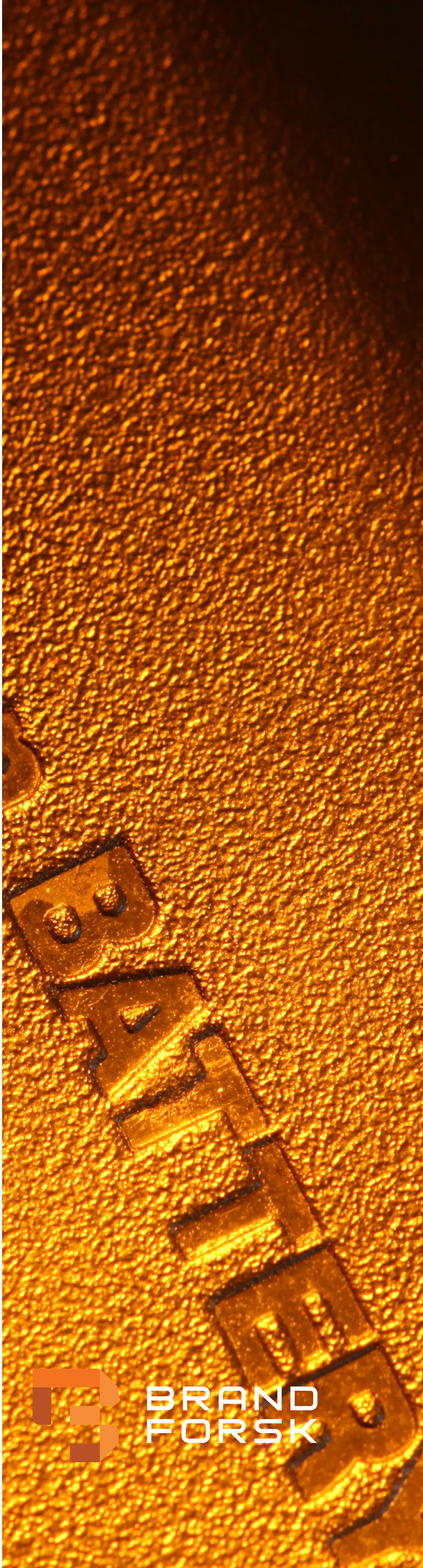

Abstract

Design rules for battery fire safety in dwellings

The report presents a review of current literature, testing and modelling in support of guidelines how to address current risks with batteries from e-bikes and e-scooters. It has been shown that a fire initiated in a battery module can have an exceedingly fast fire growth and may pose new risks that cannot be accommodated within the current design methodology. The data from measurements indicated that the fire growth in terms of heat release rates may be faster than the currently used models. The tests present typical heat release rates from open fire tests in combination with release of toxic and flammable gases from cells and modules. Using accelerating rate calorimetry, conditions when single cells enter a thermal runaway could be determined. Utilizing the information from the testing, simulations of a module were performed to investigate the effect of mass ejection from cells during the thermal runaway, complementing the knowledge how the thermal propagation was disrupted in the module.

The information gathered from literature, testing and modelling was used to propose a design fire. Although, the fully developed fire is no more severe than a usual fire the very fast fire growth rate may cause deflagration type events that compromises the fire resistance properties.

Note that while the proposals are general, they mainly influence possible future dwellings thus dissemination of current risks to the public is necessary. Some of the recommendations can be summarized as follows; Being mindful of batteries and where to charge battery modules; Keep a watch on the health of your batteries, which includes but are not limited to observing if they have been damaged in any way or become unusually hot during operation and perhaps most importantly do not charge batteries where escape routes can be compromised.

Key words: battery thermal runaway, multi-physics simulation, experiments, dwelling, design rules

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Sammanfattning

Brandsäkerhet för batterier i bostäder

I det här arbetet presenterar vi en översikt av aktuell litteratur, de utförda försöken och modeller som används som stöd för riktlinjer om hur man ska hantera nuvarande risker med batterier från elcyklar och elsparkcyklar. Det har visat sig att en brand som initieras i en batterimodul kan ha en extremt snabb brandtillväxt och kan utgöra nya risker som inte kan hanteras inom den nuvarande designmetodiken, den data som vi har inhämtat från experimenten indikerar att brandtillväxten är snabbare än vad som förväntas i de modeller som används idag. Försöken visar typiska värmeavgivningshastigheter (HRR) från de öppna brandtesterna i kombination med utsläpp av giftiga och brandfarliga gaser från celler och moduler. Genom experiment med ARC kalorimeter kunde förutsättningarna för när enskilda celler går in i termisk rusning bestämmas. De uppmätta HRR värdena kunde sedan användas i simuleringar av en modul för att undersöka effekten av att vissa celler skjuter ut sitt innanmäte under den termiska rusningen. Det ger en mer samlad bild av hur spridningsförloppet i modulen går till.

Den insamlade informationen från litteratur, försök och modellering användes för att föreslå en designbrand. Även om den fullt utvecklade branden inte är allvarligare än en vanlig brand på längre tidsskala så kan den mycket snabba brandtillväxten orsaka en deflagration som förstör brandmotståndet i en byggnad.

Även om de rekommendationer som vi ger är allmängiltiga och kan användas i fler scenarier än vid en design av ny byggnation så är det nödvändigt att sprida informationen om nuvarande risker till allmänheten. De identifierade riskerna minskas av att vara uppmärksam på batterier och var man laddar batterimoduler och att hålla koll på batteriernas hälsa, vilket inkluderar men inte är begränsat till att observera om de har skadats på något sätt eller blivit ovanligt varma vid användande.

Sökord: Termisk rusning, Multifysiksimulering, Experiment, Bostad, Designscenscenario, Dimensionerande brand

Content

Preface

The Authors are grateful for the financial support from Swedish Fire Research Board (BRANDFORSK) under contract 324-004 “Design rules for battery fire safety in dwellings” which made this work possible. We have also benefitted from scientific input from an advisory group consisting of people with different backgrounds:

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1 Introduction

Batteries are useful for storing energy for short time periods like from one day to the next. The dominant battery type today is lithium-ion batteries (LIBs) due to their good performance in terms of energy density and long lifetime and are today used for many applications ranging from electric vehicles through to handheld tools and personal devices. The LIB is also key technology to achieving sustainable and renewable electrical energy. Accordingly, they are increasingly used across various of industries in an energy storage role, e.g., energy storage for marine, aerospace, and automotive applications, grid-scale Energy Storage Systems (ESS), as well as smaller scale use in dwellings and personal consumer products. Although new technologies present opportunities, they also introduce new risks. LIBs have a safety drawback as they contain a flammable electrolyte which entails potential exothermic reactions when the battery is damaged, or brought out of its safety window regarding temperature and cell voltage, and they have the potential to end up in a thermal runaway (TR), a state of rapid self-heating. This is something that is of concern especially in homes (Bergholm, 2022) and is also a concern for the rescue services. For instance, Swedish Civil Contingencies Agency reported 262 fire incidents with hybrid or electric vehicles in Sweden during four years 2018-2021 (Bergholm, 2022), with the incident number being increased every year (from 38 in 2018 to 91 in 2021), while in New York the number of fire incidents involving batteries for e-bikes and e-scooters has risen rapidly from 22 in 2020 to 216 by the end of 2022 (Linhorst, 2023) and Norway recently had its first fatal fire caused by a e-scooter battery (TV2, 2025).

The fire safety issue is still one of the main obstacles to the application of LIBs in various applications (Wang, et al., 2019). TR and fire experiment is a straightforward method for evaluating fire risks from LIBs, but they are costly and sometimes difficult to perform. Therefore, simulations of LIB thermal runaway and fires may proof to be a cost-effective alternative to these experiments, provided that the simulations are performed properly.

Accordingly, there is a strong need to characterize both the battery vent gas and TR process through cell level testing for simulations. The input parameters for simulations include (i) onset temperature of TR, (ii) heat release rate (HRR) during TR, (iii) temperature and pressure development, (iv) vent gas release rate and (v) vent gas composition. These parameters depend on multiple factors such as cell chemistry, cell shape, state of charge (SOC), electrolyte composition, aging of the cell, failure mode, manufactures, etc. Therefore, unless a large publicly available database is established from which assumptions can reasonably be made, these parameters need to be obtained in experiments for the specific cells used in specific applications.

The characterization of battery vent gas is commonly performed in a pressure vessel in an inert atmosphere in a testing equipment built according to the UL9540A standard; see equipment at RISE (RISE, n.d.). The testing procedure is, however, nonstandard where inert gas is fed through the measurement device to be able to capture inhomogeneous temperature distributions. By monitoring the pressure and temperature inside the vessel, the vent gas volume is calculated. Furthermore, the gas composition can be analysed using e.g. gas chromatography.

On the other hand, the characterization of the self-heating process before onset of TR can be performed in an accelerating rate calorimetry (ARC) equipment. ARC can provide onset temperatures and the self-heating rate which are the input parameters for modelling thermal propagation. This, in turn, can be used to evaluate the battery design fires.

1.1 Design Fires Background

Design fires are a tool utilised by fire safety engineers to evaluate the performance of their design, be it for a building, infrastructure like a tunnel or something different like a ship. The success of the design can often therefore rely on the suitability of the design fire chosen for the scenario. Often design codes will provide simple design fires, such as the parametric fires in the Eurocodes (European Committee for Standardisation, 2002) or the "standard fire" curve of ISO 834 (International Organization for Standardization, 2019). While these simple curves are often sufficient for the assessment of structural and separating elements in typical buildings, they can fall short in scenarios with unusual fire sources or specific requirements. There are some alternative sources of design fires, such as NIST's Fire Calorimetry Database (NIST, n.d.) based on historic test data. Given that only recently has the proliferation of larger capacity LIBs occurred there is not readily available experimental data for these that can be used as design fires. Additionally, as LIBs present a reasonably unique fire load, both in the risk of self-ignition as well as the possibility for extremely rapid fire growth, and the difficulty they present in terms of extinguishment, it is not suitable to use other tests as representative of the conditions they could impose on a design. There is therefore a notable hole in the resources available to designers when it comes to testing their design against the risks posed by a LIB in a quantitative manner.

1.2 Modelling tools

There are many different battery modelling tools available which have different features and with suitability for different tasks. The primary goal of battery modelling for industry is normally to predict and optimise battery performance, typically in terms of charge/discharge characteristics but also for risk assessments. Over the past few decades, many battery models have been developed for different applications that differ in complexity, input parameters, available outputs and overall accuracy. Rapidly discharging or charging a battery creates heat. If the heat is generated faster than it is dissipated, the battery temperature increases and may cause the battery to experience a thermal runaway, i.e., uncontrolled self-heating due to exothermic chemical reactions. Even if a thermal runaway does not occur, a local hot spot may cause irreversible damage in cell components, thereby accelerating the decline of battery capacity. Much of the modelling work has been taking place within the automotive industries for development purposes and little has been spread to other application areas and end users.

1.3 State of the art

In the background of the project two different topics are discussed namely that of batteries and design rules. In this project these two topics are to be merged which is a crucial part of the development toward a society where safe use of batteries and battery modules is widespread. The modelling of fire propagation in batteries is investigated using experimental means supplemented with computational modelling to determine fire growth rates in larger modules.

Society is undergoing a transition to increasingly fossil fuel free societies with increasing use of localised power generation (Kretchmer, 2020) such as solar panels and small wind turbines. Where localised generation is implemented, it is increasingly common for batteries to be installed alongside so as to maximise the ability for the locally generated power to be stored when excess is being generated and then used locally when not generating (e.g. allowing solar to be used in evenings). The introduction of batteries into a domestic setting introduces a new risk source in the home, both as a source of ignition for fires or explosion, and subsequently as a source of high levels of toxic gases. To minimise these risks, first a good understanding of how a fire can develop from thermal runaway within a battery and how the released gases will spread around a space is needed. Only, once a good understanding of these processes has been established can suitable mitigation measures and design rules be established. This understanding can be developed both by experimental studies, and via simulations which can provide a relatively inexpensive means, both in terms of cost and time, to conduct a wide range of sensitivity studies. It is only when a range of data and the sensitivity to situation and design is established that appropriate mitigation measures can be proposed and comprehensive design guidance established.

This project aims were to give guidelines and propose design rules for battery modules placed in common dwellings. It aimed at smaller battery modules used in e-scooters and e-bikes during charging and storing. The methodology includes to use experimental data on fire development in conjunction with simulations to determine fire definitions that can be used for design fires in larger spaces.

2 Experimental work

Eight thermal propagation tests were conducted with two different battery types suitable for e-bikes or e-scooters. The tests were performed in two different setups: a pressure vessel with inert atmosphere and an open setup below an exhaust collector hood. Except evaluating thermal propagation behaviour in different atmospheres, the different setups enabled measurements of total gas production and gas composition in inert atmosphere as well as heat release rate (HRR) and total heat released (THR) in open atmosphere. In addition, two individual cylindrical cells, one from each battery type, were tested using a standard ARC setup, enabling the measurement of TR onset temperature for the individual cells, used as input for the modelling work. Below is given a short summary of the methodology and results. More detailed information is given in an article that will be incorporated as an appendix when accepted and published in suitable scientific journal.

2.1 Summary of test methodology

Eight batteries, four of each battery type, were acquired for testing. The two battery types are shown in Figure 1, hereafter referred to battery A and B. Both batteries have the same number of cylindrical 18650 cells, arranged in the same 4P10S electrical configuration, meaning that 10 cell groups are connected in series and 4 cells in each group are connected in parallel. Battery A is a typical ready-to-use e-bike battery with a robust plastic cover and integrated taillight (see Figure 2). Battery B is a cheaper variant, utilizing a simpler design with the battery cells more densely packed and without robust cover.

Figure 1. Left: Battery A, and right: Battery B.

The test schedule is shown in Table 1. All batteries were charged to 100 % state of charge (SOC) before the tests. The two individual cells were removed from the fresh modules that were later used in tests 1 and 3 and used for testing in the ARC setup.

Table 1 Test schedule

Test	Battery	Setup
1	A	Closed
2	A	Closed
3	B	Closed
4	B	Closed
5	A	Open
6	A	Open
7	B	Open
8	B	Open
9	1 cell (A)	ARC
10	1 cell (B)	ARC

Thermal runaway was initiated in 2-4 cells in one end of the batteries using a small heating element, see Figure 2. By rapid increase of the heating element temperature, TR is initiated without preheating the neighbouring cells. For battery B, the metal strip on top of the cells were added after test 3, because thermal propagation stopped early due to the ejection of cells when experiencing TR.

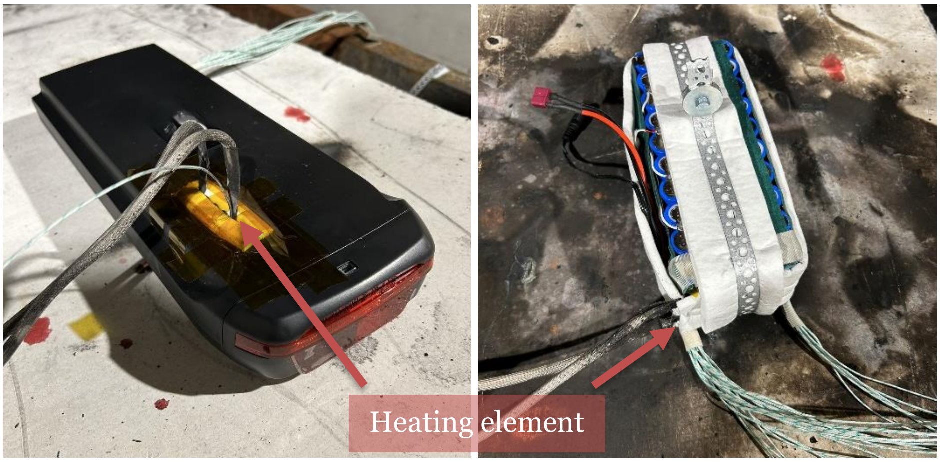

Figure 2. Battery A (left) and B (right) prepared for testing with installed heating element as well as temperature and voltage measurements.

The three setups are shown in Figure 3. The closed setup consisted of an 80-litre pressure vessel with inert nitrogen atmosphere. Using the pressure and temperature recordings within the vessel, the volume of gas released by the cell could be calculated by use of the ideal gas law. The open setup allowed the batteries to burn with good ventilation conditions. Smoke was collected by an exhaust hood and duct system and Oxygen consumption calorimetry (OCC) was used to calculate HRR and THR. The standard ARC setup allows measurement of TR onset temperature for the individual cells.

Figure 3. Closed pressure vessel setup with inert atmosphere (left), open setup below an exhaust collector hood (middle), and standard ARC setup (right).

2.2 Summary of results

Thermal propagation continued to all cells in the batteries in only two tests; tests 1 and 5. In general, thermal propagation was faster and involved more cells in battery A compared to battery B, with test 6 being an exception. In this test, only the three cells in contact with the heating element experienced TR. One possible explanation that no thermal propagation occurred could be the ejection of the cell internal jellyroll that was revealed in the post-test visual inspection. High cell mass loss during TR means that heat is ejected and not conductively transferred from the cell casing to neighbouring cells. Likely, this is also the reason for slower thermal propagation in battery B, which experienced high cell mass losses as well as complete cells that were shot away due to the pressure build-up before venting and during TR. In test 3, thermal propagation to cell group 2 took almost 13 minutes and then stopped. The adding of a metal strip on top of the cells, partly hindering the cells to be shot away, caused thermal propagation to continue much longer.

The tests showed good repeatability of the normalized gas volumes of the same battery type, indicating that the individual cell TRs are similar with respect to gas generation. The difference between the two battery types was large, 0.6 L/Wh for battery A and only 0.1 L/Wh for battery B. However, this variation could be expected based on literature data, where gas generation from LIBs during TR typically varies between 0-1 L/Wh (Bugryniec, et al 2024).

The normalized THRs follow the same trend as the normalized gas volumes, with good repeatability for the same battery type but large difference between the two battery types, 50 kJ/Wh for battery A and 10 kJ/Wh for battery B. 10-50 kJ/Wh are reasonable based on literature data from LIB fire tests, but constitute outer boundaries of what would be expected (Willstrand, et al 2024). It is also reasonable that there is a correlation between low gas production and low THR, since combustion of the flammable gases produced (H_2, CO, HCs) contribute significantly to the THR. The plastic cover of battery A will also contribute significantly, constituting almost 50 % of the total battery weight. The peak HRR was five times higher in test 5 (battery A) as compared to test 8 (battery B), see Figure 4, which is the same order of magnitude as the difference in THR.

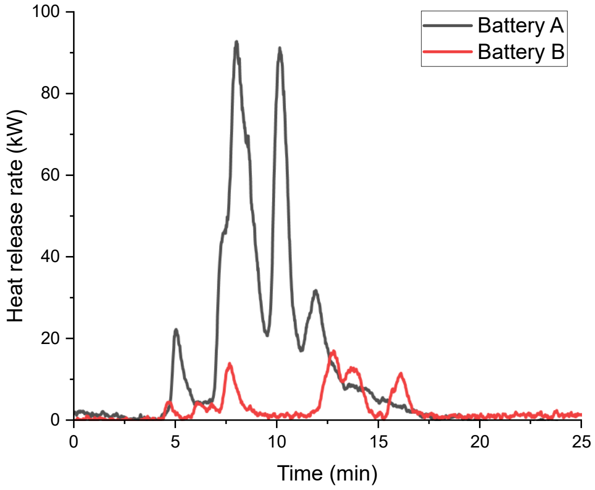

Figure 4. HRR curves from test 5 (battery A) and test 8 (battery B).

3 Modelling and simulations

Modelling of batteries, packs of batteries or battery modules are most often performed for normal working conditions however recently safety issues and abuse test modelling have become more and more important due to the relatively widespread use of LIBs in consumer applications, and it is predicted that the use of batteries will sharply increase. Safety modelling of batteries includes but is not restricted to predicting the TR of a battery (Zavalis, 2013), the propagation of thermal runaways (Larsson, et al., 2016), (Huang, et al., 2022), (Huang, et al., 2023) and emission of toxic gases from the event (Willstrand, et al., 2020). Modelling a thermal runaway is possible by utilising a thermal abuse model that can describe the time evolution of heat diffusion within the battery module and predict the elevated temperatures. The model can then be simplified to determine the spread of a thermal event (Anderson, et al., 2014) in a module. This is done by computing heat transport in the battery pack solving the heat diffusion equation numerically where the boundary conditions have to be estimated either by tabular coefficients or determined by simulation of the surroundings using a conjugate heat transfer model. Here it should be noted that many popular boundary models are included in most simulation packages and may easily be tested. Toxic elements from a TR event where the cell vents emit gas are typically transported by naturally buoyant gas flows caused by the thermal event or forced flows due to ventilation. Simulating this spread of toxic elements utilises computational fluid model (CFD) such as Fire Dynamics Simulator (FDS) where the pressure and velocities of the transported gases are solved in control volumes using Finite Volume Method (FVM). The simulation result is the tenability and may be used in a risk assessment (Willstrand, et al., 2020). A variety of commercial and open-source tools have been used in the past to simulate battery TR events. For example, the Ansys LS-Dyna was used to study the effect of mechanical abuse i.e., nail penetration, on the battery thermal event by coupling mechanical, electrical, and thermal process (Zhang, et al., 2015), (Zhao, et al., 2016). Comsol Multiphysics is a commonly used simulation tool for studying thermal propagation in battery modules by different researchers (Anderson, et al., 2014), (Feng, et al., 2016), (Larsson, et al., 2016), (Ren, et al., 2017), (Abada, et al., 2018). GT-SUITE, a multi-scale, multi-physics software platform developed by Gamma Technologies was used to simulate battery pack thermal runaway for aircraft application (Harrison, et al., 2019). It was recently shown in Refs (Huang, et al., 2022) and (Huang, et al., 2023) that GT-SUITE was another possibility for computing the thermal propagation of an event in a module with good accuracy.

3.1 Modelling

The modelling efforts in the project is based on battery type B, chosen as there is less extra plastics included in the module in comparison to type A, as described in Section 2. The aim is to further explore the effect of cell mass ejection and if it is possible to model the remaining propagation of the thermal runaway by a heat transfer model. The thermal runaway propagation is modelled by conjugate heat transfer model in Comsol Multiphysics 6.2 solving the heat diffusion equation in the cells and separate model for the air surrounding the cells. The governing equations are solved by the Finite Element Method on a typical mesh represented in Figure 5, yielding a computed temperature in each computational cell. A more detailed description and more elaborate results is presented in the paper Willstrand et al 2025.

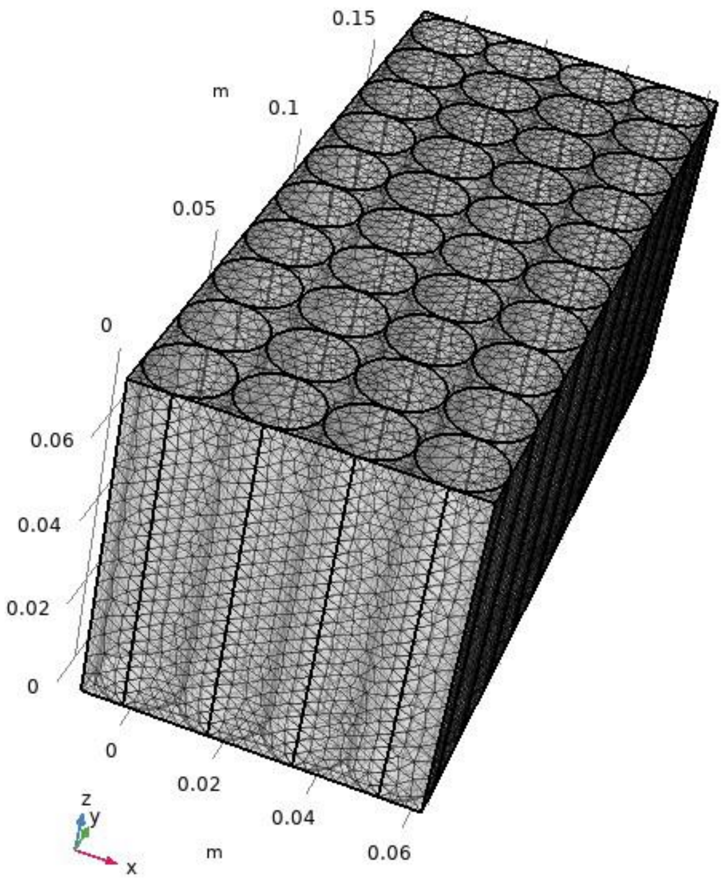

Figure 5. A typical coarse mesh for the module with air.

To evaluate the temperature increase at locations A, B, C, and D in between the first and second layer of battery cells shown in Figure 6.

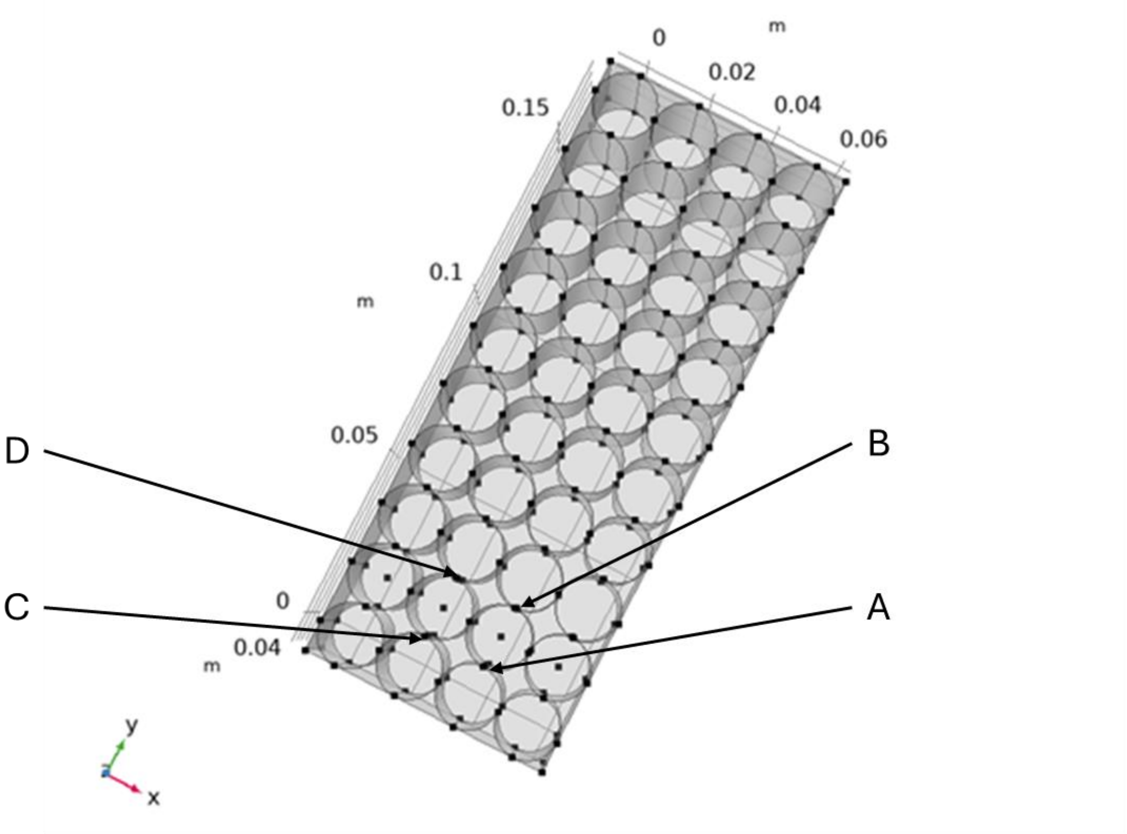

Figure 6. Temperature measuring points in the module.

The battery module is modelled by assuming a heat release rate recalculated to be released evenly over the surface of a battery cell, in this case, it is assumed to that of Battery type B from approximately 4 to 6 minutes in Figure 4. The event is initiated in the lower right corner with 90 second delay between the initiation in the next cell spreading in the first layer and then into the second layer.

3.2 Results

The resulting temperature distribution in the module can be represented by colours (Blue and yellow cold and hot, respectively.) The temperature distribution is a snapshot at 480 seconds after first cell activated, as seen in Figure 7 and 8.

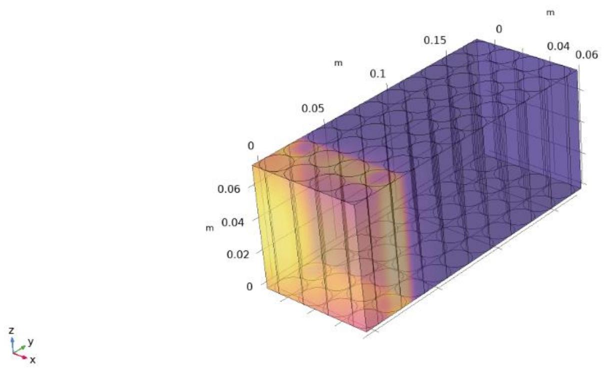

Figure 7. Temperature distribution in the battery cells after 480 seconds where 8 cells are assumed to go to thermal runaway.

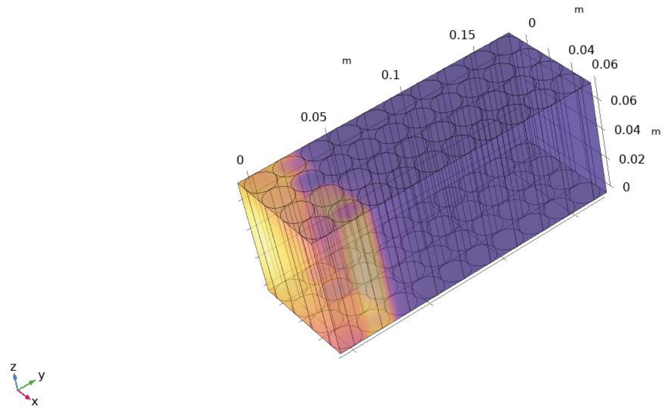

Figure 8. Temperature distribution in the battery cells where one cell ejected out of the battery module (Replaced with an air pocket.) after 480 seconds.

The evolution of heat transfer is clearly visible where the ejection of cell material can visibly impede the thermal runaway. Note that the initiation of thermal runaways is artificially stopped from propagating beyond the second layer in this case. In Figure 9, temperatures between the first and second layer and the second and the third layer is displayed in a comparison with scenario A including 8 cells (solid lines) in TR and scenario B with 7 cells (dashed lines) in TR where the mass of one cell is ejected out of the module. As expected, the temperature increase at position A, close to first initiation, is fastest while for position B there is a slow temperature rise before a sharp increase at as there is a delay between the first and second layer while the cell heats up before entering TR.

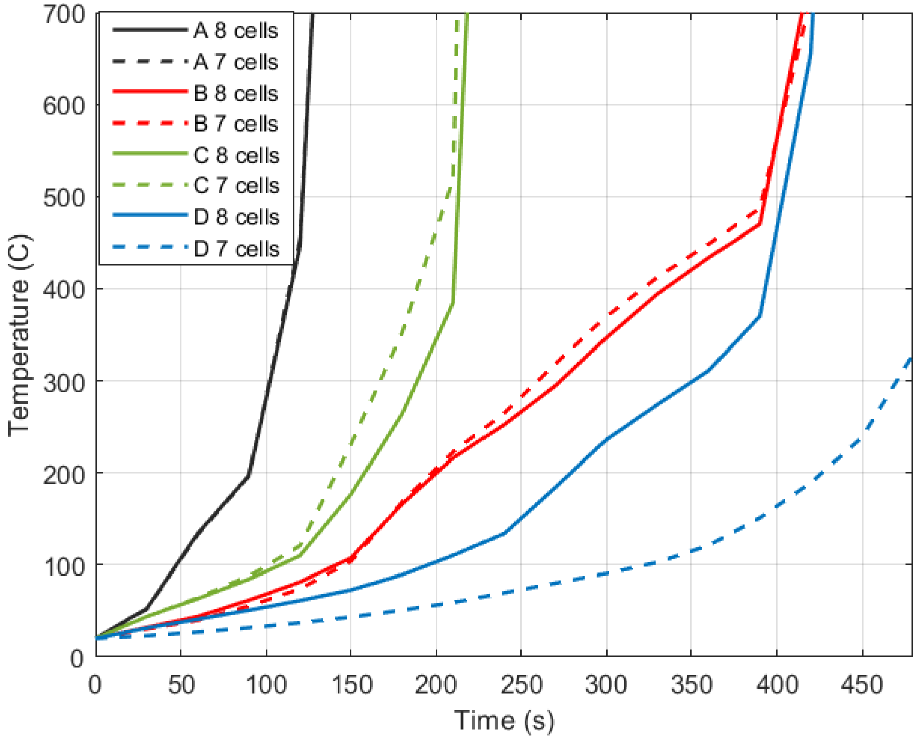

Figure 9. A comparison of the temperature history of the cases with 7 (dashed lines) and 8 (solid lines) cells in locations A, B, C and D according to Fig. 6. The difference in temperature rise is significant in the case where the blue dashed line (7 cells) lags behind the solid line (8 cells).

Note that there is a significant slowdown in temperatures (dashed lines) at Position D compared to the case with 8 cells (solid lines). Furthermore, indication of the importance of thermal inertia is visible where, less material to heat up yields higher temperatures in Positions B and C. Thermal inertia is the product of thermal conductivity, density and specific heat capacity and determines how fast a material changes its temperature to changing conditions.

3.3 Summary and discussion

In summary, the modelling efforts can complement the experimental program to understand specific results however simulating experimental results where large uncertainties are present is not an easy task. The aim of the current modelling exercise with limited physics was to evaluate if the ejection of cell mass can be modelled using heat transfer only. The case studied here is artificially modelled to recapture the propagation as it evolved in the test but stopped after the second layer. The effect of missing cell material was clearly observed and that it could in principle impede the propagation, moreover the effect of less material to heat up was also visible where temperatures at certain locations increased even more rapidly. It should be noted that this effect would only affect the overall propagation with a few seconds. There are many further things to be explored by future modelling, one of the most pertinent is to determine from the model in combination with the test data a reasonable envelope for the propagation and determining a heat release curve for the module itself. In a future paper by Willstrand et al (2025) the possible predictive capabilities will be discussed where a likelihood distribution for initiation of thermal runaway and ejection of cell material will be introduced to model a reasonable envelope for the propagation.

4 Design fires

4.1 Comparison to existing design fires

To ensure that buildings (including infrastructure) are designed to provide safety for the hazards that will be present in them, definitions of these hazards are required. The main tool for doing this with fire hazards is by using design fires. Design fires are a description of the power and speed of growth of a fire. Naturally, they range from detailed heat release rate curves, based on experimental or simulation results, through simplified curves such as the Eurocode Parametric Fires (European Committee for Standardisation, 2002) to standard fire resistance curves and periods. The success of the design can often therefore rely on the suitability of the design fire chosen for the scenario.

Fires involving e-bike and e-scooter batteries, such as the recent fatal fire in Norway, regularly occur when charging in residential settings. To establish if the design fires used currently in this situation are sufficient to cover the risks from these battery fires a comparison can be made between the experimental and simulation results described earlier and a variety of design fires typically used in these scenarios. Design fires describing fully developed compartment fires, such as standard fire curves and parametric fire curves, have primarily been ignored here. This is due to the total fuel load of an individual battery pack being small in comparison to that of a full compartment (i.e. peak HRR for the battery packs was under 100 kW while full room fires are in the region of 10 MW (NIST (2023)). The risk presented by the batteries is primarily around the risk of self-ignition and rapid fire growth. Comparisons have therefore been made with some individual items (e.g. furniture) from the NIST database, and against commonly assumed growth rates as defined in design codes. It should be noted that exceedingly fast incidents have been reported, as reported by Dahlström (2024), where a fire incident in an e-scooter was called in to the rescue services as a possible detonation. The investigators ruled out any possibility of deflagration and detonation due to a lack of materials that could otherwise cause such an event. The compartmentation of the building had however been damaged thereby allowing the fire and smoke to freely spread up to the attic. This stresses the need to have relevant design rules including current risks.

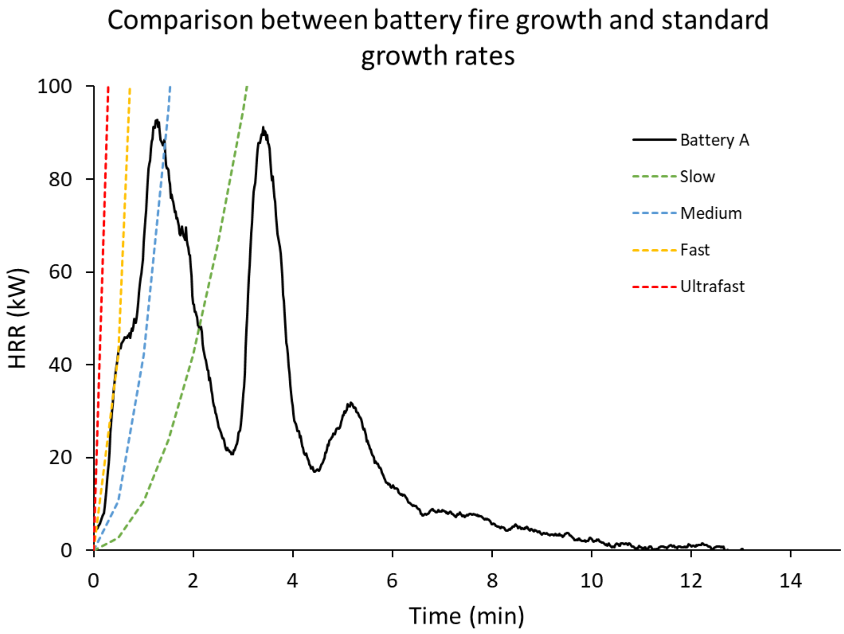

Figure 10. Comparison of experimental HRR from test on Battery A vs standard growth rates

The Eurocodes specify a medium fire growth rate for design fires in residential and office buildings, while the Eurocodes are for structural design this is a typical recommendation in guidance for other considerations as well. In Figure 10 the experimental HRR of Battery A (with time adjusted for zero minutes to match the primary fire growth) from open test 5 have been plotted against standard fire growth rates from Eurocode 1 (European Committee for Standardisation, 2002). Here we can see that the fire growth is in fact quicker than medium and at least initially follows the slope of a fast fire.

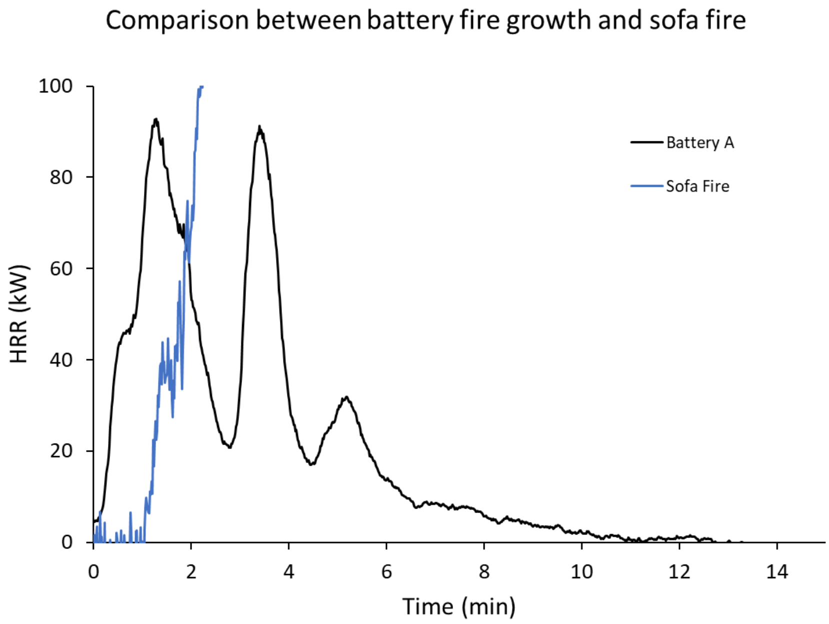

Figure 11. Comparison of experimental HRR from test on Battery A vs Sofa Fire

When compared to the growth rate of a sofa, Figure 11, from NIST's Fire Calorimetry Database (NIST 2023) however the growth rate between the battery fire and sofa, when ignited with a propane wand, are actually quite similar. This highlights that the key factor that differentiates the speed of growth of lithium batteries from other fuel sources commonly found in homes is the risk of rapid self-ignition.

4.2 Proposal for Design Fires

From the comparisons undertaken in the previous section it can be concluded that for consideration of peak fire size, current design fires are sufficient. However, when considering fire growth and the early stages of a fire typically recommended design fires are insufficient for cases of battery fires in residential or office settings. On the basis of the findings of this study it is proposed that:

- For most design situations and frameworks a speed of growth is typically specified (e.g. Eurocode structural fire design). In these situations the framework remains suitable but a ***fast*** growth rate fire should be used where batteries from e-bikes and similar may be present, rather than the medium rate that is typically specified for residential and office settings.
- For occasions where more quantitative analysis of a battery fire is being undertaken, but must still be a "reasonable worst case" (such as calculations as part of an ASET/RSET study to see the impact on time to detection depending on fire and detector location), a simplified curve over experimental results from tests like Battery A would be suitable. An example curve is shown in Figure 12.
- It is important to note that the proposals given here are based on current data. For other very detailed scenarios relating to specific batteries, then direct use of experimental results is also an option, however care should be taken given the large variation in results.

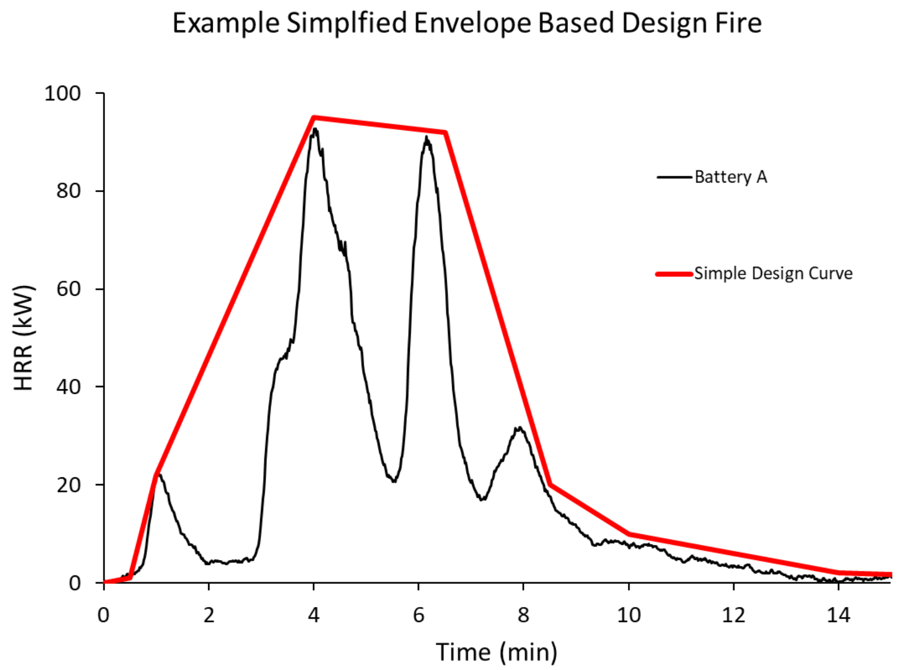

Figure 12. Example of a simplified design curve based on an envelope over the Battery A test results.

4.3 Other Considerations

There may be several reasons for having an appropriate design fire for the hazards existing in modern buildings, it may help designing new buildings and refurbishments, but also for other relevant scenarios. It is also clear from the fires that have occurred (SVT (2024), Vestfold Interkommunale Brannvesen IKS (2025)) that the risk to life is at least in part from how people store and charge batteries at home. Therefore, other measures are needed if the risk of e-bike and e-scooter battery fires is to be reduced.

Consideration from designers of e.g. new buildings and refurbishments should also be given to the inclusion of specialist facilities (e.g. dedicated cupboards, charging facilities in bike storage, etc.) for charging batteries. These should be provided in locations that encourage their use and discourage individuals from charging batteries next to escape routes unattended. These facilities should be fire separated from escape routes and consideration given to ventilation of battery off-gassing to avoid explosion risks.

Reducing the risk in existing buildings relies on encouraging safe behaviour with batteries and as such education of general population to the risks of e-bike and e-scooter batteries is required. Any education program of this magnitude would require work not just from researchers and designers but also from government bodies, fire services and media. Some of the behaviours that need to be encouraged among the population are:

- Maintaining observation of battery health, any signs of physical damage (e.g. from drops) and stopping use of the battery if found.
- Charging batteries only in locations where they can be observed (i.e. not overnight while sleeping) and not where any fire would block exits (i.e. not by the front door of an apartment or house).

5 Summary and recommendations

This report summarizes the results of the project funded by Brandforsk on design rules for battery fire safety in dwellings, note that some details have been moved to manuscript to be sent to a scientific journal, Willstrand et al 2025.

The aim with the project was to propose design rules and fires based on testing relevant for smaller battery modules used in e-bikes and e-scooters that are usually stored or charged in dwellings. It has been seen that fires and incidents caused by thermal runaways can cause fire growth to be exceedingly fast which may lead to fully developed fires. This new risk must be managed rather than proposing stricter limitations on handling of modules.

The project comprised of Task 1 to Task 4, including extending the literature review, initial testing on two types of battery modules, modelling of thermal runaways supporting the testing activities and proposing guidelines and design fires.

Testing on the two battery modules was performed in several stages and presented in Section 2, first in the pressure chamber to determine release of gases according to UL 9540a, open fire test determining the heat release from a battery module and a test on single cell to monitor under what conditions the cell went into a thermal runaway. The results from the testing were used in the modelling setup as explained in Section 3, where the heat release during the open fire tests were used as heat source in the modelling. Using a conjugate heat transfer model with appropriate boundary conditions the propagation of the thermal runaway could be observed in the module. The testing showed that some cells initiating a thermal runaway would eject most of its mass outside of the module in effect stopping the propagation in the module. An artificial test simulation comparing the case with and without ejecting material showed how the propagation was impeded. Thus, this shows that 3D Multiphysics simulations can complement the testing in understanding the outcome of the tests.

Using new design tools can be challenging due to the learning curve required and uncertainty surrounding their acceptance by approval authorities. They are often therefore deemed more of a risk than any already in-use tools and must be supported by more transparent evidence and documentation. While this report can be used as part of the supporting evidence base for the suitability of 3D Multiphysics modelling for assessing fire growth from lithium fire batteries. However fully modelling a range of battery configurations for every design project is a large amount of work and is likely not suitable for every occasion, therefore the recommendations from this work for design projects are:

- To explicitly consider the likelihood of e-bike or similar lithium batteries being stored or charged within the building.
- Due to the relatively low total fuel load of these batteries, for the purpose of structural protection and compartmentation no change to current design practices is needed.
- These batteries do however add additional ignition risks and can undergo very rapid fire growth. Current design guidance typically proposes lower rates of fire growth than those observed in the tests of this project, see section 4.1. and gas

ejection which may remotely ignite secondary fires. Therefore where design choices and calculations are dependant upon the speed fire of fire growth (e.g. in relation to egress for available egress time, detector choice and location, etc.) then:

  - For most situations using standard design frameworks an assumption of at least a fast growth rate fire should be used.
  - Where a slightly more detailed fire is required (but not a full compartment fire) for quantitative analysis, a simple envelope based design curve, see Figure 12, based on test data from this or other projects can be used.
  - For rarer projects where detailed quantitative analysis of a particular battery or battery type is required, direct use of test data is most suitable.

- The designers should explicitly consider how their design will encourage occupants to charge and store batteries in such a way that they don't block escape routes.
- It should be further noted that the testing also showed significant gas release from typical modules, and this should be accounted for in design by having proper ventilation. In apartments toxic gases can spread freely for a long time before any fire alarm is started, however this aspect of smoke and gas spread was outside of the current project and no specific recommendations can be given.

Ensuring that the correct design fires are applied in the design stage can only change the future built environment and dwellings. It is just as important the risks in current buildings are minimised, therefore the project strongly recommends that awareness of and information on how to handle the risks in current buildings is increased. To achieve this, it will require joint efforts by governments and public bodies (such as the fire service), media, industry bodies and designers as well as the work of researchers. Items that should be emphasised regarding the safety of these batteries includes being observant on the health of the module, i.e. has it been damaged or dropped, and most importantly where to charge, i.e. no charging close to exits unless there are several exits available.

Although, the ejection of battery cell material was indirectly included in the project further investigations of TR propagation in these cases however quantitative measurements of gas flows, momentum of gas and particles and temperatures are needed to quantify these risks (Li, et al, 2024). It is known that a significant amount of energy can be mediated in the venting phase, both faster and further from the initial TR such that a more severe accident can occur. Such measurements will enable modelling capabilities ejecta events (Zhang, et al, 2023).

Since the amount of hardware with battery modules will increase in the future this is an important topic to follow-up where future risks must be managed as well. There are many open questions, in this work, for example only smaller battery modules were discussed thus guidelines for larger modules e.g. such as those connected to increasingly installed domestic solar panels is needed.

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