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Lithium-Ion Battery Fires in Electric Vehicles

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Abstract

As the use of electric and hybrid vehicles increases, so do incidents resulting in them catching fire. Lithium-ion batteries cause unique fire scenarios due to them being a self-contained ignition source. Thermal runaway can be caused by any form of electrical or mechanical abuse which is likely to occur in a car crash. Additionally, as the battery breaks down, the internal components release oxygen gas, so the battery is self oxidizing. This report aims to review how the battery packs are protected in a vehicle crash, and current research into the prevention and suppression of lithium-ion batteries. Additionally, it will explore whether these methods are viable in a car battery use case, where the battery is much larger than the batteries used in consumer electronics.

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1 Introduction

Lithium-Ion batteries are everywhere in our modern world. They power our phones and laptops, power tools, and most other rechargeable electronics. Their higher charge capacity by weight and energy density compared to alternative rechargeable batteries, as seen in figure 1, makes them an obvious choice for these applications. In recent years, the prevalence of electric and hybrid vehicles making use of lithium-ion batteries has also increased [1].

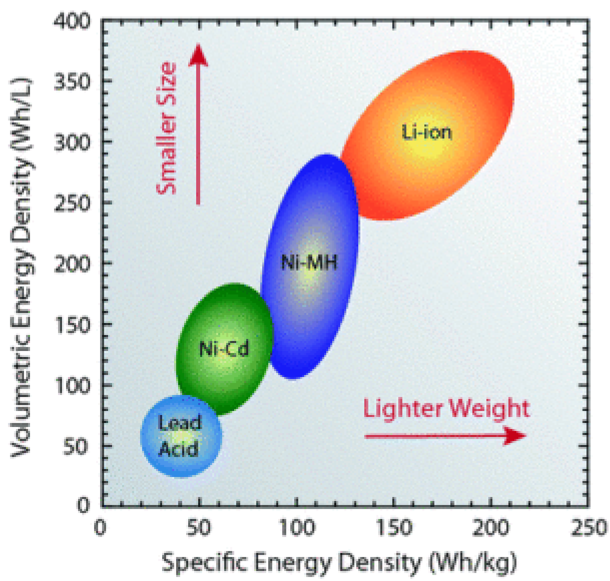

Figure 1: Lithium-Ion Batteries Compared to Other Battery Types

Despite the obvious environmental and economical benefits of electric and hybrid vehicles compared to traditional gasoline vehicles, their large internal battery packs pose a unique fire safety concern. Lithium-ion batteries pose a risk of self-ignition due to thermal runaway, and once ignited, are very difficult to put out due to them self oxidizing. Due to the nature of the fuel being the liquid electrolyte, lithium-ion battery fires are class B fires.

Per the United States National Transportation Security Board, in a 2020 report it was found that per 100 000 cars sold of each type, there were 3474.5 hybrid vehicle fires, 1529.9 gas vehicle fires and 25.1 electric vehicle fires [2].

This report aims to explore different methods of fire prevention and suppression systems that are used for lithium-ion battery fires occurring from consumer electronics and to investigate if they are feasible for use in hybrid and electric vehicles fires.

2 Discussion

2.1 Battery Chemistry and Materials

To properly understand battery fires, we must first know what they are made of, and the chemical processes which produces electricity. The four primary components of a lithium-ion battery are the anode, cathode, electrolyte, and separator. During charging the anode stores lithium ions, which are moved to the cathode during discharge. A liquid electrolyte fills the space between the cathode and anode and allow the lithium ions to flow freely through it during charging and discharging. The separator is a porous non-electrochemically active material which provides a physical barrier between the anode and cathode while still allowing free lithium-ion transfer [3].

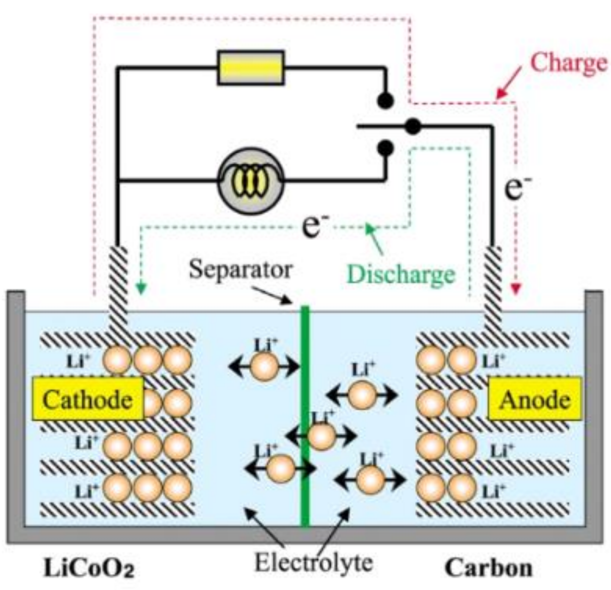

Figure 2: Basic Principle of a Lithium-Ion Battery [3]

Typically, the battery's anode is made from graphite or lithium titanate ($Li_4Ti_5O_{12}$). The cathode contains a transition metal oxide such as lithium cobalt oxide (LCO), lithium manganese oxide ($LiMn_2O_4$), or lithium nickel manganese cobalt oxide (NCM). Commonly used electrolytes are organic solvents such as ethylene carbonate ($(CH_2O)_2CO$), diethyl carbonate ($OC(OCH_2CH_3)_2$), and other cyclic carbonates. Conventional separators are made from polyethylene, or polypropylene, but as they do not participate in the chemical reaction, anything that is porous and unreactive can be used.

These components make up a single cell, which can then be combined in series or parallel with other cells to create batteries with a higher voltage rating or capacity, depending on the required specifications. For example, the Tesla Model S battery has over 7000 cells, to create a battery with a voltage of 375V and a capacity of 60kWh [4].

The above gives a very simplified explanation of the structure of lithium-ion batteries, however it should give sufficient background to start looking into how a lithium-ion battery ignites and the challenges in extinguishing one.

2.2 Ignition of Lithium-Ion Batteries

One of the previously mentioned downfalls of lithium-ion batteries is how easy it is for them to catch fire. Not only can this happen to a battery simply sitting in storage [5], when one experiences mechanical or electrical abuse, which is likely in a car accident, it as far more likely. Lithium-ion batteries have two significant mechanisms which cause them to ignite easily, as well to keep burning once ignited. These mechanisms are thermal runaway and self oxidization. Once ignited, lithium-ion batteries can burn at temperatures up to 2273K.

2.2.1 Thermal Runaway

Thermal runaway occurs when there is a heat increase within the battery. This can either be from electrical or mechanical abuse, or an external heat source. This abuse can lead to a short circuit which will generate heat within the battery. If this heat reaches a critical temperature, such as the collapse temperature of the separator which is typically around 135°C [6], the cell will begin to breakdown. This breakdown leads the temperature in the battery to continue to increase until an ignition temperature is reached [3]. Figure 3 shows how thermal runaway can occur and the result of when it does.

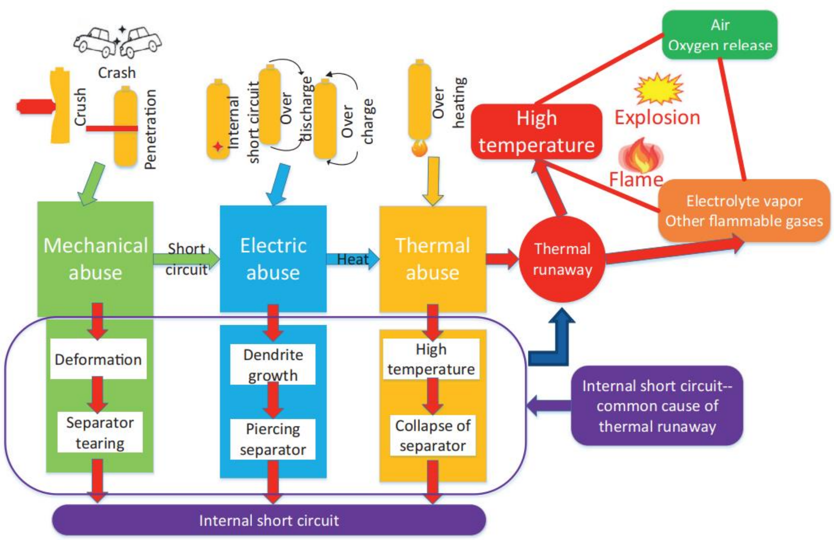

Figure 3: Thermal Runaway Process [3]

When thermal runaway occurs in a single cell, it is likely to cause a chain reaction to neighbouring cells leading to the entire battery quickly igniting. This problem becomes even greater for large batteries, such as the ones used in electric and hybrid vehicles.

2.2.2 Self Oxidization of Lithium-Ion Batteries

The second process which makes lithium-ion battery fires difficult to deal with is that they can self oxidize. In a typical fire where the fuel is a hydrocarbon, an effective method of supressing the fire is to cut off it’s supply of oxygen by smothering the fire. In the case of a lithium-ion battery fire this method doesn't work due to the fire being able to self oxidize. Since the cathode of a lithium-ion battery cell is made from a transition metal oxide, during the fire the cathode of the cell breaks down and releases oxygen gas. Using delithiated lithium cobalt oxide ($LiCoO_2$) which is a standard cathode material as an example, we can see that during the fire the molecule breaks down once a temperature of 200°C is reached [7].

$$Li_{0.5}CoO_2 \Rightarrow \frac{1}{2} LiCoO_2 + 1/6\ Co_3O_4 + 1/6\ O_2$$

Additionally, the electrolyte in the battery also releases oxygen as it breaks down in high temperature. For example, lithium ethylene decarbonate breaks down as follows.

$$(CH_2OCO_2Li)_2 \Rightarrow Li_2CO_3 + C_2H_4 + CO_2 + \frac{1}{2} O_2$$

As can be seen in the chemical equation, the electrolyte not only creates oxygen, but also produces ethylene gas, which is a flammable hydrocarbon. The products of the electrolyte start to vaporize and become the main fuel of a lithium-ion battery fire. Figure 4 shows the entire sequence of fire behavior in a lithium-ion battery.

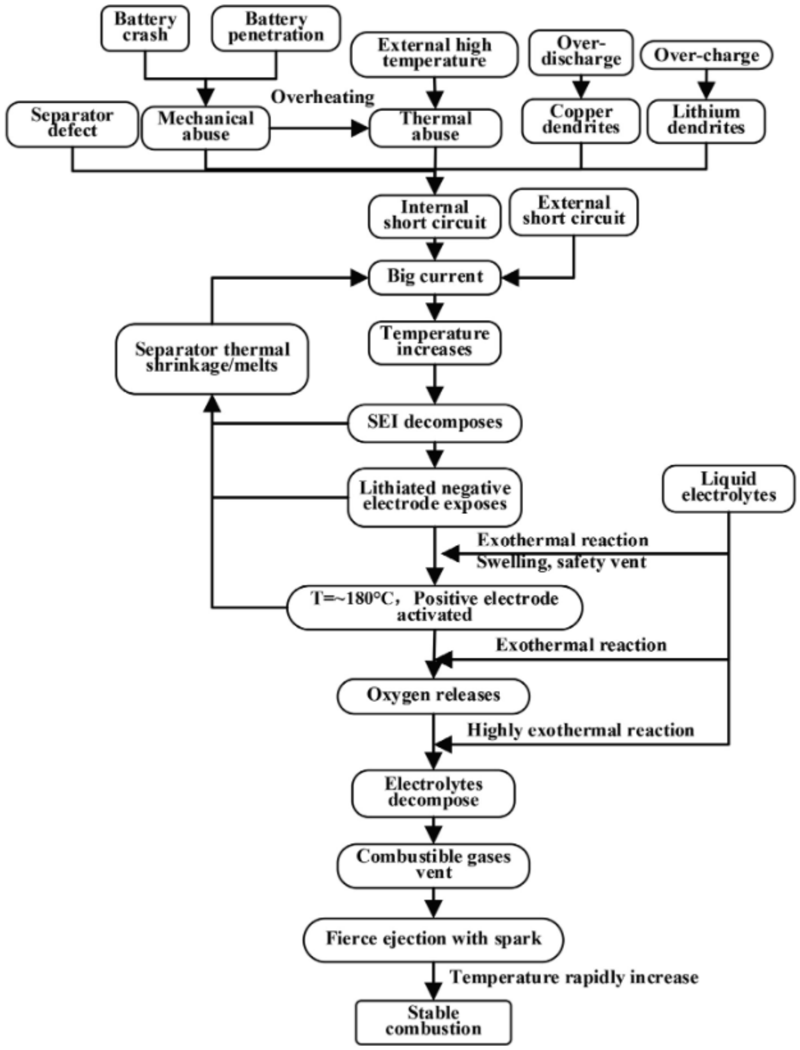

Figure 4: Entire Fire Sequence of Lithium Ion Battery [3]

2.3 Crashworthiness of Electric Vehicles

As mentioned in the previous section, mechanical and electrical abuse to the battery leads to thermal runaway, and eventual ignition. If the battery in a car can be adequately protected from abuse occurring during a crash, then the likelihood if ignition decreases without the need to modify the battery itself. The crashworthiness of a vehicle refers to ability of the vehicle to protect its passengers and cargo against damage during an accident.

All cars, including electric vehicles, have two main components with contribute to the crashworthiness. The body frame of the vehicle absorbs energy from the impact and is meant to protect the occupants and cargo of the vehicle. The chassis and drivetrain likewise absorb energy from the impact and protects other components of the vehicle, especially the battery pack which typically sits underneath the chassis [8], as can be seen in figure 5.

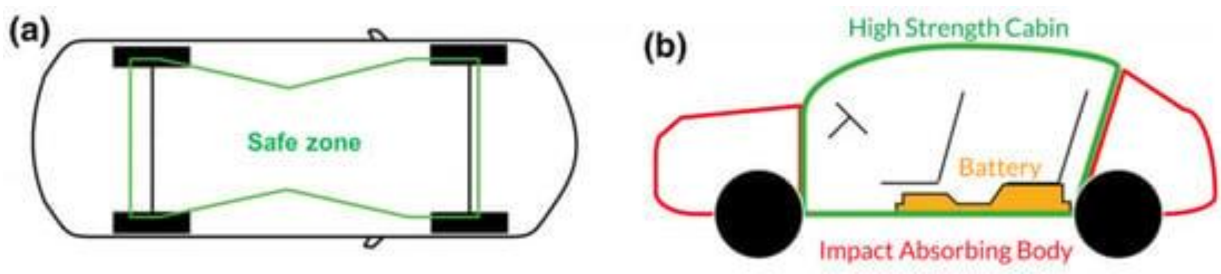

Figure 5: Placement of Battery Pack to Protect from Damage in a Crash [8]

Electric vehicles are subjected to the same crash testing and safety standards as conventional cars. Additionally, there are EV-specific standards which are directed towards ensuring the safety of specific components, specifically the battery pack. For example, “no fire”, “no explosion”, “no rupture”, and “no leakage” are set as pass criteria for UN/ECE-R100.02, ISO 12405-3, and UL 2580 standards [9]. All the listed standards can be found on page 4 of “Lessons from the electric vehicle crashworthiness leading to Battery Fire” by Chombo, Laoonual, and Wongwises.

Due to how expensive and time consuming it is to perform real-world crashworthiness testing, for the most part this data is simulated using finite element analysis (FEA). These simulations are helpful in determining what forces the vehicle experience during a crash and how much of that force is applied to the battery pack. However, most of these simulations are not capable of accounting for how the battery reacts to the forces, so they do not consider the possibility of chemical spillage or electronic components becoming exposed. In future research a more detailed model of the battery needs to be considered to properly gauge what forces are acceptable for the battery to experience.

2.3.1 Real Life EV Fire Events

There have been 51 publicly reported fire events caused by an electric vehicle experiencing mechanical abuse [8]. Two of these events occurred due to an electric vehicle driving over something, such as a tow hitch, which penetrated the battery pack causing a fire. One of these events was caused by a Tesla falling off a cliff. However, this event is insignificant in terms of designing for battery safety because even though a fire and explosion occurred, the vehicle was extremely damaged, and the driver was likely killed from the fall alone. Two of the fire events were caused by the vehicles being submerged in seawater. The salt in the water caused internal shorts in the battery leading to fire. Four of the events occurred during rollover of the vehicle. This number is likely very low due to the weight distribution from the battery being very low in the vehicle causing it to be very hard to rollover an electric vehicle. Most of these fire events, 42 of them, were caused due to crashes. This includes single vehicle crashes of the electric vehicle crashing into stationary barriers, as well as electric vehicles hitting, or being hit by other vehicles.

Some of these fire incidents were due to negligence of the operator by driving at much faster than the speed limit. However, for the fires that were caused at low speeds, or from more typical accidents that occur daily, steps should be taken to try to prevent the battery packs from igniting from the experienced trauma.

2.4 Fire Prevention Methods

One way to increase the fire safety of these batteries is to increase the tolerance to abuse of lithium-ion battery packs to reduce the risk of ignition from the mechanical abuse that will inevitably occur in a car accident.

2.4.1 Modified Separator

One existing method to help prevent ignition within lithium-ion batteries is to use a separator that can withstand higher temperatures. The purpose of this is to prevent the separator from breaking down, causing an internal short leading to thermal runaway.

One proposed material for use as an improved separator is a paper-based ceramic separator. This consists of a paper substrate wet coated using a duo-polymer and a ceramic nano powder. In experiments with this separator, it showed a thermal stability of up to 200°C, which is an improvement of the previously mentioned 135°C of standard polyolefin separators. Although this increased thermal stability is clearly an improvement over standard separators, the paper separators still have a significant drawback. Due to the paper separators being thicker than standard separators, 60μm compared to 25μm respectively, they have a worse electrochemical performance. The cell capacitance between the two are very similar between both, however the resistance of the cell is considerably higher in the paper separator, having a resistance of 76mΩ compared to the 22mΩ of a standard separator [10]. While this difference is negligible in small use cases, such as lithium ion 2032-coin cell battery, when scaling up for use in a larger battery, such as a car battery containing over 7000 cells, this increased resistance would cause significant performance decreases.

2.4.2 Modified Cathode

The separator is not the only component of the cell which can be modified to improve thermal stability. Within the cathode of a battery some of the cobalt can be replaced in the crystal lattice with aluminum. This has shown to improve the thermal stability of the cathode at the expense of capacity. Another explored cathode modification is to coat the cathode with titanium dioxide (TiO_2). This coating process was found to not affect the lattice of the cathode but did improve its discharge capacity and thermal stability [3].

2.4.3 Modified Electrolyte Solution

As previously mentioned, the products from the electrolyte are the main fuel for the fire. Therefore, by modifying the electrolyte, it is possible to increase the fire safety of the battery. One potential modification to the electrolyte is to use a non-flammable phosphonate electrolyte. The phosphonate electrolyte has a strong fire retardancy, while giving similar electrochemical performance to conventional electrolytes. Additionally, it is possible to use tris(2,2,2-trifluoroethyl) phosphate as an additive to conventional electrolytes to help with flammability. Although the performance effects of these additives have not been rigorously tested, it is hypothesized that the introducing them into the battery will degrade the capacity of the battery or shorten its lifetime [3].

2.5 Fire Suppression Methods

Now that we've explored possible ways to prevent a lithium-ion battery fire from starting, the next step is to investigate how to extinguish one if ignition does occur.

2.5.1 Water Suppression

The obvious first thought is to use water to supress a lithium-ion battery fire. In testing this was found to be impractical due to the amount of water required. In an experiment done by the Fire Protection Research Foundation, it took over 2600 gallons of water to extinguish the test battery

[11]. This conclusion was later verified in an uncontrolled environment when, in 2021, a Tesla caught fire after a crash. In order to extinguish that fire, 28000 gallons of water was used. To put that number in perspective, a fire involving an internal combustion engine car typically requires only 300 gallons of water [12].

2.5.2 Gas Suppression Agents

Multiple gaseous fire suppressing agents have been tested on lithium-ion battery fires to differing degrees of success. When CO_2 was used to extinguish a fire either the fire did not extinguish, or reignition occurred after the fire was put out [13]. This occurred as CO_2 does not have a very high cooling capacity, and due to the lithium-ion battery self oxidizing, it is not capable of suffocating the fire.

Other gaseous fire-extinguishing agents that have been tested with lithium-ion batteries are Halon 1211 and Halon 1301. These yielded better results than CO_2, with the fires being extinguished and no re-ignition event occurring [14]. It is important to note that the above experiments were done on small batteries, ranging up to containing one to eight cells. More experiments will need to be done on larger batteries to ensure that these agents are still effective for larger fires. Another concern with using Halon is that the large negative environmental impact they have. Since the goal of popularizing electric vehicles is to limit the environmental impact, these Halon agents should be avoided, despite being extremely effective.

2.5.3 Dry Powder Suppression Agent

The most typically used dry powder used on lithium-ion battery fires is an ABC powder consisting of ammonium dihydrogen and ammonium sulfate. Dry powders offer three extinguishing mechanisms, which are cooling, chemical suppression, and isolation and suffocation. When the dry powder is applied to the fire, it decomposes which absorbs heat from the fire. Additionally, the decomposition of the powder generates products which can capture free flame radicals, which chemically supresses the fire. Figure 6 shows the cooling and chemical suppression mechanism. Finally, the dry powder can isolate the fuel from oxygen. For example, ammonium phosphate powder immediately melts and forms a covering on the fuel creating a physical barrier [14].

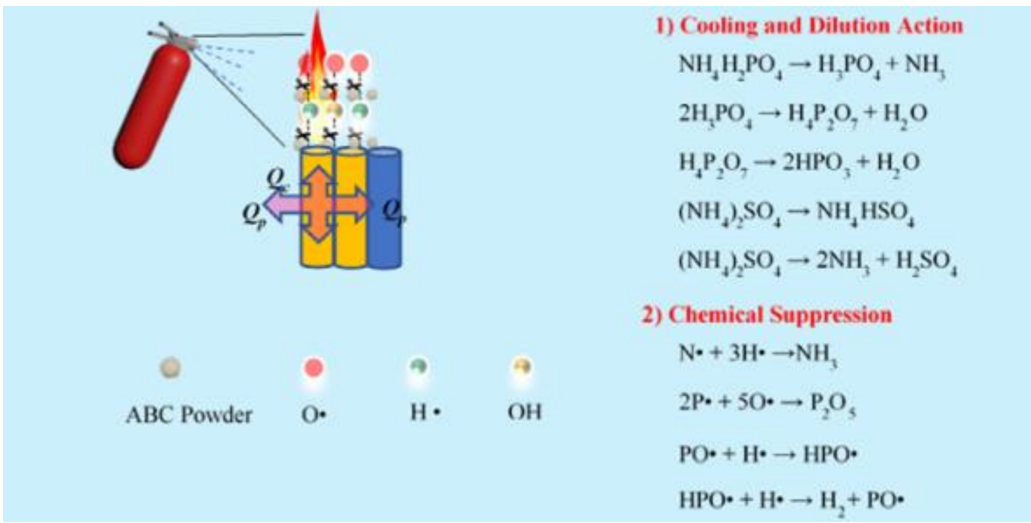

Figure 6: Cooling and Chemical Suppression of ABC powders [14]

In experiments where ABC dry powders were used to extinguish lithium-iron phosphate batteries, which are a type of lithium-ion battery, the powder was successfully able to extinguish the fire. It is important to note however that in these experiments the powder was sprayed from a range of 40-80 cm. This poses a problem as in the case of a car battery, it will be difficult to apply the powder to the base of the fire due to the battery's location underneath the chassis of the vehicle. Additionally in these test cases it took around 2000kg of powder to properly extinguish the test fire [14]. In an uncontrolled environment, or on a larger battery, the amount of powder required might become unfeasible.

2.5.4 Modified Current Collector

As with trying to prevent a lithium-ion battery fire by modifying the battery, there has been research done into modifying the battery to also contain a fire suppression agent. A current collector in a battery is a metal foil that connects the electrodes of each cell within a battery. These current collectors are typically made of copper, but researchers at Stanford and SLAC have created a design with an embedded polymer coated in copper. Additionally, it is possible for that polymer layer to contain a fire retardant with in, as can be seen in figure 7.

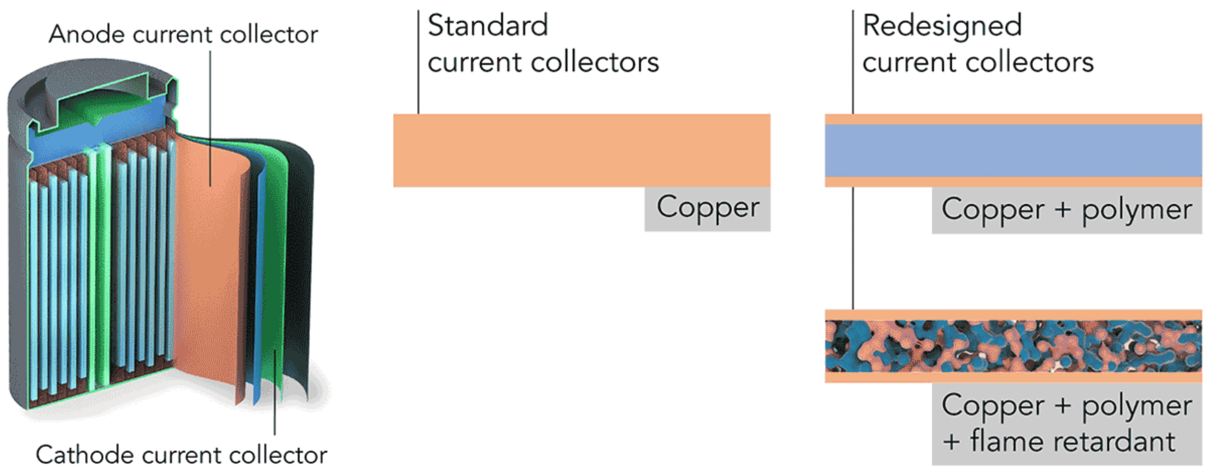

Figure 7: Standard and Redesigned Current Collectors [15]

During a battery fire the copper will breakdown releasing the fire retardant to extinguish the fire. The cited article does not say what fire retardant is being used inside the current collector, however assuming a dry powder does not react with the polymer or copper, that is likely to be the most effective option. Not only do these redesigned collectors help with fire safety, but they have been found to be 80% lighter, which although doesn't affect the electrical properties, can increase the range of an electric vehicle by up to 10% [15]. Testing has only been done on these novel collectors in small scale tests, which can be seen in figure 8.

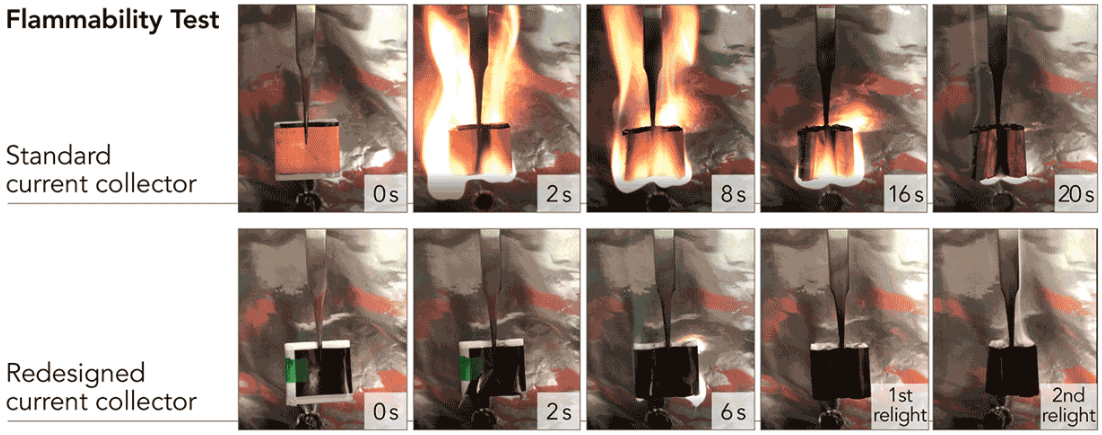

Figure 8: Redesigned Collector Flame Test [15]

However, since this fire suppression system is built into the battery, in a larger scale it should be able to prevent the fire from growing to a too large to be supressed easily.

3 Conclusions and Recommendations

Most of the research that has been done into the lithium-ion battery fires is related to their use in consumer electronics, such as laptops and phones. As such, methods for preventing and supressing lithium-ion battery fires have only been reliably tested in small scales. Vehicles have an additional concern when it comes to protecting their batteries as they are more likely to experience large forces in the case of a car accident. Increasing the crash worthiness of electric vehicles to minimize abuse is important in increasing the fire safety of electric vehicle. However, that is beyond the scope of the report. The two points of focus were how to prevent a battery from igniting after experiencing abuse, and how to extinguish the battery once it has caught fire.

In order to prevent battery fire, different modifications to the battery were proposed. Modifying the main four components of a lithium-ion cells, the cathode, anode, electrolyte, and separator have showed promising results in small-scale tests. These modifications include using materials that offer improved thermal stability, have a higher breakdown temperature, and in the case of the electrolyte, using less flammable solutions. To verify that these modifications are feasible in larger batteries used in electric vehicles, more experimentation is required.

Additionally conventional fire suppression agents, such as water, CO_2 and halons are either ineffective, or have too many detrimental side-effects to be feasible. Dry powder agents show more promising results in small-scale tests, but once again more research and experimentation to how they work in larger fire scenarios is recommended. Modifying the current collector of the battery to enable fire suppression to start as soon as the fire occurs is likely the best way to supress the fire.

Overall electric and hybrid vehicles are a step in the right direction when it comes to having a more sustainable future. Steps are being taken to ensure the fire risk of these vehicles is kept low, and that if a fire does occur, we can put it out. However, there is room for more specific research to be done on the fire safety of lithium-ion batteries in the automotive industry before they can overtake traditional internal combustion engine cars as the most common vehicles on the road.

References

[1] IEA, “Electric vehicles – analysis,” *IEA*, 2022. [Online]. Available: https://www.iea.org/reports/electric-vehicles. [Accessed: 07-Apr-2023].

[2] National Transportation Safety Board. 2020. Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles. Safety Report NTSB/SR-20/01. Washington, DC.

[3] Q. Wang, B. Mao, S. I. Stoliarov, and J. Sun, “A review of lithium ion battery failure mechanisms and fire prevention strategies,” *Progress in Energy and Combustion Science*, vol. 73, pp. 95–131, 2019.

[4] T. Bruen and J. Marco, “Modelling and experimental evaluation of parallel connected lithium ion cells for an electric vehicle battery system,” *Journal of Power Sources*, vol. 310, pp. 91–101, 2016.

[5] X. He, F. Restuccia, Y. Zhang, Z. Hu, X. Huang, J. Fang, and G. Rein, “Experimental study of self-heating ignition of lithium-ion batteries during storage: Effect of the number of cells,” *Fire Technology*, vol. 56, no. 6, pp. 2649–2669, 2020.

[6] C. J. Orendorff, “The role of separators in lithium-ion cell safety,” *Interface magazine*, vol. 21, no. 2, pp. 61–65, 2012.

[7] Q. Wang, J. Sun, and G. Chu, “Lithium ion battery fire and explosion,” *Fire Safety Science*, vol. 8, pp. 375–382, 2005.

[8] P. Victor Chombo, Y. Laoonual, and S. Wongwises, “Lessons from the electric vehicle crashworthiness leading to Battery Fire,” *Energies*, vol. 14, no. 16, p. 4802, 2021.

[9] Ruiz, V.; Pfrang, A.; Kriston, A.; Omar, N.; van den Bossche, P.; Boon-Brett, L. A review of international abuse testing standards and regulations for lithium ion batteries in electric and hybrid electric vehicles. Renew. Sust. Energ. Rev. 2018, 81, 1427–1452.

[10] M. W. Raja, R. N. Basu, N. C. Pramanik, P. S. Das, and M. Das, “Paperator: The paper-based ceramic separator for lithium-ion batteries and the process scale-up strategy,” *ACS Applied Energy Materials*, vol. 5, no. 5, pp. 5841–5854, 2022.

[11] Long, T., Blum, A., Bress, T., & Cotts, B. (2013). *Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results* (Publication). Quincy, MA: Fire Protection Research Foundation.

[12] C. Farivar, “Federal regulators warn of risks to firefighters from electrical vehicle fires,” *NBCNews.com*, 20-Jun-2021. [Online]. Available: https://www.nbcnews.com/business/autos/federal-regulators-warn-risks-firefighters-electrical-vehicle-fires-n1271084. [Accessed: 07-Apr-2023].

[13] S. Yuan, C. Chang, S. Yan, P. Zhou, X. Qian, M. Yuan, and K. Liu, “A review of fire-extinguishing agent on suppressing lithium-ion batteries fire,” *Journal of Energy Chemistry*, vol. 62, pp. 262–280, 2021.

[14] H. Rao, Z. Huang, H. Zhang, S. Xiao, in: ICTIS 2015 – 3rd Int. Conf. Transp. Inf. Safety, Proc., 2015, pp. 865–870.

[15] D. Johnson, “The lithium-ion battery with built-in fire suppression,” IEEE Spectrum, 24-Jun-2021. [Online]. Available: https://spectrum.ieee.org/liion-batteries-more-efficient-fireproof. [Accessed: 07-Feb-2023].