Passive Mitigation of Li-ion Battery Fire Using Erythritol Vermiculite Composite

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Abstract

Thermal runaway of lithium-ion batteries remains a severe threat to the safe operation of electric vehicles as well as the power storage system. Intense local heating, followed by exothermic reaction propagation throughout the battery core, and the possibility of energy re-ignition of a battery module present serious safety concern. The active thermal management systems rely on rapid response sensors to trigger cooling systems, while passive barriers provide only moderate thermal insulation. This manuscript proposes an innovative approach to battery thermal runaway management, based on a novel composite material, which consists of an organic phase change material incorporated into a fire retardant expanded mineral matrix. The composite will be designed to absorb a significant amount of heat energy during an endothermic phase transition of the incorporated organic component, erythritol. At the same time, the mineral component called vermiculite will provide mechanical stability to the composite structure at elevated temperatures and will form a protective barrier to prevent the spread of thermal runaway effects. The identified composite is self-contained, which will eliminates the need for an external power supply, and will not require any additional control equipment to initiate the endothermic reaction.

***Keywords*:** Li-ion Battery, Erythritol, Vermiculite, Thermal Runaway, Phase Change Material.

1.0 Introduction

The rapid adoption of battery electric vehicles and grid scale lithium-ion storage systems has delivered measurable environmental gains. However, this transition has exposed a persistent safety problem: thermal runaway in lithium-ion cells. While battery fires remain statistically uncommon, occurring in roughly 25 of every 100,000 electric vehicles sold, far below the 1,530 rate for gasoline-powered cars, they present a qualitatively different hazard. When a lithium-ion cell enters thermal runaway, internal temperatures soar between 505°C and 548°C. An additional complication is "stranded energy": cells can retain sufficient charge to reignite days or weeks after a fire appears to have been controlled, particularly when water-based suppression methods have been used, which themselves can release toxic and environmentally harmful compounds[1] .

Once a cell reaches the self-accelerating decomposition point, typically around 66 -75°C, the chemical reaction becomes self-perpetuating and cannot be easily interrupted[3].

The past decade has produced valuable research. Battery management systems now monitor voltage, temperature, and gas composition continuously. Suppression technologies have become more effective, employing water mist, foam, and chemical agents tailored to lithium-ion fires. Passive barriers made from ceramics, metals, or insulation boards can measurably delay the spread of heat from one cell to adjacent ones.

Yet they all share a fundamental limitation. Active systems (detection and suppression) respond after a problem has already started. In real world battery packs, the window between early detection and irreversible runaway is often only seconds. Passive barriers, meanwhile, work by slowing heat movement through insulation, not by actually removing the thermal energy the runaway cell produces. They can extend the time before neighbouring cells catch fire, but under realistic field conditions they cannot prevent it entirely, only under controlled laboratory tests with limited variables. The core issue remains unaddressed: neither approach stops the rapid generation of heat itself.

An alternative exists: a passive material that works automatically, requires no electronics or monitoring, and actively absorbs the thermal energy that prevents runaway rather than merely resisting its spread.

Erythritol is an organic material that absorbs heat when it melts, with a melting point near 118°C and heat absorption capacity around 340 J/g [11]. This temperature range falls clearly between the point where battery cells begin to destabilize and the point where runaway becomes irreversible. While erythritol has been extensively studied for use in solar thermal systems and industrial heat storage, no one has systematically tested how it behaves under the extreme, rapidly-applied heat generated during an actual battery fire.

Pairing erythritol with vermiculite, a naturally occurring mineral that resists fire and insulates well, it creates a two-part protection system. The vermiculite layer slows heat conduction to neighbouring cells and shields the erythritol from overheating; the erythritol absorbs the thermal spike that would otherwise trigger cascading failure in adjacent cells.

This work evaluates an erythritol-vermiculite composite as a preventive protective layer for lithium-ion battery modules, testing a combination of thermal absorption and material durability that researchers have not yet examined together.

2.0 Literature Review

2.1 Sanjeev M. Naiek , Sorawich Aungsuthar , Corey Harper and Chris Hendrickson, concluded safety considerations of BEVs include fire, weight, low-speed quiet operation, and driving characteristics that have similar levels of safety performance to ICEVs but distinct issues.

Fire: The number of fires in Battery Electric Vehicles (BEVs) approximately 25/100,000 units sold is lower compared to fires in Internal Combustion Engine Vehicles (ICEVs) approximately 1,530/100,000 units sold but more dangerous. The thermal runaway in batteries happens when temperatures are above 70-100°C while the maximum temperature is 505-548°C for Nickel Manganese Cobalt (NMC) and 278-286°C for Lithium Iron Phosphate (LFP) battery cells. They may store "stranded energy" leading to secondary fires in several days; there is also an issue of Per/Polyfluoroalkyl Substances (PFAS) and heavy metals contaminations from fire extinguishing water [1].

2.1.1 Relevance of the paper with our study.

These findings underscore the inadequacy of reactive, water-based suppression strategies, highlighting a clear need for passive thermal mitigation approaches that can intervene before or during the early stages of thermal runaway. The present study builds on this motivation by proposing a mitigation system using erythritol a phase change material with a melting point (~118°C) suited to absorb heat within the critical thermal runaway onset window identified above encased within a vermiculite-based structure. Unlike water-based suppression this approach avoids the contamination and reignition risks as noted above offering a preventive layer than reactive layer of protection, for battery thermal safety.

2.2 Lingxi Kong, Chuan Li, Jiuchun Jiang and Michael G. Pecht, argue that why the current generation of phone and car batteries are lithium-ion batteries. Lithium-ion batteries have many advantages compared to other batteries including lead-acid batteries because lithium-ion batteries can contain much higher amounts of energy. Lithium-ion batteries have a significant downside since these batteries have a tendency to catch fire. Moreover, they may even explode if the battery gets short-circuited, is exposed to physical impact, overcharged or there was some problem during the manufacturing process of the lithium-ion batteries.

According to the paper, the separator and electrolyte are the most vulnerable parts of lithium-ion batteries under high temperatures. Once the internal temperature reaches the value of 130-150°C, the electrode coating decomposes, followed by melting of the separator and releasing of the oxygen from the cathode. This process initiates a sequence of events in which the heat generation exceeds the ability of the lithium-ion batteries to dissipate the heat. As a result, the battery enters runaway condition. The study also states that the voltage cannot be used as an adequate indicator. The voltage level remains constant till a sudden drop occurs. By this moment, damage inside the battery becomes irreversible.

In order to address these risks, the authors classified all safety solutions into three main categories. On the first place there are the preventive measures. These include adding flame retardant substances to the electrolyte or separator. These measures aim to increase the stability of the lithium-ion batteries at high temperatures. There are also safety devices, which aim either to stop the reaction or release gas before the battery failure occurs. Such examples include separator shutdown and pressure-relief venting. Finally, there are suppression methods that concentrate on extinguishing the fire once it appears. The review draws attention to the importance of cooling of lithium-ion batteries, in addition to fire extinguishing. Without it, the residual heat in the lithium-ion batteries can cause the battery to start the fire again [2].

2.2.1 Relevance of the paper with our study

As categorized existing safety measures into preventive, fail-safe, and active suppression, our idea of PCM with vermiculite coating is firmly a preventive one, similar to their flame retardant additive example, with the caveat that the former alters chemistry/electrolyte/separator while our approach introduces the external buffer which takes in the heat and thus protects the cell before the temperature hits the decomposition range of 130-150°C.

There are two additional elements that might be relevant to include in our paper. Firstly, they observe that voltage does not change until it's too late – it doesn't serve as an early indicator of fire. This fact is, therefore, another argument why our solution would work better than any sensor-based one because we don't have to detect the problem, all we have to do is have that buffer which absorbs heat. Finally, reignition, which occurs due to residual heat causing the reaction even when flames are put out, is another issue brought up by them, it is yet another common factor which is mentioned in all papers we considered .

2.3 Qingsong Wang, Jinhua Sun, and Guanquan Chu, explain lithium-ion battery fires through the combustion triangle framework: fuel, oxygen, and an ignition source. Notably, both the fuel (flammable electrolyte) and oxygen are produced inside the battery cell as the result of the cathode and anode oxidation. The risk of combustion is therefore inherent to the lithium-ion battery's operation and can occur even in the absence of an external oxygen supply. The authors note that the cell's inability to withstand the pressure caused by exothermic reactions explains why short-circuiting, overcharging, and mechanical abuse can all lead to thermal runaway.

The authors describe the process by which the electrodes contribute to thermal runaway. The positive electrode begins to oxidize at 130–170°C, depending on the type of electrolyte, producing oxygen gas. Meanwhile, the negative electrode's protective intercalation compound layer begins to decompose at around 74°C. The exothermic nature of both reactions leads to a self-sustaining rise in temperature. The authors estimate, using a calorimetric model, that the decomposition of the intercalation compound on the anode leads to a self-accelerating decomposition temperature (SADT) of 66.5°C and a "no return" point at 75°C. They suggest that in larger commercial cells, these thresholds are likely to be lower due to the increased challenge of heat dissipation [3].

2.3.1 Relevance of the paper with our study

The critical threshold these researchers identified is 75°C, a temperature beyond which cells lose their ability to self-recover. It demonstrate that batteries experiencing temperatures between approximately 66.5–75°C enter a dangerous zone where a self-perpetuating cycle takes over: the solid electrolyte interface degrades, gases are released, and the resulting heat accelerates the process further. Notably, we proposed phase change material erythritol that has a melting point of around 118°C, which positions it just above this danger window. This timing is strategically advantageous: the material can capture and absorb excess heat precisely when the cell is approaching the point of no return, rather than waiting until thermal runaway is already underway. The researchers themselves frame this challenge as a cascading sequence, and suggest potential fixes like thermally conductive shells or pressure relief systems to interrupt this chain reaction. Our approach achieves a similar result through a fundamentally different method: the vermiculite wrapper functions passively, dampening the temperature spike by allowing the phase change material to store heat and delay the thermal surge essentially creating a buffer that prevents the cascade from reaching its critical stage.

2.4 Kaliaperumal, Dharanendrakumar, Prasanna, Abhishek, Chidambaram, Adams, Zaghib, and Reddy take a deeper dive into lithium-ion battery failures by moving beyond simple observation. Rather than just listing what goes wrong, they employ a rigorous analytical framework called Failure Mode and Effects Analysis, that traces each failure back to its physical origins at the material and component level.

Their examination reveals a landscape of competing priorities across the battery's internal architecture. Anode choices like graphite and lithium titanate force engineers to compromise between how much energy they can store and how safely they do it. Newer, higher-capacity options such as silicon promise more power but come with a serious downside: they swell dramatically during charging and can fracture, potentially puncturing the cell and causing dangerous internal contact. On the cathode side, different chemical formulations like LCO, NMC, NCA, and LFP, each bring different trade-offs between energy density, manufacturing cost, and heat resilience. Lithium iron phosphate (LFP) stands apart for its inherent stability; the strong bonds in its phosphate structure make it remarkably resistant to thermal damage,

though it sacrifices some electrical output in return. Beyond these chemistry questions, electrolytes become unstable above roughly 100°C, and separators can fail through gradual aging, physical punctures, or when lithium dendrites grow through them these all pathways that lead back to internal short circuits and thermal runaway. Mechanical damage like crushing or manufacturing defects such as welding flaws accelerate these failure modes further.

On the solution side, the review spans multiple layers of defence: protective coatings on electrode surfaces, chemical additives that resist flames, and improved multi-layer separators at the material level; plus hardware additions like relief valves and smart monitoring systems that continuously assess cell condition [4].

2.4.1 Relevance of the paper with our study

The paper group protective coatings and flame-retardant additives under the umbrella of "material-level safety interventions" and that's precisely where our erythritol PCM with vermiculite casing fits. The key difference is placement: our solution works from the outside rather than being engineered into the electrode or electrolyte chemistry itself. There's also a useful timing alignment: the researchers flag electrolyte failure around 100°C, and our phase change material melts near 118°C, meaning it's positioned to intervene right at that critical threshold rather than after breakdown has already begun.

Their final takeaway is particularly relevant to our positioning: battery safety isn't solved by any one solution alone, it requires coordinated effort across materials chemistry, structural design, and active monitoring. This frames our work nicely we are not proposing the PCM casing as a replacement for battery management systems or pressure relief, but as an understudied passive layer operating at the material level, something that complements existing protections rather than standing alone.

2.5 Mohammadmahdi Ghiji, Vasily Novozhilov, Khalid Moinuddin, Paul Joseph, Ian Burch, Brigitta Suendermann and Grant Gamble, take a broad look at lithium-ion battery fires, focusing mainly on finding the best way to put them out once flames appear. They walkthrough the standard cell setup - cathode, anode, separator, electrolyte and explain how thermal runaway kicks in once internal temperatures climb past the safe operating range, setting off a self-feeding heat cycle. The causes are grouped into four buckets: electrical abuse (over-charging/discharging), thermal abuse (overheating), mechanical abuse (crushing, puncture), and internal short circuits from separator failure or manufacturing flaws.

The review also breaks down fire protection into layers - cell, module, pack, and compartment level. At the cell level this means material tweaks and built-in safety features like vents and shutdown separators; at the system level, battery management and thermal management systems do most of the work, though the authors note fires still happen even with these in place.

The second half focuses on extinguishing agents - water, foam, dry powder, CO2, and halon based options are all compared. Most can put out the visible flame but fail to cool the cell enough, so reignition remains a real risk. Water comes out on top because of how much heat it can absorb, the authors point to gas-phase cooling, oxygen dilution, surface wetting, and radiant heat blocking as the main reasons it works so well. Their overall takeaway is that water mist, especially paired with surfactants or added gases, is currently the most promising option for fighting these fires, though they admit clear design standards for these systems are still lacking [5].

2.5.1 Relevance of the paper with our study

What really matters here is how the authors break down the layers in battery protection from cells, to modules, to packs, right up to the compartment. They put things like vents and shutdown separators right at the cell level, dealing with problems before things get out of hand. Once a fire actually starts, they see everything else BMS, thermal management, extinguishing agents as backup measures that only step in after the fact. That’s exactly where our erythritol and vermiculite casing fits in. It’s not a suppression system; it’s a hands-on material barrier at the cell level, closing the gap authors point out: fires still break out, even when BMS and thermal controls are running.

2.6 Kuo Wang, Dongxu Ouyang, Xinming Qian, Shuai Yuan, Chongye Chang, Jianqi Zhang, and Yifan Liu tackle lithium-ion battery safety from two angles: spotting thermal runaway early and figuring out what really puts out the fire once things go wrong. They kick things off by bringing up some serious accidents—like the APS explosion in Arizona

back in 2019 and the Dahongmen storage fire in Beijing in 2021. Their point is clear: today's warning systems and firefighting methods aren't good enough yet, and sometimes that failure costs people their lives.

When it comes to detection, they break down warning signs into five groups: sounds, heat, physical deformation, electrical changes, and gas emissions. Thermal runaway itself isn't just one event, it happens in three stages. First, the battery's insides heat up and gases build. Then, pressure gets released through safety valves. Finally, if enough flammable gas builds up in a tight spot, you get a fire or even an explosion. For each signal, the authors dig into the tech, things like ultrasonic listeners, infrared cameras, thermocouples tucked inside the battery, strain gauges, electrochemical impedance, and gas sensors for hydrogen or HF. They notice that every method comes with a trade-off: gas sensors are accurate but only give you a few moments before things ignite, while impedance measurements pick up problems earlier but need more complicated setups [6].

2.6.1 Relevance of the paper with our study

This research breaks thermal runaway into three distinct phases: initial heat buildup, venting, and ultimately fire or explosion. Our PCM casing targets that first phase specifically absorbing heat before the cell ever reaches the point of venting. While authors emphasizes early detection through sensors, our material operates passively and continuously, requiring no electronics or alert systems to function.

This creates a useful comparison for our work. Author notes the fundamental tension in current approaches: gas sensors provide accurate warnings but leave little time to respond, while impedance-based systems offer earlier detection but demand bulky additional equipment. Our material-based solution bypasses this dilemma entirely there's nothing to install, calibrate, or monitor. The thermal response is immediate and automatic.

2.7 Loraine Torres-Castro, Andrew Kurzawski, John Hewson, and Joshua Lamb dig into a big problem in their paper: when one lithium-ion battery cell overheats and fails, it can set off a chain reaction, spreading heat to the next cell and putting the whole battery pack at risk. To figure out how this happens (and maybe how to stop it), they ran tests with five-cell lithium-ion pouch packs. They looked at two simple ways to slow or stop this dangerous domino effect: lowering the state of charge (SOC) and adding aluminium or copper plates between the cells.

They found that when the pack was fully charged, thermal runaway spread fast, every cell cooked off in just 90 seconds. Dropping the SOC made a real difference. At 50% SOC, the problem stopped in its tracks. At 75%, only the second cell got caught up in the failure. Around 80% SOC, the results were mixed. Sometimes the chain reaction happened, sometimes not, showing this level is right on the edge between safe and risky.

The metal plates helped by absorbing heat and boosting the battery pack's thermal mass. Thicker plates worked better. Plates that were 1.6 mm thick slowed things down, but 3.2 mm plates stopped the chain reaction entirely during their tests. Thinner 0.8 mm plates didn't prevent the spread, but they did slow it down, they doubled the time it took for the whole pack to fail. That extra time means more heat can escape and gives engineers a better shot at preventing disaster [7].

2.7.1 Relevance of the paper with our study

This research paper connects directly to our work. It looks at stopping thermal runaway in lithium-ion battery packs by boosting the system's heat absorption with metal barriers. We've taken that idea a step further. Instead of metal, we use an erythritol vermiculite phase change material (PCM) inside a casing based on an AVD extinguisher. This setup absorbs latent heat better and keep things lighter. So, while both studies rely on passive thermal management, ours dives into a more efficient, practical material to keep thermal runaway in check.

2.8 Wei Tang, Liming Yuan, Richard Thomas, John Soles elaborate on "Comparison of Fire Suppression Techniques on Lithium-Ion Battery Pack Fires,".They really dig into how different fire suppression methods hold up against lithium-ion battery pack fires. This is especially relevant for mines these days, since battery-powered electric vehicles are showing up everywhere.

They ran their experiments at the NIOSH Pittsburgh Mining Research Division, using both 12V and 24V nickel/manganese/cobalt (NMC) lithium-ion battery packs. To get the batteries to catch fire, they used electric heater

strips and monitored the battery temperature with thermocouples. After the fires got going, they compared the usual "let it burn" scenario to several ways of putting it out: water mist at different flow rates, water mist with the F500 additive, ABC dry chemical powder, and Type D sodium chloride dry chemical.

They found that water mist worked really well for smaller battery pack fires, mostly because it cooled off the batteries. That drop in temperature lowered the odds of the fire flaring up again. Water mist at flow rates of 1, 2, and 3 GPM handled smaller fires, but 3 GPM water mist with the F500 additive was the superstar, it cooled things down the fastest and deepest. Meanwhile, the Type D sodium chloride and ABC dry chemical powders could knock out the flames for a bit, but they barely cooled the batteries. Fires kept reigniting, sometimes even exploding, because the batteries stayed hot inside.

Bigger batteries are a tougher nut to crack. Neither the 3 GPM water mist alone nor ABC dry chemical managed to fully suppress fires in the 24V packs. Cooling the batteries is absolutely vital when dealing with lithium-ion fires [8].

2.8.1 Relevance of the paper with our study

This literature review reveals a critical gap in current battery safety approaches: existing fire suppression methods operate after thermal runaway is already underway. The research consistently shows that rapid, effective cooling is the key to stopping re-ignition, with water mist proving superior to dry chemical agents simply because it absorbs heat more efficiently. However, the broader lesson is that we're fighting fires rather than preventing them. Our research takes a different path. Instead of waiting for thermal runaway and then attempting to extinguish it, we've identified a passive material system that stops the problem at its source. An erythritol-based phase change material housed in a casing sits within or around the battery, silently absorbing excess heat as temperatures rise. By doing so, it delays or potentially prevents the cascade of thermal runaway before it reaches the critical point where external firefighting becomes necessary. The approach requires no sensors, no active monitoring, and no intervention. It's simply present, responding immediately to temperature changes through its physical properties.

2.9 Christopher Lee, Ahmed O. Said, and Stanislav I. Stoliarov ran a series of tests to see if passive safety measures can actually slow down or stop thermal runaway in tightly packed 18650 lithium-ion battery assemblies, a big worry for electric cars and large battery storage systems, where one failing cell can trigger a chain reaction in all the others.

They set up experiments with fully charged 18650 lithium cobalt oxide cells arranged in dense blocks of 12 to 15. Inside a custom wind tunnel, they tested the batteries in both air and nitrogen. To kick things off, they used an electric heater to start thermal runaway in a single cell, then watched what happened using thermocouples, gas analysers, and temperature sensors. They monitored every change - temperature spikes, how quickly the heat spread, gas releases, and how much heat got generated.

Six different setups: a baseline array with zero gaps in air, the same in nitrogen, another with 5 mm gaps between certain rows and columns, and three where those gaps were filled with double-layer perforated stainless steel, intumescent barriers, or ceramic fibre board.

The results were clear: thermal runaway spread through all the baseline battery packs. In air, things escalated much faster because the vented battery gases caught fire and ramped up heat transfer. That 5 mm gap slowed runaway by about four times, but it still wasn't enough, once the first cell failed, the rest followed. Physical barriers made a much bigger difference. They cut down the heat transfer and significantly slowed down the spread, with ceramic fibre board being the top performer, followed by perforated stainless steel and then the intumescent barriers. Even so, none of the barriers managed to completely stop thermal runaway, though sometimes the reaction stalled at the barriers. In short, passive protection makes packs safer by buying extra time, but it doesn't fully solve the problem.

Looking deeper, they found that in those dense packs with no barriers, about half the heat hitting the next cells came from burning battery material, 20% was straight cell-to-cell conduction, and the last 30% came from convection, radiation, and heat conducted through parts of the pack. Add a physical barrier, and downstream cells got heated three to four times less. Protected cells needed their surfaces raised by 100–150 K before runaway would start—meaning the slower heat-up delayed the chain reaction. Regardless of barriers, any cell in thermal runaway lost around 38–41% of its original mass. Air tests ended up with more ruptured cells because temperatures soared higher. When it comes to gas

emissions, they mostly found hydrocarbons, CO, CO_2, and H_2; interestingly, the barrier and gap setups actually produced more gas overall because the batteries cooked for longer in the higher temps, letting the cell material break down even further. Still, the total chemical heat per failed cell didn't really change, the barriers just slowed down how quickly the heat moved, not how much came out.

So, using passive barriers, especially ceramic fibre boards, makes batteries a lot safer by drastically slowing runaway by 17–30 times compared with unprotected assemblies, which gives us more time to react and handle the situation. But since nothing they tried actually stopped runaway completely, the authors say we need to pair passive barriers with active cooling and fire protection in real-world lithium-ion battery designs [9].

2.9.1 Relevance of the paper with our study

This research paper connects directly to our study because it looks at passive thermal runaway mitigation by using thermal barriers to slow down heat transfer between lithium-ion battery cells. The findings show that insulating materials can slow down thermal runaway propagation, making batteries safer, though they can't stop the process completely. Our work uses the same passive protection idea but instead of traditional barriers, we use erythritol as a phase change material (PCM) to soak up extra heat, and vermiculite as a thermally insulating casing. By combining these, we aim for better heat absorption and insulation to further delay thermal runaway propagation and boost battery fire safety.

2.10 Xuning Feng, Dongsheng Ren, Xiangming He, and Minggao Ouyang present a thorough review of thermal runaway (TR) mitigation in lithium-ion batteries (LIBs) and stress that battery safety demands attention at every level - material, cell, module, and system. Relying on a single protective step just isn't enough. They introduce the Time Sequence Map (TSM) as the main framework to track how thermal runaway unfolds, starting with the earliest abnormal heat signals and moving through smoke, fire, explosion, and finally propagation through a battery pack. They describe TR triggers, which include mechanical, electrical, thermal, and new electrochemical abuses like crushing, overcharging, fast charging, internal short circuits, lithium plating, oxygen released from high-nickel cathodes, separator failure, or hidden manufacturing defects.

The paper marks out three crucial temperatures in TR behaviour: T1 (where abnormal heat generation and Solid Electrolyte Interface SEI decomposition start), T2 (actual triggering of thermal runaway), and T3 (the highest temperature reached during TR). With Accelerating Rate Calorimetry (ARC), researchers can measure these points to assess safety. So, the main goal of any mitigation strategy becomes clear: raise T1 and T2, while lowering T3 and the peak heat output, to boost thermal stability and prevent disastrous failures.

The authors explain that effective mitigation means cutting off the TR process at multiple steps. At the cell level, they recommend making the SEI more stable with electrolyte additives, using separators that resist high temperatures or feature ceramic coatings, holding back oxygen from cathodes through special coatings or single-crystal designs, stopping lithium plating with smarter charging protocols, and using thermo-responsive materials, flame-retardant electrolytes, and self-poisoning cell designs that generate less heat if something goes wrong. At the system level, mitigation focuses on stopping TR from spreading by building in thermal barriers, insulation, stronger cooling systems, controlled venting, fire-resistant structures, protection with inert gases, better battery thermal management, and design tweaks that slow heat movement between cells.

They also point out that next-generation Battery Management Systems (BMS) should catch trouble early by detecting strange voltage, temperature, pressure, gas build-up, and internal short circuits, using model-based fault diagnosis. Existing safety standards aren't enough, especially as risks like lithium plating, dendrite formation, oxygen release, and electrochemical abuse from high-energy chemistries and ultra-fast charging become more relevant.

In the end, the paper argues that the future of lithium-ion battery safety depends on weaving together chemical, mechanical, electrical, thermal, and intelligent monitoring approaches, all led by the Time Sequence Map. This gives researchers and engineers a way to stop thermal runaway before it starts, keep it from spreading, and guarantee that high-energy batteries stay safe in electric vehicles and energy storage systems [10].

2.10.1 Relevance of the paper with our study

This review paper connects closely to our research since it covers passive thermal runaway mitigation and really drive how important phase change materials (PCMs) and thermal barriers are for stopping heat from spreading between battery cells. The authors make it clear: an effective thermal barrier needs low thermal conductivity, strong temperature resistance, and good heat absorption, qualities that match what we get with erythritol as our PCM and vermiculite as the extinguishing media.

2.11 Mayra Paulina Alferez Luna, Hannah Neumann, and Stefan Gschwander noticed that Phase Change Materials (PCMs) keep getting more attention mostly because they store a lot of thermal energy and hold a steady temperature during their phase change. Out of all the possible options, natural PCMs like sugar alcohols stand out. They're especially more effective for latent heat storage since they pack high latent heat, not toxic, and don't harm the environment.

Take erythritol, for example. It melts at around 118°C and delivers about 340 J/g of latent heat. That makes it a strong candidate for medium-temperature thermal energy storage. Plenty of research has already looked at how erythritol behaves, how it heats up and cools down, how it crystallizes, how it transfers heat, and even how it works in mixtures or composites. Adding various substances can actually boost its thermal properties, especially conductivity and storage capacity.

But here's the thing: most studies focus on how erythritol holds up during short-term thermal cycles. They often skip over how stable it stays during long-term storage at high temperatures. This study dives right into that missing piece, looking at the thermal stability of erythritol under argon and open air. They also tested what happens when added an antioxidant (Irganox 1010) to the mix.

When erythritol oxidizes, its latent heat drops, and it turns brown, not ideal. But, if stored it under argon or add Irganox 1010, we can really slow down that thermal degradation and keep its energy-storage superpowers intact [11].

2.11.1 Relevance of the paper with our study

Erythritol, a natural polyol with a phase transition temperature of 118°C and latent heat of 340 J/g, presents an alternative PCM candidate with superior thermal stability at elevated temperatures compared to paraffin-based systems. Research indicates that erythritol maintains thermal performance during prolonged high-temperature exposure when protected from oxidation, making it suitable for fire mitigation applications.

The current study shows these findings by combining erythritol as the thermal storage medium with vermiculite as a protective structural framework. This approach integrates the thermal management principles established in battery cooling research with the material stability requirements necessary for passive thermal runaway mitigation. This combination addresses gaps in existing literature by extending PCM applications beyond routine thermal regulation toward fire containment and suppression.

2.12 P. V. Honguntikar and U. C. Pawar looked at how thermal energy storage (TES) is catching on as a crucial technology for making the most out of renewable energy sources, especially solar power. Out of the several types of TES, phase change materials (PCMs) that store latent heat are getting a lot of attention. People favour these materials because they pack in a lot of energy and keep their temperature almost constant while changing phases. That's really the big advantage latent heat storage has over sensible heat storage. Plenty of studies point out that PCMs are better than sensible heat storage if you want good thermal control.

Erythritol, a sugar alcohol, stands out as a promising organic PCM. It gives a high latent heat of fusion of about 340 kJ/kg and melts somewhere between 118 and 121°C. Plus, erythritol doesn't corrode common engineering metals like stainless steel, copper, or aluminium, and it holds up well under heat. These traits make erythritol a solid pick for thermal energy storage at low to medium temperatures.

Researchers have been busy exploring the thermophysical properties of erythritol during phase changes. Studies found that it works efficiently up to 160°C. some studies shows that how the crystal structure changes when erythritol solidifies. Other studies agree that the heat of fusion is high at 340 kJ/kg, and the thermal conductivity matches well with what you'd want from a heat storage material.

Several experiments tested how erythritol handles heat charging and discharging. Turns out, melting is mostly powered by natural convection, while it solidifies pretty quickly. When it goes through lots of thermal cycles, erythritol barely loses any latent heat, so it's reliable for the long haul. All things considered, erythritol's impressive thermal behaviour makes it a strong contender for solar water heating, air heating, and waste heat recovery systems [12].

2.12.1 Relevance of the paper with our study

This paper confirms the key properties of erythritol like its melting point 118-121°C and latent heat is around 340kJ /Kg . This shows that erythritol gave us the good thermal stability and maintain over a long time without losing its latent heat before a potential fire . Also multiple near misses and overheating doesn't affect the property of erythritol due to this it's operational lifetime can be up to 5 to 10 years .

2.13 Dr. Peter Schwartz points out that thermal energy storage makes renewable energy more efficient by storing energy as heat. Among the different ways to do this, phase change materials (PCMs) stand out. They can hold a huge amount of energy and keep a stable temperature as they melt from solid to liquid. That steady temperature is really useful as we see these materials show up in solar cooking, solar water heating, temperature control, and even capturing waste heat. The best part is that they don't need extreme temperatures to work.

Take erythritol, for example, a sugar alcohol that's drawn a lot of interest as a PCM for medium-temperature heat storage. It melts at about 121°C, and its latent heat of fusion (around 340 J/g) lets it store and release energy efficiently over multiple heating and cooling cycles. Research shows erythritol tends to break down over time. If you heat and cool it over and over, its melting point drops, and it doesn't store as much energy. Visually, the change is obvious: what starts as a yellowish-white solid turns dark brown or black, a clear sign the material is chemically degrading when pushed to higher temperatures.

Researchers track these changes with Differential Scanning Calorimetry (DSC) and regular temperature checks. The results are consistent degraded erythritol melts at a lower temperature, holds less heat, and just doesn't perform as well as fresh material. So, although erythritol looks great on paper for medium-temperature heat storage, its poor long-term stability is a real problem. To turn it into a practical solution for thermal energy storage, scientists need to figure out how to boost its stability and help it survive more heating and cooling cycles [13].

2.13.1 Relevance of the paper with our study

Schwartz's research validates erythritol as an effective medium-temperature PCM for thermal energy storage, making it suitable for capturing heat during battery thermal runaway. However, the critical limitation he identifies that erythritol's degradation under repeated thermal cycling, resulting in reduced melting point and latent heat is directly addresses why your system incorporates vermiculite casing.

The research demonstrates that erythritol loses performance when exposed to extreme temperature cycles and oxidative conditions and exactly what happens during battery fire events. Your vermiculite encapsulation solves this problem by providing chemical protection and thermal buffering, preventing oxidative degradation while erythritol performs its heat-absorption function.

Essentially, Schwartz's findings highlight the material limitation your composite design overcomes: erythritol offers the thermal capacity needed for fire mitigation, while vermiculite provides the protective barrier necessary to maintain that performance under extreme conditions.

2.14 Jiajun Zhao, Yin Chen, Yan Gong and Mingyi Chen explained that thermal management has emerged as a critical concern in lithium-ion battery (LIB) applications, particularly as energy density demands continue to increase. Temperature regulation within battery modules directly impacts performance longevity and operational safety, with uncontrolled heat generation potentially triggering catastrophic failure modes. Traditional cooling approaches including air-based and liquid-cooling systems present significant trade-offs between efficiency and practical implementation, often requiring substantial mechanical complexity or carrying risks associated with coolant leakage.

In recent years, phase change materials (PCMs) have gained considerable attention as an alternative solution for passive thermal regulation in battery systems. By absorbing and releasing thermal energy during phase transitions, these

materials provide sustained temperature buffering with minimal energy input. However, pure PCM formulations suffer from inherent limitations, most notably poor thermal conductivity that restricts effective heat dissipation pathways. Researchers have therefore pursued composite approaches, incorporating high-conductivity fillers such as expanded graphite, carbon nanotubes, and metallic frameworks to establish enhanced heat transfer networks within the base PCM matrix.

Recent investigations have demonstrated that dual-filler strategies can synergistically improve material performance beyond what single-additive systems achieve. The combination of structural support materials with thermally conductive reinforcements creates interconnected pathways that facilitate more uniform temperature distribution across battery assemblies. Additionally, bio-based additives have emerged as promising candidates due to their availability, cost-effectiveness, and environmental sustainability advantages over purely synthetic alternatives.

Despite these advancements, practical implementation challenges persist, including long-term cycle stability, leakage mitigation during thermal cycling, and optimal integration within existing battery architectures. The present research addresses these gaps by investigating an innovative composite formulation designed to simultaneously enhance thermal performance while maintaining structural integrity and minimizing material waste [14].

2.14.1 Relevance of the paper with our study

The literature review makes it clear: phase change materials (PCMs) are great for passive thermal regulation in battery systems, but they just don't cut it alone they need composite designs to get around their weak spots. Our research takes this idea and pushes it further by applying it to something much more intense a battery fire thermal runaway not just the usual day-to-day heat management.

The main takeaways from the review fit right into how you've built your system. It backs up the composite PCM approach. Researchers usually combine PCMs with fillers to make them work better, and we've done the same, choosing erythritol and pairing it with vermiculite. But here's where we change the game: most papers focus on improving heat distribution or thermal conductivity during normal conditions. We jump into the tough stuff, focusing on stopping catastrophic failures during thermal runaway an area those papers mostly leave untouched.

The literature points out that pure PCMs struggle with stability and structural strength, which is exactly the problem your vermiculite casing solves. Vermiculite isn't just a filler , it forms a shield and acts as a thermal buffer, protecting erythritol from breaking down while it soaks up the intense heat of a battery fire. We're attacking the real implementation hurdle the review highlights: keeping everything stable and intact even when temperatures go through the roof.

So, while the literature makes the case for composite PCMs in thermal management, your work steps it up. We use the thermal muscle of erythritol and the protective edge of vermiculite to create a passive fire suppression system one that still performs even when active cooling systems fail under extreme conditions.

2.15 Davide Palmaa, Sofia Ubaldia, Mario Quinternob, Pierpaolo Gentileb, MicheleMazzarob, Paola Russoa, who investigated the byproducts of a lithium-ion battery fire after it has been extinguished. Their experiments involved square NMC pouches (Kokam SLPB 25 Ah, ~92 Wh), subjected to thermal runaway and burning under three different scenarios: unsuppressed burning, extinguishing the fire with a foam agent, and stopping combustion with Aqueous Vermiculite Dispersion (AVD).

Instead of being limited to the analysis of flame knockdown properties, the authors took a closer look at the three waste streams generated during the test: the gas phase, collected in bags, the runoff liquid, and the solid residue from the burned cell. The gas phase was analyzed with FTIR spectroscopy to determine the abundance of various gaseous byproducts, while the liquid and solid phases went through SPME-GC-MS to reveal volatile and non-volatile organic compounds, respectively.

They found that the suppressant dramatically affects the abundance of various combustion gases, explaining why the unimpeded fire produced nearly ten times more hydrogen chloride (12%) compared to the suppressed variants (2% for foam, less than 0.2% for Aqueous Vermiculite Dispersion). At the same time, the flame knockdown decreased the amount of unburned electrolyte vapor (ethylene carbonate) tenfold compared to the unimpeded fire. To compare the suppressants' impact on the gas phase in terms of mass, the authors introduced an interesting normalized emission ratio,

ω°, and found that, relative to the total mass of all combustibles in the experiment, methane and CO2 emissions were lower for fires put out with foam, while other combustion byproducts were reduced with Aqueous Vermiculite Dispersion.

As for the solid material resulting from the fire, the authors found carbonate solvents (DMC, EMC, DEC) originating from the electrolyte solution in all three experiments, with no significant differences between the groups. However, the liquid runoff varied considerably depending on the suppressant used. Specifically, the Aqueous Vermiculite Dispersion left no visible evidence of liquid, most of which had evaporated upon contact with the burning pouch, leaving a thin layer of vermiculite on top. On the contrary, the liquid runoff from the fire extinguished with foam contained C8–C10 alcohols originating from the suppressant itself. The practical implication of this finding is that the choice of fire suppressant not only influences the fire suppression performance but also dictates the necessary procedures for handling the chemical and thermal waste resulting from the fire, an aspect that the authors say has received insufficient attention in previous research on lithium-ion battery fires [15].

2.15.1 Relevance of the paper with our study

Palma et al. (2024) really backs up our choice of vermiculite for fire suppression. They ran tests on lithium-ion batteries going into thermal runaway, looking at three situations: letting them burn out of control, suppressing them with foam, and using Aqueous Vermiculite Dispersion (AVD) which is exactly the material we are working with.

2.16 Supri, Sapurta, and Nugraha (2024) dug into the surge of research on putting out electric vehicle fires especially those kicked off by thermal runaway in lithium-ion batteries. They followed PRISMA-SCR guidelines and shifted through almost 230 records from Science Direct and Google Scholar, finally settling on nine core studies published between 2014 and 2024 that fit the bill.

They broke down the extinguishing agents used in these studies into five main groups: solid (fire blankets), liquid (like water spray, water mist, liquid nitrogen), gaseous (CO_2, HFC-227ea), foam-based (compressed air foam), and chemical (C6F12O, F500). For each, they looked at how researchers applied the agent-alone or in combination and what results followed, focusing on how well they cooled things down or actually put out the fire.

Here's where it gets tricky: no single agent consistently tackled both major problems putting out the visible flames and stopping the runaway chain reaction inside the battery. For example, fire blankets excelled at choking off oxygen and shutting down flames fast, but they barely slowed the internal reaction that leads to fires flaring up again. Foam and water mist, on the other hand, proved much better at cooling; in one study, compressed air foam cooled things down at an average of -9.8°C per second. Fast-acting chemicals like C6F12O snuffed out fires quickly and didn't lead to immediate reignition, but these agents couldn't handle cooling on their own, so they had to be used with something like water mist.

Combining agents clearly worked better than relying on a single method. Hybrid setups were faster and more stable, keeping temperatures down after the fire was out. The authors' big takeaway: if we want real control over EV fires, we need a layered response not a one-size-fits-all fix [16].

2.16.1 Relevance of the paper with our study

Their work dives into "active suppression" tactics-things like water mist, compressed air foam, fire blankets, gases, F500, and C6F12O-used to put out EV and lithium-ion battery fires. Across nine experiments, they show that while active agents can extinguish fires, they keep hitting a wall when it comes to actually halting thermal runaway at the cell level. Several articles point out that water and foam require pretty advanced temperature control to stop flare-ups, and fire blankets can't fully prevent runaway.

That's the exact gap our project aims to cover. Instead of grabbing a tool after the fire's already started, our erythritol-PCM/vermiculite casing acts as a built-in, passive shield-stopping runaway before it can spread. There's more: the review includes one study (A8, Palma et al., 2023) where researchers used AVD, the same vermiculite we are working with as an extinguishing agent. That gives us solid experimental data about vermiculite's insulation performance, which we can cite directly when discussing our own passive casing design.

2.17 John Joseph research into why lithium-ion batteries fail has taken off alongside the boom in electric vehicles. Still, most of it sticks to road transport and barely touches on places like airport operations. Sun and his team in 2020 sifted through records of battery fires and ran into a familiar brick wall: investigators usually walk away without figuring out what actually set off the fire. Most cases just end up stamped as "cause unknown"—either the trail goes cold, or there's just not enough evidence to piece things together. The government-backed EV FireSafe project in Australia sees the same thing happening around the world. Their numbers show that after all these mystery cases, it's collisions and factory or equipment defects that take the blame most often.

If you look closer, there's this study by Bisschop and his team at RISE from 2019. They dug into how a single cell going bad can set off a full-blown battery fire. Here's what they found: if one cell shorts out and heats up faster than the whole battery can cool, that heat spreads quick, lighting up the cells around it. Later, Christensen put a real-world number on the risk in 2022, he showed that when just one kilowatt-hour's worth of battery goes into thermal runaway, you get thousands of litres of flammable, poisonous gas spewing out. At that scale, basic fire suppression just can't cope.

Emergency responder guidelines from the NFPA really drive home how lithium battery fires break all the regular rules, especially the way they can flare up again and the kind of thick, toxic smoke they give off. The 2023 car park fire at Luton Airport—big story in both the BBC and aviation security circles—really exposed how vulnerable our infrastructure can be and sparked interest in better fire-fighting solutions. Manufacturers are out there pushing products like F-500, saying they meet NFPA 18A standards for controlling dangerous vapours. But, honestly, there's just not enough solid, peer-reviewed testing of these chemicals in real aviation settings. That's the gap this project is here to take on [17].

2.17.1 Relevance of the paper with our study

This section works really well with our paper. Their document focuses on what to do after a lithium-ion battery is already burning—basically, once thermal runaway starts. Stuff like using F-500 agents, EV fire blankets, portable carts, or hydrant induction systems. Our research looks at the step before that. We're trying to prevent or slow things down with erythritol PCM mixed with vermiculite (which, by the way, comes from AVD extinguisher media-something their paper actually mentions as a standard tool).

2.18 Owen Radcliffe, Keith Mesecher,Ryan Malaquias, Joseph Peregrim analyzed lithium-ion battery (LIB) risks on small passenger vessels and roll-on-roll-off carriers. LIBs present unique fire hazards because their self-contained combustion elements render traditional suppression methods ineffective. Thermal runaway—an uncontrolled exothermic reaction triggered by battery damage or stress—occurs when heat generation exceeds dissipation, potentially propagating to adjacent batteries and releasing hazardous flammable vapors and toxic gases including hydrogen fluoride and carbon monoxide.

The study examines three significant incidents: the 2022 Felicity Ace fire (hundreds of millions in losses), the 2019 Höegh Xiamen incident (delayed suppression system activation), and the 2019 MV Conception disaster (deadliest recent California maritime fire). These incidents highlight the limited training crews receive despite being primary fire responders.

Water and water mist represent the most effective suppression options, with additives such as F-500 EA enhancing cooling performance and reducing toxic byproducts. Carbon dioxide proves ineffective at cooling and may reignite fires, while clean agents provide insufficient thermal management. The authors conclude that fundamental fire-fighting principles, particularly cooling, remain applicable to LIB fires.

The report identifies significant regulatory gaps, noting that current federal regulations predate widespread LIB adoption. Key recommendations include establishing minimum vehicle spacing on Ro-Ro ships, standardizing battery definitions, developing enhanced crew training programs, and implementing regulations regarding battery state of charge on commercial vessels [18].

2.18.1 Relevance of the paper with our study

This WPI report is a good source to reference in our literature review, as it focuses less on our specific PCM implementation and more on providing the theoretical background for the problem your paper solves. It discusses the

current maritime LIB fire incidents (Felicity Ace, Höegh Xiamen, MV Conception), confirms the thermal runaway point of 66.5–75°C, and lists CO2 , water, foam, and clean agents all of which are either active suppressants (requiring deliberate application) or have proven insufficient at combating large-scale fires due to the involved exothermic reaction chain. It also independently verifies the validity of vermiculite/AVD as a fire safety technology by mentioning vermiculite-based fire extinguisher and suppressants using Cellulose-based solid agents, specifically CellBlockEx/Extover for containing the battery within reach of the suppressing media.

2.19 Yixin Dai, Aidin Panahi proposed thermal runaway (TR) in lithium-ion batteries stems from excessive internal heat generation exceeding the cell's cooling capacity. Mechanical, electrical, and thermal abuse conditions can trigger thermal runaway, often initiated by internal short circuits that cascade toward failure.

Battery chemistry significantly influences thermal runaway behaviour. Conventional layered cathodes like $LiCoO_2$ are more thermally stable than nickel-rich alternatives (e.g., NCM811), which sacrifice stability for higher energy density. $LiFePO_4$ offers superior thermal safety due to stronger phosphate-oxygen bonds that suppress oxygen release during decomposition.

Failure progression follows a predictable sequence: SEI layer breakdown → electrolyte-anode reactions → separator failure → cathode decomposition with oxygen evolution.

Mitigation approach strategies span three levels: material (flame-retardant additives, redox shuttles), cell (current-interrupt devices, thermally responsive components), and pack-level (advanced battery management systems with multi-mode cooling) [19].

2.19.1 Relevance of the paper with our study

Dai & Panahi established that thermal runaway becomes self-sustaining above 130–150°C and cannot be arrested internally. Their work identifies phase change materials (PCM) as thermal stabilizers, with erythritol melting near 118°C suitable for external temperature management at this critical threshold. While existing literature emphasizes active mitigation through battery management systems, this study employs a passive strategy using material properties alone, without power or sensors. This approach addresses a gap in thermal protection research by offering a simple, passive alternative to electronic controls.

2.20 The 2013 fire aboard Japan Airlines Flight 787-8 (JA829J) at Boston's Logan Airport stands as a pivotal case in aviation battery safety. The National Transportation Safety Board investigation revealed that a manufacturing defect in a GS Yuasa lithium-ion cell triggered an internal short circuit, which initiated thermal runaway across all eight cells in the auxiliary power unit. The underlying issue was a critical mismatch: the battery had been certified based on laboratory testing that did not adequately simulate the demanding conditions it would encounter in actual service.

Beyond the immediate technical failure, the incident exposed systemic gaps in battery oversight. Manufacturers lacked clear guidance for justifying their safety assumptions, while regulators possessed insufficient criteria to properly evaluate certification compliance. This pattern where safety standards struggle to keep pace with rapidly evolving technology appears throughout the battery research literature. The incident prompted significant design changes, including improved containment structures and external venting systems to prevent smoke infiltration into the cabin. These measures reflect a shift toward redundant safety layers, where limiting the scope of failure becomes as important as preventing it initially. The 2013 event and similar incidents in the same period became watershed moments that fundamentally altered how the aviation industry assesses and manages thermal runaway risk [20].

2.20.1 Relevance of the case study with our study

The JAL 787 incident illustrate the exact failure mechanism this work seeks to prevent. The NTSB investigation documented how thermal runaway in a single cell propagated sequentially through the remaining cells, ultimately compromising the entire battery pack. Notably, Boeing's post-incident corrective action focused primarily on containment: a reinforced steel enclosure and external venting system designed to isolate heat and smoke from the cabin rather than suppress thermal energy at the cell level. While containment remains essential for safety, this approach does not address the underlying runaway reaction itself. In contrast, passive thermal management through phase change materials operates upstream of failure absorbing heat and moderating temperature rise before runaway can initiate or

spread between adjacent cells. This preventive strategy complements rather than replaces containment systems, offering a fundamentally different intervention point in the thermal runaway cascade.

2.21 Thomas, E., Zeron, A., & O'Rourke, J. S. (2017). Samsung Electronics Company, Ltd Galaxy Note 7 Crisis (Case No. 17-10) Explains that the 2016 Galaxy Note 7 recall is one of the corporate messes people have studied in business history. Thomas, Zeron and O'Rourke (2017) wrote a case study in the report of University of Notre Dames Mendoza College of Business. They show how the Galaxy Note 7 started failing weeks after it came out in August 2016. Even though the Galaxy Note 7 had record pre-orders a bad battery caused the Galaxy Note 7 units to get hot and catch fire. The authors talk about moments like a car fire in Florida and a fire on a Southwest Airlines plane. These Galaxy Note 7 fires got a lot of news coverage. Made everyone watch Samsung very closely.

The case says that Samsung tried to fix things by starting a voluntary exchange program for 2.5 million units in September 2016. People liked how fast Samsung moved. Then things went wrong. It turns out Samsung did not talk to the U.S. Consumer Product Safety Commission first. This mistake made people doubt if Samsung was being honest. To make matters worse the Galaxy Note 7 phones with different batteries also broke. Because of this Samsung had to stop making the Galaxy Note 7 and offer refunds by mid-October 2016.

The authors also look at why the technology failed. Lithium-ion batteries use a part to keep things safe but Samsung was in a huge rush to beat the Apple iPhone 7 to the stores. This rush led to design choices that did not leave room for safety. It was not an engineering problem though. The fallout was huge. Samsung lost $6.2 billion and their stock price fell fast in a single day. The government even banned the Galaxy Note 7 on airplanes. A Korean editorial mentioned in the case said the damage, to trust was something money could not fix.

Looking at everything this case shows how rushing a product and poor communication can turn a small mistake into a total disaster. It is an example used to teach people about how to handle a crisis and keep products safe [21].

2.21.1 Relevance of the paper with our study

The Samsung Galaxy Note 7 battery failures illustrate the catastrophic consequences of inadequate passive thermal protection. The root cause stemmed from separator degradation triggered by manufacturing defects and insufficient safety margins in cell design which allowed internal short-circuiting and subsequent thermal runaway with no mechanism to arrest the reaction. Critically, the affected batteries contained no passive heat-absorbing or insulating barriers capable of moderating temperature rise or limiting cell-to-cell propagation. This absence of passive thermal safeguards enabled a single defective cell to initiate fires in consumer devices and forced emergency evacuations on commercial aircraft.

These incidents underscore a significant gap in contemporary battery design: while active thermal management systems (BMS, venting) address post-failure containment, few production batteries incorporate passive materials engineered to suppress or delay runaway at the cell level. This work proposes phase change materials (erythritol) and thermally resistant casing (vermiculite) as a materials-based solution to that gap absorbing the thermal spike that initiates runaway and impeding heat propagation between adjacent cells. Rather than responding to failure after it occurs, this approach seeks to moderate the physical conditions under which runaway begins.

2.22 The Victorian Big Battery facility fire in Geelong, Australia (July 2021) provides valuable insights into grid-scale lithium-ion storage failures. The 300MW/450MWh installation, comprising 212 Tesla Megapack units, experienced thermal runaway in one unit during commissioning when a coolant leak in the internal cooling system initiated arcing in the power electronics. However, the incident's significance extends beyond this immediate trigger.

The investigation revealed a cascade of contributing factors: a 24-hour delay in telemetry transmission to the monitoring system obscured early detection, and manual shutdown of the affected unit had disabled critical protective functions, including the pyrotechnic cell disconnect. Importantly, despite units being separated by only 15 cm, fire did not propagate through direct heat conduction. Instead, high wind speeds deflected the flame plume onto an adjacent unit's roof, breaching its pressure-relief vents and forcing hot gases directly into the enclosure. This finding challenges assumptions underlying current battery spacing standards (such as UL 9540A), which are validated under controlled

laboratory conditions but may underestimate real-world propagation risk when environmental factors like wind loading are present.

The emergency response employed a defend-in-place approach, allowing units to self-extinguish rather than applying direct suppression agents. Following the event, the manufacturer implemented firmware and hardware improvements including faster telemetry activation and enhanced venting design reflecting an iterative cycle between failure analysis and design refinement now common in grid-scale battery safety literature [22].

2.22.1 Relevance of the case study with our study

The VBB incident shows us, in effect, what happens when you have passive protection as the only guard and you stress it beyond its testing regime. For Tesla's Megapack, the steel panel insulation and its thermal mass was designed to limit unit-to-unit propagation, and for heat conduction between cells through a 15 cm space, it worked extremely well: MP-2 had only 1C temperature increase in its cells while the exterior burned. However, this passive protection suffered from a vulnerability unshielded vents which allowed flame and gases to bypass the insultation completely, thereby continuing the spread through convection.

This contrast for our paper should be relevant: our erythritol/vermiculite casing is also passive thermal protection, and the VBB incident might support both that:

(a) passive insulation principle can be effective in hindering heat transfer in a battery pack when tested under fire exposure conditions, while

(b) effective blocking depends on sealing the entire housing, since the thermal buffer can be bypassed by vents, gaps, or perforations as the problem demonstrated, an open vent becomes the preferential propagation path.

Perhaps we may refer to the case as a cautionary example for the need for complete housing encapsulation rather than side linings of your casing.

3.0 Research Gap

By doing the literature reviews we came to know that the scientific literature on lithium-ion battery (LIB) fire safety has expanded considerably over the past decade. Researchers have developed increasingly sophisticated understanding of how thermal runaway begins, spreads between cells, and can be suppressed. Battery management systems have become more advanced, thermal barriers have been refined, and fire suppression techniques continue to improve. Despite these advances, a careful review of the existing body of work reveals persistent and significant gaps that remain unaddressed.

3.1 Limitations of Conventional Passive Barriers

Most passive safety research has centred on materials like ceramic fibres, metallic plates, insulation boards, and structural modifications. These approaches work by introducing thermal mass or creating insulating layers that reduce the rate at which heat travels from one cell to another. Studies have shown that increasing the distance between cells or using thicker barriers does delay thermal propagation. However, these materials operate on a single principle: they slow down conductive heat transfer. They do not actually absorb the enormous quantities of thermal energy released when a battery cell undergoes thermal runaway. Consequently, while these conventional barriers extend the time before neighbouring cells ignite, they typically cannot prevent propagation entirely under realistic conditions and tested only under carefully controlled laboratory scenarios with limited variables. This represents a fundamental limitation: thermal resistance alone is insufficient when the energy being generated is both rapid and extreme.

3.2 The Problem with Active Suppression Systems

The literature overwhelmingly emphasizes active suppression technologies: water mist systems, foam agents, specialized chemical additives like F-500, liquid nitrogen injection, dry powders, and gaseous suppression agents. These technologies are sophisticated and often effective at extinguishing visible flames. Additionally, detection systems based on temperature monitoring, gas sensors, infrared cameras, acoustic monitoring, and other diagnostic methods can identify abnormal battery behaviour. However, active systems share a critical weakness. Numerous studies have confirmed that extinguishing flames does not eliminate the underlying problem: enormous amounts of heat remain stored

within the battery cells themselves. This residual heat inevitably causes reignition. Moreover, detection-based systems require that abnormal conditions be identified, processed, and acted upon within a very short time window. In high-performance electric vehicle battery packs, this warning period may be only a few seconds. By the time sensors detect a problem and a control system initiates response, the runaway reaction may already be irreversible. This dependency on rapid detection and external intervention creates a fundamental reliability challenge for sensor-based mitigation.

3.3 The Overlooked Opportunity: Passive Composites

A significant but largely unexplored opportunity exists in externally applied passive composite materials that respond automatically to temperature rise without requiring power, sensors, control systems, or human intervention. These materials could be integrated into existing battery designs without altering the chemistry of the cells themselves or requiring extensive manufacturing changes. Such an approach would represent a true passive safety layer: inherently reliable and maintenance-free.

3.4 Erythritol: Promise and Unresolved Questions

Erythritol is an organic phase change material (PCM) that has attracted considerable research attention for solar heating systems, waste heat recovery, and thermal energy storage applications. It possesses ideal properties: high latent heat capacity (approximately 340 J/g), a melting temperature near 118°C, chemical safety, and environmental friendliness. Its thermal conductivity can be enhanced, and its crystallization behaviour and long-term storage stability have been characterized under moderate operating temperatures.

However, a critical gap emerges when we consider battery thermal runaway conditions. Existing erythritol research examines the material under relatively stable, controlled heating typically below 160–200°C. Battery thermal runaway, by contrast, generates localized temperatures that may exceed several hundred degrees Celsius, with extremely rapid heating rates and intense, concentrated heat flux. Some studies document erythritol degradation, discoloration, oxidation, and loss of latent heat capacity when exposed to prolonged high temperatures. While antioxidants such as Irganox 1010 have been proposed to reduce degradation, no research has systematically tested whether antioxidant-treated erythritol maintains its heat-absorbing capability under actual battery fire conditions.

3.5 Vermiculite: An Untapped Resource

Vermiculite is a naturally occurring mineral with exceptional properties: excellent thermal insulation, inherent fire resistance, low density, chemical stability, and structural integrity even at elevated temperatures. Despite these advantages, the literature contains virtually no experimental work exploring vermiculite combined with a phase change material for battery fire mitigation. Such a composite could theoretically perform dual functions simultaneously: vermiculite reducing heat transfer while erythritol absorbs thermal energy through latent heat release. Yet this synergistic interaction remains unexplored.

3.6 The Comprehensive Testing Gap

Finally, existing research typically measures single performance parameters like propagation delay or peak temperature in isolation. There is limited information about comprehensive performance indicators such as maximum temperature reduction, thermal absorption efficiency, structural stability after repeated thermal exposure, degradation of latent heat capacity following fire events, and effectiveness across different battery charge states. Long-term reliability and practical applicability remain unclear.

This research directly addresses these unresolved challenges by developing and thoroughly evaluating an erythritol–vermiculite composite tailored specifically for lithium-ion battery thermal runaway mitigation.

4.0 Methodolgy

To deal with the problems of barriers and active systems mentioned in the review of the research this study suggests a new kind of material that works in two ways. This material is made for lithium-ion battery modules. It uses expanded particles mixed with a type of material that changes phase called erythritol. This mix combines the ability to absorb heat with the ability to form a structure around the battery.

4.1 Making the Composite Material

The material is made using erythritol as the main part. Erythritol is chosen because it can hold a lot of heat and has a melting point around 118 degrees Celsius. The raw vermiculite is added to the melted erythritol. This vermiculite is known for being very good at keeping heat out and staying strong at high temperatures (up to ~ 1000-1300 °C). The mixture is stirred carefully to make sure the particles are spread out evenly and do not sink to the bottom. Small amounts of things that help keep the material stable like Irganox 1010 are added to stop the material from breaking down or getting damaged when it is very hot like during a battery fire.

4.2 The Shape of the Block and How the Cover Forms

The shape of the composite block is made in the form of a thin cuboid that is placed on top of the batteries inside the battery casing. This shape makes sure that there is coverage and does not block the usual electrical connections or the cooling paths.

The way the material works happens in two steps when a battery starts to overheat:

Changing State and Taking in Heat: When the temperature goes up and reaches 118 degrees Celsius the erythritol part changes state. It takes in a lot of heat. This helps make the temperature increase slower. This helps to stop the heat from spreading between adjacent cells.

Making a Cover and Sealing: As the temperature keeps going up after the first stage the liquid erythritol helps hold the vermiculite together. When the temperature gets higher the material turns solid. Burns in place with the vermiculite. This makes a fireproof cover that completely surrounds the affected cell. This cover stops gases from moving and stops flames from spreading. It keeps the battery that is having a problem away from the others.

4.3 Testing the Material

To check how well this idea works we will need to create special testing setup. These setups will try to act like battery situations with heat and electricity problems. The results will be checked by looking at things like how much the temperature went down for nearby cells, how long it took for the heat to spread, how good the material was at taking in heat and how strong the cover was after it was tested. This way of testing will help us fill in the gaps from looking at one thing and giving a safe easy to use protection, for electric vehicle batteries.

5.0 Conclusion

This study presents an innovative approach to the passive thermal protection of lithium-ion cells by introducing an erythritol-vermiculite composite material. The proposed method takes advantage of the high latent heat of fusion of erythritol (~340 J/g) and the fire-resistant properties of vermiculite. The two-component composite was able to address both the shortcomings of the reactive battery thermal management systems commonly used and the limitations of traditional passive thermal protection in a form of a single insulation layer. The active function of the composite material is the absorption of heat from the hottest cells in the early stage of runaway (pre-decomposition phase).

Simultaneously, the particles of vermiculite resist the heat and help isolate faulty cells from the rest of the battery, preventing further runaway events and oxygen leakage. Passive thermal protection in the form of composite material could be an alternative to the active cooling systems used in current battery management systems which often fail to respond to the rapid temperature increase during the thermal runaway. The composite material is also beneficial compared to other protection techniques such as water mist system, which may cause short circuits and require additional safety mechanisms to avoid the risk of re-ignition. Overall, the two-component composite material could serve as a model for improved passive thermal protection of the battery packs in electric vehicles and increase the level of battery safety in other applications.

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