

Experimental Evaluation of Thermal Barrier Materials used in Battery Electric Vehicles

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Abstract

With stringent regulations enforced to cut down vehicular emissions, original equipment manufacturers (OEMs) are in a transition phase of electrifying their vehicle fleet and Li-ion battery (LiB)-based energy storage systems remain at the forefront of vehicle electrification, predominantly due to their higher energy densities compared to other energy storage alternatives. However, there is always a safety risk associated with LiBs. The existing LiB technologies are extremely sensitive to ambient temperatures and have inherently flammable liquid electrolyte. When used for vehicular applications they shall encounter several scenarios which can potentially lead to a Li-ion battery fire, an event commonly referred to as “thermal runaway”. Numerous safety measures (both active and passive) are generally adopted to ensure the safety of LiBs used in automobiles. Stringent regulatory targets such as the one mentioned in the ECE 324 R100 Rev 3 for the European market, or the GB 38031-2020 for the Chinese market, mean a resound passive fire safety mechanism needs to be deployed in Li-ion battery packs used in automobiles. In this paper, a system-level picture of passive fire mitigation strategies for Li-ion battery packs is presented. Different types of thermal barrier materials (TBMs) suitable for passive fire protection at pack, module and cell levels have been investigated. The performance of TBMs are evaluated experimentally using three different test procedures. The results reveal the most suitable type of TBMs for pack, module and cell-level passive fire protection of LiBs.

Keywords: Thermal barrier materials, Thermal runaway, Thermal propagation, Fireproof battery enclosures, Pan-fire test

1. Introduction

In an effort to tackle the global climate crisis and adverse effects of global warming, governments across the world began enforcing regulatory measures to cut down the carbon emissions from various industries. The transport industry in particular is undergoing a drastic transition due to the policy and regulatory changes enforced to limit the overall carbon footprint associated with this industry. The automotive industry in particular is steering away from fossil fuel-based internal combustion engines to electrified powertrains. This has resulted in a significant number of vehicles in the market being Hybrid electric vehicles (HEV), battery electric vehicles (BEV) and others such as fuel cell electric vehicles (FCEV). Li-ion battery (LiB) based energy storage systems in these vehicles (especially in HEVs and

BEVs) are extremely popular in the market today. Long cycle life, and high power densities make the LiBs an attractive option to be used as energy storage devices for transport applications [1]. However, LiBs have inherently flammable liquid electrolyte and if LiBs are operated beyond their normal operating conditions they are susceptible to a highly exothermic energy release process often referred to as thermal runaway (TR). Thermal hazards associated with Li-ion batteries are well documented in the literature. In general, there are three main categories of abuse scenarios which can trigger an event of TR as shown in Figure 1. Mechanical abuse is when LiBs are subjected to extreme levels of forces or stress which causes them to deform destructively. Such scenarios are highly probable in the event of a vehicle crash or collision where the HV battery can either get crushed or penetrated which can lead to TR. Thermal abuse scenarios occur when LiBs are operated outside the safe operating temperature limits prescribed by the cell manufacturer. The multi-stage mechanism of

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Abbreviations	
ATH	Alumina trihydrate
BEV	Battery electric vehicles
BMS	Battery management systems
CFRP	Carbon fibre reinforced polymer
DUT	Device under test
EMI	Electro magnetic interference
FCEV	Fuel cell electric vehicles
GFRP	Glass fibre reinforced polymer
HV	High voltage
ISC	Internal short circuit
LFP	Lithium iron phosphate
LiBs	Lithium-ion batteries
LPG	Liquified petroleum gas
NMC	Nickel manganese cobalt
OEMs	Original equipment manufacturers
PP/PE	Polypropylene/Polyethylene
PU	Poly urethane
REES	Regenerative electrical energy storage
SAP	Super absorbent polymers
SEI	Solid electrolyte interface
SMC	Sheet moulding compound
SOC	State of charge
SOH	State of health
TBMs	Thermal barrier materials
TC	Thermocouple
TP	Thermal propagation
TR	Thermal runaway

TR during thermal abuse is shown in Figure 2. During stage 1 when the temperature reaches 65 °C or more [2] the decomposition of the solid electrolyte interface (SEI) begins, and at temperatures over 90 °C exothermic nature of the SEI decomposition can be strongly observed. Due to the decomposition of SEI the exposed anode reacts with liquid electrolyte generating highly flammable organic gasses such as CH₄, C₂H₆ and non-flammable gases such as CO₂. As the temperature keeps rising during abuse conditions the cell goes into stage 2 of TR which is characterised by the melting of the polymer separator. This results in an internal short circuit (ISC) of the electrodes and a huge amount of heat is released along with the rise in cell temperature. As the temperature goes over 200 °C the transition metal cathode begins to decompose along with the flammable liquid electrolyte due to which there is an exponential rise in cell's temperature and the cell enters final stage of TR. Electrical abuse conditions occur when LiBs are operated outside the safe electrical limits as specified

by the cell manufacturer. Numerous active safety measures are introduced through the BMS of an HV battery pack to keep LiBs within their safe operating limits, however as mentioned earlier during the event of a vehicle crash, the likelihood of occurrence of the above mentioned abuse conditions are fairly high which can ultimately result in a LiB fire. Numerous papers are available in the existing literature which explores a variety of TBMs used for TR or TP mitigation. These are discussed in detail in Section 3. However the method of evaluating the effectiveness of barrier material will greatly depend upon numerous factors such as the form factor of the cells, cell chemistry and trigger mechanism of thermal runaway. Also, test setups play a crucial role in determining the effectiveness of TBMs. Z.Li et al. [3], have discussed in detail regarding the effect of enclosure affecting the thermal propagation time between the cells. Hence, in this paper the authors have aimed to address the methods associated with evaluating thermal barrier materials by referring to two legislative standards which are widely adopted inside the automotive industry. To begin with hazards and challenges posed by LiB fires are discussed in detail in Section 2. Section 3 gives an overview of existing legislative standards associated with passive fire protection of LiB-powered vehicles. These two sections give the necessary background on the characteristics of LiB TR and help in establishing boundary conditions for analysing potential thermal barrier materials (TBMs). Section 4 discusses in detail regarding different types of TBMs and explores the latest fire mitigation strategies deployed by different OEMs. This section highlights how factors like form factor of a cell and the intended area of application (i.e., pack, module or at cell level) affect the choice of TBM. Sections 5 and 6 dwell in detail on the experimental investigation carried out during this research in evaluating different types of TBMs suitable for pack, module and cell-level fire mitigation.

2. Characteristics of Thermal Runaway

Understanding the characteristics of TR is important in identifying the target material specifications of TBMs. TR of LiBs have two distinct features, one being the jet fire and the other being the hot particle ejecta. The jet fire is a high-velocity, high-temperature flame released during the final stage of TR. During the final stage of TR, the flammables inside the cell (as discussed in Section 1) get ignited owing to the high temperatures and sparks coming out of the cell in TR. G.Wang et al.[4] have revealed a four-stage mechanism behind particle ejection during LiB fires as shown in Figure 3. At

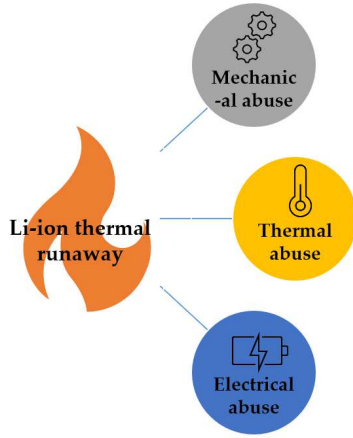


Fig. 1: Thermal runaway triggers

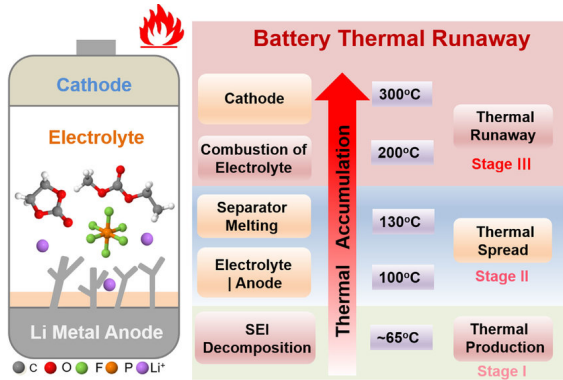


Fig. 2: Stages of thermal runaway [2]

Stage 1, the battery is in its initial state and TR has not begun. At Stage 2, due to the thermal degradation, there is a non-homogeneity in cell temperature and gas generation rates inside the cell. Consequently, due to the pressure difference between the layers of the jelly roll, the electrode materials begin to fracture [4]. This coupled with binder decomposition could lead to pulverization and inter-particle fracture [4]. Due to the pressure gradient inside the cell, the generated gasses are channeled towards the head space of the cell. These gasses drag the pulverized metal debris along with them and ejecta is thrown out of the cell. H.Chen et al.[5] have reported images (see Figure 4) captured using high-speed cam-

eras to reveal more insights about the jet fire and particle ejecta during TR of 21700 cylindrical cells with NMC cathode. From Figure 4, the sparks, hot metal particles and other cell derbies are observed to be ejected out of the cell during TR [5]. In this study, the maximum flame height was measured to be 35 cm with a peak heat release rate of 3.5 kW. The peak heat release rate during the jet fire could be very different for other form factors. Larger prismatic cells have been reported to have a peak heat release rate of 37 kW, 40 kW and even 65 kW [5]. The heat release rate will very much depend on the SOC of the cell, cell chemistry and the form factor. Generally, small cylindrical cells have small capacities and hence smaller heat release rates. The flame temperatures also vary according to the above-mentioned factors with general peak temperature over 800 °C being widely reported with instances of peak temperatures over 1200 °C can also be found. The high-temperature jet fire along with the hot particle ejecta poses a significant risk of thermal propagation inside the battery which might lead to a devastating scenario. Hence it is highly important to keep these key characteristics of TR in mind while formulating passive fire protection strategies to reduce or contain an event of TR and prevent/delay cascading thermal propagation inside an HV battery pack.

3. Legislative Standards

With regards to passive fire protection of LiB used in road vehicles, two regulatory standards are of primary focus in this paper. The first is the fire resistance test mentioned in annexe 9E of the European regulation ECE 324 UN R100 Rev 3 [6], often called the pan-fire test. Pan-fire test mentioned in the European regulation aims to ensure safety when LiBs are subjected to external fires resulting from fuel spills of vehicles involved in a crash or collision. The tests involve subjecting a vehicle or battery pack to a fire coming from a gasoline-filled pan in a controlled environment for a fixed duration. In the latest revision of the regulatory standard, an LPG-powered fire is also included as a substitute for the gasoline pan-fire. The LPG burns more cleanly compared to gasoline and produces more repeatable test conditions [7]. The average flame temperatures are between 750-850 °C for gasoline fires while LPG fires have higher average flame temperatures between 850-1000 °C [8]. There shouldn't be any explosions or projectiles coming out of the battery pack for the duration of the test for a pass. The 5-minute window time mentioned in the Chinese GB 38031-2020 standard is often used to test a pack against thermal propagation. The

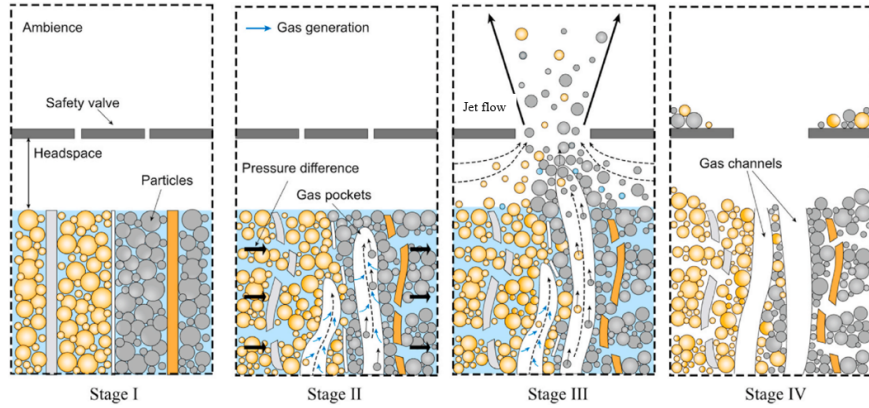


Fig. 3: Mechanism behind hot particle ejecta during TR [4]

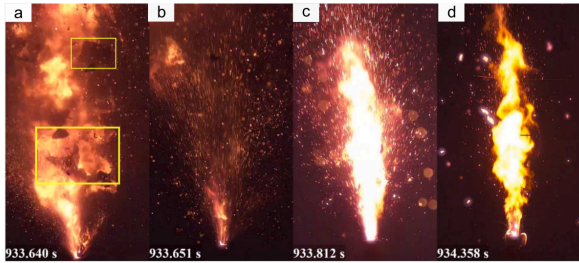


Fig. 4: a) Cell debris being ejected out b) Sparks of hot metal particles c) Sparks with jet flame d) Subsiding of sparks and steady flame evolution [5]

standard talks about a five-minute window time after an occurrence of a thermal event inside a battery pack. Between a successfully triggered TR and when the flame is observed outside the pack, a guaranteed period of 5 minutes is required to pass the test [9]. Based on the regulatory targets fire mitigation strategies can be deployed at pack, module or at cell level as discussed in the following sections.

4. Thermal Barrier Materials

Different classes of TBMs used in LiB packs are shown in Figure 5. Different classes of TBMs will be suitable for different levels (pack, module or cell) of fire protection. In this paper, a modular battery architecture (see Figure 5) is considered for the structure of a battery pack, as modular battery architecture is widely adopted by several OEMs. The basic battery enclosure consists of a top cover, structural cross members, cell modules, side impact members and a battery tray. The top cover becomes crucial for occupant protection from LiB fires,

while the cross members are crucial for delaying thermal propagation between modules. While the battery tray with the bottom cover becomes crucial for protection against external fires.

4.1. Intumescent Coatings

Intumescent coatings are among the lightest forms of fire protection materials. Intumescent coatings are widely used in the building industry to protect structural steel in an event of a fire. Intumescent materials expand in thickness when exposed to high temperatures producing a highly insulating layer of carbonaceous char. The char layer is stable at high temperatures and prevents further heat flow through the material, thereby protecting the material behind it. The formation of the char layer is often referred to as the foaming of intumescent material. The foaming process is highly endothermic and the chemical reactions generally begin over a temperature of 180 °C. Due to the chemical reactions gasses like CO₂, NH₃ and H₂O are formed which results in foaming of the coating. Several concepts, binder systems and additives are used for intumescent paints. Ammonium polyphosphate, pentaerythritol, melamine and titanium dioxide are the common raw materials used in intumescent paints [10]. While it is common to have high foaming intumescent coatings (up to 80-100 times the original thickness) in the construction industry, due to the constraints of space and packaging such high foaming intumescent can't be used for automotive applications. Generally, intumescent materials for automotive applications have a foaming rate anywhere between 3-15 times the original coating thickness. For instance, 1 mm thick intumescent coating can expand up to 15 mm in thickness during the char formation (if the

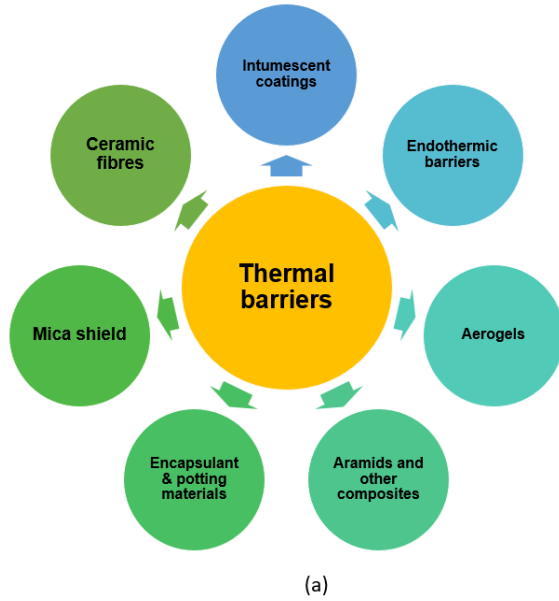
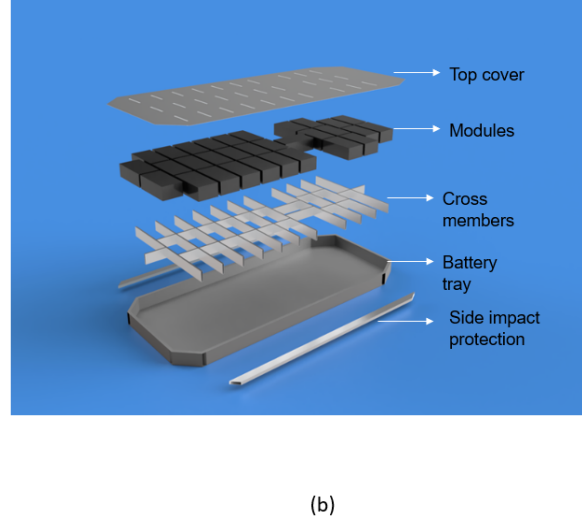


Fig. 5: (a) Different types of TBMs, (b) Structure of a modular battery pack

foaming rate is 15). The higher the thickness of the char layer, the better are the insulating properties.

4.2. Mica and Ceramic composites

Micas are a group of silicate minerals that are mined out for use in several high-temperature applications. Mica shields are common in furnaces and glass windows of boilers due to their excellent high-temperature stability and low thermal conductivity. Rigid mica shields have excellent heat resistance even at temperatures over 1000 °C. Mica also offers excellent blast protection making it suitable for dealing with particle ejecta during TR. The high dielectric strength of mica makes it suitable for use inside the HV battery pack. However, mica is a highly dense material with typical values around 2100 kg m⁻³. Rigid mica shields are easier to integrate during the manufacturing process and are often placed between the battery pack and top cover offering enhanced occupant protection. Some models of Tesla and Lucid have mica shields (see Figure 6)[11] between the pack and top cover for mitigating the fire hazards of LiBs. To reduce weight thin layers of mica lamination are used on ceramic fibre matrix to form sandwich composites. Most common products in the present market adopt a sandwich structure, where core of the composite material is made up of highly insulating ceramic fibres which offer low thermal conductivity and lightweightness, while the surface layers are laminated with thin

mica sheets. The sandwich structure offers high thermal insulation at minimal thickness and weight when compared to rigid mica shields. This is mainly due to the superior mechanical and thermal properties of the ceramic fibre core. Figure 6 shows GM Hummer's battery module [11] where a thin layer of mica is used above the cell vents possibly to reduce the effects of particle ejecta during TR.

4.3. Encapsulants and Potting Materials

Encapsulating foams are mostly based on polyurethane (PU) or silicone foams. These materials offer low thermal conductivity and have very low density. Encapsulating foams are usually injected to fill the voids inside the battery pack and act as an insulating media between adjacent cells. This type of fire protection can be suitable for delaying thermal propagation between the cells. Potting materials follow the same principle as encapsulants while they are primarily based on insulating resins. Encapsulants are common among cylindrical cell-based battery packs. This is because the packing factor for cylindrical cells is generally less than that of pouch or prismatic cells, as they tend to form voids between them. However, PU foams themselves don't have high-temperature stability and they might disintegrate over 300 °C. As discussed in Section 1, during TR temperatures of the cell can go much higher than 300 °C. PU foams with flame re-

tardant additives seem to have better high-temperature resistance [12]. However, very high temperatures are often observed for prismatic and pouch cells with high levels of heat release due to their higher cell capacities. The low energy release of cylindrical cells coupled with highly insulating encapsulating foams can be effective in delaying cell-to-cell thermal propagation. Figure 6 shows the encapsulated battery packs of two OEMs.

4.4. Endothermic Barriers

Endothermic barriers are the ones which can absorb heat energy. Endothermic barriers are usually studied for cell-level protection of packs comprising of prismatic or pouch cells. These barrier materials are usually filled with some energy-absorbing materials which when subjected to high temperatures will absorb the heat energy from the cell undergoing TR. Hydrated mineral fillers are often used as energy-absorbing fillers. One of the most common hydrated mineral fillers is alumina trihydrate (ATH), where each molecule of ATH contains 3 molecules of water. Endothermic fillers are combined with highly insulating materials to reduce heat flow. Becher et al.[13] have investigated a composite thermal barrier made up of aramid fibres in a phenolic resin matrix filled with dehydrated super-absorbent polymers (SAP). Here the filler absorbs water/moisture and when the temperature of the cell increases the heat energy is absorbed as specific heat and latent heat of vaporisation of water. The composite material having a honeycomb structure offers enough stiffness to deal with the expansion forces of the cell. The endothermic barrier was tested against delaying TP using NMC 811 prismatic cells and it was observed that with a 1.9mm TBM thickness, the cell-cell propagation was delayed well over the 5-minute window time as specified in GB38031-2020. B. Bausch et al.[14] have developed a cost-effective bio-degradable endothermic barrier for delaying TP between the cells. Here a hydrogel-based endothermic filler was used. The developed material is both flexible and compressible with a compressibility of 1MPa for 10% compression making it suitable for dealing with high compressive forces due to cell expansion in an event of TR.

4.5. Aerogels

Aerogels are the lightest form of TBMs. These are extremely porous solid materials which have the lowest thermal conductivity of all materials (as low as 0.01 W/mK) [15]. Aerogels are mesoporous (pores of 2-50 nm in diameter) in nature and exhibit 90-99.8% porosity [16]. Silica aerogels are commonly used as TBMs

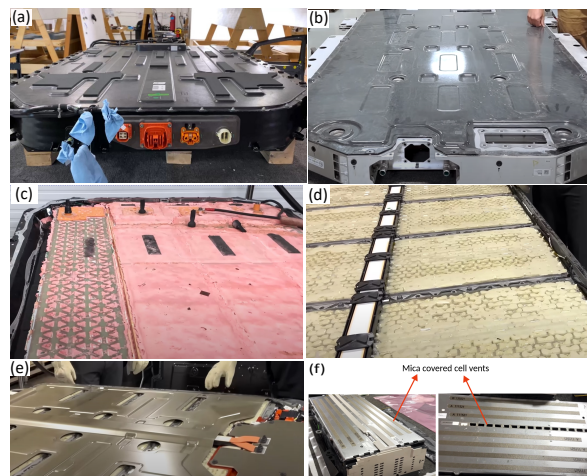


Fig. 6: a) SMC top cover- Ford Mustang Mach E b) SMC bottom cover- Hyundai Ioniq 5 c) Pink PU foam encapsulant - 2022 Tesla Model Y d) White encapsulant- Rivian R1T e) Rigid Mica shield- Lucid Air f) Mica covered cell vents- GM Hummer EV [11]

between the cells in an HV battery pack. Generally, silica aerogel (which is brittle but super-insulating) is combined with flexible fibres to have the best of both worlds and help in manufacturing. Aerogels are delicate and dusty materials which need to be contained or laminated. Recently, GM Motors have announced the use of aerogel-based cell barriers for their newly launched all-electric Ultium platform [17]. H. Yu et al.[18] have developed a sandwich composite with aerogel sandwiched between copper sheets, where the copper sheets with their high melting points are good for shielding against radiative heat transfer while the aerogel acts as an insulator reducing the heat flow between the cells. However, due to the high voltage inside the battery pack exposed copper can pose a significant risk of arcing. Although aerogels offer excellent insulating properties cost and manufacturing difficulties associated with them are some key limitations of the material in wider adoption.

4.6. Composite Battery Enclosures

Polymer composite materials are gaining popularity as the material of choice for EV battery enclosures due to their superior fire resistance capabilities and lightweightness. Glass fibre polymer composite materials are widely studied and have made their way into composite battery enclosures. Generally, composites are made up of four important components,

- **Fibre:** Fibres are mainly used for giving strength and low thermal conductivity to the material. Glass

fibre composites are widely used mainly due to their high-temperature stability and low thermal conductivity. Moreover, glass fibres are much cheaper when compared with the likes of carbon fibre. Non-woven SMC (sheet moulding compound) is a viable option for mass-scale manufacturing and is being extensively used in battery enclosures.

- **Resins:** Apart from binding fibres some resins offer flame retardancy to the composite material. Especially, phenolic resins offer excellent flame retardant properties [19] and phenolic SMC-based battery enclosure materials can be found in the market. However, other organic resins can burn to produce toxic fumes rich in gasses like carbon monoxide.
- **Fillers:** One of the simplest and easiest approaches to enhance the fire retardancy of composites is by adding inorganic fillers in the resin system. Materials like calcium carbonate and even sand can be used as inorganic fillers, basically inorganic fillers displace resins and fibres meaning there is less combustible to burn [20]. However, adding fillers might have implications for the structural properties of the composites.
- **Opacifiers:** Opacifiers are often added to increase the resistance towards radiation heat transfer.

Current generation battery packs tend towards adopting a hybrid battery enclosure design. Here the battery tray is often made up of aluminium while the top and/or bottom covers are made up of SMC. Hyundai Ioniq 5 has an SMC underbody cover for protection against external fire (see Figure 6) while the Rivian R1T uses a CFRP bottom cover [11]. Ford Mustang Mach E, Ford Lightning and Lucid Air's battery pack contain an SMC top cover for enhanced occupant protection. While cross members in the 2022 Tesla Model Y were made up of a phenolic SMC [11]. Other major limitations of polymer composites are their poor electromagnetic interference (EMI) shielding properties. All the electrical components need to be protected from external electromagnetic noise and metals offer inherent EMI shielding. Composite materials are usually added with conductive fillers (based on carbon) to enhance their EMI shielding properties.

5. Experimental Evaluation of TBMs

Having briefly discussed different types of TBMs, in this section performance of the TBMs is experimentally

evaluated using three different test cases, for evaluating materials suitable for pack, module and cell-level thermal protection.

5.1. The Pan-Fire Simulation Test

5.1.1. Test Setup

For evaluating TBMs suitable for pack-level protection from external fires such as the one mentioned in Section 3, a pan-fire simulation test was performed. The test set-up comprises of 1.2 m×1.2 m×1.2 m furnace powered by propane burners. Figure 7 shows the front view of the furnace which has four windows to allow mounting of flat, horizontal or vertical test specimens. The test substrates can either be a single piece with a maximum dimension of 1m×1m or four smaller pieces with dimensions 350 mm×350 mm. However, the heat exposure is only across 300×300 mm as 50 mm on all the sides of the test substrate is taken up by the fixture which is used to hold the test substrate. The hot faces of the test substrates are covered with TBMs and the cold faces of the test substrates are covered with a 25 mm thick mineral wool insulation which is backed by a 5 mm thick steel plate. This is done to minimise heat loss on the cold face. If the cold face is not insulated, the thermocouples can't accurately measure the failure temperature of the test substrate due to heat losses. One (1.5 mm diameter) mineral-insulated K-type thermocouple and one copper disc K-type thermocouple (12 mm diameter) are placed 15 mm apart and installed at the centre of substrate's cold face as shown in Figure 8. The reason for using two cold-face thermocouples of different types is to avoid loss of temperature data due to the destruction of thermocouples themselves due to exposure to sustained high temperatures. Due to the destructive nature of the test, it is important to capture the data right in the first attempt. Five K-type 3 mm (diameter) mineral-insulated control thermocouples are placed to control the gas temperatures of the furnace. The thermocouples are set 170 mm in front of the hot faces of the test substrate. The thermocouples are placed inside the furnace using a 10 mm (diameter) steel pipe. The positions of the control thermocouples and the burners are illustrated in Figure 7. The total duration of the test is 13 min which includes a 3-minute warm-up time allowing the average temperature of the furnace to be above 850 °C, a criteria mentioned in UN R100 regulation.

5.1.2. Material Selection

Table 1 shows the list of selected materials for the pan-fire simulation test. Material A and B are intumescent coatings from two different manufacturers which

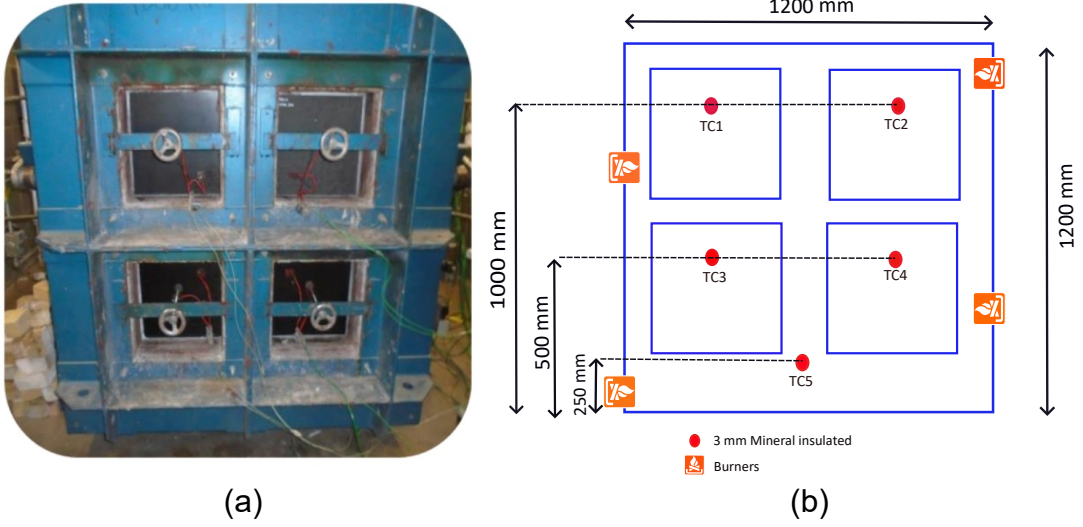


Fig. 7: (a) Front view of the furnace, (b) Position of control thermocouples and burners

Table 1: List of selected materials for the pan-fire simulation test

Materials	Type	Substrate
A	High foaming intumescent	Aluminium
B	Low foaming intumescent	Aluminium
C	Mica-ceramic fibre composite	Aluminium
D	Intumescent mat	GFRP

Table 2: Properties of TBMs

Material	Thermal conductivity (W/mK)	Density (kg m ⁻³)	Thickness (mm)
Material A	0.2-0.4	1250	1
Material B	0.2	1450	1
Material C	0.11	250	2
Material D	0.2	1100-1200	1.5

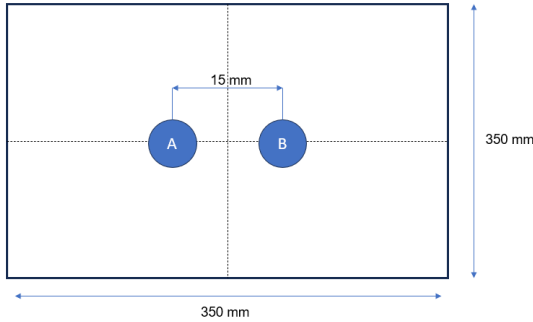


Fig. 8: Position of thermocouples on cold face of the substrate

are coated on 1.5 mm thick NS4 (Aluminium 5251) grade aluminium. Both the coatings have same dry film thickness and differ by the time required for curing. This grade and thickness of aluminium is common in battery enclosure design and hence it was used in this study. Material C is a 2 mm thick mica lam-

inated ceramic fibre composite bonded onto an aluminium substrate using structural adhesives. Material D is a 1 mm thick intumescent mat bonded to continuous glass fibre-epoxy composite (52 vol% of glass fibre) which was manufactured using vacuum-assisted resin infusion. GFRP is gaining momentum as a material of choice for battery enclosures as discussed earlier and hence considered for this study. The non-woven intumescent mat can also be integrated into the composite layup process and can become an integral part of the structure. Material properties of the above four materials are given in Table 2 and the values are obtained from the manufacturer's datasheet. The pre-test specimens are shown in Figure 9.

5.2. The Live Cell Test

5.2.1. Test Setup

For evaluating the performance of the materials which are suitable to be used between battery modules as a cover for cross-members of a battery pack the TBM must withstand the jet fire and hot particle ejecta. The

important criterion here is to prevent the burn-through of cross-members which are usually aluminium extrusions. For testing the TBMs suitable for delaying inter-module propagation, battery abuse testing was carried out where the test substrate was placed in the path of vent ejecta. For this study, fully charged cells whose parameters are described in Table 3 are used. The prismatic form factor was chosen over cylindrical or pouch cells. This is because pouch cells don't have a defined safety vent for the discharge of the cell ejecta during TR and this can result in the discharge of cell ejecta in arbitrary directions. Using 18650 cylindrical cells for

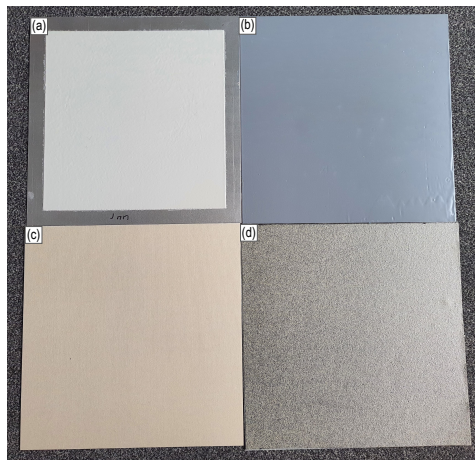


Fig. 9: Pre-Test: (a) High foaming intumescent; (b) low foaming intumescent; (c) mica-ceramic composite; (d) intumescent mat on GFRP

screening TBMs suitable for battery enclosures is proposed [21] and is available as the UL 2596 "Test Method for Thermal and Mechanical Performance of Battery Enclosure Materials". However, the use of 18650 cells in UL 2596 won't be an accurate representation of energy released during a TR of high-energy cells which are often used in BEVs by many OEMs. For abuse testing nail penetration is chosen as the trigger method. This triggering method is often criticised in the literature for lacking the repeatability aspect of the test, however, Becher D et al. [13] have observed that the nail penetration trigger is more appropriate as no additional energy is introduced into the cell and reduces the number of variables in the test. Also, ensuring a consistent mass loss ratio before and after the TR of the cell helps to assert the repeatability of the test conditions [13]. The test setup is shown in Figure 10. A pneumatic ram shall be utilised to trigger the prismatic cell into TR by penetrating the nail through the underside of the cell. The cell is securely held between two fixtures inside a steel casing and the casing itself is bolted to a fixture which is held

above the pneumatic ram assembly. The whole test rig (cell with its casing + the pneumatic ram assembly) is rigidly held in place by two supporting rocks as shown in Figure 10. A 4 mm steel nail is used for puncturing the cell and the feed rate of the nails is set as per SAE J2464-2021 [22]. The test substrate has dimensions of 600×800 mm. Two glass fibre thermocouples one on the hot face and the other on the cold face of the test substrates were used. The hot face thermocouple is placed

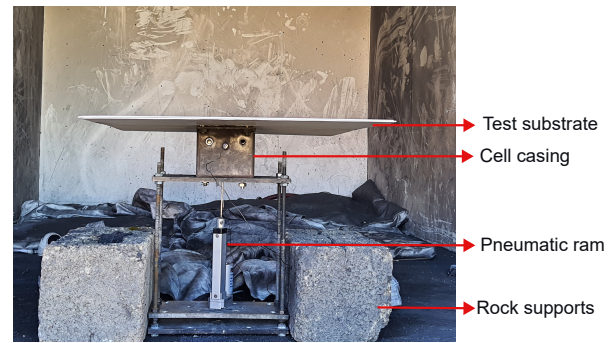


Fig. 10: Test setup

over the cell vent and is bent upwards towards the test substrate to touch the surface. The cold face thermocouple is stuck on the back face of the test substrate directly above the cell vent. Such a large test substrate is used to prevent flames from whipping around the test substrate thereby influencing the readings of cold face thermocouples. The test substrate is bolted to the cell casing so that it remains intact during TR. Apart from the thermocouple data which is logged every second, the tests are captured with three cameras showing the front, top and side views of the test assembly. After TR, a minimum cool-down period of 1 hour is observed before dismantling the test setup.

Table 3: Specification of used battery cell

Properties	Specifications from data sheet
Operating voltage	2.8-4.2 V
Cell capacity	86 Ah
Weight	1383 g
Form factor	Prismatic
Cathode	NMC 811
Anode	Graphite
Safety mechanism	Cell vent
Manufacturer	SVOLT

5.2.2. Material Selection

One out of the four test substrates is a 600×800 mm GFRP panel, and the other test substrates are 5251 (NS4 grade) aluminium plates with 800×600×1.5 mm as their dimensions. The GFRP panel was covered with material D (intumescent mat). Material C (mica laminated ceramic sandwich) is bonded to the aluminium substrate using flame retardant adhesives. Material E is an ablative material, which is carried on a fibre matrix. Ablative materials don't char like intumescent materials, they work by gradually eroding or vaporizing, creating a layer of gas that insulates and deflects the heat away. Ablative materials are widely used in the space industry for the thermal protection of spacecraft during atmospheric re-entry. The material is flexible as it is a fabric and hence will be suitable for use inside complex battery enclosures. Material F is made up of thin sheets of mica impregnated with silicone resin and reinforced with glass cloth. The material is similar in properties to that of material C.

5.3. The Hot Plate Test

5.3.1. Test Setup

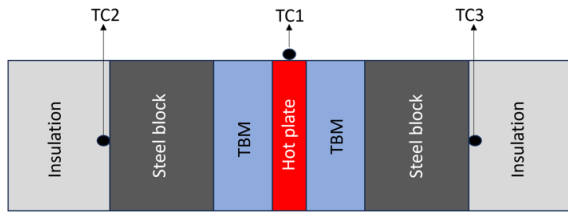


Fig. 11: Hot plate test set-up

The previous sections dealt with tests screening TBMs suitable for pack and module-level protection. This section deals with the material screening test for evaluating cell-level thermal barriers (between cells). The test discussed in this section is generally suitable for evaluating barriers for pouch and prismatic cells only. The test involves dropping a hot plate which is at a temperature of 850 °C between two TBMs. The TBMs are sandwiched between two steel blocks whose size is calibrated to represent the thermal mass of 115 Ah NMC prismatic cells. The setup emulates a scenario where the centre cell (represented by the hot plate) goes into TR to study the insulating properties of TBM in reducing the heat transfer between adjacent cells (represented by steel blocks). Figure 11 shows the experimental setup. K-type thermocouples are attached to the hot plate and thermocouples are installed on opposite faces of steel blocks to monitor the steel block's temperature.

The dimensions of the TBMs are 210 mm×80 mm×2 mm.

5.3.2. Material Selection

Materials are chosen using a weighted decision matrix. As majorly discussed in Section 4.5, aerogels are a popular choice for cell-level barriers. Thickness, thermal conductivity, compressive strength and manufacture-ability were highly ranked parameters in the decision matrix. The compressive strength of cell-level barriers is important as the material needs to deal with the compressive forces from the cell during its lifetime. Pouch cells have compressible foams between them to accommodate cell expansion and contraction during the lifetime of the cell. Endothermic barriers as discussed in Section 4.4 are offered by several manufacturers for cell-level barriers. For this test, one aerogel material and two endothermic barriers are chosen.

6. Results

6.1. The Pan-Fire Simulation Test

The gas furnace is heated as per the UL 1709 hydrocarbon heat curve. Figure 12(a) shows the gas temperatures recorded by the control thermocouples. As it can be observed from the figure, the thermocouples which are in front of the test substrates (TC1 to TC4) exhibit a similar behaviour. At the 2-min node, the four thermocouples read 731 °C, 774 °C, 826 °C and 806 °C (TC1-TC4 respectively). At 3-min node the readings are 876 °C, 925 °C, 935 °C and 900 °C for thermocouples TC1 to TC4 respectively. This shows by the start of the test all the test specimens are exposed to gas temperatures well over the 850 °C mark as mentioned in the ECE 324 UN R100 legislation. Initial fluctuations in TC1's temperature could be possibly due to the turbulence in the flame coming from the burner adjacent to it. With time a steady state is reached and hence TC4's reading stabilises. Due to the position of thermocouple TC5, which is at the bottom middle portion of the furnace, this thermocouple reads consistently lower gas temperatures compared to other control thermocouples.

6.1.1. Material A

Figure 12(b) shows the cold face temperatures of the test substrate covered with material A which was measured using the disc and probe thermocouples. As it can be seen from the figure the cold face temperature rises steadily with time. For the first one minute, the disc thermocouple reads slightly higher values than the probe thermocouple but this trend is reversed after the

Table 4: Material list for live-cell tests

Materials	Material type	Test substrate
Material C	Mica ceramic fiber composite	Aluminium
Material D	Intumescent mat	GFRP
Material E	Ablative material in fiber carrier	Aluminium
Material F	Mica impregnated with silicone resin with glass cloth reinforcement	Aluminium

first minute. At the 3-min node, both thermocouples read temperatures in the range of 270-300 °C. The heat-withstanding ability of the materials is judged from this moment onwards as the warm-up duration of the furnace is achieved. At the 6-min node, the thermocouples read a value of 358 °C and 380 °C (disc and probe respectively). At the end of 7 min (node 8) into the test both the thermocouples read temperatures less than 450 °C. The 500 °C mark is breached only after 10 min into the test and the 600 °C mark is breached by the probe thermocouple, possibly due to a localised hot spot in the test substrate after 12 min into the test. In this instance, the furnace's average temperature is well over 1000 °C.

6.1.2. Material B

Material B has the highest average cold face temperature of all samples within the warm-up duration. As seen from Figure 12(c) there is a huge difference between the temperatures logged by disc and probe thermocouples for material B. At the 3-min node, the probe-type thermocouple for material B reads 644 °C while the disc thermocouple reads a value of 394 °C. The reason for such a difference could be a localised hot spot at the position of the probe thermocouple where there might be a burn-through of the aluminium substrate. This observation is consistent as the probe thermocouple begins to read values resembling the furnace temperature after 3 min into the test. Note the probe and disc thermocouples are 15 mm apart. As the hole becomes bigger due to the continuous melting of aluminium, the disc thermocouple begins to read values resembling the furnace temperature. After 1-min node, the disc thermocouple also shows a drastic increase in temperature but this rate of rise in temperature happens with a time delay. This time delay might be the time taken by the metal to melt near the position disc thermocouple. From the data, it can be concluded that a localised hot spot was first formed at the position of the probe thermocouple and then the melting of metal slowly propagated towards the position where the disc thermocouple was installed. Hence there rise in temperature of the disc thermocouple happens after a time delay concerning the behaviour

of the probe thermocouple. At 4-min both thermocouples go over 600 °C, indicating burn through of test substrate.

6.1.3. Material C

Figure 12(d) shows the cold face temperatures of the test substrate covered with material C. The thermocouple readings rise steadily for the initial two minutes. Between nodes 2.4 to 2.6, the temperature curve of the disc-type thermocouple was seen to flatten for a bit and begin to rise again. At the 3-min node, the probe thermocouple reads a value of 380 °C and the 600 °C mark was breached by the probe thermocouple around 5 min into the test. The disc thermocouple didn't cross the 600 °C mark even after 8 min into the test. At 8 min into the test there difference between the readings of the probe and disc thermocouples was about 100 °C. The reason for such a huge difference in temperatures recorded by the two thermocouples would indicate the failure of the material due to localised hotspots, this means the thermocouples will not be in their intended position and hence high differences in the temperature values are observed. Not all the thermocouples survived the test and hence some values are missing for disc-type thermocouples.

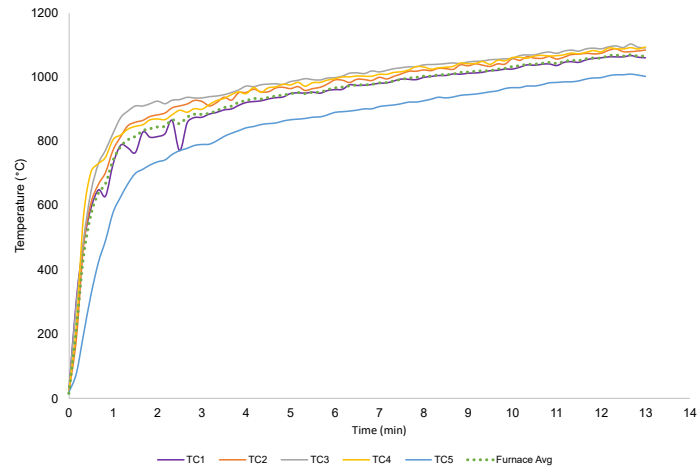
6.1.4. Material D

Figure 12(e) shows the cold face temperatures of material D. During the first three minutes there is a gradual rise in temperature values recorded by both thermocouples. At minute three the cold face temperature is around 200 °C and the difference in values measured by thermocouples is about 20 °C. This difference increases gradually with time, indicating the position of the failure point. At about 8 min into the test, the difference in measured temperatures by the two thermocouples was about 100 °C.

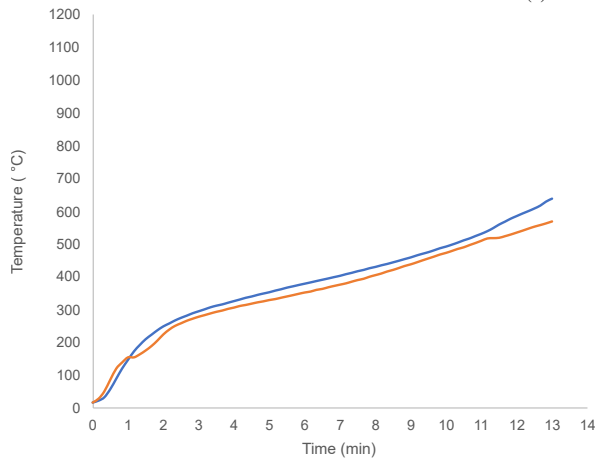
6.2. The Live-Cell Test

6.2.1. Material D

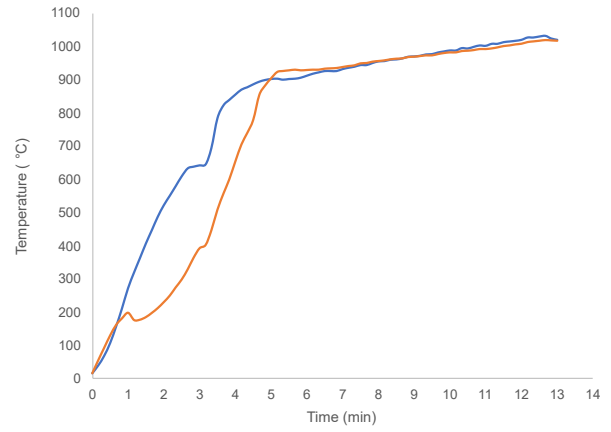
In the first case, material D which is at a distance of 15mm from the cell vent is subjected to cell ejecta.



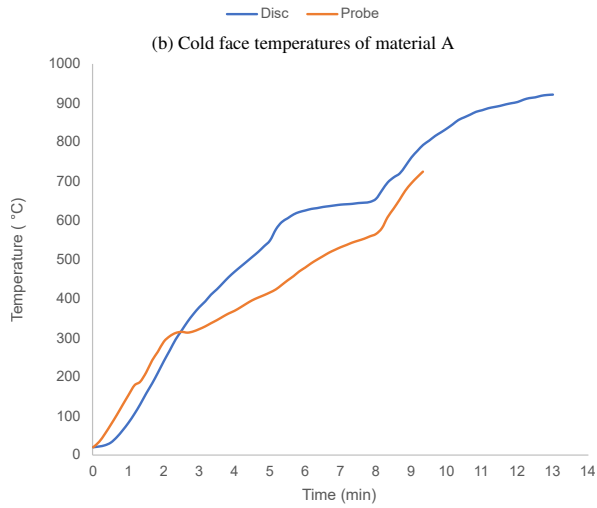
(a) Heat curve of the furnace



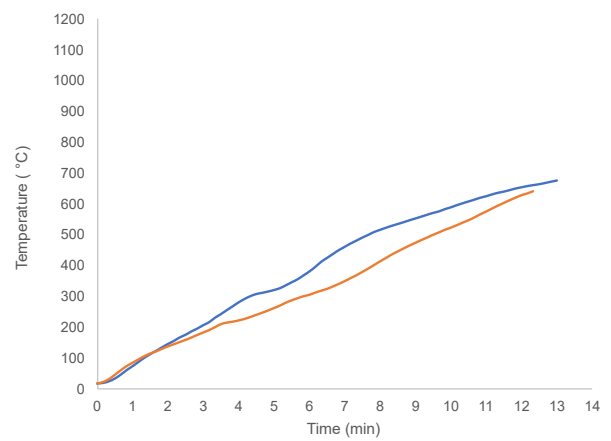
(b) Cold face temperatures of material A



(c) Cold face temperatures of material B



(d) Cold face temperatures of material C



(e) Cold face temperatures of material D

Fig. 12: Measured temperatures

This distance will be referred to as vent space. The vent space is chosen to represent typical distances inside a battery pack and is kept constant for all the experiments in this study. Figure 13 shows images of different stages

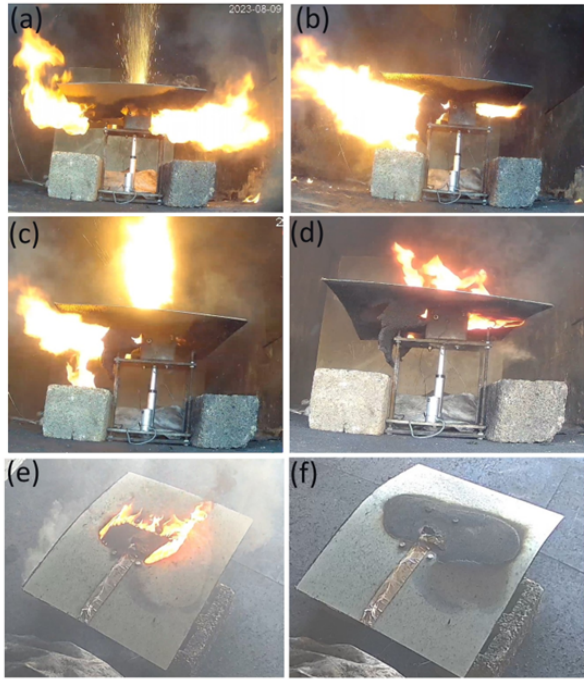


Fig. 13: Material D: a) Burn through due to hot particle ejecta b) Subsiding of sparks c) Evolution of jet flame through the substrate d) Subsiding jet fire and beginning of afterburn e) Afterburn of epoxy resin f) All the fire stopped and loss of material stiffness

of the test. Immediately after the observation of the first flame, the high-velocity particle ejecta accompanied by high-temperature jet fire seems to have burnt through the test substrate as the sparks can be observed on the top of the test substrate. The sparks continue for 7-10 s after which the jet flame can be seen at the top of the test substrate. About 30 s into the test, the jet fire subsides and a steady flame can be observed. This is referred to as the after burn as the TR is complete and it is the epoxy resin in the GFRP that begins to burn due to high temperatures. The resin continues to burn for a total duration of 5 min before all the flames are extinguished. This is followed by an hour of cool-down period before the test set-up was disassembled. At the end of 5 min into the test, the GFRP panel can be seen to sag down, this is because the panel has lost its stiffness as the resin was burnt away.

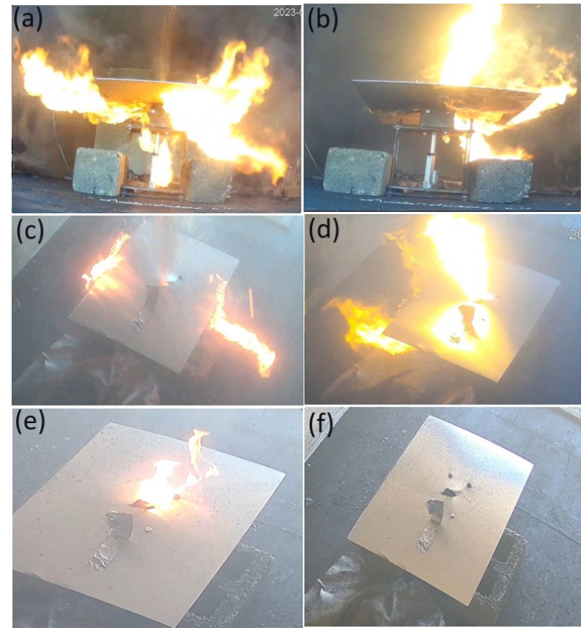


Fig. 14: Material C: a) Burn through due to hot particle ejecta b) Jet fire through the top c) Sparks through the top d) Dis-attached cold face thermocouple e) Afterburn f) End of test

6.2.2. Material C

Figure 14 shows the live cell test of material C which covers the aluminium substrate. The video footage reveals that there was a burn-through of the material as hot metal ejecta was observed from the cold face of the test substrate. This was observed for 3-6 s. This was followed by a jet flame which lasted for about 30 s after which it began to subside. The afterburn period was short compared to material D as material C has no flammable content. All flames were extinguished around 3.5 min into the test, after which an hour cool-down period began. The cold face thermocouple detached from the test substrate due to the burn-through of aluminium.

6.2.3. Material E

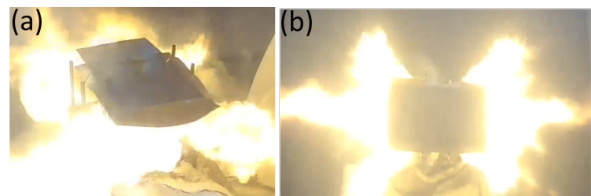


Fig. 15: Material E: a) Side view no flames or sparks through the top b) Top view of cold face

Material E (ablative material) was tested with identical test conditions and no burn-through of the aluminium test substrate was observed (see Figure 15). At the centre of the hot face, there is a black region observed and the material has expanded locally at the centre of the hot face. The cold-face aluminium shows no signs of thermal runaway and remains intact. The maximum cold face temperature was observed to be 247 °C which is perfectly fine for an aluminium substrate, while the maximum hot face temperature recorded was 1195 °C.

6.2.4. Material F

Figure 16 shows the various stages of the test for material F (mica laminated glass fibre composite). Material F had a much thicker layer of mica when compared to material C and hence for the first few seconds into the test, there was no burn-through of the test substrate. However eventually about 15 s into the TR, the sparks and flames can be observed on the top of the test substrate indicating a burn-through of the material. The maximum flame temperature recorded was 1054 °C.

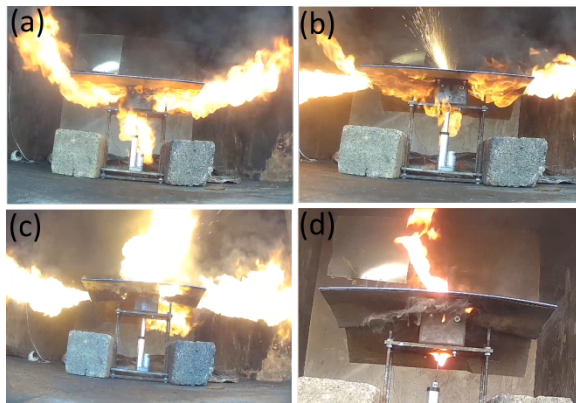


Fig. 16: Material F: a) No burn through for initial few seconds b) Burn trough of test substrate with sparks through top c) Jet fire through top d) Subsiding flames

6.3. The Hot Plate Test

Figure 17 shows the thermocouple data of the hot plate tests. The steel blocks for the two endothermic materials are initially at 6 °C while the aerogel material blocks are at 14.5 °C. The temperature begins to rise after dropping the hot plate in between the barriers for all three materials. At the end of 5 min, the steel blocks in the aerogel setup have an average temperature of 47 °C while both the setups with endothermic barriers have a temperature close to 60 °C. The setup with endothermic barriers has a higher temperature than the aerogel

setup until around 22 min after which the aerogel set-up has a higher temperature. None of the setups breached a 100 °C mark for the steel block temperature. The rate of cooling of the hot plate was observed to be higher for the endothermic barrier setups when compared to that of the aerogel setup. At the end of 35 min both the endothermic barriers reached temperatures close to the temperatures of the steel block while the aerogel setup's hot plate took longer to attain thermal equilibrium with steel blocks.

7. Discussions

7.1. The Pan-Fire Simulation Test

The maximum cold face temperatures of all the test samples are plotted against time to compare the performance of four TBMs as shown in Figure 18. As it can be seen materials A and D are exhibiting high insulating properties as they consistently record lower cold face temperatures. For the first 6 min of the test, material D records a lower temperature than material A, after which material A records significantly lower back face temperature. This is because as the GFRP panel goes over a temperature of 300 °C, the highly flammable epoxy resin begins to burn. Melting of aluminium begins around 8 min into the test for material C as there is a sharp rise in recorded temperatures and the readings tend towards the furnace temperature. Post-test specimens are shown in Figure 19. As expected material B has no aluminium left while for all the other material samples the TBM remains attached to the test substrate. The fragile intumescent char can be observed on materials A and D and due to the thicker char layer (about 15 mm for material A and 10 mm for material B) the heat flow across the test substrates was relatively low. The key reason for the poor performance of material B is the low char thickness. Based on the manufacturer's data the foaming rate of the material is 3-5 times the dry coating thickness which in this case was 1mm. Hence the char thickness won't be greater than 5 mm. That thin layer of char is just not insulating enough to prevent heat flow hence resulting in the melting of the test substrate. A dry coating thickness of 1mm was fixed for intumescent coatings because going for thicker coatings will have a substantial weight penalty. Material C (2 mm thick mica laminated sandwich composite) didn't have the insulating performance of the other insulating materials due to its fixed thickness. As the average furnace temperature is over 900 °C shortly after a few minutes into the test, a localised hot spot might have caused the ceramic composite material to break exposing the

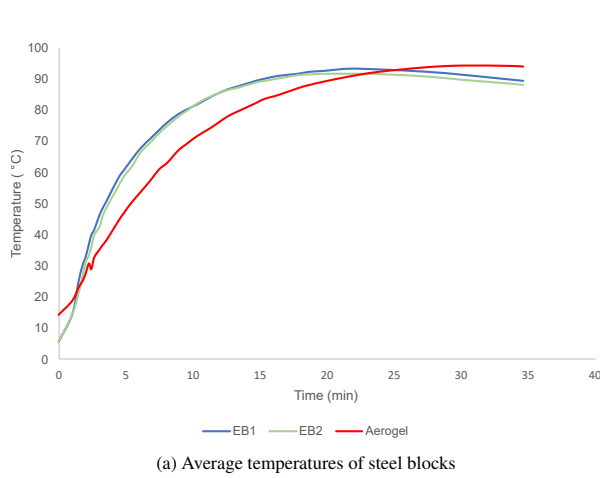
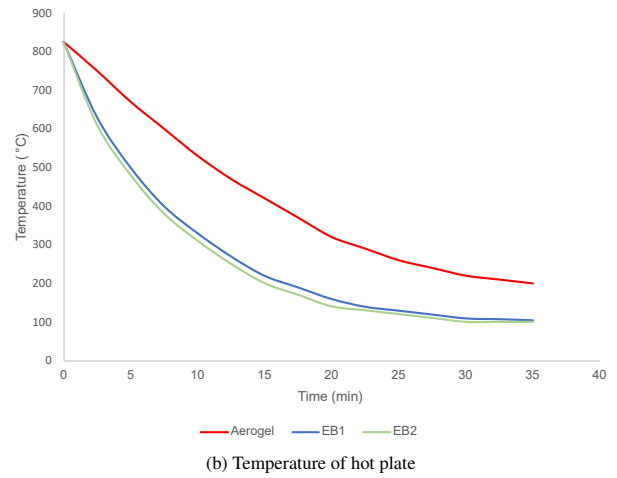


Fig. 17: Outcome of the hot plate test

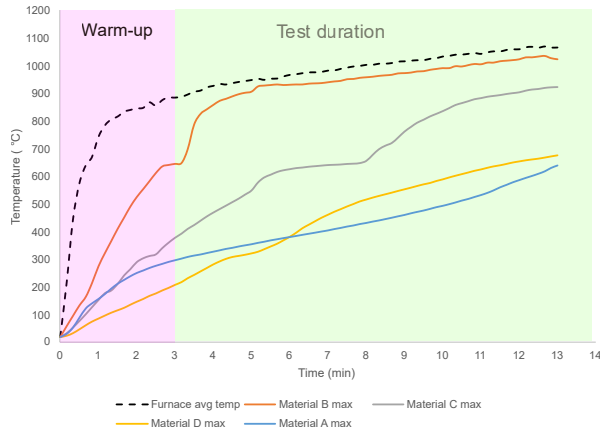


Fig. 19: Cold faces of a) Material A b) Material D c) Materials C d) Material B

aluminium substrate to high temperature. As it could be observed from Figure 19 the top mica lamination seems to be broken thereby exposing the ceramic fibres which might have lost their stability at those temperature levels. The material is rated for operations just below 1000 °C. In general, material C will be able to prevent the burn-through of aluminium for a duration of a little more than 5 min (including the warm-up time) and a little more than 3 min excluding the warm-up time of the furnace. Material C is substantially lighter (see Table 2) and hence the thickness of material can be increased to achieve better insulating performance. The summary of test results is presented in Table 5. For the GFRP the decomposition temperature of epoxy resin is used for

determining the pass criteria while for aluminium substrates temperatures over 600 °C are considered as failure. The warm-up time is not considered for defining the pass criteria. From the observations of temperatures recorded by the two different types of thermocouples (probe and disc), it can be concluded that when there is a substantial difference in values recorded by the two types of thermocouples the material was seen to perform poorly. A huge difference in values recorded by probe and disc thermocouple was observed in materials B, C and D, all of which failed to meet the pass criteria. Also, this can be visually seen from Figure 19. It is important to emphasise that the heat flux inside the gas furnace is less than what is observed in the actual LPG burner test. This is because in Annexe E of UN R100[6] the warm-up time is just 1 minute as opposed to the observed 3 minutes duration in the case of the furnace used in this test. However, at such high temperatures, it is the temperature gradient that majorly drives the heat transfer rather than the boundary conditions. Hence the degree of variability in the material's performance when subjected to heat fluxes similar to the actual test scenario should be small.

7.2. The live cell test

After the cool-down period, all the test substrates were removed and observed. Figure 20(b) shows the cold and hot faces of the test specimen protected with material C. Failure of material C is likely due to the layer of mica being too thin. The surface mica lamination along with the ceramic fibre core might be a very light solution but such a thin mica layer is too fragile and can't withstand the impact of hot metal particles at high velocities. Once the mica layer is gone the ceramic

Table 5: Summary of test results

Materials	Heat resistance (Including warm-up time)	Test result	Pass criteria	Comments
Material A	10 min to cross 600 °C	Pass	No burn through of substrate for minimum 5 min	High char thickness , after 10 min small hole is observed on aluminium substrate due to localised hot spot
Material B	2.5 min to cross 600 °C	Fail	No burn through of substrate for minimum 5 min	Low char thickness, test substrate completely melted at end of test
Material C	5.3 min to cross 600 °C	Fail	No burn through of substrate for minimum 5 min	Significant burn through of aluminium test substrate observed at end of the test
Material D	4.5 min to cross 300 °C	Fail	No burning of resin for 5 min	Residual strength of the composite is poor due to complete burning of resin

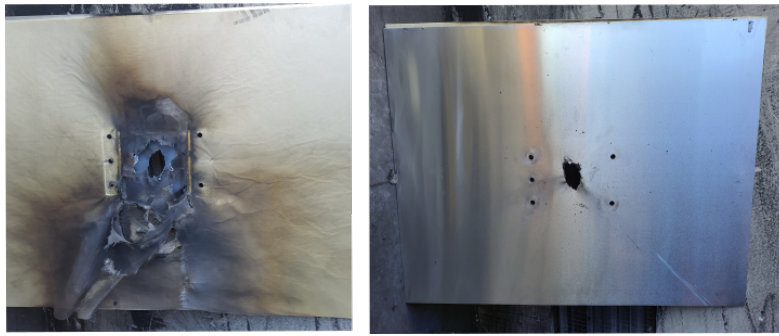
fibre which has a low thermal conductivity cannot withstand the high flame temperatures over 1100 °C. That has ultimately led to the burn-through of the aluminium substrate in no time. The post-test image of material D is shown in Figure 20(c). From the figure, it can be observed that at the centre of the hot face (near the vent) due to the extreme velocities of the jet fire and hot metal particles, the intumescent char layer was blown away exposing the GFRP panel. The flames propagated along one plane due to which there is a black char layer along that plane. Due to the bolts used for constraining, the substrate flames didn't propagate along that plane and hence we have white patches along that plane. At the cold face around the centre of the test substrate, the path of burnt epoxy resin could be observed. However, the edges of the panel are intact with the resin implying a highly concentrated flame and impact. Also, the char which wasn't directly in the line of cell ejecta remained intact and prevented the burning of the resin. The major reason for the failure of material D is the limitation of the intumescent material itself. Intumescent materials need time for charring, the discharge of heat during TR is too rapid for the intumescent material to react and form a protective char layer. Also, unlike the external fire scenario, the hot metal ejecta during the cell TR will destroy the char layer if there is any char formation. The intumescent char is extremely fragile and soft and doesn't stand a chance of dealing with the metal ejecta and jet fire. Also, space inside a battery pack is very

limited and there might not be enough space for the intumescent layer to expand. Hence, intumescent materials might be a good choice for protection against external fires but can't be used for delaying internal propagation.

Figure 20(a) shows the post-test specimen covered with material E. The ablative material (material E) not only prevented the burn-through of aluminium but was also able to keep the temperature of the cold face very low. The peak observed cold face temperature was below 250 °C when the peak temperature on the hot face was 1100 °C. Ablative material produces a highly insulating gas layer and the formation of this gas layer is endothermic, so heat is absorbed, unlike materials like mica which reflect heat. Because of this, the fibre matrix remains stable and able to withstand the hot metal projectiles. Also, a small localised expansion of the ablative material is observed and small metal projectiles seen to be struck on the ablative material as seen in Figure 21. What this means is the material not only prevents heat flow but also can reduce the risks of electrical arcing inside the battery pack as the movement of these hot metal projectiles is constrained by the TBM. The ablative material is tested on other sets of test substrates and with different material thicknesses. The ablative material is also tested for cells of high capacity, and tested against facing ejecta of multiple cells whose information can be found in Appendix A. The material has also been tested for the UL2596 test. A comparison of the UL2596 test and the tests with large pris-



(a) Post test material E: Hot face(left and center), Unaffected cold face (right)



(b) Post test material C: Hot face (left), Cold face (right)



(c) Post test material D: Hot face (left) and Cold face (right)



(d) Post test material F: Hot face (left), Cold face (right)

Fig. 20: Postmortem of test substrates

Table 6: Summary of live-cell test for the evaluation of module barriers

Materials	Observations	Test results	Pass criteria
Material C	Burn through of aluminium during the test, first material failure due to extreme heat and hot metal ejecta	Fail	No burn through of test substrate
Material D	Burn through of GFRP substrate First failure due to extreme heat and hot metal ejecta	Fail	No burn through of test substrate
Material E	No burn through of aluminium substrate and back face temperature lower than 250	Pass	No burn through of test substrate
Material F	No burn through for the first few seconds but eventually material failed with a burn through	Fail	No burn through of test substrate



Fig. 21: Hot particle attachment on ablative material

matic cells can be found in [Appendix B](#). Figure 20(d), shows the post-test specimen of Material F. Material F has a highly localised impact when compared to material C. The burn-through hole diameter in material F was smaller in comparison to material C. In material C the collapse of the fibre core was very evident, however, in case of material F such a collapse of the fibre core is limited to the center of the test substrate. Materials F and C are compared with each other as they have similar material properties. As mentioned earlier material F is more rigid and heavy in comparison to material C. The mass loss ratio of the cells was 55.2%, 54.4%, 56.3% and 53.9% for the four test cases which are well above EUCAR hazard level 4 and indicate consistent TR behaviour of the cells. Table 6 summarises the details of the live cell test for module barriers.

7.2.1. The hot plate test

All the TBMs survived the test, as all of them have temperature resistance over 1000 °C. The super-

insulating properties of the aerogel barrier are evident from the test data, as it consistently recorded lower steel block temperatures than the endothermic materials. Although the endothermic barriers may not be as super-insulating as aerogels their energy-absorbing nature can be observed from the hot plate's temperature data (see Figure 17). The endothermic materials draw heat from the hot plate thereby letting the plate cool down faster. Table 7 shows the summary of the hot plate test. Based on the test results, all the TBMs evaluated will be able to meet the 5-min window time mentioned in Chinese the standard GB38031-2020. However, it is important to note that the steel blocks represent the thermal mass of a high-capacity prismatic cell. The steel block's thermal mass needs to be calibrated every time based on requirements. Replacing the steel blocks with actual intended cells might be an option but there is always a chance of TR with live cells, meaning extra health and safety measures and complicated test set-up.

Table 7: Hot plate test summary

Material	Max temp of steel blocks	Time to max temp
Aerogel	94.4°C	30 (min)
Endothermic barrier 1	92.2°C	21.9 (min)
Endothermic barrier 2	91.7°C	21 (min)

8. Conclusion

The experimental investigation of different types of commercially available TBMs has revealed the extreme conditions a material needs to endure to protect the occupants inside a BEV. All the materials for this paper

are sourced from tier 2 or tier 3 automotive suppliers based in Europe. Based on the experimental observations, high-foaming intumescent materials are found to be suitable for protecting battery packs from external fires (pack-level protection). The heat shielding performance offered by intumescent coatings is significantly better than fixed thickness-based TBMs. An ablative material was found to be suitable for delaying inter-module thermal propagation as it successfully withstands high temperature and abrasive conditions. The good performance of the ablative barrier is predominately attributed to the superior insulation of the ablative layer which enabled the well-engineered fibre core to remain stable and offer good resistance to the abrasive particles coming from the cell in TR. For delaying thermal propagation at the cell level, both aerogels and endothermic barriers performed very well. But with the addition of endothermic fillers, the cell barrier not only prevented the heat flow between the hot plate and steel blocks but also aided in faster cooling of the hot plate. Hence, in a battery pack endothermic barriers will not just prevent the heat transfer between the cells but will also aid in faster cooling down of the cell in TR. Hence, it will be more beneficial to have such TBMs between the cells rather than super-insulating aerogel materials. Overall, in all three tests, the best-performing materials share some form of energy-absorbing phenomena associated with them. For instance, in intumescent coatings, the char formation is endothermic, while in the ablative material, the ablation process is endothermic and the endothermic fillers used in cell barriers absorb heat energy. Hence, for a successful thermal barrier material (TBM) along with properties like low thermal conductivity and high-temperature resistance, the energy absorption capability becomes extremely vital. Hence, this should be factored in when engineering a TBM. Other factors for the poor performance of TBMs tested during this study is due to the lack of understanding about the conditions these materials need to endure to be successful. For instance, formulating the coating thickness of intumescent material based on target temperature rather than target heat flux might have resulted in poor performance of material B in the pan-fire simulation test. Underestimating the flame temperatures of Li-ion jet fires and the effect of high-velocity hot particle ejecta might be the possible reasons for the poor performance of material C in the live-cell test. Moreover, the importance of highly accurate material validation procedures in the material development process is highlighted in this paper. All the test setups used in this paper are formulated to evaluate materials which meet the industry standards. The conditions created during the tests are highly indicative

of the type approval tests as mentioned in Section 3. The feedback on the performance of TBMs was shared with the material suppliers for further improvement of their products.

9. Acknowledgements

This work was supported by Balance Batteries Ltd in collaboration with AIS Ltd. The authors would also like to thank all the material suppliers who have sent the required samples for this study.

Appendix A. Evaluation of Material E against different test conditions

The material E which successfully passed the live cell test was subjected to a variety of test conditions. The material E was bonded to 0.6 mm steel which is typically used for battery enclosures. This time two 86 Ah SVOLT cells were triggered instead of one. The setup is shown in Figure A1. To simultaneously trigger cells into TR, a dual synchronised ram was used.

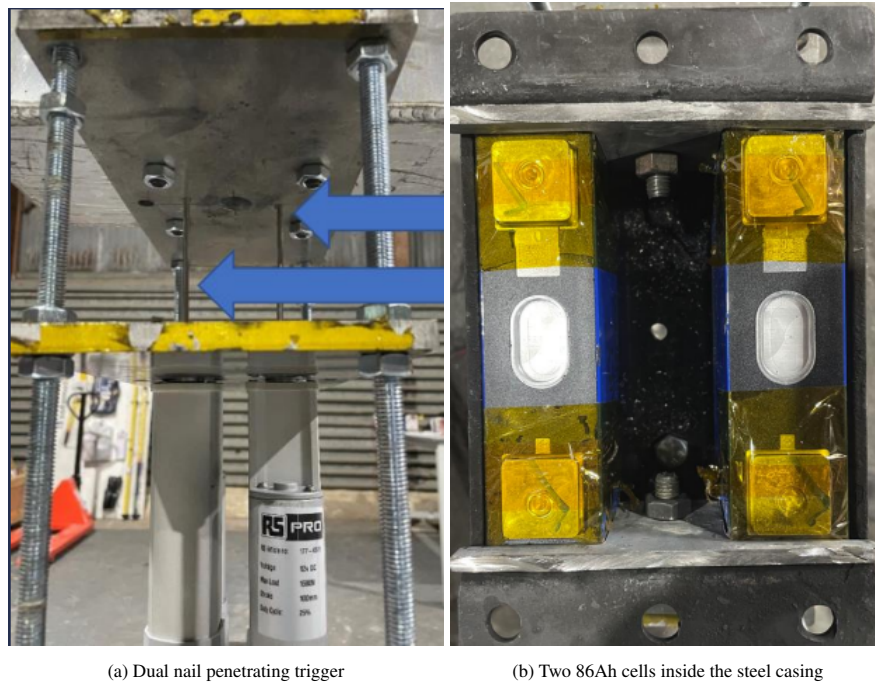


Fig. A1: Dual cell test

Figure A2 shows the hot and cold faces of the test substrate. Two localised expansion/projection can be observed on the exposed face of the ablative material. Two such regions can be observed and this is due to the ejecta of 2 cells impacting the material. The cold face of steel showed no signs of TR and was completely protected by the ablative barrier.

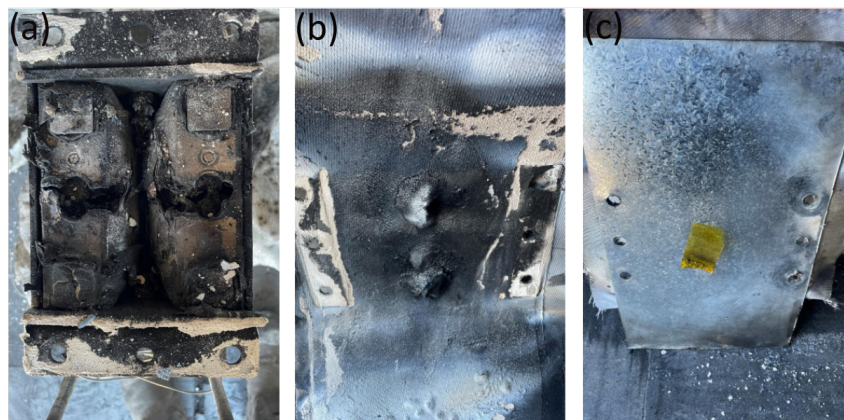


Fig. A2: a) Cells after TR; b) Hot face of the test substrate; c) Unaffected cold face

Figure A3 shows material E protecting the steel substrate from vent ejecta of two 86Ah cells trigger simultaneously via a synchronised dual nail. The material E has been subjected to vent ejecta of varieties of cells from different



Fig. A3: No burn through of test substrate facing cell ejecta of two 86Ah cells

manufacturers. and the performance of the material is extremely promising.

Appendix B. Live Cell Test vs UL 2596

The UL 2596 as discussed in [21] is a recently published and widely accepted test methodology for evaluating the thermal and mechanical performance of materials suitable for battery enclosures. The test is designed primarily for fast screening of composite materials suitable for battery enclosures. The test substrate is placed on top of a pressurised steel container which houses cylindrical 18650 cells as shown in Figure B1. Dealing with the pressure is

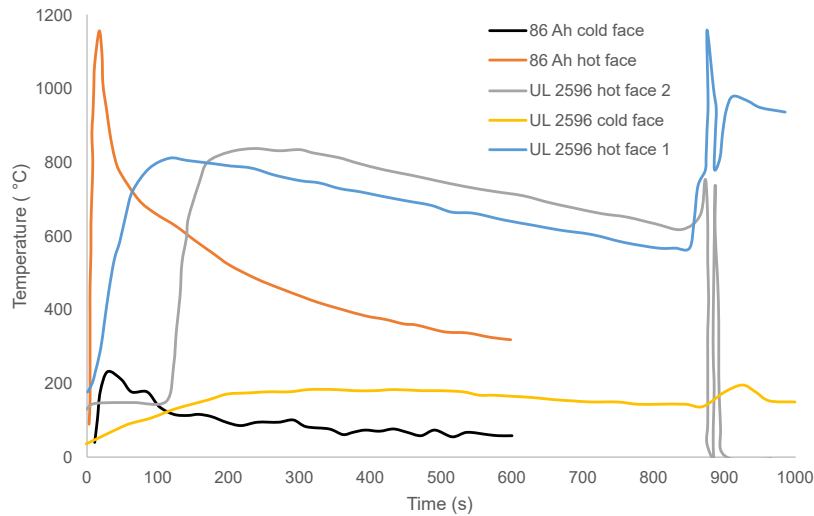


Fig. B1: Comparison of Large format prismatic cell test vs UL 2596

a bit of a challenge for composite materials while for metallic substrates this is not a primary concern. Most of the substrates for the live cell test are primarily metals. Also, the intended battery pack design considered for this study is not based on cylindrical cells. The smaller 18650 cylindrical cells are uncommon in current generation BEVs. As discussed in the earlier sections the energy release during TR depends majorly on the cell chemistry and its size. The large format NMC 811 prismatic cells are widely used for BEVs in the European market. So, to better represent real-life large format prismatic cells were used and because the majority of the test substrates are metals the steel casing was not pressurised as metallic substrates have little concerns in dealing with the sort of pressures mentioned in UL 2590. Material E (ablative material) was also subjected to the UL 2596 test to obtain a comparison between the two test methods. Figure B2 shows the hot and cold face temperatures when an aluminium substrate is subjected

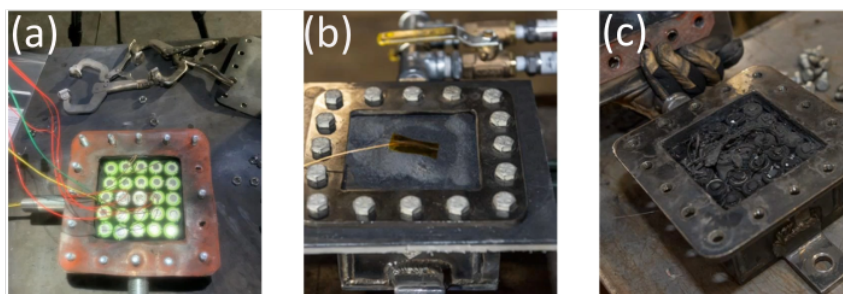


Fig. B2: a) Pre-Test cells; b) Post-test cold face thermocouple; c) Post-test cells

to both UL 2596 with material E bonded on the hot face. As it can be observed the peak hot face temperatures using the 86Ah cell is much higher when compared to the hot face temperatures in the UL 2596 test. Also, the UL 2596 is longer when compared to the live cell test, this is because the centre cell in the UL 2596 is triggered using a heating pad as opposed to nail penetration. Once the centre cell goes into TR it takes some time for other cells to absorb the heat and go into TR. As expected due to less severity of the flame temperatures the UL 2596 test records a lower cold face temperature. The tests are repeated multiple times to ensure the repeatability of test results. All the tests and data for this comparison were provided by AIS Ltd to be incorporated into this study.

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