Protocols for Mitigating Cladding Risk Support Package

D.01 – Cladding and Materials

Version 2

Date: 13 March 2024

Aboriginal acknowledgement

Cladding Safety Victoria respectfully acknowledges the Traditional Owners and custodians of the land and water upon which we rely. We pay our respects to their Elders past, present and emerging. We recognise and value the ongoing contribution of Aboriginal people and communities to Victorian life. We embrace the spirit of reconciliation, working towards equality of outcomes and an equal voice.

Application of Minister's Guideline 15

These documents contain information, advice and support issued by CSV pursuant to Minister's Guideline 15 - Remediation Work Proposals for Mitigating Cladding Risk for Buildings Containing Combustible External Cladding. Municipal building surveyors and private building surveyors must have regard to the information, advice and support contained in these documents when fulfilling their functions under the Act and the Regulations in connection with Combustible External Cladding on buildings:

a) which are classified as Class 2 or Class 3 by the National Construction Code or contain any component which is classified as Class 2 or Class 3;

b) for which the work for the construction of the building was completed or an occupancy permit or certificate of final inspection was issued before 1 February 2021; and

c) which have Combustible External Cladding.

For the purposes of MG-15, Combustible External Cladding means:

a) aluminium composite panels (ACP) with a polymer core which is installed as external cladding, lining or attachments as part of an external wall system; and

b) expanded polystyrene (EPS) products used in an external insulation and finish (rendered) wall system.

Disclaimer

These documents have been prepared by experts across fire engineering, fire safety, building surveying and architectural fields. These documents demonstrate CSV's methodology for developing Remediation Work Proposals which are intended to address risks associated with Combustible External Cladding on Class 2 and Class 3 buildings in Victoria. These technical documents are complex and should only be applied by persons who understand how the entire series might apply to any particular building. Apartment owners may wish to contact CSV or their Municipal Building Surveyor to discuss how these principles have been or will be applied to their building.

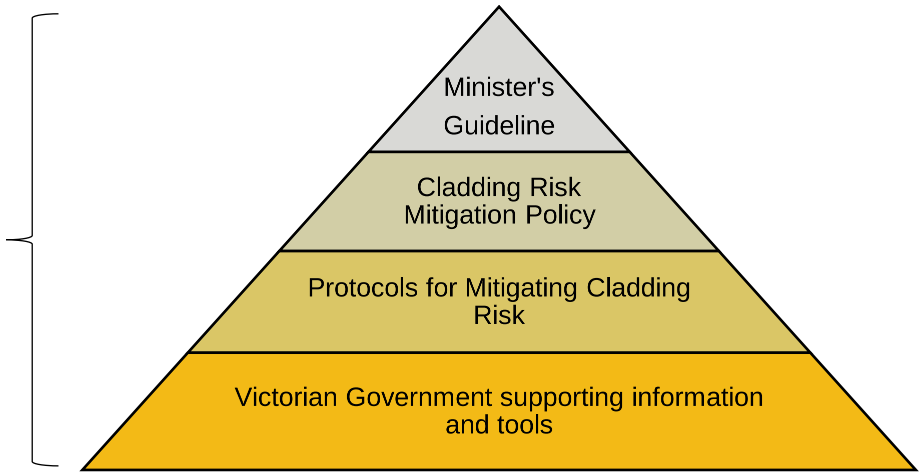
CSV reserves the right to modify the content of these documents as may be reasonably necessary. Please ensure that you are using the most up to date version of these documents.

Document Notes

The Protocols for Mitigating Cladding Risk (**PMCR**) is an approach developed by Cladding Safety Victoria (**CSV**) on behalf of the Victorian Government to consistently and systematically address the risk posed by the presence of combustible cladding on Class 2 and Class 3 buildings (being multi-storey residential structures). For many buildings, combustible cladding on the facade:

- does not present a high enough level of risk to warrant substantial or complete removal of the cladding; but
- presents enough risk to warrant a tailored package of risk mitigation interventions to be introduced that provide a proportionate response to the risk.

Framework



Some buildings may be of a construction type or size or may only comprise limited elements of combustible cladding such that no intervention or removal of cladding is required.

A set of documents has been assembled to describe the purpose, establishment, method and application of the PMCR. The full set of PMCR documents and their relationship to each other is illustrated in the diagram that follows.

There are **seven** related streams of technical document in the PMCR document set:

A. Authorisation	Codifies the Victorian Government decisions that enable PMCR activation.
B. CRPM Methodology	Specifies the Cladding Risk Prioritisation Model (CRPM) method used for assessing cladding risk and assigning buildings to three risk levels.
C. PMCR Foundation	Defines the PMCR method, objectives and the key design tasks.
D. Support Packages	Captures the relevant risk knowledge and science-based findings necessary to systemise and calibrate PMCR application.
E. CSV Cladding Risk Policy	Codifies decisions that enable PMCR activation.
F. PMCR Interventions	Identifies and describes the interventions that the PMCR method can employ to mitigate risk associated with combustible cladding.
G. Implementation	Specifies the standards and procedures that guide PMCR application.

The document set has been developed by CSV. Each document has a function in supporting the delivery of the PMCR and in communicating the PMCR risk rationale and method.

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Abbreviations

Term	Meaning
ACP-FR	Aluminium Composite Panel – Flame Retardant
ACP-PE	Aluminium Composite Panel with a polyethylene core
AS	Australian Standard
BFR	Brominated Flame Retardant
CCP	Composite Concrete Panel
Cladding Cluster	A group of SOUs being connected with combustible cladding as identified by IFSCAN
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSV	Cladding Safety Victoria
EIFS	Exterior Insulated Finishing System
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite Systems
FGI	Fire Growth Index
FPI	Fire Performance Index
FR	Flame Retardant
HCBDD	Hexabromocyclododecane
HRR	Heat Release Rate
ICA	Insurance Council of Australia
IF-SCAN	Initial Fire Spread in Cladding Assessment Number
NCC	National Construction Code
PMCR	Protocols for Mitigating Cladding Risk
PS	Polystyrene
pHRR	Peak Heat Release Rate
QT	“Quick ‘n’ Tuff” (Commercial brand of EPS cement matrix product)
RMIT	Royal Melbourne Institute of Technology
SOU	Sole Occupancy Unit as defined in the current National Construction Code
THR	Total Heat Release
TTI	Time to Ignition
VBA	Victorian Building Authority
VCT	Victorian Cladding Taskforce

1 Summary

This document has been developed to analyse the performance of combustible cladding products when exposed to fire. The objective is to provide important context for Cladding Safety Victoria (CSV) when considering its decision making with respect to primary material focus within the PMCR.

The document strengthens CSV's material focus and decision making by resolving the following key research questions:

- Which combustible cladding products present the highest fire-spread risk within the Victorian setting?
- What is the required amount of flame-retardant material needed to significantly reduce the risk of fire spread via external cladding?

The objective of this document is to analyse common combustible cladding materials and their response to fire. It is acknowledged that the complexities inherent in the combustion processes, and the many methods available for measuring material fire performance, can make direct material comparisons challenging.

A literature review was undertaken to ascertain which fire behaviour parameters and measurements were the most critical for assessing external wall cladding materials. Fire performance characteristics such as the time to ignition, effective heat of combustion, peak heat release rate and total energy released were reviewed to develop indices for both Fire Performance and Fire Growth for material fire behaviour comparisons. The materials were then evaluated through the chosen indices to provide justification for the cladding products that are considered primary to CSV's funding scope, in the context of both fire behaviour and material prevalence within the Victorian built environment.

The review indicated that ACP-PE and EPS have both the highest Fire Growth Index of the materials reviewed and the lowest (or least favourable) Fire Performance Index amongst the cladding materials reviewed.

The literature review supported the assumption that ACP-PE and EPS present as both the most prevalent in the Victorian built environment, and the materials presenting the highest risk of cladding fire spread in the Victorian context. Additionally, the literature review highlighted that the risk of cladding fire spread is significantly reduced where materials have percentages of flame-retardant fillers that are equal to or greater than the percentage of flammable polymer present.

2 Introduction

When a building has combustible cladding on the facade, an **intervention** may be necessary to enhance life safety and reduce cladding fire risk to an acceptable level.

The level of risk created by the presence of combustible cladding varies substantially from building to building. Accordingly, a decision to **intervene** and the extent of **intervention** required must also vary.

The Victorian Government has authorised the use of **15 interventions** to mitigate cladding risk. The authority for their use is contained in *Minister's Guideline 15* (**MG-15**) and supported by the *Cladding Risk Mitigation Framework (***Framework***)*.

The Guideline and Framework are intended to:

- support Municipal Building Surveyors (**MBS**) in rating the cladding risk of a building and determining what level of intervention is required to ensure that the building has achieved an Acceptable Cladding Risk); and
- inform owners about how their building is assessed with regard to cladding risk and the structured way in which Remediation Work Proposals are developed to bring their building to an acceptable level of cladding risk.

Cladding Safety Victoria (**CSV**) is assisting MBSs and owners by providing information about the cladding risk associated with each building and the steps necessary to remedy that risk. This information is provided in the form of a Remediation Work Proposal (**RWP**), that applies the cladding risk methodologies developed by CSV over three years.

A threat barrier analysis can be used to represent how risk-mitigating actions can function to respond to a problem. The CSV method employs this analysis technique to identify the central problem (the 'top event'), in this case a cladding fire, and depict how risk associated with the problem can be mitigated through the implementations of barriers (interventions) designed to control the key hazards identified.

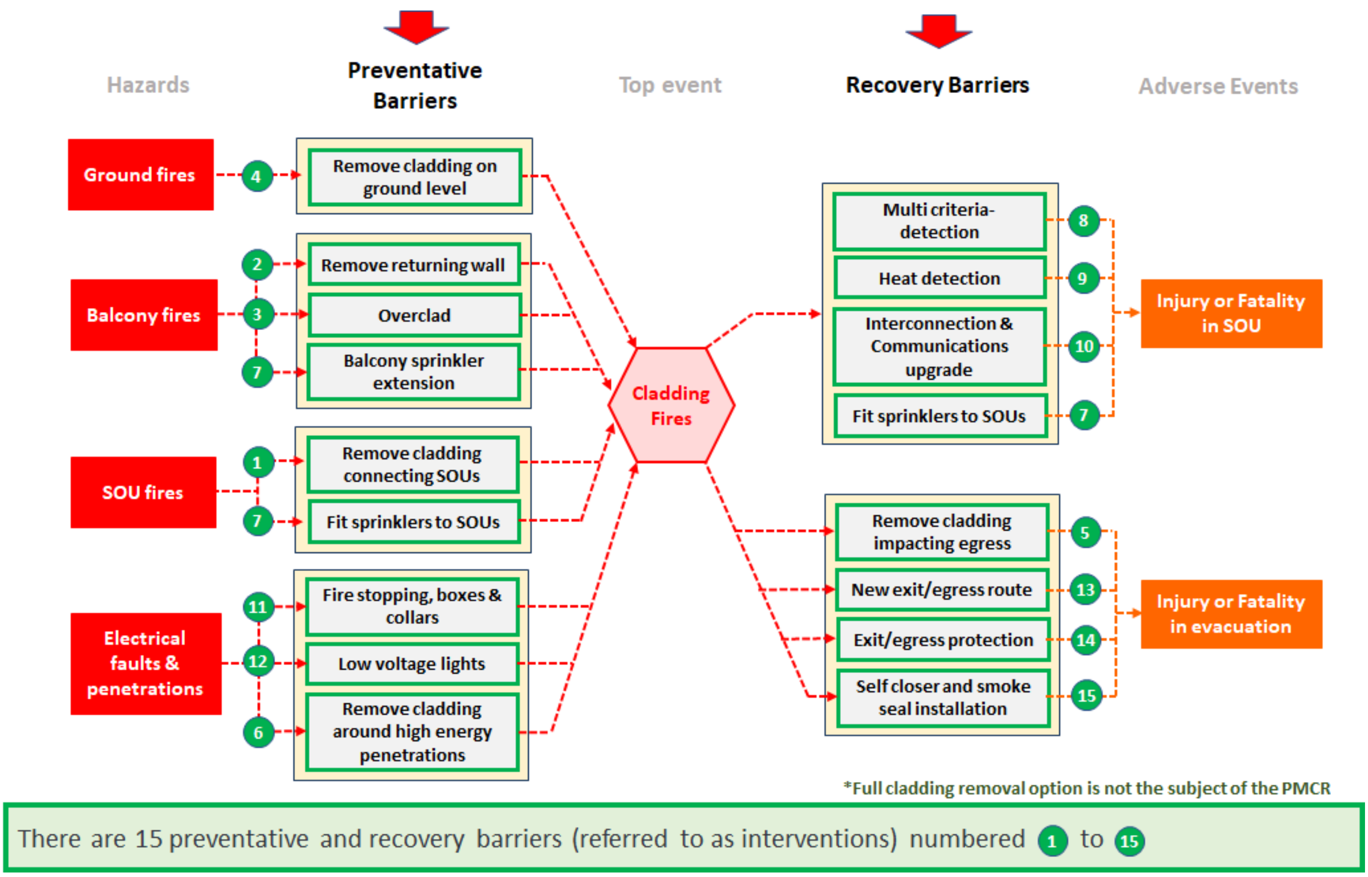

Figure 1: Threat barrier analysis

The 15 interventions in the threat barrier analysis act in different ways to mitigate cladding fire risk.

Each intervention may:

- Respond to one or more of the four identified hazards;
- Function to prevent an ignition source from spreading fire to cladding (i.e. interventions that reduce the likelihood of a fire igniting cladding); and/or
- Function to reduce the adverse impacts for building occupants once a fire has reached cladding (i.e. interventions that reduce the consequences of a cladding fire).

Any risk mitigation solution designed under the Framework must target credible hazards on a building and balance both cladding ignition likelihood and consequence considerations.

2.1 Purpose of this document

This document forms a set of five Support Packages that provide supporting scientific evidence behind the design of PMCR and each of the interventions. This document attempts to technically answer the following research question relating to these interventions:

Research Question 1	Which combustible cladding products present the highest fire-spread risk within the Victorian setting?
Research Question 2	What is the required amount of flame-retardant material needed to significantly reduce the risk of fire spread via external cladding?

It is known that some combustible cladding presents an inherent risk to building occupants due to poor fire properties and fire-spread, but it is less understood as to where the threshold lies for related fire behaviour parameters. The research methodology in this document combines a review of relevant literature, expert judgements, and material flammability testing. A full list of references is provided at the end of the document.

3 PMCR material eligibility: cladding products are in or out of scope

To appropriately encapsulate the intended risk reduction that PMCR aims to facilitate, an identification of combustible cladding materials that present the greatest fire risk bares a large importance. This understanding will act to aid CSV in quantifying the scale of each individual solution as the building generated Initial Fire Spread in Cladding Assessment Number (IF-SCAN) shares a heavily proportional relationship with cladding eligibility.

3.1 Background

In addition to the findings within this document, CSV's consideration of material eligibility is made with consideration to the recommendations provided by the Victorian Cladding Taskforce (VCT) and the Victorian Building Authority (VBA) in collaboration with external fire testing agencies. These recommendations were provided in response to several catastrophic building fires across Australia and the world that highlighted fire safety risks arising from use of non-compliant external wall cladding [1]. Investigations launched by these organisations comprised expert judgements, literature reviews, and large-scale simulations and testing.

Key findings from these organisations and their investigations were that:

1. Both EPS and select ACP materials exhibited poor fire characteristics; and they
2. Presented unacceptable potential of fire risk; and
3. That both are the most proliferated typologies of combustible external cladding adopted in the Victorian building landscape since the 1990s.

The resultant emphasis made on EPS and ACP that contains a high polyethylene content is made on the basis of scientific research and industry expert judgement that suggests these two materials pose the greatest life safety risk. Judgements, which can be validated through both materials implications in Grenfell, Lacrosse, Neo 200 and other fires [2] [3] [4]. Although multiple other combustible materials exist in the Victorian building landscape, research conducted highlighted that these materials exhibit both significantly better fire performance characteristics and reduced prevalence in the built environment when compared directly with ACP-PE and EPS.

Furthermore, work being undertaken by CSV corresponds with legislative and regulatory action that has been implemented to prevent the use of combustible cladding, since the dangers that combustible cladding present became apparent.

Ministerial declaration

The Minister for Planning declared that as of 1st February 2021, "certain high-risk external wall cladding products" are prospectively prohibited from use in building works in Victoria on Type A or Type B construction [5]. This declaration was accompanied with descriptions of affected materials as:

- Aluminium composite panels (ACPs) with a core of less than 93 per cent inert mineral filler (inert content) by mass in an external cladding as part of a wall system; and
- Expanded polystyrene (EPS) products used in an external insulation and finish (rendered) wall system.

This declaration superseded Minister's Guideline MG-14, which was revoked the day that the declaration took effect.

3.2 Materials overview and properties

Targeted combustible cladding interventions under the PMCR are based on those combustible cladding materials that are shown to spread fire rapidly across external facades. For this reason, despite the background drawing emphasis on EPS and ACP with high polyethylene content, to allow for a more robust decision-making process regarding eligibility, other materials that have perceived lower risk profiles will also be discussed in this paper to ensure their risk profiles. Materials to be discussed include:

Cladding materials previously identified as high risk	***Other popular cladding materials considered in this analysis***
1. ACP-PE	1. ACP-FR
2. EPS	2. EPS-FR
	3. Composite timber
	4. Composite Concrete Panel (CCP)/QT

Before proceeding into literature surrounding flame behaviour, it is essential to understand the properties and characteristics of each these materials.

3.2.1 Cladding materials previously identified as high risk

As noted above, empirical evidence developed for the VCT took the position that both EPS and ACP-PE have deemed to be of high risk to fire-spread and subsequently increases residential consequence to the safety of building occupants. It is widely considered that the extensive adoption of combustible cladding was led by a multitude of design and construction factors that converged to make certain lightweight cladding appear desirable.

Hossain et al. attribute rising concerns of carbon emission, global warming, and energy efficiency during building lifecycles to be the reason that EPS and ACP were adopted as cladding alternatives [2]. Both materials are lightweight, cost-effective, easily manufactured, and provide an aesthetic finish to buildings.

Aluminium Composite Panel (ACP)

Aluminium Composite Panel (ACP) products comprise of two thin aluminium sheets that are bonded either side of a core to form a sandwich panel design. The core typically is a composition of organic polymeric material (such as Polyethylene and/or Ethylene Vinyl Acetate (EVA)), inert fillers [6], and occasionally flame-retardant minerals.

Within Australia, industry has currently differentiated the differing risk posed by combustible cladding types. This is best seen in the ICA's four-part classification of ACP-PE, where different ratios of PE to non-PE filler are viewed as posing different cladding risk levels. These classifications purposefully differentiate between the polymer content percentages of the internal core, signifying the flammability risk being posed by the polymeric material as opposed to the aluminium skins. Higher polymer content is associated with increased combustibility and more rapid-fire spread.

The Insurance Council of Australia (ICA) [7] classifies ACP into four categories according to the composition of the internal core and its polymer content ratio. The four classifications are:

1. ICA Category A – or ACP- PE	*Where the internal core contains between 30-100% polymer content*
2. ICA Category B – or ACP- FR	*Where the internal core contains between 8-29% polymer content*
3. ICA Category C – or ACP- A2	*Where the internal core contains between 1-7% polyme content*
4. **ICA Category D – or ACP- A1/NC**	*Where the internal core contains no trace of polymer content*

The filler used within the internal core aims to reduce the polymer content to acceptable levels. This can be achieved with the use of either inert filler, flame-retardant filler, or any combination of the two materials. As such, while the polymer concentration within the core is a good indicator for the fire risk, it does not truly offer a holistic indication of the fire risk as no distinguishment is made between the two types of fillers.

A more robust classification would offer suitable ranges for ACP internal cores that have a flame-retardant material, most commonly found as aluminium hydroxide and magnesium hydroxide. These materials undergo an endothermic reaction and release water vapour which will simultaneously absorb heat and dilute the volatile gases, thus, slowing down the combustion of the polymer.

Expanded Polystyrene (EPS)[1]

Expanded polystyrene (EPS) is a lightweight plastic material that is a product of refined oil and gas that has been polymerised and expanded to form EPS [1] [8]. It is a well-established, lightweight insulation material that is used in various application due to its favourable thermal insulation properties whilst also having a high impact resistance [9].

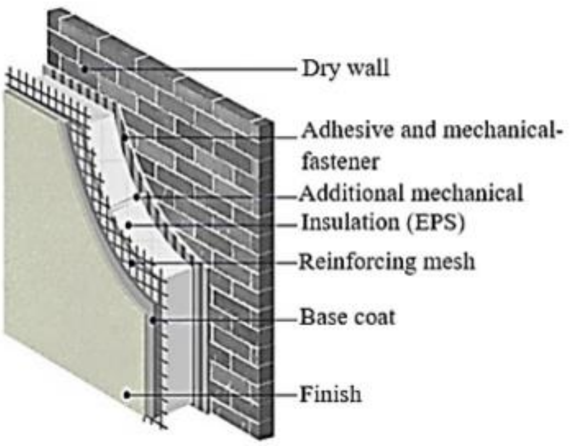

Figure 2: EPS as commonly found in an EIFS wall system ***[2]***

Used in Externally Insulated Finishing Systems (EIFS), or External Thermal Insulation Composite Systems (ETICS), EPS is typically covered by a render system that seals the raw material. The render system may vary but consists normally of 1-2 base coats and a finish coat that embeds

[1] Extruded Polystyrene (XPS), another type of foam polystyrene, is also eligible. However, it is extremely uncommon among buildings within CSV's scope of works.

some form of alkali resistant reinforcing mesh (such as fibreglass) to offer water resistance and increase durability and crack resistance [10]. The resultant product is similar in appearance to rendered concrete and the render coat provides some level of heat resistance. Use of EPS in Victoria is widely known and has been increasingly documented in the last two decades [1].

The VCT Interim Report 2017 suggests that anecdotally, there is an increased prevalence of wall systems consisting of EPS panels in Victorian construction when compared to other Australian jurisdictions, which is likely because of the cooler climate and the need for improved thermal insulation performance [1]. Despite the actual and perceived benefits that EPS provides, these wall systems are prone to surface damage, problems relating to moisture ingress, and have an increased potential of combustibility. Unfortunately, when exposed to fire/flame, EPS may shrink away, melt and ignite, adding to the initial fire [11].

It is recognised that rendered EPS products do not have the same calorific value per square metre to that of ACP-PE material – as such the PMCR does treat this material in some circumstances as having a different (lower) cladding risk exposure. This is particularly relevant to horizontal fire-spread, whereby EPS is shown to not spread horizontally at travel rates of concern [12]. This allows the PMCR to be applied in a manner that is proportionate to the cladding risk presented on the facade.

3.2.2 Other popular cladding materials considered in this analysis

As discussed previously, Expanded Polystyrene and Aluminium Composite Panels are not the only combustible cladding materials used within building and construction. Other materials that exist in the Victorian landscape that are considered in this document include:

ACP – Flame Retardant

As discussed earlier, ACP – Flame Retardant (ACP-FR) is a category of ACPs that contain inorganic filler material within the core of the composite panel. These fillers can behave as either:

- Inert filler, reducing the total volume of flammable material within the core, and providing no other significant impact on the flame retardance (e.g. CaCO3); or
- Flame retardant filler, undergoing endothermic degradation in the presence of heat, thereby cooling the burning organic material (e.g. $Mg(OH)_2$, $Al(OH)_3$).

The composition of the ACP core and parameters surrounding the safe limits for organic material is discussed later in this document, with results indicating that ACP core compositions with higher flame retardant to polymer ratios, display cladding fire spread outcomes comparable to the flame retardant to polymer ratios acknowledged by the Insurance Council of Australia (ICA) for Category B ACP.

EPS – Flame Retardant

The ignitability of EPS can be reduced with the addition of a Brominated Flame Retardant (BFR), namely the brominated cyclo-aliphatic hydrocarbon hexabromocyclododecane (HCBDD). Similar to ACP-FR, EPS with a BFR additive is referred to as Expanded Polystyrene – Flame Retardant, or EPS-FR. Typically, EPS-FR is known to contain a HBCDD content of between 0.5-0.7% [10]. The method by which HBCDD operates to reduce the severity of a flame is by capturing free radicals (highly oxidising agents) produced by the combustion process, which are essential to flame propagation [13]. EPS-FR is known to have better ignition performance when compared to regular EPS, reducing the risks posed by small fire sources such as electrical penetrations and cigarettes. When exposed to higher heat fluxes however, EPS-FR is known to burn in a similar manner to EPS [10]. In fact, testing commissioned by the Victorian Building authority was undertaken to observe the performance of EPS-FR.

Conclusions were that the EPS tested has a similar propensity for vertical fire spread as ACP-PE with 100% polyethylene [14].

Composite Timber

Similarly to EPS and ACP, the recent push for a reduced carbon and energy footprint in buildings has driven interest in more efficient timber use in the construction industry [15].

Timber composite products can be used as external cladding materials that provide the natural appearance of timber, while reducing the level of maintenance usually associated with timber cladding.

As is common with many cladding products, the addition of polymers (plastics) can increase the structural flexibility and durability of external cladding materials, however it is important to note that as the amount of polymer increases, so too does the products level of combustibility and volatility in fire scenarios.

Common examples of timber composite products include polyethylene and phenolic resins as part of their composition, with many of these products incorporating fire and flame retardants to enhance the material's response to fire.

It is noted that some timber composite products can be installed in bushfire zone areas where the expectation is that products must be able withstand heat flux exposure levels up to and including 29kW/m^2 (i.e. BAL 29). Additionally, some composite timbers have shown promising results after being subjected to AS 1530.3 tests. These ratings of fire protection bode well for alignment to the overall design of the CRPM and PMCR, which are designed to operate within a Golden Window of suppression between 20 minutes to 25 minutes.

With this in mind, CSV is continuing to undertake testing on several different compositions of composite timber to determine where within the product tolerance scale these types of materials fall (tolerable or intolerable). The specific testing being performed, and the scale on which the results from these tests are used to create, are detailed later in this document. Additionally, this document will be revised with these test results as soon as they are available.

Composite Concrete Panel (CCP)/QT

Composite Concrete Panel (CCP) is a cladding material comprised of recycled EPS within a cementitious mixture. EPS, when used alone as part of a rendered wall system, is known to exhibit poor fire characteristics. When used within a concrete matrix however, these poor fire characteristics are heavily reduced. Some CCPs have been tested to achieve external wall (EW) classification in accordance with AS 5113 and have a BAL FZ rating, and as such, is not included as a material requiring intervention as part of CSV material scope.

Note: This list includes the cladding materials most commonly found within the Victorian building landscape and is not posed to be a comprehensive list of all cladding materials. Other materials not mentioned within this document will be assessed by a registered fire safety engineer on a case-by-case basis.

4 Literature review of critical flame behaviors

A critical component of PMCR solutions is to proportionately assess the level of risk reduction required for each design, and as such, quantifying the fire behaviours of combustible cladding material is a necessity. This section will provide a summary of literature surrounding the behaviours of materials such as EPS, ACP-PE, and various ACP-FR compositions.

This document is focused on evaluating the fundamental fire-related characteristics of the raw material both in isolation and as part of a rendered/finished product. This section incorporates literature that examines the raw material in both scenarios. While the primary focus remains on the raw material testing, noteworthy insights have been taken from studies involving finished product, particularly in the case of ACP and EPS. The cladding finish will be specified throughout.

It's well documented that there are various means in which a cladding material can interact with its local environment in the event of exposure to fire to propagate unacceptable risk to a building and its occupants. This results in numerous fire behaviour characteristics being used to gain a holistic indication of the propensity of a material to impact a building fire.

Three key fire behaviours have been identified to proportionately assess risk reduction of flame ignition, severity, and spread that can be further explored as other subsidiary measurements through derivation.

4.1 Ignition and combustion

Two pivotal factors in the assessment of the safety and suitability of a material to resist the effects of fire are ignition and combustibility, which refer to a materials propensity to burn when exposed to heat, and the point at which combustion occurs, respectively.

Ignition is a measure of the ease with which a material can be ignited, signifying the point at which the material reaches a minimum temperature or heat flux condition required for sustained combustion. It is described by McLaggan et al. [16] as the key risk for flame propagation and acts a pivotal role in initiating combustion.

Therefore, the **Time to Ignition (TTI),** or the duration taken for a material to reach this critical point, is a crucial parameter that influences the overall ignition and combustion process. TTI is measured in seconds and is typically found via cone calorimetry, in which a constant heat flux is applied to a material. A material that takes longer to reach ignition is intuitively the one that is considered to exhibit a greater thermal resistance.

Combustion, in turn, is the chemical reaction between a material and an oxidizing agent, typically oxygen, that is triggered by an activation energy. This reaction usually results in the production of heat and light in the form of flame. The rate at which this reaction happens is high, due to both the nature of the chemical reaction itself as well as the energy that is generated being more than what can escape into the surrounding medium, thus increasing the temperature to accommodate this increase of energy dispersion [17].

The **Heat of Combustion (HOC)** is a term used to quantify the amount of energy per unit mass released from the combusting material and can be used to both measure and compare the efficiency and volatility between materials. It is measured in megajoules per kilogram (MJ/kg) and is typically found using bomb calorimetry or microscale combustion calorimetry.

4.1.1 Time to Ignition (TTI)

A cone calorimeter test conducted by Mckenna et al. [18] shows that polyethylene sandwiched between aluminium skins experiences a TTI between 75-100 seconds when subject to a 50 kW/m2 heat flux. EPS was also subjected to the cone calorimeter test by Zhou et al. [19], finding the TTI for an EPS ETICS specimen to be 51.7 seconds, also under a 50 kW/m2 heat flux. Irvine et al. [20] showed the correlation between the TTI and external radiant heat flux intensity for polystyrene and polyethylene, concluding that the time to ignition for each material decreases significantly as the heat flux increases. Samples of each raw material were subjected to heat fluxes of up to 100 kW/m2, with polyethylene igniting after only 12 seconds and polystyrene after just 3 seconds.

4.1.2 Heat of Combustion (HOC)

McKenna et al. [18] subjected samples of bare polyethylene to a bomb calorimetry test and a microscale combustion calorimetry test and found the measured heat of combustion of PE to be between 43 and 46.5 MJ/kg. Zhou et al. [19] found the heat of combustion of EPS to be between 29 and 30.59 MJ/kg using a cone calorimeter. For reference, timber exhibits a heat of combustion of 18.6 MJ/kg [10].

Since the heat of combustion is measured in MJ/kg, the results of these experiments give us values irrespective of the density of the material. This can be problematic as EPS is far lower in density than PE. In the context of their usage in cladding systems, polyethylene found within ACP typically has a density of between 900-950 kg/m^3, while EPS usually has a density of around 15 kg/m^3. Since the density of PE is far greater than that of EPS, the fuel load per unit area on the facade of a building would be much greater than the heat of combustion values may suggest. This must be taken into account during any discussion of the heat of combustion of these materials.

Table 1: Combustibility and ignition data of ACP-PE and EPS

Material	**ACP-PE**			**EPS**		
Material Composition	*99% PE 1% CA* [12]	*LDPE 100%* [18]	*LDPE 100%* [18]	*99% PS 1% BR* [12]	*Unspecified – Assumed to be 100% PS* [19]	*Unspecified – Assumed to be 100% PS* [21]
Testing Type	*Raw Material*	*With 0.5mm Aluminium Skin*		*Raw Material*	*Top layer of 2mm PCM & 1mm CM*	*Raw Material*
Time to Ignition [Seconds]	31	75*	100*	32	51.7	40.5 (37-54)
Heat of Combustion [MJ/kg]	46.62	44.9	44.75	39.2	30.59	40.18

Table 2: Combustibility and ignition data of ACP-FR

Material	ACP-FR								
Material Composition	*76% PE 19% $CaCO_3$ 3% Other* [12]	*39% PE 56% $Mg(OH)_2$, 2% Ca, 3% Other* [12]	*LDPE with 64-69% $Al(OH)_3$* [18]	*LDPE with 65-70% $Mg(OH)_2$* [18]	*LDPE with 65-71% $Mg(OH)_3$* [18]	*28% EVA with 72% $Al(OH)_3$* [12]	*PE/EVA 33% with 64% $Mg(OH)_2$* [12]	*ACP 45.3% $Mg(OH)_2$ 43.9% PEVA#*	*ACP 49.8% PEVA 48.1% $CaCO_3$#*
Testing Type	*Raw Material*		*With 0.5mm Aluminium Skin*			*Raw Material*			
Time to Ignition [Seconds]	26	66	77*	105*	105*	75	90	69.67	44
Heat of Combustion [MJ/kg]	40.96	20.56	13.1	13	13.35	13.07 (12.94-13.29)	15.93 (15.88-15.99)	29.75*	36.14*

* Effective Heat of Combustion

Testing commissioned by CSV

4.2 Fire growth behaviour

Once ignition has occurred, understanding the severity and likelihood of fire propagation are essential to determine the impact that a fire event can cause. Fire growth behavior is best characterised as the dynamics of how a fire propagates and evolves into a fully developed fire. It is influenced by a multitude of factors such as material properties, ignition sources, and heat flux exposures.

White et al. [10] defines flame spread as the process of progressive ignition along a continuous surface. After ignition of fuel source has occurred, a release of heat increases the temperature and heat flux to the fuel, which consequently incurs further pyrolysis and combustion, which increases the oxygen consumption and creates more heat until a fire is fully developed [20]. To measure the parameters of this process is therefore indispensable in relation to risk.
In this section, fire behaviours such as peak Heat Release Rate (pHRR), the time taken for the material to reach pHRR, and Total Heat Release (THR) will be discussed.

4.2.1 Peak Heat Release Rate (pHRR) and Total Heat Release (THR)

An essential characteristic in analysis to quantitatively determine how large a fire can grow is the Heat Release Rate (HRR). Babrauskas and Peacock [22] discuss its importance in fire hazards, as the heat generated from material combustion will provide the requisite thermal energy to facilitate fire growth and spread. It is measured in watts or watts per square metre and a larger HRR value is indicative of a greater propensity to facilitate fire growth. Heat release rate is often calculated using calorimeter testing procedures such as cone calorimetry and open-burning calorimeters. Furthermore, literature also heavily utilises the measure of a materials peak HRR to identify the peak intensity of a fire [2] [22]. This peak is the highest observed HRR over any time interval of the test. It is measured in either kW or kW/m^2 and is found using the same testing procedures.

Various studies have been conducted to quantify the magnitude of HRR values observed for both EPS and ACP-PE materials. Results have then been compared to other material typologies and multiple international testing standards to conclude on the fire spread results produced. Notable studies include the testing led by BRE Global [23], who undertook investigations into the burning behaviour of various non-ACM (ACP) cladding products so that the external fire spread risks could be gauged. ACP cladding materials were used as calibration tests and saw that in each case that these calibration tests exhibited significantly worse fire performances in relation to fire spread and growth. A timber crib ignition source[2] was used that saw a peak heat release of 300kW and a total heat release of 450MJ. This is an important benchmark for comparison of how much a material contributes to fire development as it is the difference between this benchmark and the testing total that shows or disproves contribution. In these tests, the two ACP-PE tests saw an average peak heat release rate of 1459 kW, which account for an almost 500% growth compared to the crib. Additionally, the time taken for peak HRR to occur was 8.7 minutes and 20.6 minutes respectively. Of the other 22 samples tested, none exhibited a peak HRR of greater than 600kW/m^2.

EPS cladding through literature has a far lower pHRR than ACP-PE but it is still considered high relative to other cladding products. Zhou et al. [19] investigated the fire behaviours of EPS in external thermal insulation systems (ETICS) via both numerical model and cone calorimeter. The cone calorimeter tested heat fluxes of 30kW/m^2 and 50kW/m^2. The peak heat release rates were observed as 173kW/m^2 and 218.83kW/m^2 respectively.

Additional studies and tests that have been undertaken investigating EPS and/or ACP include:

1. *Irvine et al.* [20] – *"Fire hazards and some common polymers"*

   Irvine et al. investigated frequently used construction industry polymers for their fundamental fire behaviours and found PE to have a HRR of approximately 1000-1050 kW/m^2 at 50kW/m^2 heat flux and at approximately 1500kW/m^2 at 100kw/m^2. They likened the 50kW/m^2 external radiant heat flux to a fire out in the open and 100kW/m^2 to a fully developed compartment fire.

2. *McKenna et al.* [18] – *"Fire behaviour of modern façade materials – understanding the Grenfell Tower fire"*

   Mckenna et al. tested fire behaviours of various facade products using micro- and bench-scale methods. Data collected yielded results that indicated ACP-PE exhibited 55 times greater pHRR than the least flammable panels tested.

3. *McLaggan et al.* [16] – *"Flammability trends for a comprehensive array of cladding materials"*

   McLaggan et al. used the University of Queensland Cladding Materials Library to analyse the fire performances of various ACPs, insulations, aromatics, and thin film samples. For tests regarding HRR for varying incident heat flux, the greatest pHRR observed was for an ACP with a 99% PE core, that had a pHRR of 1000 kW/m^2 at 60kw/m^2 heat flux.

Additionally, total heat release rate proves to be another defining parameter as it is a measure of total heat output over time for a constant heat flux. It is measured by calculating the area under the heat release rate curve when it is plotted against time. THR is measured in joules or joules per square metre. Compared to pHRR which measures the most intense moments of a fire, THR is a cumulative measure of the heat output over time.

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[2] The timber crib ignition source was tested and aimed to impose an incident heat flux of 45-75 kW/m^2 1.5m above ground level.

Table 3: Heat Release Rate data for ACP-PE and EPS

Material	**ACP-PE**			**EPS**		
Material Composition	*99% PE 1% CA* [12]	*LDPE 100%* [18]	*LDPE 100%* [18]	*99% PS 1% BR* [12]	*Unspecified – Assumed to be 100% PS* [19]	*Unspecified – Assumed to be 100% PS* [21]
Testing Type	*Raw Material*	*With 0.5mm Aluminium Skin*		*Raw Material*	*Top layer of 2mm PCM & 1mm CM*	*Raw Material*
Peak Heat Release Rate $[kW/m^2]$	724.65 (504.52-944.79)	1364	1123	291.11 (283.87-298.36)	218.13	370.21 (278.22-462.2)
Time to Peak Heat Release Rate [Seconds]	155 (130-180)	190	250	85.5 (75-96)	88.1	62.5 (60-65)
Total Heat Release $[MJ/m^2]$	93.30 (88.13-98.47)	105.4	106.6	28.22 (26.42-30.02)	42.34	42.34

Table 4: Heat Release Data for ACP-FR

Material	**ACP-FR**								
Material Composition	*76% PE 19% $CaCO_3$ 3% Other* [12]	*39% PE 56% $Mg(OH)_2$, 2% Ca, 3% Other* [12]	*LDPE with 64-69% $Al(OH)_3$* [18]	*LDPE with 65-70% $Mg(OH)_2$* [18]	*LDPE with 65-71% $Mg(OH)_3$* [18]	*28% EVA with 72% $Al(OH)_3$* [12]	*PE/EVA 33% with 64% $Mg(OH)_2$* [12]	*ACP 45.3% $Mg(OH)_2$ 43.9% PEVA#*	*ACP 49.8% PEVA 48.1% $CaCO_3$#*
Testing Type	*Raw Material*		*With 0.5mm Aluminium Skin*			*Raw Material*			
Peak Heat Release Rate $[kW/m^2]$	543.06 (493.42 - 592.71)	206.11 (204.51 - 207.71)	195	123	144	145.30 (145.2-145.4)	136.72 (131.68-141.76)	181.93	372.21
Time to Peak Heat Release Rate [Seconds]	158 (146-170)	107.5 (100-115)	266*	271*	254*	105	190	126.67	158.67
Total Heat Release $[MJ/m^2]$	104.65 (89.30-120)	83.77 (83.43-84.12)	59.6	70.9	65.07	56.90 (55.78-58.01)	80.86 (78.99-82.73)	82.96	114.48

* Calculated manually

Testing commissioned by CSV

5 Discussion

The use of fire performance and fire growth indices as an indicative tool (FPI and FGI) is a well-known and widely considered approach to assessing the fire behaviour of polymers [24]. The appeal of the indices is that the FPI and FGI values incorporate material characteristics such as the peak heat release rates combined with the ignition time given specific conditions. General statements about fire behaviour are difficult to make due to the complex nature of combustion reactions, however, FGI and FPI values capture a broad range of material characteristic and performance information, and as such, can provide a useful indication of material fire behaviour.

5.1 Material fire characteristic indices

5.1.1 Fire Performance Index (FPI)

The Fire Performance Index of a material can be characterised as the ratio between Time to Ignition (TTI) and peak Heat Release Rate (pHRR).

$$FPI = \frac{TTI}{pHRR}$$

Materials that demonstrate rapid ignition and elevated pHRR are indicative of inferior performance in fire scenarios. Moreover, even with a high TTI, a material could still manifest suboptimal fire behaviour if accompanied by an exceedingly high pHRR. Consequently, a decrease in the pHRR corresponds to a concomitant decline in the flame resistance characteristics of the material under scrutiny.

5.1.2 Fire Growth Index (FGI)

Fire Growth Index is the result of dividing pHRR by the time taken to reach pHRR (*tpHRR*).

$$FGI = \frac{pHRR}{tpHRR}$$

A lower value for Fire Growth Index (FGI) suggests a heightened level of flame-retardant efficacy, as it necessitates a prolonged duration and increased energy input for the peak Heat Release Rate (pHRR) to be reached. This phenomenon underscores the material's ability to mitigate fire propagation by impeding the rapid escalation of heat release, thereby affording additional time for fire suppression measures to be enacted and potentially limiting the extent of fire damage. Consequently, materials exhibiting lower FGI values are deemed to offer superior flame-retardant performance due to their capacity to delay and attenuate the onset of critical fire events.

5.2 ACP-PE flame retardant performance analysis

Nguyen et al. [25] discuss thresholds for both FPI and FGI, noting that a material with an FPI of 0 can be considered non-combustible. For FPI > 0 and FGI > 3, the material is considered highly combustible, while materials with an FPI > 0 and 2 < FGI ≤ 3 are considered to be 'less combustible with a lower fire growth possibility'. Materials with an FPI > 0 and 0 < FGI < 2 are considered to be of low combustibility.

Table 5: Thresholds for FPI and FGI

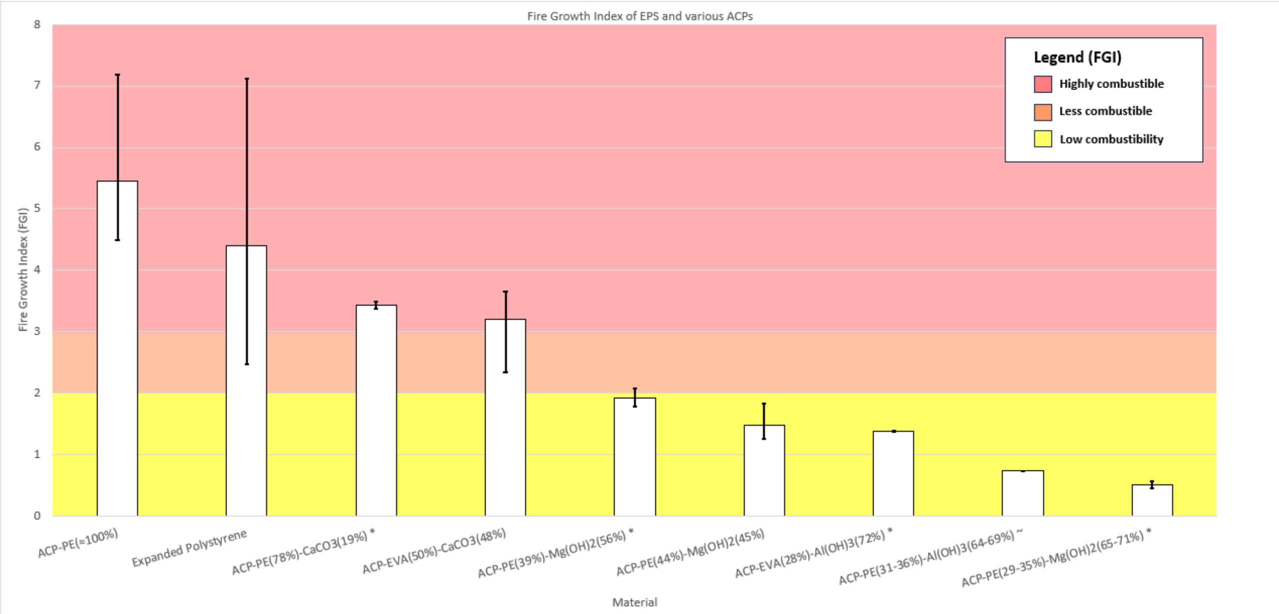
	FPI	FGI
Highly Combustible	> 0	>3
Less Combustible	> 0	2 < FGI ≤ 3
Low Combustibility	> 0	0 < FGI ≤ 2
Non-Combustible	0	0

Table 6: FPI and FGI of ACP-PE and EPS

Material	**ACP-PE**			**EPS**		
Material Composition	*99% PE 1% CA*	*LDPE 100%*	*LDPE 100%*	*99% PS 1% BR*	*Assumed 100% PS*	*Assumed 100% PS*
Fire Performance Index	0.0427	0.0557	0.0890	0.109	0.237	0.132 0.117
Fire Growth Index	4.675	7.179	4.492	3.405	2.476	4.637 7.111

Table 7: FPI and FGI of ACP-FR

Material	**ACP-FR**								
Material Composition	*76% PE 19% CaCO3 3% Other*	*39% PE 56% Mg (OH)2, 2% Ca, 3% Other*	*LDPE with 64-69% Al (OH)3*	*LDPE with 65-71% Mg (OH)2*	*LDPE with 65-70% Mg (OH)2*	*28% EVA with 72% $Al(OH)_3$*	*PE/EVA 33% with 64% $Mg(OH)_2$*	*ACP 45.3%FR 43.9%PE*	*ACP 49.8% PEVA 48.1% Inert*
Fire Performance Index	0.0479	0.320	0.538	0.729	0.626	0.5162	0.658	0.564	0.119
Fire Growth Index	3.437	1.917	0.733	0.566	0.452	1.384	0.452	1.437	3.197



* Data available for only two tests

~ Data available for only one test

Figure 3: Fire Growth Index of EPS and various ACPs

As shown in Figure 3, ACP-PE, EPS, ACP-PE with 19% $CaCO_3$, and ACP-PE with 49.8% PE and 48.1% inert filler are all highly combustible, exhibiting very high fire growth rates in comparison to all other tested materials. The addition of the inert filler, $CaCO_3$, to the polymer core of the composite panels reduced the FGI considerably, albeit not to a degree necessary to lower the material from the highly combustible range. As a result, all the materials above the highly combustible threshold (FGI > 3) must be included as part of the PMCR program.

All of the tested ACP-FR materials fall below the low combustibility threshold, with as little as 45.3% $Mg(OH)_2$ and 43.9% PE satisfying the FGI < 2 requirement. This result highlights the important role flame retardant additives have in the core, suppressing the burning organic polymer by undergoing endothermic degradation. Additionally, we can take the composition of this material and develop a ratio of organic material to flame retardant that can be considered to exhibit low combustibility:

$$\begin{gathered} Organic\ Material : Flame\ Retardant \\ 43.9 : 45.3 \\ \sim 1 : 1 \end{gathered}$$

To validate this, CSV sponsored multiple ISO 13785-1:2002 intermediate scale facade tests to be performed on the ACP-FR from which the 1:1 ratio is derived. The results from these tests were promising, showing a lack of fire spread across the test specimens. Such results validate the 1:1 organic material to flame retardant ratio as an effective maximum concentration to mitigate fire spread across a building's facade. As such, the established ratio of 1:1 organic material to flame retardant can be considered as the minimum allowable ratio for ACP-FR to exhibit low combustibility. For guidelines as to when this new ratio can be applied, please refer to document E.01 – Cladding Risk Policy – Trivial and Tolerable Cladding Risk.

Notably, this ratio cannot be applied to inert filler material as the filler will not act to reduce fire spread in the same manner as a flame-retardant filler. Alternatively, we can see that ACP-EVA with 28% EVA and 72% inert filler exhibits an FGI of 1.384, well below the FGI ≤ 2 threshold for 'low combustibility'. This data shows us that, for an ACP with inert filler, we can set a minimum allowable threshold of 71% inorganic inert filler for the ACP core to exhibit low combustibility, in line with ICA category B or better.

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7 Appendices

Appendix A: PMCR document set and flow