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Flammability trends for a comprehensive array of cladding materials

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Highlights:

- Organic content is shown to correlate poorly with fire performance
- Residue in an inert atmosphere may be useful for rapid screening purposes
- Cladding materials within generic categories behave very differently
- Specific cladding materials with potential low flame spread are highlighted

Abstract:

The flammability of materials is a key component of modern cladding fires. Vertical flame spread is a complex phenomenon which is, amongst others, a function of thermal inertia, ignition temperature, and heat release. The recently published Cladding Materials Library contains the needed flammability data to help engineers perform fire risk assessments on buildings. Cladding fire research has previously generally focused on expensive and time consuming full-scale testing, or on the chemical composition, with little regard to the flammability or other performance metrics. Here we show common trends in the ignition and burning behaviour for cladding materials in a systematic bench-scale study using the Cladding Material Library. The organic content is shown to be a poor indicator of the fire performance, as represented by the heat release rate. A simple and highly conservative model indicates the relative behaviour of a diverse range of cladding materials. This analysis supports competent engineers to select which specific buildings require further investigation based on performance, and to aid development of remediation solutions. The differences within categories of materials, e.g. high-pressure laminates, are large and thus the performance should be tailored for the specific building material. This work complements but does not replace full-scale system testing.

Keywords: modeling; risk assessment; performance-based design; flame spread; fire growth; ignition; heat release rate; hazard evaluation; façade fires

1. Introduction

Cladding fires are a modern problem which challenge the classic fire safety strategy. The traditional fire safety strategy in buildings relies on the concept that there is no vertical spread of fire. This was typically prevented through the use of vertical compartmentation and non-combustible materials to prevent upward or downward spread of flames. Fire spread between neighbouring buildings is also heavily influenced by the material selection in a façade system. Within a building, different levels are also connected by stairwells which are heavily protected to ensure safe egress and prevent the spread of smoke.

The use of modern materials and systems has challenged that strategy. The introduction of flammable materials whose behaviour is not quantified or integrated into the strategy therefore represents an unknown and unaccounted for fire risk. The use of these materials globally has been rampant across the last 2–3 decades with little to no consideration for how the fire strategy of a building is influenced by this. The Queensland Government requires the investigation of all buildings which were built or renovated after 1994 [1].

Aluminium composite panels (ACPs) have been receiving much focus in the cladding fire challenge, and the remediation and mitigation efforts have been heavily concentrated on these materials. Fundamentally, ACPs are the symptom of a larger problem, and the fire risk of other flammable components within a cladding must equally be assessed. These include high-pressure laminates, timber claddings, weatherproof membranes, and insulation. The problem is particularly difficult as these materials are included as part of a system which has interactions between components, and introduces the issue of elements such as mechanical fixings. Many of the remediation strategies around the world have yet to address whether or not non-ACP materials pose a risk for the specific buildings they are included within.

In Queensland, a framework [2] was developed to deliver the needed flammability data to fire engineers who were tasked with performing initial fire risk assessments for buildings. This framework arms engineers with the basic data needed to make assessments for the remediation and investigation of existing buildings. The data collected from all publicly-owned buildings in Queensland, Australia is published in the Cladding Materials Library [3], and contains the chemical composition, thermal degradation, heat of combustion, ignition characteristics, burning behaviour, and flame spread. The complexity of the database is such that guidance is provided to practitioners to describe its usage and interpretation [4] so that the data is used correctly.

This has resulted in an extensive database of common cladding materials, and gives insight into the performance of the materials being used in actual buildings. A plethora of data is available to be analysed to assess cladding materials and their relative performance. This acts as a first step to aid choices in remediation and investigation, but it does not substitute full-scale testing. The goal is to enable rational decision-making, as all combinations of systems cannot realistically be tested at full-scale and sophisticated models have not been validated in this space.

The aim is to understand the ignition and flammability of common cladding materials, and whether there are performance metrics which can be used. To achieve this, materials encountered in the Cladding Materials Library [3] are studied and the key trends between different materials are noted. This is used to assess whether a commonly used chemical composition metric in Australia is appropriate for assessing cladding materials. A simple model is applied conservatively to help gain insight into the potential relative performance of different materials.

2. Materials

The materials in this project are taken from publicly owned buildings in Queensland, Australia. A total of 1,091 samples were taken, of which detailed flammability testing was performed on 20 materials. These materials are all published in the Cladding Materials Library [3]. The sample preparation techniques and methods used to test the samples are described briefly below, and a full description [5] and an examination of the sensitivities [6] can be found elsewhere.

Samples were initially either taken in the form of 40 mm diameter discs removed from buildings using a hole-saw, or as 1 × 1 m^2 sheets taken from buildings. The encapsulation for all samples was removed, and testing was focused solely on the core material. This was so that the fundamental material behaviour could be assessed, without the added complications of composite effects which would be present in full products. This means that the aluminium skin was removed from ACPs, and the metal sheet was removed from insulation sandwich panels. The fire behaviour of products is an added level of complexity which can be studied later, and is outwith the scope of this work.

3. Methods

Thermogravimetric Analysis (TGA) was performed using a Netzsch STA449 F3 Jupiter (ISO 11358-1 [7]). A heating rate of 20 °C min^{-1} was used in a range from 50–800 °C, with one test in air and one test in nitrogen, each with a gas flowrate of 150 ml min^{-1}. Sample mass was 10.1±0.4 mg (error as standard deviation across 1,238 tests) for ACPs, and the mass was reduced for light weight insulations or materials where insufficient mass could be collected, e.g. adhesives. Alumina (Al_2O_3) crucibles with a volume of 70 µL and no lid were used. Results are in the form of mass and mass loss as a function of temperature, and the mass residue.

Quantitative material identification for all the materials presented in this paper has been performed [5,6] but is not presented here.

The heat of combustion was obtained using bomb calorimetry (ISO 1716 [8]). Three trials were performed in a Parr Instruments Calorimetric Thermometer Model 6772, and the result presented as an average and standard deviation. For materials that did not readily ignite, a material with a known heat of combustion – benzoic acid – was used to ensure ignition and that sufficient energy was released. The heat contribution of the benzoic acid was then removed afterwards.

The critical heat flux was determined using a conical heater supplied by Fire Testing Technology (East Grinstead, UK). This was according to Annex H of ISO 5660 [9] but without gas analysis or a load cell. Samples of 100 x 100 mm^2 were exposed to a range of heat fluxes until there was at least one case with ignition and one case of no ignition, separated by at most 1.0 kW m^{-2}.

Flammability testing was performed in an ISO 5660 cone calorimeter [9] supplied by Fire Testing Technology (East Grinstead, UK). Heat fluxes of 35, 50 and 60 kW m^{-2} were used with two repetitions of each. In some cases 80 kW m^{-2} was used to give a wider spread of results. A wire mesh with a metal retaining frame was used in all tests due to the expansion of many materials, and the standard was otherwise followed. Ceramic wool was used as insulation at the rear surface, and replaced between tests. The results presented are the heat release rate as a function of time, mass as a function of time, total energy released, time to ignition, peak heat release rate, and the mass residue. Additionally, the ignition temperature, total heat transfer coefficient at ignition, and apparent thermal inertia were calculated using the method outlined by Long *et al.* [10].

4. General heat release results

The Cladding Materials Library is currently in the form of a database which is free and open to access, which means any materials referred in this manuscript can be referred to at any time. The materials must be summarised in some form to aid discussion, analysis and comparisons. The materials have been grouped into basic categories where there is a degree of commonality (Table 1) – for example, charring materials with a specific physical form – but the behaviour within these categories is still wide. The intention of the summary then is to aid discussion and is not a classification. If the materials are to ultimately be classified, then this should be done based on identified performance metrics which are deemed suitable. The samples IDs refer to aluminium composite panels (ACPxx), insulation (INSxx), sarking or weatherproof membranes (SRKxx), or “other” materials (OTHxx).

The descriptions in this manuscript generally do not refer to the full chemical composition as it is not needed for the level of comparisons made here. Nonetheless, the chemical compositions are all available in the database [3].

The heat release rate as a function of time gives an indication of the relative and distinct behaviours of different cladding materials (Fig. 1). A short description of each category is given, indicating the general trends of the materials in each category. For the sake of clarity, only results for a single incident heat flux, 50 kW m^{-2}, are presented at this stage. The influence of incident heat flux is presented in a later section. Two repetitions are presented for each material.

Table 1. Summary of basic categories of materials in the library.

Material description	Shorthand label	Sample IDs
ACPs with an organic core and may contain fire retardants, inorganic fillers, processing aides, etc.	ACPs	ACP01, ACP02, ACP03, ACP05, ACP07, ACP09, ACP11, ACP15
Materials with only a thin layer of organic material	Thin film	ACP06-S1, ACP10, SRK01-S1
Thermosets, generally aromatic compounds containing combinations of phenol resin and cellulose	Aromatics	ACP04, OTH01, OTH04
Insulation materials	Cellular	INS01, INS02, INS05, INS06
	Non-cellular	INS03, INS04

ACPs have a wide range of burning behaviour depending on their formulation (Fig. 1, top left). Materials which are pure or nearly pure thermoplastics behave as non-charring solids, such as ACP03 and ACP07. These are characterised by very rapid burning rates (500–900 kW m^{-2} heat release), no residue, and short burning durations (300 s). ACPs containing inorganic filler tend to have lower heat release (100–275 kW m^{-2}) and longer burning durations (400–1400 s). Some of the ACPs behave similar to charring materials as a char layer builds up and insulates the underlying virgin material from external heat. In general, the heat release for most of these materials is nonetheless relatively consistent throughout the duration of flaming.

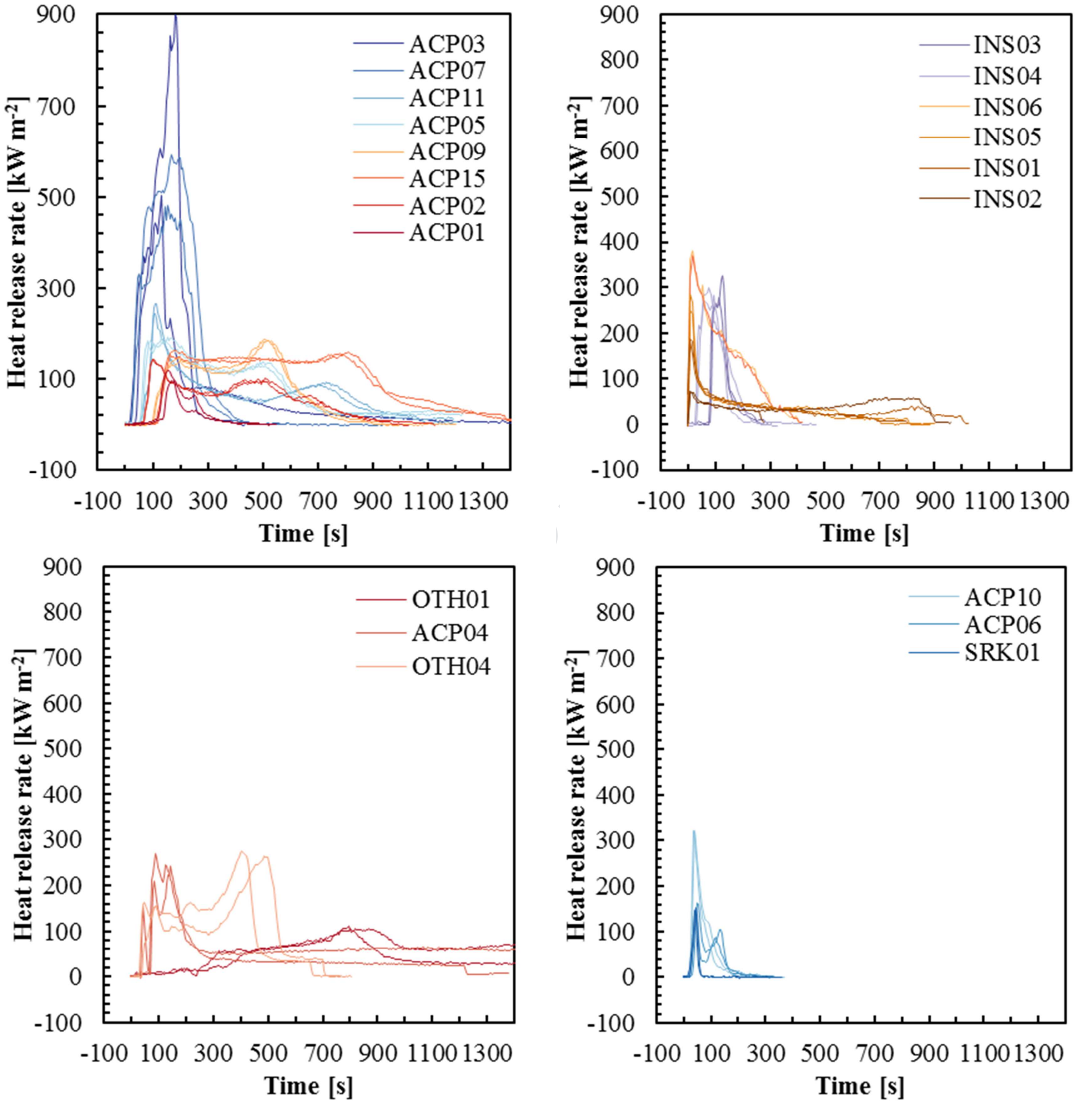

Fig. 1. Heat release rate per unit area as a function of time for ACPs (top left), insulations (top right), aromatics (bottom left) and thin film samples (bottom right).

A number of key trends are noted for insulation materials (Fig. 1, top right). The total energy released by these materials, as indicated by the integral of the heat release, can be seen to be substantially lower than ACPs despite much larger sample thicknesses (up to 100 mm compared to up to 6 mm for ACPs). This is partially due to the low density of modern insulation materials leading to low sample mass. For cellular materials, the extremely low thermal inertia causes the surface to heat rapidly, and ignition is achieved quickly [11]. These have strong charring-like behaviour, with a relatively short peak heat release followed by significant decay for the remaining duration of the test. Once a critical char depth is established, insufficient heat can reach the virgin fuel to generate adequate pyrolysis gases, and hence extinguishment occurs.

The two non-cellular insulations – INS03 and INS04 – both undergo melting and otherwise behave as non-charring thermoplastics. The melting leads to regression of the surface from the heat flux of the cone, and thus a lower heat exposure is experienced. Consequently, the results are somewhat lower than what may be deemed the true values. This behaviour, epitomised by expanded polystyrene, is encountered regularly in the literature [12,13].

The aromatic formulations all generally behave as charring materials. The behaviour of the three materials is still nonetheless quite varied, depending on the ratio of cellulose to phenol resin, and on the binder used. The best performance is observed in OTH01 which is a high pressure laminate with a phosphorous-based compound. Its higher density and inorganic additive lead to a significantly longer ignition time, with a consistently low rate of heat release due to the lower thermal inertia and increased charring respectively. The other two materials both ignite more rapidly and have distinct peaks. From this, it is clear that the aromatic-based formulations have a wide range of performance.

Finally, the heat release of materials where the organic component is only a thin layer are shown. ACP06 and ACP10 consist of a thin layer of adhesive binding an aluminium profile to two encapsulating aluminium sheets. The final material in this group, SRK01, is a weatherproof membrane comprising a layer of polypropylene with an aluminium backing, and interwoven glass fibre reinforcement. The materials in this category are somewhat distinct in their physical geometries, but ultimately the thin layer of thermoplastic polymer leads to sharp heat release before the material is quickly consumed and no fuel remains to sustain the flame.

5. Trends in ignition

Ignition is a key risk for flame spread propagation. The two major parameters which affect the time to ignition are the ignition temperature and the thermal inertia. The latter term is obtained from cone calorimeter tests performed at different incident heat fluxes, and is a measure of how rapidly a material heats up. For the case of materials with extremely low thermal inertias, such as insulations, then the ignition is rapid regardless of the ignition temperature. The thermal response parameter (TRP) is a function of these two terms (defined later in Eq. (5), and is thus used to give a more generic assessment of the relative performance of different materials [14]. Each of these parameters – critical heat flux, ignition temperature and apparent thermal inertia – is plotted against organic content in Fig. 2 for all the materials.

The critical heat flux for the majority of ACPs lies within the range of 13–18 kW m^{-2}, and has little to no dependence on the organic content expressed as a percentage (Fig. 2, top left). Organic content here refers to carbon-based material, and includes materials such as polymers and waxes. This is used in preference to terms such as “polyethylene content”, as this is only a single example of a polymer, and there are likely to also be other minor components present such as lubricants and processing aides which contribute to the equally flammability. One of the major outliers for this trend is ACP15, which has predominantly Mg- and Ca-based inorganic components, such as magnesium hydroxide, magnesium carbonate and calcium carbonate. X-ray Diffraction (XRD) was used to characterise the inorganic composition of crystalline materials in more detail [6]. This showed that compared to another similar ACP with Mg-based inorganics (ACP05), ACP15 had lower magnesium hydroxide, but higher calcium carbonate, and additional Si-based inorganics such as kaolinite, which is a form of clay, and quartz. These appear to significantly improve the critical heat flux (28.0 kW m^{-2} compared to 16.8 kW m^{-2} for ACP05) despite the similar total organic content, and this would be is beneficial to be able to resist ignition and flame spread.

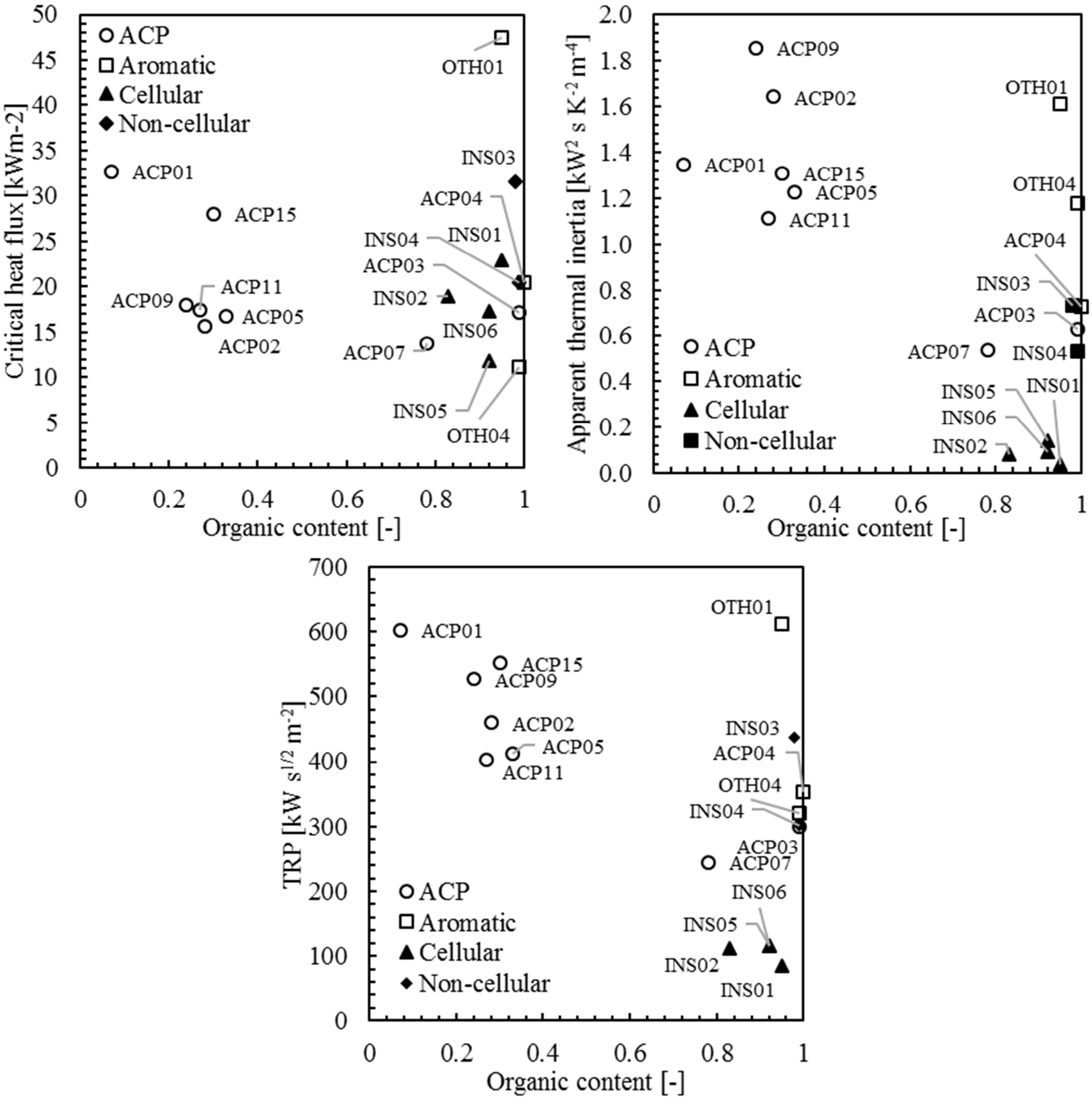

Fig. 2. Polymer content against critical heat flux for flaming ignition (top left), apparent thermal inertia (top right), and TRP (bottom).

There is a wide range of apparent thermal inertias, as calculated from the time to ignition across a range of heat fluxes in the cone (Fig. 2, top right). This is primarily due to the modern insulation materials, which have extremely low thermal inertia in order to reduce building energy usage and improve sustainability. Polyethylene normally has a reasonably low thermal inertia, as represented by ACP03 and ACP07, but this is substantially increased by the addition of inorganic components, as represented by the other materials in the ACP grouping. There is however no linear trend, and all the materials with fire retardants or inorganic fillers have increased thermal inertia. It is surprising that ACP01, which is predominantly inorganic and would be expected to contain highly dense materials with high thermal conductivity, is within a group with the other ACPs. The aromatics reasonably fall in the same ranges as ordinary ACPs.

TRP ultimately gives the best indication for resistance to ignition since it combines both parameters (Fig. 2, bottom). Here, the ACPs at both the extreme ends of the range (ACP01 at low polymer content and ACPs 03 and 07 at the high end) show distinct differences in behaviour. The low thermal inertia of polyethylene results in a reduced TRP, where the critical heat flux for the ACPs is similar. The extremely low thermal inertia of the foams is reflected in the TRP, leading to very short ignition times, in the region of 1–10 s. The phenolic composite OTH01 performs extremely well, with the highest TRP of all materials. This is despite the fact that its composition is overwhelmingly organic. This highlights one of the issues in using the organic content as a metric for assessing the viability of cladding materials. The reasonably high TRP of INS03 is most likely an artefact of its melting behaviour, and in larger-scales it might not be expected to perform so well. Overall, many of the ACPs have reasonable resistance to ignition compared to other materials in the façade, such as insulation and various thermoplastics.

6. Trends in burning behaviour

The trends in the burning behaviour are shown for all the cladding materials. In each case, the data is presented for an incident heat flux of 50 kW m^{-2}. The data was plotted for other heat fluxes but there were no significant changes in the trends. Nonetheless, the effect of the incident heat flux is covered in a subsequent section.

A reasonable trend in the organic content against peak heat release rate is observed for ACPs (Fig. 3, top left). The organic content has been one of the common methods for rapid assessment of cladding materials. There are still large disparities in the heat release for materials with relatively low organic contents (mass fraction <0.35). The difference for ACP02 and ACP11 – which both contain aluminium hydroxide in the same proportion but ACP02 includes vinyl acetate in its polymer matrix – is in the order of a 100% increase for the peak heat release rate. This 100% increase illustrates the problem with using organic content as an indicator of fire performance.

Most notably however, the shortcoming of using the organic content can be seen for all the non-ACP materials. The heat release rate for all these materials is significantly lower than the pure thermoplastic ACPs (ACP03 and ACP07) despite the fact they have similar or the same organic contents. The most extreme cases of this are for a phenolic composite (OTH01) and a foam (INS02) where the heat release is only in the range of 75–125 kW m^{-2}. The coefficient of determination, R^2, of a linear trend for all materials is 0.168 but this is not plotted for clarity.

A more generalised correlation can be found by plotting the TGA residue at 800 °C in an inert atmosphere against the peak heat release rate (Fig. 3, top right). The coefficient of determination for the same materials as above (i.e. all except thin film) is improved to 0.653. This may be more effective as a rapid screening evaluation, but still has limitations. This improvement in the correlation is due to the fact that the propensity for char formation is taken into consideration. This is beneficial for fire performance, as the heat feedback from the flame is inhibited by the insulating properties of the char. This is mainly beneficial over long periods but is still well reflected in the peak heat release rate as the char layer is developing during the initial stages of heat exposure. The ACPs are shown to have the highest residues, most likely due to the very large quantities of fire retardant included to adequately improve their performance.

Overall, for a rapid initial assessment using low cost methods then it appears that the residue in an inert atmosphere is suitable for obtaining an estimation of the peak heat release of a material. TGA tests are more rapid than cone calorimeter tests, require less material from buildings, and require less sample preparation, thus requiring less labour. Nonetheless, the screening would be as a means to cross-reference to the fire performance and would not be adequate by itself.

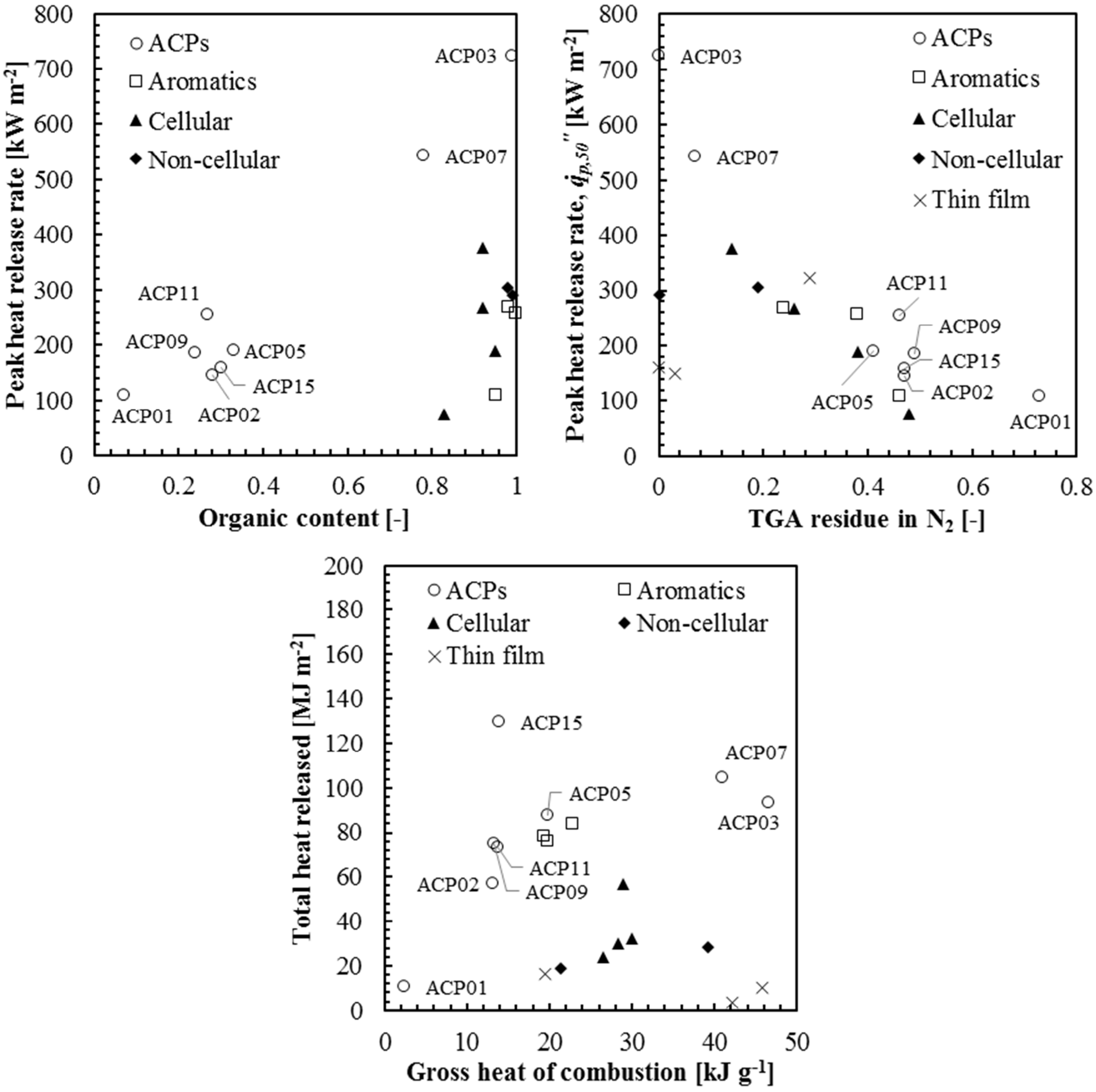

Fig. 3. Flammability trends of organic content against peak HRR (top left), inert residue at 800 °C against peak HRR (top right), and heat of combustion against the total heat released (bottom).

A breakdown in the trend can be seen for the thin film materials, and for one of the non-cellular insulations (Fig. 3, top right). For the thin films, the depth of the polymer layer is such that the burning rate cannot reach a maximum steady rate of burning. The flame growth following ignition is a feedback loop where heat from the flame increases the rate of volatiles generated, which increases the flame heat flux. When the polymer layer is thin, then this process is not able to reach a steady state and instead a decay phase initiates and extinction is reached rapidly.

Finally, the gross heat of combustion is shown against the total heat released (Fig. 3, bottom). The gross heat of combustion is a parameter which gives the total possible energy that can be released by a material under ideal conditions, and includes condensation of moisture vapour. While the net heat of combustion may be more pertinent, the gross heat of combustion is used in this comparison for simplicity. There appears to nonetheless be little correlation between the gross heat of combustion and the total heat released, suggesting that there are a large number of other phenomena which are complicating the analysis. One of these is likely to be combustion inefficiency, where insufficient oxidiser can reach the fuel surface in the cone calorimeter test. The rate of energy released is then reduced compared to the pure oxygen conditions in the bomb calorimeter. Another complication is the thickness of different materials in the cone testing, leading to higher total heat released when assessed per unit area. The heat transfer conditions will change depending on the thickness of the material e.g. whether or not the material is thermally thin or not, and thus more heavily influenced by boundary conditions.

The change in incident heat flux can lead to differences in the burning behaviour depending on the type of material. This behaviour is well known for many polymer-based materials [15]. The results of peak heat release rate for all materials at three incident heat fluxes – 35, 50 and 60, or 80 kW m^{-2} in some rare cases – are shown in Fig. 4.

The change in peak heat release rate (PHRR) is relatively constant for the ACPs with inorganic components. Many of the materials converge on the same PHRR (~200 kW m^{-2}) when exposed to 60 kW m^{-2}. The significantly higher PHRR for thermoplastics at 60 kW m^{-2} exposure is concerning since it suggests higher burning rates in the worst cast scenarios. Higher heat release rates increase the flame length which in turn increases the length preheated by the flame. This may lead to accelerating flame spread velocities which can propagate rapidly up a building.

The results of the polyester wool insulation, INS03, are poor due to the melting and regression of the surface. Furthermore, the material is highly heterogeneous leading to inconsistencies in the peak heat release rate. In contrast, the superior manufacturing quality and uniformity of expanded polystyrene, INS04, shows a more consistent trend despite the same difficulties with melting and surface regression. One of the polyurethane-based polyisocyanurate (PIR) cellular foams, INS05, shows a substantial decrease when exposed to higher heat fluxes. The formulation of PIR foams is highly complicated, and often a plateau in the behaviour is noted at moderate to high heat fluxes [16]. This is due to the extremely low thermal inertias, the chemical composition, and the formation of a protective char. At higher heat fluxes, the char is generated more rapidly and less pyrolysis gases released in the initial stages of exposure. The other insulation materials otherwise show a typical relationship with the incident heat fluxes. The highest heat release rates are consistently recorded for INS06, which is a rigid polyurethane foam.

The PHRR of aromatics shows little dependence in the incident heat flux. The charring nature of the materials means that the char layer which forms will begin to reduce the heat flux from the cone heater received by the material in-depth. As a result, heat is propagated by the hot char at a rate which is not heavily influenced by the external heat. A change in oxygen conditions, i.e. increased oxidiser flow, may however rapidly increase the burning rate.

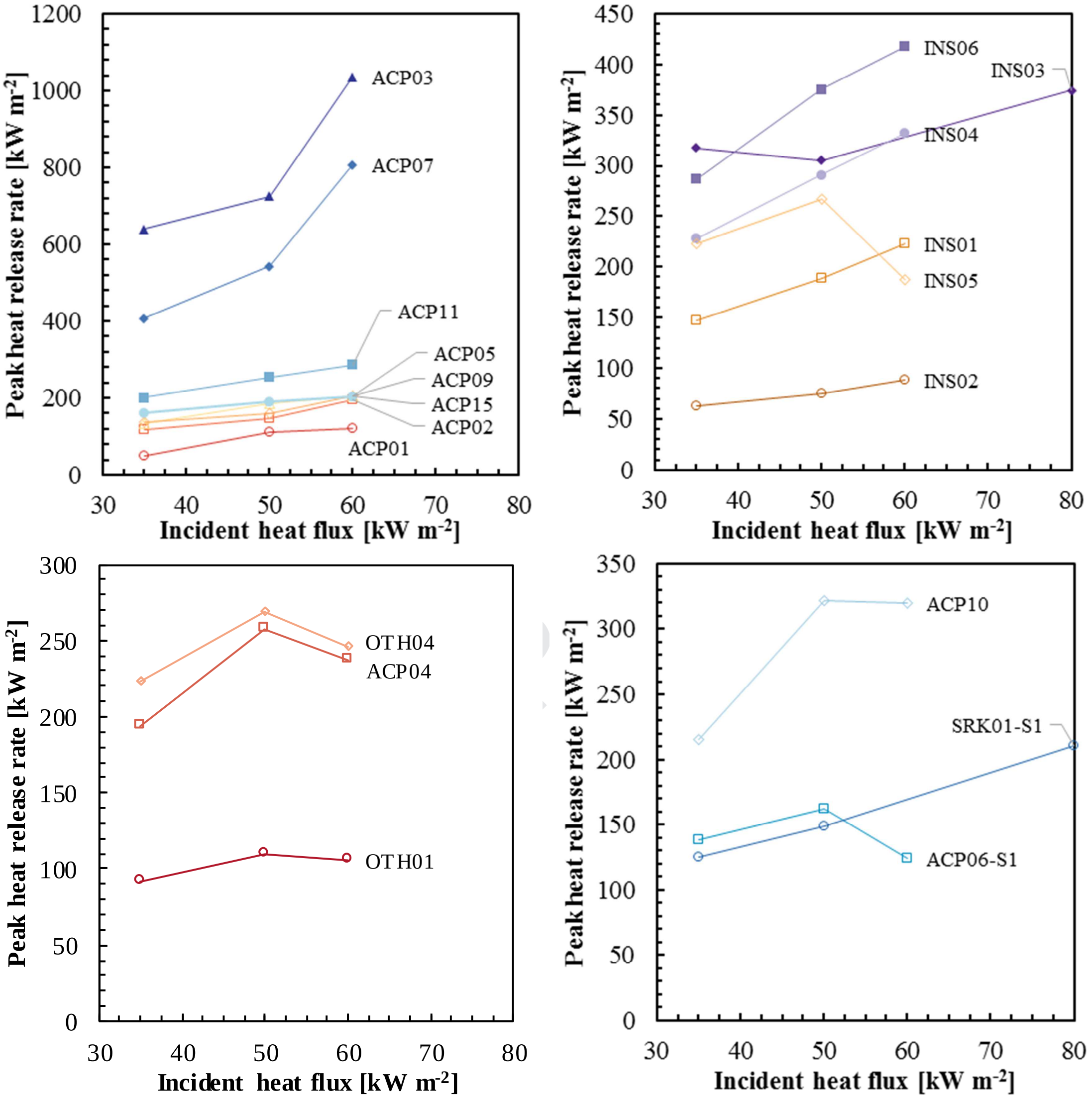

Fig. 4. Peak heat release rate for various incident heat fluxes in the cone calorimeter – ACPs (top left), insulations (top right), aromatics (bottom left), and thin films (bottom right). It should be noted that the magnitude of the ordinate axis is not consistent between plots.

Consistent behaviour is recorded in the PHRR of the weatherproofing membrane, SRK01due to the high quality manufacturing process which guarantees a constant thickness of material. For the other two thin films, ACP06 and ACP10, then the adhesive is not constant along the thickness of a panel, or between panels. The change in resin quantity is known from the mass measurements of each sample, and thickness measurements using digital callipers. The net result of this is that there is large variability in the results. This means that the performance is dictated more by the quantity of resin on a specific panel than by the incident heat flux. For ACP10, the estimated resin mass was approximately in the order of 1–2 times higher in 50 kW m^{-2} than the other heat fluxes. Only a limited number of samples were received, and thus this error could not easily be eliminated. These materials are a clear example where additional work is required but which are completely neglected. They are common replacement materials for “flammable” cladding (e.g. ACP03) but there is no assessment of their fire performance. These materials can only be used if their performance is known and quantified, so the fire risk can be assessed.

7. Model application

Ignition and heat release are two fundamental aspects in flame spread, particularly for vertical or wind-aided flame spread. The application of a simple model allows insight into the potential flame spread performance of cladding materials by accounting for the combined contributions of the ignitability and the burning behaviour.

The steady flame spread velocity for concurrent flow conditions for a thermally thick solid is given by Eq. (1) [17]:

$$v_p = \frac{4}{\pi} \frac{\dot{q}_f''^2 (x_f - x_p)}{k\rho c \, (T_{ig} - T_\infty)^2} \tag{1}$$

Where v_p is the spread velocity, $\dot{q}_f''$ is the heat from the flame over the pyrolysis length $x_f - x_p$, the term x_f is the flame height, x_p is the pyrolysis height, the lumped parameter $k\rho c$ is the thermal inertia, $T_{ig}$is the ignition temperature and $T_\infty$is the ambient temperature. Quintiere *et al.* [18] found the following relationship for the flame height against a vertical wall (Eq. (2):

$$x_f = k_f \dot{Q}_f'' x_p \tag{2}$$

Where k_f is an empirical constant and $\dot{Q}_f''$ is the heat release per unit area of the material. The latter is obtained from the cone calorimeter testing, using the peak heat release rate for tests with an incident heat flux of 50 kW m^{-2}. Substituting Eq. (2) into Eq. (1) yields Eq. (3):

$$\frac{v_p}{x_p} = \frac{4}{\pi} \frac{\dot{q}_f''^2 (k_f \dot{Q}_f'' - 1)}{(T_{ig} - T_\infty)^2 kpc} \tag{3}$$

Which gives an estimate of the flame spread velocity for a given pyrolysis height. This contains two parameters, among others, which have been drawn out by other authors. Quintiere *et al.* [18] highlighted the significance of the *a* parameter in describing the contribution of the heat release of material to the upward flame spread propagation, Eq. (4):

$$a = k_f \dot{Q}_f'' - 1 \tag{4}$$

While Tewarson [14] has given the thermal response parameter (*TRP*) as a fundamental material property to describe ignitability and hence subsequent flame propagation, Eq. (5):

$$TRP = (T_{ig} - T_\infty)\sqrt{k\rho c} \tag{5}$$

A critical condition can further be highlighted as the ‘*a*’ parameter tends to zero. Rearranging Eq. (4) for a = 0 then gives an estimation of the critical heat release rate required to maintain positive, i.e. accelerating, flame spread. This is found to be $\dot{Q}_f''$ = 100–160 kW m^{-2} for values of k_f = 0.006–0.01 kW^{-1} m^2. Thus, in cases where the heat release is sufficiently small then upward flame spread is predicted to not occur.

Table 2. Summary of computed properties relevant to vertical flame spread.

ID	Category	a - Eq. (4)	TRP kW $s^{1/2}$ m^{-2} Eq. (5)	v_p/x_p s^{-1} Eq. (3)
INS02	Cellular	-0.25	112	-15.58
OTH01	Aromatic	0.09	613	0.19
ACP01	ACP	0.10	602	0.21
ACP15	ACP	0.59	552	1.55
ACP02	ACP	0.45	459	1.71
ACP09	ACP	0.85	527	2.44
ACP05	ACP	0.90	413	4.18
ACP06-S1	Thin film	0.62	307	5.20
ACP11	ACP	1.55	402	7.62
INS03	Non-cellular	2.05	437	8.56
ACP04	Aromatic	1.57	352	10.05
OTH04	Aromatic	1.68	320	13.04
INS04	Non-cellular	1.91	301	16.71
SRK01-S1	Thin film	0.49	115	29.21
ACP10	Thin film	2.22	243	29.88
ACP03	ACP	6.25	300	55.05
ACP07	ACP	4.43	244	59.43
INS01	Cellular	0.88	85	98.51
INS05	Cellular	1.67	116	98.94
INS06	Cellular	2.76	115	165.94

These properties have ultimately been calculated and summarised for all the cladding materials studied (Table 2). For this, k_f has been taken to be 0.01 kW^{-1} m^2, and $\dot{q}_f''$ has been assumed a constant value of 25 kW m^{-2} [17,18], although values in the literature vary from 20–60 kW m^{-2} [19,20]. The aim of this is a comparison, and thus the selection of these constants is arbitrary. The heat release of the material, $\dot{Q}_f''$, was taken from the peak heat release rate in the cone, as described earlier. This will have a tendency to overestimate the flame spread in all cases, but will be particularly conservative for the case of charring materials with high thermal inertia, namely the cellular insulation foams. This is due to the fact that their peak heat release is short, while the burning time is much longer as the char layer builds up. Later literature [12,21] has suggested that an average peak should be taken but there is not a clear definition of what form this should take. This would thus require assumptions about which timescale should be selected, and also how to best eliminate the effects of smouldering which will contribute heat release in the later stages for some materials. For this reason, the conservative use of peak heat release rate for $\dot{Q}_f''$ is maintained.

A negative parameter is predicted for INS02, a phenolic foam insulation. Other ACPs and OTH01 also have values close to zero (i.e. <1.0), suggesting little potential for flame spread. On the other end of the scale, the thermoplastics and the insulation foams with very low thermal inertias are expected to have rapid rates of spread. This is based on the very high heat release rates leading to large flame heights for the thermoplastics, and rapid surface heating for the insulations due to their thermal inertia. These predictions have an apparent good qualitative agreement with results obtained in vertical Lateral Ignition and Flame spread Tests (LIFT). However, until detailed analysis is performed on the vertical flame spread then a full comparison and assessment cannot be made.

The two ACPs with only aluminium hydroxide as the filler, ACP02 and ACP11, show vastly different behaviour. This suggests that the addition of vinyl acetate in ACP02 would significantly inhibit the propensity for flame spread. The magnesium hydroxide-based ACPs – ACP15, ACP09 and ACP05 – all suggest little spread potential but there is a wide range for these materials. The aromatics – ACP04, OTH01 and OTH04 – show a wide range of potential flame spread. The phosphorous-based flame retardant, high density and high phenol resin content of OTH01 contribute to very low heat release and a high charring yield. Conversely, both ACP04 and OTH04 contain no retardants and may be expected to spread flame in the event of a fire.

Ultimately, these materials are included as part of a system and there will be complicated interactions between the different elements. Some work has been performed [22] to investigate the interactions between different ACPs and insulations separated by a cavity, which has also been represented by the seven full-scale tests commissioned by the Government in the UK [23]. The intermediate-scale tests gave the opportunity to identify the contribution of individual components, which can be tied into the Cladding Materials Library data and the analysis here. Qualitatively, the results presented in the simple model here are in agreement with the behaviour in the intermediate-scale tests, the large-scale tests commissioned in the UK, and large-scale tests performed as part of this project. More thorough analysis is required and significantly more testing is required to robustly connect material-level and full-scale façade fire behaviour.

Through methodical and thorough understanding of the materials and systems used, the eventual development of simple models may be possible. This allows engineers to adequately design façade systems, instead of using arbitrary metrics such as polyethylene content which provide no evidence of performance. Optimisation of buildings by balancing a flammability index with other design objectives [24] will enable more efficient and effective buildings in the future.

8. Conclusions

- The cladding crisis encompasses all materials in the system, and is not limited to ACPs. The organic content is shown to be a poor indicator of fire performance and ignitability for ACPs, and has no application to non-ACPs, which account for around half of the materials. For rapid initial screening, the TGA residue in nitrogen appears to offer some improvement in the correlation with peak heat release rate. TGA tests are rapid, require little material from buildings, and require relatively little sample preparation.
- A systematic assessment of the fire behaviour of different components in a cladding system have been shown and described. The different components are shown to have

very different performances, and even within a single category there is a wide range of performance.

- A simple model to inform on potential vertical flame spread identified materials likely to undergo rapid spread rates and those where spread is less likely to occur. Some phenolic-based materials and heavily retarded charring-forming materials were indicated to not promote spread, while pure thermoplastics, cellular insulation and some thin film organics were expected to perform poorly. There is apparent good agreement with the vertical flame spread LIFT results but this requires in-depth analysis of the flame spread results to be certain.
- Further work is required to understand the interaction between materials and effects observed at larger-scales. Material-level analysis acts as an initial step in building knowledge, and ensuring maximum value can be gained from expensive full-scale tests.

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10. References

[1] Department of Housing and Public Works – Queensland Government, Guideline – For assessing buildings with combustion cladding, Version 2, (2019) 1–58. http://www.hpw.qld.gov.au/SiteCollectionDocuments/GuidelineAccessCombustibleBuildings.pdf.

[2] J.P. Hidalgo, M.S. McLaggan, A.F. Osorio, M. Heitzmann, C. Maluk, D. Lange, J. Carrascal, J.L. Torero, Protocols for the Material Library of Cladding Materials – Part I: Framework, UQMLCM2019-01, St Lucia, Australia, 2019. https://espace.library.uq.edu.au/view/UQ:733236.

[3] M.S. McLaggan, J.P. Hidalgo, A.F. Osorio, M. Heitzmann, J. Carrascal, D. Lange, C. Maluk, J.L. Torero, The Material Library of Cladding Materials, Data Collection, (2019). doi:10.14264/uql.2019.441.

[4] J.P. Hidalgo, M.S. McLaggan, A.F. Osorio, M. Heitzmann, C. Maluk, D. Lange, J. Carrascal, J.L. Torero, Protocols for the Material Library of Cladding Materials – Part IV: Use and interpretation, UQMLCM2019-04, St Lucia, Australia, 2019. https://espace.library.uq.edu.au/view/UQ:0aec94c.

[5] M.S. McLaggan, J.P. Hidalgo, M. Heitzmann, A.F. Osorio, C. Maluk, D. Lange, J. Carrascal, J.L. Torero, Protocols for the Material Library of Cladding Materials – Part II: Sample preparation and testing methodologies, UQMLCM2019-02, St Lucia, Australia, 2019. https://espace.library.uq.edu.au/view/UQ:e4fe2d0.

[6] M. Heitzmann, M.S. McLaggan, J.P. Hidalgo, A.F. Osorio, C. Maluk, D. Lange, J. Carrascal, J.L. Torero, Protocols for the Material Library of Cladding Materials – Part III: Sensitivity studies, UQMLCM2019-03, St Lucia, Australia, 2019.

https://espace.library.uq.edu.au/view/UQ:1d87ca0.

[7] Internation Standards Organisation, ISO 11358-1: Plastics -- Thermogravimetry (TG) of polymers -- Part 1: General principles, (2014).

[8] British Standards Institution, BS EN ISO 1716:2010 Reaction to fire tests for products — Determination of the gross heat of combustion (calorific value), Brussels, 2010.

[9] British Standards Institution, BS ISO 5660-1:2015. Reaction-to-fire tests — Heat release, smoke production and mass loss rate. Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement), Brussels, 2015.

[10] R. Long, J.L. Torero, J. Quintiere, A.C. Fernandez-Pello, Scale And Transport Considerations On Piloted Ignition Of PMMA, Fire Saf. Sci. 6 (2000) 567–578. doi:10.3801/IAFSS.FSS.6-567.

[11] D.D. Drysdale, Fundamentals of the Fire Behaviour of Cellular Polymers, Cell. Polym. 4 (1985) 405–419. doi:10.1007/978-94-009-3443-6_4.

[12] T.G. Cleary, J.G. Quintiere, Flammability Characterization of Foam Plastics. NISTIR 4664, Gaithersburg, MD, 1991. doi:10.6028/NIST.IR.4664.

[13] J.P. Hidalgo, J.L. Torero, S. Welch, Experimental Characterisation of the Fire Behaviour of Thermal Insulation Materials for a Performance-Based Design Methodology, Fire Technol. 53 (2017) 1201–1232. doi:10.1007/s10694-016-0625-z.

[14] A. Tewarson, Flammability Parameters of Materials: Ignition, Combustion, and Fire Propagation, J. Fire Sci. 12 (1994) 329–356. doi:10.1177/073490419401200401.

[15] A.B. Morgan, M. Bundy, Cone calorimeter analysis of UL-94 V-rated plastics, Fire Mater. 31 (2007) 257–283. doi:10.1002/fam.937.

[16] J.P. Hidalgo, J.L. Torero, S. Welch, Fire performance of charring closed-cell polymeric insulation materials: Polyisocyanurate and phenolic foam, Fire Mater. (2018) 1–16. doi:10.1002/fam.2501.

[17] K. Saito, J.G. Quintiere, F.A. Williams, Upward Turbulent Flame Spread, Fire Saf. Sci. 1 (1986) 75–86. doi:10.3801/IAFSS.FSS.1-75.

[18] J.G. Quintiere, M.T. Harkleroad, Y. Hasemi, Wall Flames and Implications for Upward Flame Spread, Combust. Sci. Technol. 48 (1986) 191–222. doi:10.1080/00102208608923893.

[19] G. Grant, D. Drysdale, Numerical modelling of early flame spread in warehouse fires, Fire Saf. J. 24 (1995) 247–278. doi:10.1016/0379-7112(95)00022-L.

[20] Y.P. Lee, M.A. Delichatsios, G.W.H. Silcock, Heat flux distribution and flame shapes on the inert facade, Fire Saf. Sci. (2008) 193–204. doi:10.3801/IAFSS.FSS.9-193.

[21] T. Cleary, J. Quintiere, A Framework For Utilizing Fire Property Tests, Fire Saf. Sci. 3 (1991) 647–656. doi:10.3801/IAFSS.FSS.3-647.

[22] B. Garvey, J. Ogilvie, J. Carrascal, D. Lange, C. Maluk, M.S. McLaggan, A.F. Osorio, J.L. Torero, J.P. Hidalgo, Experimental methodology to study the fire contribution of cladding materials, in: S. Grayson (Ed.), Proc. Interflam, Interscience Communications Ltd, London, UK, 2019.

[23] BRE Global, BRE Global Client Report – BS8414-1:2015+A1:2017 test, DCLG test 1, Watford, UK, 2017. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/648789/DCLGtest1_BS_8414_Part_1_test_report_Issue1.2.pdf.

[24] M. Bonner, G. Rein, Flammability and Multi-objective Performance of Building Façades: Towards Optimum Design, Int. J. High-Rise Build. 7 (2018) 363–374.

Figure captions

Fig. 1. Heat release rate per unit area as a function of time for ACPs (top left), insulations (top right), aromatics (bottom left) and thin film samples (bottom right).

Fig. 2. Polymer content against critical heat flux for flaming ignition (top left), apparent thermal inertia (top right), and TRP (bottom).

Fig. 3. Flammability trends of organic content against peak HRR (top left), inert residue at 800 °C against peak HRR (top right), and heat of combustion against the total heat released (bottom).

Fig. 4. Peak heat release rate for various incident heat fluxes in the cone calorimeter – ACPs (top left), insulations (top right), aromatics (bottom left), and thin films (bottom right). It should be noted that the magnitude of the ordinate axis is not consistent between plots.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: