Fire Safety Engineering Research Group
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THE UNIVERSITY OF QUEENSLAND
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Protocols for the Material Library of Cladding Materials - Part I: Framework

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Executive Summary

Recent fire events in buildings containing cladding materials, such as aluminium composite panels (ACP) and insulation materials, have raised concerns regarding the risk that façade systems may pose to the safety of building occupants and emergency services.

The façade system has to be treated as part of the fire safety strategy and therefore its performance needs to be assessed in the context of the overall fire safety strategy of the building. Qualified fire safety engineers are responsible for understanding this risk based on a quantification of the external fire spread rate and the vulnerabilities of the fire safety strategy of the building to such an event.

The same approach applies in the case of existing buildings. A comprehensive fire risk assessment needs to be conducted by a qualified fire safety engineer. Upon completion of that assessment, the competent fire safety engineer can propose remedial works whenever appropriate and quantitatively demonstrate that the life safety of building occupants can be guaranteed within adequate engineering safety margins. Building façades are however very complex systems, whose performance under fire conditions depends on multiple details, e.g. materials, fixings, installation, maintenance, cavity barriers, window connections, etc. The performance of the system is in many cases very sensitive to individual parameters and also to the complex couplings between them. Therefore, the fire performance of the façade system may be significantly affected by any change in any of these variables.

Worldwide, as in Australia, several frameworks are being proposed to assess the risk of fire spread. In some cases the approach followed attempts to establish a hazard classification for cladding materials based only on the percentage of polymer and inert material present on the rainscreen (ACP). This is the case for the approach proposed by the Insurance Council of Australia (ICA). Classifications of this type are based on the results of large scale tests. In particular, a series of seven full-scale fire tests (BS 8414-1) sponsored by the Ministry of Housing, Communities and Local Government (MHCLG) in the UK and performed by BRE Global. The BRE report only provides a limited set of data for specific conditions, which must be considered with extreme care when data within the BRE report is extrapolated into other conditions.

Outcomes from full-scale BS 8414 façade tests shall be interpreted in the context of the Approved Document B, which as indicated in its paragraph 1.b of Appendix A, these data are only to be used as test evidence by appropriately qualified Fire Safety Engineers. Approved Document B recognises that the data applies only to the exact configurations tested. Thus, extrapolation must be done with careful engineering judgement.

Competent fire safety engineers must be proficient in the use of tools and data that enables quantification of the performance of façade systems during fire. Such tools and data must include the detailed performance of materials and systems. The level of information required for a quantitative performance assessment is much more extensive than what can be provided by a pass-fail (compliance) framework. As a result, approaches based on simple material composition do not provide qualified fire safety engineers with a path for any type of quantification, besides a series of limited full-scale demonstrative test results.

To date, there is no sufficient scientific and peer-reviewed information that establishes the relationship between the percentage of inert material in any polymer and vertical flame spread rates. The presence of inert materials may reduce the effective heat of combustion, which is one of several variables affecting flame spread. The presence of inert materials can also affect other properties of the polymer that could potentially result in the opposite effect. None of these relationships can be established from the existing large-scale test data base. Predicting the actual fire performance of different types of materials is not a trivial task given the different processes a material undergoes during a fire. Therefore, classification of the hazard requires understanding phenomena beyond the material identification and heat of combustion. The phenomena affecting flame spread include ignition (flame formation), energy release (heat of combustion and burning rate), heat feedback, flow characteristics among other mechanisms supporting flame spread.

A further limitation is that the existing evidence is provided for a narrow range of polymers. There still remains a large number of polymers, additives and fire retardants that have not been analysed. As an example, the screening protocol developed by BRE focused on the identification of the core material inside ACPs. Out of 2,104 samples received by BRE for testing, a total of 1,396 (66%) were rejected. The focus of the BRE study was on ACP's therefore materials that did not form part of an ACP (but that could be part of a façade system) were not tested.

The University of Queensland, in collaboration with the Non-Conforming Building Products (NCBP) Audit Taskforce in the State of Queensland, has proposed an engineering framework which enables a robust methodology to assess the fire hazard of cladding materials in existing buildings based on a thorough understanding of the relevant fire phenomena. To enable this, a comprehensive material library with relevant fire performance information on façade systems is being developed and will be made public. The methodology is not intended to determine if any specific façade design is safe or not; instead it provides the data necessary for a competent fire safety engineer to conduct the necessary analyses that determines the safety of the façade system in the context of the fire safety strategy of the building and based on a specific set of materials, configuration and other conditions that may be relevant.

The methodology developed to build the material library consists of two testing protocols: (i) a screening testing protocol that enables a quick testing turnout and quick identification of the product type, and (ii) a detailed testing protocol that enables the fire performance of the material to be characterised. The screening testing protocol aims at (A) a material identification and (B) an assessment of the thermal decomposition, which is to be applied to every cladding material. The detailed testing protocol consists of the screening tests and further incorporates a characterisation of (C) the heat of combustion; (D) ignition parameters such as critical heat flux for ignition, thermal inertia and time-to-ignition under different heat fluxes; (E) burning behaviour (heat release rate, burning rate and effective heat of combustion); and (E) flame spread parameters of particular selected materials. The detailed testing protocol thus delivers all the data necessary for a fire safety engineers to conduct a comprehensive engineering assessment – fundamental for the future development of tools to assess fire spread of façade systems. Cross-referencing data from both protocols will allow a comprehensive characterisation of a wide range of materials. The protocols developed by The University of Queensland have taken an approach that aims to categorise a wide array of materials, including those which are not ACPs.

This methodology is based on well-established testing frameworks widely accepted in the fire safety community and on research on the performance of ACPs and insulation materials at The University of Queensland and the University of Edinburgh. It is extremely important to reiterate that the material library does not provide a characterisation of the fire risk associated with the use of cladding materials; instead, the material library provides data and tools to inform competent fire safety engineers. This framework adds value at a small cost to allow competent engineers to make good decisions that satisfy the aims of life safety and property protection.

1 Background

The Fire Safety Engineering Research Group at The University of Queensland (UQ) has proposed a fire testing protocol at the request of the Non-Conforming Building Products (NCBP) Audit Taskforce in the State of Queensland. The aim of this protocol is to generate a database (Material Library) consisting of a characterisation of the fire performance of multiple cladding materials (hazard classification) including aluminium composite panels (ACP), insulation materials, and any other potentially combustible product that may be included in a façade system.

Recent fire events in buildings containing ACPs and insulation materials in the United Kingdom, the United Arab Emirates and Australia have raised concerns regarding the safety risks that these systems pose to building occupants and emergency services personnel. In the State of Queensland (Australia), the NCBP Audit Taskforce was established to address this issue. The Fire Safety Engineering Research Group at The University of Queensland (UQ Fire), closely collaborating with the Queensland Fire and Emergency Services (QFES), provided independent expert advice to the NCBP Audit Taskforce to assist the development of recommendations for enhancing public safety.

In recent years academics within The University of Queensland have actively researched the fire performance of cladding products such as ACPs and insulation materials, which has been motivated by the lack of publicly available data regarding the flammability of these products and absence of tools to identify the fire risks of façade systems. Initial stages of this research have focused on developing a practical testing protocol that enables fire safety engineers to quantify the fire behaviour of cladding materials and generate comprehensive risk assessments based supported by relevant experimental data. The testing protocol aims at assessing the hazard of cladding materials using a multi-scale testing approach ranging from the characterisation of the material chemical composition up to flame spread at bench-scale. The testing protocol also includes an assessment of the ignitability and burning behaviour of the cladding materials. Large-scale tests, albeit desirable as a demonstration of the performance of cladding products and particular façade systems under specific conditions, are not initially included within the scope of this protocol. Although large-scale tests may provide the opportunity to complete the full-characterisation of the products along the proposed testing, their cost, timeframe, and complexity negate the perceived advantages. The approach proposed then focuses on the fundamental fire behaviour for an extended number of materials at the bench scale, rather than a large-scale approach with a limited number of façade systems. Large-scale testing may still be incorporated in the future, particularly once a significant database of materials have been added to the proposed Material Library and façade designs are made available by designers.

It is extremely important to highlight that the Material Library does not provide a characterisation of the fire risk associated with the use of cladding materials. The Material Library is a tool to inform competent fire safety engineers regarding the fire hazard from these materials. For instance, the same cladding used in two different buildings could pose a very different risk for the life safety of the occupants. Life safety of building occupants and emergency services personnel during and after a fire can only be quantified within the scope of the defined fire safety strategy. Therefore, the purpose of the Material Library is to complement the fire risk evaluation of façade systems containing cladding materials such as ACPs and insulation materials. The Material Library will assist the decision-making of fire safety engineering practitioners. This dataset will be publicly available to enable improving the safety of the community in Queensland, Australia and worldwide.

The database may be continously updated with the support of the fire safety engineering community and product manufacturers willing to share technical data that can feed into the Material Library.

2 Fire safety issues involving combustible cladding

2.1 The Fire Safety Strategy and external fire spread

One key intent of worldwide building fire safety codes relies on the premise that no external fire spread will occur. Code-based solutions (e.g. Deemed-to-Satisfy (DtS) solutions in the National Construction Code in Australia) implemented within these codes correspond to standard solutions that deliver a fire safety strategies that guarantee the life safety of building occupants.

These implicit fire safety strategies do not allow for the possibility of external fire spread. In the context of prescriptive solutions, the fire is assumed to be contained in the room of origin (compartmentation). Thus, any type of external fire spread will result in loss of compartmentation and failure of the implicit fire safety strategy. Furthermore, fire brigade intervention procedures do not consider multiple floor fires. There should therefore not be an expectation that the fire brigade will guarantee suppression and rescue in the event of a fire spreading among multiple floors.

If external fire spread occurs, life safety may be threatened as the fire safety strategy of the building is not guaranteed to perform adequately under these circumstances. If the fire safety strategy is sufficiently robust – that is a number of redundancies are included in the design – then the life safety of building occupants may be unaffected by external fire spread. Nevertheless, fire safety codes do not guarantee this. If reliance is to be placed on the redundancies then, this needs to be assessed in an explicit manner and outside the realm of prescriptive approaches (DtS solutions).

Thus, the risk that cladding materials pose to the life safety of building occupants (including emergency services personnel) is determined by:

(i) The potential external fire spread through the building façade system, and;

(ii) The response of the fire safety strategy of the building to this event.

This risk is to be established by competent fire safety engineers, who shall:

(i) Quantify, to the extent and precision possible, the external vertical and horizontal fire spread rate and the contribution of the façade fire to the onset of internal fires away from the compartment of origin;

(ii) Identify the vulnerabilities of the current fire safety strategy of the building to such an event, and;

(iii) Identify the risk that an external fire poses to adjacent buildings.

Upon the completion of that assessment, competent fire safety engineers can propose any necessary remedial works so that the life safety of building occupants is guaranteed with adequate engineering safety margins.

The Building Code of Australia (BCA), similarly to other international codes, shares the same intent: code-based (DtS) solutions (and therefore its implicit fire safety strategies) rely on the assumption that external fire spread does not occur and that compartmentation is satisfied. However, relaxation of code requirements for building attachments and other elements has led to ambiguities in the fire safety codes requiring proper evaluation by properly qualified fire safety engineers.

Fire safety engineers are responsible for an adequate design of the fire safety strategy. The challenges posed by external fire spread to the fire safety strategy of existing buildings are, for instance:

(i) Example 1: strategies relying on staged-evacuation and pressurisation;

(ii) Example 2: strategies relying on a single stair; or

(iii) Example 3: strategies for communicated spaces.

These are simple examples that depend on the robustness of the different layers of the fire safety strategy designed for any specific building.

2.2 General mechanisms of external fire spread in buildings

Three general mechanisms of external fire spread may be obtained in a building:

(i) Through **relative deformations of the structure and the façade system**, allowing for penetrations that enable the fire to travel from one compartment to another. To control the external fire spread through this mechanism, it must be ensured that the thermal deformations of the structure and the façade system are compatible in the event of a fire. Thermal deformation of the structure and the incapacity for the façade system to cope with this fire-induced deformation may enable the smoke and flames to travel into compartments away from the compartment of origin. A fundamental quantification of this problem relies on analysing the mechanical response and compatibility of the structure and the façade system in the event of a fire. This analysis must also account for the detailing of the structure-façade connections; restraining conditions, cavity barriers, etc. Due to the increased complexity of façade systems (and also structural systems), full-scale system tests have generally been proposed to assess potential worst-case scenarios (e.g. ASTM E2307, which however only assesses the deformation of the façade system but not the structure).

(ii) Through the **ignition of the compartment fuel loads due to the heat flux from the projected external flames** from the floor below. To control the external fire spread through this mechanism, it must be ensured that the radiation impacting the compartment above from the external plume is not sufficient to ignite fuel loads inside compartments away from the compartment of origin. A fundamental quantification of this problem relies on a heat transfer analysis between the external fire plume and the fuel loads in compartments away from the compartment of origin. Engineering solutions are based on designing adequate floor projections or spandrels preventing the external fire plume from igniting the floor above. The presence of glazing has to be considered because the failure of glazing can also be a mechanism by which the fire can progress into adjacent compartments. Similarly to (i) above, full-scale tests may be found to assess this spread mechanism in façade assemblies (e.g. SP Fire 105, LEPIR 2 or MSZ 14800-6:2009).

(iii) Through **ignition and flame spread of the facade components (cladding or insulation material) due to any potential ignition source (e.g. external fire or local ignition)**. To control the external fire spread through this mechanism, it must be ensured that the façade materials and façade systems do not allow a flame to spread vertically or horizontally. A conservative engineering solution relies on the use of non-combustible materials. If combustible materials are used, a thorough ignition and flame spread analysis must be carried out. The ignition and flame spread analysis must aim at meeting the objective of preventing the spread of fire to adjacent compartments. If any kind of flame spread is to be allowed, then a competent fire safety engineer should be able to establish that additional components of the fire safety strategy will deliver sufficient redundancies that an adequate outcome can be guaranteed. This implies fully revisiting the fire safety strategy and is outside the remit of prescriptive design. Similar to (i) and (ii), the increased complexity of systems may lead to the use of full-scale system tests, which can be used as test evidence towards a detailed performance analysis of the fire safety strategy (e.g. BS 8414-1).

In any of the above-mentioned fire spread mechanisms, any life safety assessment would consist of quantifying the fire spread rate at the façade as this directly affects the performance of the fire safety strategy of the building.

The competent fire safety engineer must be provided with tools and data to enable the quantification of the performance of a façade system under fire conditions. These data must include the performance of materials and systems in a quantitative manner. Test data based on a pass-fail framework (AS 1530.1-1994:R2016, AS 5113:2016) can only be used by a competent fire safety engineer as test evidence towards a detailed performance analysis of the fire safety strategy. It should be noted that if a prescriptive framework is to be followed, a conservative solution based on non-combustibility must be used, as stated by code-based solutions, albeit limiting innovation in the built environment.

2.3 Assessing complexity: fire testing regimes

Within the context of defining an adequate fire safety strategy, fire safety engineers are responsible for assessing the risk that a facade system may pose to the functionality (life safety, operations or property protection) of the building. This assessment requires an explicit quantification of the external fire spread risk based on the performance of the system (and its components).

The overall system performance depends both on the performance of every single component of the façade system as well as the interaction between all of these components. To date, an adequate quantification of the performance based on first principles is not possible due to the lack of adequate data and models. Without a comprehensive data set of the fundamental performance of materials and systems (based on first principles), competent fire safety engineers are unable to provide an adequate performance assessment, and consequently, an evaluation of the impact of an external fire spread to the building functionality.

Fundamental data is urgently required. However, given the extended number of existing materials and façade/cladding systems, this is a very complex task. Several fire testing regimes are available to provide the relevant data. These fire testing regimes are generally embedded in fire safety design frameworks:

(i) A **pass-fail testing regime**: this approach refers to a framework in which a reference performance criterion is established. Two examples of this approach are shown below:

  - AS 1530.1-1994 (R2016), the combustibility test, in which the temperature within a small furnace is set as performance criterion and if the material tested releases an amount of energy lower than a critical value, the material passes the test and is deemed non-combustible.
  - EN ISO 1716, the heat of combustion test used in the European reaction-to-fire framework EN 13501-1. The heat of combustion is the performance criterion, and if the material tested results in a value lower than a critical value, the material passes the test and is deemed class A1 or A2.
  - AS 5113:2016, based on BS 8414 and ISO 13785-2, façade scenario test in which a system is tested using an established wood crib fire at the bottom of the façade and thermocouples are used to identify flame spread. To allow for more materials to be used, scenario tests have been established where assemblies are being tested to demonstrate an adequate extent of fire spread. While these tests are presented within a pass/fail framework, they are only to be used as test evidence for a competent fire safety engineer. This is explained in detail in BR 135, which is the document accompanying the original design of this test.

(ii) A **performance testing regime**: this approach refers to a framework that has identified the fundamental phenomena governing the problem, and test outputs (data) may be used quantitatively in the design by competent engineers. Some of the previous tests can be used as performance tests if sufficient data is collected from the test and assessed rationally.

A pass-fail testing regime needs to be extremely conservative in nature, given that it must work for all sorts of scenarios independent of the complexity of the problem. An example is the general requirement (or intent) that non-combustible materials must be used in façades if a code-based solution is used. Given the conservative nature of this approach, this requirement means effectively that practitioners do not need to understand the complexity of the system if all materials are non-combustible. Additionally, compliance testing tends to prescribe a single scenario (boundary condition). Thus, its use is restricted to situations where that boundary condition is relevant. For a boundary condition to be relevant a professional assessment is necessary. It is rare when a boundary condition can be deemed universal and compliance testing does not need the involvement of a qualified professional.

The use of a compliance testing approach is most likely not adequate when new materials or systems are introduced in the market without a clear understanding of the challenges that these new systems might bring to the validity of the testing procedure. The suitability of the compliance testing approach must be therefore revised with new systems that may threaten the suitability of the current framework. This is the reason why a compliance scenario test can only be used in the context of a fire engineering analysis and as test evidence of performance. This form of testing has no standalone value. In further discussion, this form of testing will be considered just another form of performance testing.

A performance-testing regime needs to provide quality data and tools so that engineers can adequately use them. This implies a significant level of instrumentation, far beyond the level of instrumentation used in any existing compliance test. Performance testing usually requires the generalisation of several fire scenarios, so that different failure modes or behaviours may be identified. This approach allows engineers to optimise solutions based on the identified hazards and performance criteria.

Both compliance and performance testing regimes can be applied in two differentiated approaches:

(i) The **material approach**: this approach refers to a testing regime focused on the performance of a single component (material), tested in isolation.

(ii) The **system approach**: this approach refers to a testing regime focused on the performance of the system as a whole, based on the interaction of its components (materials).

The scale, i.e. physical size of the test specimens, is another important factor to consider, whether material, bench, intermediate or full-scale testing is pursued. Ideally, full-scale is generally desired from a demonstration point of view as it represents the closest model to reality. Full-scale testing, if applied as a performance-testing regime, is highly recommended to inform the engineers regarding fire spread velocities and failure modes to be referenced for design or risk evaluation.

Although full-scale tests provide the opportunity to complete the full-characterisation of the product along the proposed testing, their cost, timeframe, and complexity negate the perceived advantages. The right scale must be defined by an understanding of the relevant phenomena. Extrapolation of bench-scale data to full-scale, whilst possible, must be applied with great care. An intermediate-scale approach is a cost-effective solution, however, it requires fundamental data at the material and bench scale so that data can be interpreted adequately.

For the issue of external fire spread risk for building facades, the extensive number of materials and systems does not enable a full-scale system testing approach to be practically applied to all existing facade systems. Additionally, the performance identified in this test is strictly dependent on the exact configuration tested.

2.4 International approaches to addressing the issue

Several approaches attempting to address the fire safety issues of façade systems and tall buildings may be found around the world. Unfortunately, these approaches lack a shared holistic approach to the problem. Several attempts have focused on simplifying the problem based on a one size fits all solution, such as prescribing allowed materials or testing requirements. Testing requirements can be found at different scales, from bench to full scale. A review of some of these approaches is presented below.

2.4.1 Material-scale testings

An example of a material-scale testing approach is the protocol proposed by the Insurance Council of Australia (ICA). This protocol aims at providing a hazard identification for ACP-type materials for assessment and reporting of the residual risk in buildings containing these materials, and which may be suitable for both building owners (to make decisions) and underwriters (to set premium). The ICA has proposed a series of categories based on the content of organic polymer and inert material in the ACPs – initially, it was proposed a classification based solely on the content of polyethylene (PE) and ethylene-vinyl acetate (EVA).

A series of issues may be identified with the framework proposed:

(i) Clear definition of risk term and end-use of the hazard classification.

- The proposed protocol has as a purpose "to provide a methodology to assess the residual risk for both building owners (to make decisions) and underwriters (to set premiums)". It is unclear whether the definition of risk adheres to "the risk of a building material potentially sustaining external fire spread" or "the risk that external fire spread may pose to the life safety of building occupants". The former definition of risk requires understanding the material/product/system performance under specific conditions of fire exposure. The latter requires further understanding of the performance of the building, determined by its fire safety strategy and its vulnerabilities to external fire spread through the building façade.
- The hazard classification can only provide information regarding the potential fire spread risk, and not a conclusive risk to building occupants (including emergency services personnel) since this ultimately depends on the robustness of the fire safety strategy, its components and their dependence on the rate of vertical flame spread. For example, an extremely robust fire safety strategy with multiple redundancies can tolerate a fast rate of vertical flame spread than a lean fire safety strategy with limited redundancies. Information about the potential for fire spread via the external façade of a building must be presented in a form in which it can be used by competent fire safety engineers to establish the safety of building occupants in a quantitative assessment. A simple classification is not sufficient for this purpose.

(ii) Limited data sample size from existing ACPs to develop a robust hazard classification based on a dense statistical distribution.

- From the publicly available references, it is unclear the number products studied to date that yields the three categories defined in the 'BRE Global ACP/Insulation BS 8414-1 Fire Tests' report for the Ministry of Housing, Communities and Local Government (MHCLG) in the UK or the four categories established by the Insurance Council of Australia. A large sample size, of the order of hundreds to thousands of products, is required to provide an extensive dataset to provide a robust framework that enables a hazard classification based on a screening test method.
- The four categories established by the ICA strongly rely on the early classification developed by BRE Global. In their report for the MHCLG, BRE Global acknowledged that "to European Standard there is a wide range in the calorific value within Category 2". They affirm that "we don't know how much less and how that compares to the other manufacturers that also state their FR product is around 30% PE. Until more information can be obtained from the manufacturers, at this point all we can do is assume that FR ACP's with stated 30% PE in their core, would have a similar Calorific value to ALPOLIC-fr and the tested Category 2 product in the BRE reports".
- Due to the limited amount of information published to date, it is unknown the effect that different content and nature of fire retardants or fillers may have to overall fire performance of the plastics cores, other than the ones studied in the available references.

(iii) Limited data from existing types of insulation materials and other materials to develop a robust hazard classification.

- The report from BRE Global identifies three types of insulation materials: foil-faced PIR, foil-faced phenolic foam, and stone wool. Whereas these three insulation materials represent the main spectrum of insulation products in the European market, several other insulation materials may be available, such as expanded polystyrene (EPS), glass wool, polyurethane foam, cellulose-based insulation, plastic-wool insulations or even phase-change materials. Additionally, several formulations may be found for the same type of insulation material, such as the urethane-based insulations which can present multiple chemical formulations, thus performance, or cellulose-based materials which can employ different binders.

- The screening protocol developed by BRE, presented in the report ‘Building Safety Programme: Monthly Data Release – October 2018’, has focused on the identification of the core material inside ACPs. Out of 2,104 samples received by BRE for testing, a total of 1,396 (66%) were rejected because they were not ACPs.

(iv) Performance criteria used to develop hazard classification.

- The hazard categories established for these products are based on the determination of a calorific value (heat of combustion). The performance of the ACPs is demonstrated via seven full-scale tests, which combined ACPs and insulation materials. This performance was assessed based on a pass/fail framework. This extrapolation ignores the complex fire dynamics linked to the mechanism of flame spread such as the rate of energy release and the energy feedback between the flame and the fuel.
- The heat of combustion as a performance criterion only provides the energy available in the material and not the rate at which that energy is released (HRR). In fact, values of heat of combustion for solid materials can generally be classified in different fuel categories: (i) non-fire retarded hydrocarbon-based materials, (ii) fire-retarded hydrocarbon-based materials and (iii) cellulosic materials. Whereas the fire spread phenomenon may be related to the heat of combustion of the fuel, it does not dictate a performance indicator for the fire spread hazard. Only if the heat of combustion is extremely low, as proposed by the Euroclasses framework (EN 13501-1) may a flame not be sustained.
- Whereas full-scale façade tests provide a relative assessment of performance for a specific scenario under certain conditions of installation, these only provide a demonstration of performance which should be used as a guide by the competent fire safety engineer, rather than as a simple pass-fail criterion.

(v) Clear definition of the testing methods to be applied in the protocol.

- Whereas the protocol refers to two renowned testing agencies in Australia, it is not clearly defined what the testing methods are for “an identification of ACPs with a 100% confidence”.

2.4.2 Intermediate-scale systems testing

Intermediate-scale testing is an attractive option due to the economic and time constraints of large-scale testing. However, the complexity of façade systems has generally meant that there have not been adequate ways to obtain representative results on a smaller scale. During the development of many of the large-scale test methods, there were some conclusions that fire safety engineering was not ready for the complexity of the problem associated with façades (Babrauskas, 1996).

The recent push for sustainability and reduced energy consumption has brought the area of façade systems back into focus. As a result, there has been greater interest in revisiting intermediate-scale tests which can adequately assess the performance of systems or try to predict results on a larger scale. One of the main bodies of work has been undertaken by FM Global (Nam and Bill, 2009). A parallel plate setup was adopted where a burner was positioned in the cavity of two parallel plates where the materials to be tested are mounted. The heat release and flame length were measured to assess whether the system would promote flame spread, and acted as a method for benchmarking the performance of materials against the full-scale 25 ft and 50 ft corner tests (7.6 and 15.2m, respectively). From this, a number of materials could be discarded with the reasonable belief that they would not be able to pass the full-scale methods. Thus, the goal of the method was to predict pass/fail in the larger-scale tests to reduce costs but could not be used directly in any fire safety engineering calculations.

Work to understand the dynamics in cavities has also been performed using parallel plate systems (Foley & Drysdale, 1995 and Livkiss et al., 2018). These bodies of work give descriptors of the flame length, energy release, apparent heat exposure to the materials, and gas velocities but represent early works in the area and have not yet been used to assess façade systems containing flammable materials or otherwise realistic façade configurations. This added complexity and the interactions between both elements on either side of the cavity add an additional layer of intricacy which will need to be evaluated in future to enable their application in fire safety engineering.

2.4.3 Full-scale façade systems testing

Over the past three decades, there have been numerous attempts to develop a large-scale testing and classification method for the certification of façade systems in a pass-fail framework. Notable examples include the British Standard test methods described in the BS 8414 series of standards and classified according to BR135; as well as the German DIN 4102-20 test method; and the ISO 13785-2 test method. A summary of current approaches is given in a report published recently by the European Commission which summarises a project to develop a harmonised testing and classification method for Europe (Boström et al., 2018). All testing approaches are in principle the same and comprise a vertical façade construction mounted on some substrate or frame which has a hearth at the base of the wall, intended to represent a compartment on fire inside of a building. During the test, the façade system is challenged via flames exiting the hearth opening and impinging on the façade surface, or via the starter track or window detail (whichever is installed) around the hearth where the fire may enter any cavity incorporated in the system. During and after the test a number of measurements are taken and observations made. These are then related to performance requirements for classification. Minor variations exist, related to performance requirements in different countries or territories, and these are discussed further below. In Australia, the recently adopted AS 5113 is similar to the BS 8414 series of tests. There are differences however, for example, the British Standard test has certain times incorporated into the performance criteria for vertical flame spread based on temperature measurement at subsequent rows of thermocouples and these are not incorporated in the Australian Standard.

Overall, the document developed by Boström et al. identifies 12 different testing standards for façade systems both in Europe and including the ISO test method. Of the large-scale testing methods referred to, there is no consistency in the performance criteria implicit in these tests. These different criteria may include horizontal and vertical flame spread both external and internal to the construction; an evaluation of the connection between the floor and the façade; smouldering; falling parts; smoke output; heat exposure to windows above the hearth opening and detailing, for example in the form of window frames and openings included away from the hearth opening. Some of the test methods also include a return wing on the vertical wall representing an internal corner in the façade of a building. Effectively, each of these test methods addresses a different fire scenario or combination of scenarios which are deemed to be of concern when the vertical compartmentation of a building is challenged. None of the test methods addresses all of the fire scenarios which could result from challenging the compartmentation via the facade. This situation is reflective of the lack of agreement in the international community of the risks posed by fire spread via facades.

Attempts to harmonise façade testing and certification internationally have largely failed to date. This is a result of the varying approaches to testing, the different scenarios incorporated in each test, and the resulting different performance requirements incorporated in the different test methods. The adoption of a test method in any one country would require the inclusion in the proposed test method of all performance requirements which are implicit in the current regulations, or a change in the existing regulations effectively excluding some of the scenarios currently incorporated in them. The different test methods also all use different hearths and different fuels, some include extinguishment after a given period, and so represent different fire scenarios and different fire exposures.

One example of a previous effort by the European Organisation for Technical Approvals (EOTA) to harmonise testing methods in Europe is described in Technical Report N073 (EOTA PT4 Task group, 2013). This document proposed a small- and a large-scale testing method largely similar to BS 8414 and DIN 4102-20, with different fire exposures as well as minor changes in the geometry of the test rig carried forward from these tests resulting in the designation of these as a large-scale and a medium-scale test method. This testing method was not adopted. At the time of writing, there are two proposals currently under review in Europe. One is based on what is effectively an evolution of the EOTA proposals and based on the BS8414 series and DIN 4102-20. Another is based on a test and classification method which effectively averages all of the existing test methods and assesses different combinations of all performance criteria present in the existing test methods (Boström et al., 2018).

Before these could be adopted, however, there needs to be an understanding of how the different performance criteria affect one another and are affected by the conditions of the test. For example if a window type penetration is included in the façade wall above the hearth then the scenario of fire re-entry to a vertically adjacent compartment is tested. Fire re-entry can result in a new fire and the subsequent additional heat supply to the façade that can promote further spread. Nevertheless, it could also be argued that by creating a gap in the façade construction this reduces the input that the initial fire has to vertical flame spread over the wall beyond this level. The question then arises: would the inclusion of window detailing in a test similar to the British Standard test positively or adversely affect the performance of systems in comparison to the performance requirements in the current British Standard test? Many other similar questions exist for the other scenarios addressed in the existing test methods which makes it extremely difficult to foresee the development of a test method which adequately addresses all possible scenarios. These test methods therefore only have merit in a simple pass / fail regulatory environment where there is no expectation of any detailed engineering analysis and where there is no possible variation in the risk scenario to be considered. For systems as complex as modern façade systems, the use of these test methods without further engineering analysis in support of a proposed solution should, therefore, be extremely limited.

3 The Material Library of Cladding Materials framework

3.1 Context

The University of Queensland, in collaboration with the Non-Conforming Building Products (NCBP) Audit Taskforce in the State of Queensland, have proposed a framework to provide a robust methodology to assess the fire hazard of cladding materials in existing buildings based on a thorough understanding of the relevant fire phenomena.

To enable this, a comprehensive database (material library) with relevant fire performance criteria to assist the fire safety engineering community is developed. The methodology is not intended to determine if any specific façade design is safe. It is intended to provide the data necessary for a competent fire safety engineer to conduct the analysis necessary to determine the safety of a façade system corresponding to a specific set of materials, a specific configuration and a specific building context.

The Material Library of Cladding Materials is to be used within the context of the following framework:

(i) The risk that products pose to the life safety of building occupants (including emergency services personnel) is determined by (i) the potential external fire spread through the building façade system and (ii) the response of the fire safety strategy of the building to this event.

(ii) This risk is to be established by competent fire safety engineers, who shall (i) identify (quantify to the extent and precision possible) the fire spread rate and the contribution of the façade fire to the onset of internal fires and (ii) identify the vulnerabilities of the current fire safety strategy of the building to such an event. Upon the completion of that assessment, the competent fire safety engineer shall propose remedial works (where necessary) so that the life safety of building occupants is guaranteed with adequate engineering safety margins.

(iii) The competent fire safety engineer must be provided with tools and data to enable the quantification of the performance of a façade system under fire conditions. These data must include the performance of materials and systems in a quantitative manner, rather than based on a pass-fail (compliance) framework. It should be noted that if a compliance framework is to be followed, a conservative solution based on a non-combustibility criterion should be provided, as implicitly stated by code-based solutions.

(iv) In order to develop data and tools to inform the competent fire safety engineer, there are two possible approaches:

  a) A **material data approach** that, if thoroughly developed, is a cost-effective path that allows understanding of the individual performance of the components based on fundamental principles. However, the extrapolation of these data to a system behaviour must be done with extreme care.

  b) A **system data approach** that allows understanding of the macroscopic performance of the system under specific conditions, without necessarily establishing a good understanding of the fundamental behaviour of its components. This is a costly approach and is limited by the validity of the testing scenario, the establishment of sufficient detailing of the system to enable extrapolation of the results, and the use of adequate and sufficient instrumentation to allow a good interpretation of the behaviour.

(v) Given the lack of public research and available data in this area, combined with the unidentified number of different cladding systems and materials in existing buildings, a material data approach, while more conservative in nature, is the preferred approach. A comprehensive database is urgently required to assist the fire safety engineering community.

3.2 Aim

The Material Library of Cladding Materials aims to develop an extensive database of cladding materials based on their fire performance as individual components, which database may enable a future hazard classification. The database is a tool for qualified, competent fire safety engineers to enable an adequate fire hazard identification and quantification of the potential fire spread of cladding materials.

The fire performance of cladding materials (ACP, insulation, and any other materials such as sarking) will be defined based on well-established testing frameworks widely accepted in the fire safety engineering community. These frameworks are based on experience acquired through research on the performance of ACPs and insulation materials at The University of Queensland and the University of Edinburgh.

3.3 Testing description

The framework corresponds to a multi-scale approach of individual components, from the material identification at micro-scale up to the flame spread on the material at the bench scale. This approach allows incorporating the increasing complexity as the scales increase. A fundamental characterisation of the fire hazard of materials requires every single step in the identification of the following characteristics.

3.3.1 (A) Chemical composition

The chemical composition of samples is identified using a combination of Fourier-transformation Infrared (ATR-FTIR) (ASTM E1252) and Energy Dispersive X-Ray Fluorescence spectroscopy (EDXRF) (ASTM F2617, ASTM D6247). ATR-FTIR is used to identifies all mid-infrared active functional groups and through that identify the polymer binder/resin and the presence of fire retardants, processing aids, fillers etc. The main purpose of the EDXRF analysis is to identify the elemental composition of the sample. Using standard less EDXRF analysis, the element composition can be quantified. Provided that the constituents (e.g. polymer, additives, fire retardants) are known, or have been identified with ATR-FTIR, the actual compound composition (not just elemental composition) can be determined.

The application of these techniques to identify the exact chemical composition of materials is limited to specific compounds with relatively simple chemistry. This is, for example, the case of cores of aluminium composite panels consisting of a single polymer and a single fire retardant or filler. In the case of materials with multiple fire retardants or fillers, the uncertainty in the determination of exact compositions increases. In the case of polymers such as foams, with complex molecular chains, the identification of exact chemical composition is not feasible; e.g. the case of urethane- or isocyanurate-based foams where several monomers can be used in the polymerisation process of the foams.

It should be noted that both ATR-FTIR and EDXRF are surface sensitive, meaning that the majority of chemical information comes from the first 15 µm. This makes this method sensitive to material inhomogeneity, e.g. through thickness concentration gradient or inhomogeneous particle/filler size.

3.3.2 (B) Thermal decomposition

The thermal decomposition in the kinetic regime is assessed using thermogravimetric analysis (TGA) in oxidative and non-oxidative conditions (ISO 11358-1, ASTM E1131-08). This thermal analysis method characterises the conditions necessary for the onset of thermal decomposition and the mass fractions of volatile compounds present in materials and the mass fraction of residue during or after thermal decomposition.

The non-oxidative test conditions allow quantification of the mass fraction of volatile material, which is represented as pyrolysates and products from the decomposition of additives. The oxidative test conditions determine whether the residue is of organic or inorganic nature and whether oxidative conditions alter the reactions. The rate of thermal decomposition reactions is assessed by applying the first derivative to the mass-temperature data (DTG).

Thermogravimetric analyses provide a distinctive signature of the material decomposition processes, which are intrinsically related to the fire performance criteria such as ignition or burning behaviour.

3.3.3 (C) Heat of combustion or gross calorific value

The heat of combustion or gross calorific value is the total energy available in a substance for a combustion process, which is determined using a bomb calorimeter apparatus. This standard technique (ISO 1716) characterises the energy released as heat when a substance undergoes complete combustion at a constant volume with an excess of oxygen.

The heat of combustion represents the maximum amount of energy available to be released in a combustion process. While the heat of combustion provides an indication of the fire hazard of materials; this parameter is insufficient to indicate the rate at which materials release heat (burn).

3.3.4 (D) Ignition behaviour

The ignition behaviour determines the conditions that lead to the formation of a flame is assessed using reaction-to-fire tests, either a Mass Loss Calorimeter (ISO 13927) or a Cone Calorimeter (ISO 5660) bench-scale standard instruments. The critical heat flux for ignition, the apparent thermal inertia and the estimated ignition temperature are the main parameters to be identified.

The critical heat flux for ignition is a parameter commonly used in fire safety engineering that indicates the minimum rate of energy flux necessary to ignite the material when a spark (pilot) is present an the material is exposed to those heating conditions for an infinite amount of time. If a series of assumptions in heat transfer coefficients and conductive losses are made, the critical heat flux for ignition may be converted into an ignition temperature, which allows comparing the hazard of different materials.

Under heat fluxes above the critical heat flux for ignition, the time for the material to ignite is dependent on the thermal properties of the material: thermal conductivity, density and specific heat capacity – the product of these defines the thermal inertia. A simplified model of ignition may be achieved using the thermal inertia and ignition temperature.

3.3.5 (E) Burning behaviour

The burning behaviour is characterised under several radiant flux exposures using the Cone Calorimeter apparatus (ISO 5660), which determines the energy released per unit of time and unit area by the material (heat release rate per unit area). Additional fundamental parameters such as the effective heat of combustion and fuel production rates are also characterised.

The heat release rate is one of the most important parameters to characterise fire growth, generally associated to spread of flame over the surface of materials. The burning behaviour of materials is characterised by the heat release rate per unit area, characteristic of the material at different heat fluxes, and which determines the size (characteristic length) of the flame – relevant for flame spread analyses.

3.3.6 (F) Flame spread behaviour

The flame spread behaviour is examined using the lateral ignition and flame spread (LIFT) bench-scale standard test method (ASTM E1321), which determines the conditions to sustain flame spread once the material ignites, the flame spread rate as a function of external radiant flux, and the flame spread parameter. Lateral and upward flame spread analyses are carried out to identify rates of flame spread.

3.4 Development of the Material Library

Due to a large number of unidentified existing materials in buildings, it is not feasible to undertake a complete material characterisation. In order to optimise the elaboration of the Material Library, two testing protocols are proposed a screening testing protocol and a detailed testing protocol.

The intent is to enable fire engineers to cross-reference data from both protocols in order to achieve a comprehensive understanding of the factors influencing external flame spread and apply them to a specific building to determine the hazards involved. This will inform the preparation of building risk assessments and performance solutions.

Additional products may be tested using the ‘screening testing’ and ‘detailed testing’ protocols, and further included in the ‘Material Library’. This continuing screening of materials will guarantee the robustness of the hazard classification and the seamless processing of new products.

3.4.1 Screening testing protocol

The **screening testing protocol** consists of a conservative and robust approach aiming at providing a distinctive identifier for materials; i.e. a unique signature of the material that distinguishes from other materials. This identification may consist of a determination of the exact chemical composition (e.g. 100% -CH_2- if pure polyethylene), the distinctive thermal decomposition (e.g. the Arrhenius-type decomposition reaction and residue of the material), or a combination of both. The former is ideal for simple materials that may no experience complex molecular changes during manufacturing. However, that approach is not feasible for other materials such as urethane-based foams, which are the product of complex polymerisation processes.

Due to the variable molecular complexity of many combustible materials, the screening consists of a material identification (A) and an assessment of the thermal decomposition through thermogravimetric analysis (B). Additionally, methods to identify the chemical composition may include uncertainty in the assessment – this is discussed in further reference ‘Protocols for the Material Library of Cladding Materials’.

The testing methods associated with these analyses are small-scale, which enable a quick testing turnout. An indicative fire performance of the material may be obtained combining results from techniques A and B. However, this information must be analysed in conjunction with outcomes of the detailed testing protocol developed to establish the actual material flammability properties.

3.4.2 Detailed testing protocol

The **detailed testing protocol** aims at a multi-scale characterisation of the material. This consists of the screening testing protocol tests – material identification (A) and characterisation of thermal decomposition (B) – and characterisation of the gross heat of combustion (C), ignition (D), burning (E) and flame (F) spread behaviour.

Due to the large number of tests required to accomplish a full material characterisation, the detailed testing protocol is only feasible for particular materials. However, wherever possible, it is recommended that a full-characterisation is pursued for new materials not identified in the Material Library.

The data provided by the detailed testing protocol provides fundamental flammability data that can be used in a quantitative assessment. It should be noted that the extrapolation of the data to a system behaviour, where a product and a system may experience an interaction, must be done with extreme care.

3.5 Use of the Material Library

It should be noted that the flame spread behaviour ultimately represents the fire hazard. However, adequate characterisation of this requires an assessment of the previously described phenomena. The information presented can therefore be used to identify less conservative criteria in decision-making that is based on quantitative, fundamental analyses. For instance, a particular material that may be classified as combustible may not be able to experience ignition even at high heat fluxes. These type of decisions are for the engineers to be analysed and justified within a comprehensive engineering analysis, rather than based on a prescriptive pass-fail framework.

The 'Material Library' does not provide a complete characterisation of the fire risk associated with the use of cladding materials, but a tool to inform competent fire safety engineers regarding the fire hazard from cladding, insulation and sarking materials. The 'Material Library' is intended to provide publicly available quantitative data for different cladding panels, insulation and sarking materials. This data will provide fire engineers with a tool to complement a comprehensive risk assessment based on the risk posed by any combustible cladding material which has undergone the 'screening testing'.

The use of flammability parameters extracted from the 'Material Library' to quantitatively determine the rate of flame spread in façade systems still requires further research to be developed. Therefore, extreme care must be applied in the extrapolation of these parameters to other scales. These parameters, however, will provide fundamental data to assist the continuing development of tools and the performance assessment of actual systems composed of multiple materials (ACP, insulation, sarking, etc.). Further testing of systems at the intermediate and full scale, with an adequate level of instrumentation, are recommended after the establishment of the Material Library.

3.6 Scope of materials to be identified

It has generally been assumed that the ACP solely represents the fire spread problem in façade systems. Whereas there is evidence that this may be the case for ACPs with 100% polyethylene cores, several other materials have been identified in existing buildings, e.g. ACPs with other types of polymeric binder, laminated products, and multiple types of insulation and sarking materials. Furthermore, more materials can be expected to enter the market in the future, driven by economic and energy efficiency drivers among others.

In most cases, these materials are expected to interact with each other in a system, thus increasing the complexity of the assessment. Given the increasing number of materials identified and the unknown behaviour for many of these due to the limited available data, the Material Library represents the perfect vehicle to incorporate this information, which is to be publicly available and aimed at supporting the fire safety engineering community.

3.7 The role of The University of Queensland

The Fire Safety Engineering Research Group (UQ Fire) within the School of Civil Engineering, in close collaboration with the School of Mechanical and Mining Engineering and The University of Queensland, has provided a framework based on the state-of-the-art research in the performance of façades and cladding materials, such as insulation materials and aluminium composite panels.

The objective of UQ Fire is to develop a robust framework based on well-established research, which is to be made available for the benefit of Queensland and the global community. UQ Fire declares no conflicts of interest in this area, and has no commercial interest.

4 Terminology

The terms used within this document are described below.

ACP	aluminium composite panel
BCA	Building Code of Australia
Binder	adhesive used in the manufacturing or processing of composite materials
Boundary condition	physical parameters used to describe the interaction of a system with its surroundings as described in a mathematical model
Burning	flaming or smouldering combustion
Chemical composition	molecular composition of a material
Combustion	exothermic oxidative chemical reaction
Combustible	in a regulatory context, combustible refers to materials that fail the non-combustibility test (AS 1530.1 or IS 1182) in a scientific context, combustible refers to the ability of an organic compound (gas, liquid or solid) to oxidise and generate heat
Cone Calorimeter	bench-scale tire test apparatus used to identify the ignition and burning properties of materials
DtS	Deemed-to-satisfy
Detailed testing	refers to the set of tests to provide a full-characterisation of the fire behaviour of materials. It includes a material identification, a thermogravimetric analysis, determination of ignition, burning and flame spread properties
EDXRF	Energy Dispersive X-Ray Fluorescence
Effective heat of combustion	constant during the combustion of materials is less than the value of the theoretical gross heat of combustion
External heat flux	heat flux at the surface of the sample from an external source. Equivalent term to incident radiant heat flux, incident heat flux, or Irradiance
Fire safety strategy	expected behaviour of the building occupants and building systems in the event of a fire
Fire spread	growth of the fire – refer to flame spread
Flame spread	propagation of the flame over a solid or liquid fuels
Flaming	related to the establishment of a flame

Flammability	the ability of a material to cause combustion or fire
FTIR	Fourier-transform infrared spectroscopy
Gross calorific value	amount of heat released by a specific quantity once it is combusted and the products have returned to an initial temperature
Heat of combustion	energy released when a substance undergoes complete combustion with oxygen
Ignition	initiation of a sustained flame
Inert filler	miscellaneous chemical compounds used in the manufacturing or processing of composite materials
Insulation	material with low thermal conductivity
Irradiance	(at a point of a surface) the quotient of the radiant flux incident on an infinitesimal element of the surface containing the point, and the area of that element
Mass loss	mass of test specimen consumed during thermal decomposition or combustion
LIFT	Lateral Ignition and Flame Spread Test Apparatus
Material	a physical thing with specific qualities or characteristics (composition, flammability, etc.) that are assumed homogenous
NCBP	Non-Conforming Building Products
NCC	National Construction Code
Pyrolysis	process of thermal decomposition of solids which results in the generation of flammable gases (pyrolysates)
Polymer	large, chain-like molecule made of monomers
Product	refers to an element or system composed of multiple materials
QFES	Queensland Fire and Emergency Services
Sarking	sheathing or covering thin material
Screening testing	refers to the set of tests to provide a reference indicator
TGA	thermogravimetric analysis
Thermal decomposition	decomposition of the molecular structure of materials due to heat
Thermal inertia	material thermal property result of the multiplication of the thermal conductivity, density and specific heat capacity
XRD	X-ray diffraction

5 References

AS 1530.1-1994 (R2016). Methods for fire tests on building materials, components and structures Combustibility test for materials. SAI Global Limited

AS 5113 (2016). Fire propagation testing and classification of external walls of buildings. SAI Global Limited.

ASTM D6247 (2010) Standard Test Method for Determination of Elemental Content of Polyolefins by Wavelength Dispersive X-ray Fluorescence Spectrometry. ASTM International, West Conshohocken, PA

ASTM E1131-08 (2014) Standard Test Method for Compositional Analysis by Thermogravimetry. ASTM International, West Conshohocken, PA

ASTM E1252 (2013) Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis. ASTM International, West Conshohocken, PA

ASTM E1321 (2013) Standard Test Method for Determining Material Ignition and Flame Spread Properties. ASTM International, West Conshohocken, PA

ASTM E2307 (2015) Standard Test Method for Determining Fire Resistance of Perimeter Fire Barriers Using Intermediate-Scale, Multi-story Test Apparatus. ASTM International, West Conshohocken, PA

ASTM F2617 (2015) Standard Test Method for Identification and Quantification of Chromium, Bromine, Cadmium, Mercury, and Lead in Polymeric Material Using Energy Dispersive X-ray Spectrometry. ASTM International, West Conshohocken, PA

Babrauskas, V. (1996). Facade fire tests: Towards an international test standard. *Fire Technology*, 32, 219–230. https://doi.org/10.1007/BF01040215

Boström, L., Hofmann-Böllinghaus, A., Colwell, S., Chiva, R., Tóth, P., Moder, I., Sjöström, J., Anderson, J., and Lange, D. (2018). Development of a European approach to assess the fire performance of facades. *European Commission DG GROW*. ISBN 978-92-79-88000-1. https://doi.org/10.2873/954759

BR 135 Classified external cladding systems. BRE Global

BRE Global ACP/Insulation BS 8414-1 Fire Tests For Department of Communities & Local Government, http://www.insurancecouncil.com.au/assets/aluminium%20protocol/BRE_NOTES_ANEXURE.pdf. Accessed: 03/07/2018

Building Safety Programme: Monthly Data Release - October 2018. Ministry of Housing, Communities & Government, United Kingdom, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/751218/Building_Safety_Data_Release_October_2018.pdf. Accessed: 12/11/2018

BS 8414-1 (2015). Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems applied to the masonry face of a building. British Standards Institute

BS 8414-2 (2015). Fire performance of external cladding systems. Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame. British Standards Institute

DIN 4102-20 (2017). Fire behaviour of building materials and building components - Part 20: Complementary verification for the assessment of the fire behaviour of external wall claddings

EN 13501-1 (2009). Fire classification of construction products and building elements. Part 1: classification using data from reaction to fire tests.

EOTA PT4 Task group (2013) Technical Report N073: Large Scale Fire Performance Testing of External Wall Cladding Systems.

Insurance Industry Aluminium Composite Panels Residual Hazard Identification/Reporting Protocol (2017) Insurance Council of Australia, http://www.insurancecouncil.com.au/issues-submissions/issues/insurance-industry-aluminium-composite-panels-residual-hazard-identificationreporting-protocol, Accessed: 04/07/2018.

ISO 1182 (2010) Reaction to fire tests for products -- Non-combustibility test. International Organization for Standardization

ISO 1716 (2010). Reaction to fire tests for products -- Determination of the gross heat of combustion (calorific value). International Organization for Standardization

ISO 5660 (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). International Organization for Standardization

ISO 11358-1 (2014). Plastics -- Thermogravimetry (TG) of polymers -- Part 1: General principles. International Organization for Standardization

ISO 13927 (2015). Plastics -- Simple heat release test using a conical radiant heater and a thermopile detector. International Organization for Standardization

ISO 13785-1 (2002). Reaction-to-fire tests for façades -- Part 1: Intermediate-scale test. International Organization for S 135tandardization

ISO 13785-2 (2002). Reaction-to-fire tests for façades -- Part 2: Large-scale test. International Organization for Standardization

Foley, M. and Drysdale, D.D. (1995). Heat transfer from flames between vertical parallel walls. *Fire Safety Journal*, 24, 53–73. https://doi.org/10.1016/0379-7112(94)00033-C

LEPIR Test (2015). Large scale Fire Performance testing of External wall cladding systems. LNE

Livkiss, K., Svensson, S., Husted, B., and van Hees, P. (2018) Flame Heights and Heat Transfer in Façade System Ventilation Cavities. *Fire Technology*, 54, 689–713. https://doi.org/10.1007/s10694-018-0706-2

MSZ 14800-6 (2009). Fire resistance tests. Part 6: Fire propagation test for building facades

Nam, S. and Bill, R.G. (2009). A New Intermediate-scale Fire Test for Evaluating Building Material Flammability. *Journal of Fire Protection Engineering*, 19(3), 157–176. https://doi.org/10.1177/1042391508101994

Ogilvie, J. (2017). Fire performance of ACP Façade Systems. Master of Engineering Thesis. The University of Queensland

SP FIRE 105 (1994). Issue 5. Large scale testing of facade systems. SP Boras Sweden

The Building Regulations 2010. Fire safety: Approved Document B – Volume 2, Buildings other than dwelling houses. HM Government, Ministry of Housing, Communities & Local Government

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