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RESEARCH ARTICLE

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The development process of a candidate screening test for cladding products

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Abstract

The ongoing cladding crisis within the United Kingdom has elevated the need for designers and risk assessors to have the knowledge and tools to evaluate the fire safety of proposed and existing cladding systems. This paper documents efforts to develop a test that could be used to evaluate the fire safety hazards of cladding products that were either proposed for use in design or that were found on existing buildings. Specifically, the products of interest were composite products (i.e., those comprised of multiple layers). The conceptual approach of the European harmonised system was used as a basis for investigating whether a small-scale test could be used to evaluate product fire hazards. A relevant fire scenario was identified, this was linked to candidate large-scale reference tests, and this was linked to performance in a candidate small-scale test. The candidate test showed remarkable agreement with the reference large-scale test, however, many issues were also identified. It was found that, even when specifically intended to accommodate composite products, the small-scale test was unable to always evaluate hazards. Thus the authors were left with the conclusion—regardless of the testing system, there are always products that will not fit the testing system, however hard one tries.

KEYWORDS
façade fires, hazard evaluation, small-scale testing

1 | INTRODUCTION

Since the Grenfell Tower fire on the 14th of June 2017, the attention of industry and (to some extent) the general public has been drawn towards the intricacies of the testing methods that are used to secure fire safety within the built environment. Within a UK context, where the fallout from the fire has been particularly acutely felt, this scrutiny has led to the abandonment of legacy British Standards[1,2] and deep unease at the use of large-scale testing for systems (as opposed to products).[3,4] Uncertainty about the safety (or otherwise) of the UK's existing housing stock has also led to a crisis within the mortgage industry that has left homeowners unable to sell their properties.[5,6] There is, therefore, a need to assess these existing buildings—preferably with minimal cost and disruption to residents.

Internationally, various tools and methods have emerged and continue to be developed that allow practitioners to better understand the hazards presented by external wall materials, products and systems. For the use of this work, a *material* is a singular homogeneous substance. A *product* is manufactured and sold as a singular item—this may or may not be a singular material, or a combination of multiple materials constituting a composite. A *system* is a group of elements that are combined to create an end use construction assembly—this constitutes the individual products used, their layup and configuration and fixing and mounting mechanisms. In Europe, the European

Commission has commissioned the development of a harmonised large-scale cladding test[7]; NFPA EFFECT™[8] was also created as a risk assessment tool to aid in fire risk assessments, and assess mitigation measures; and in Australia, the Queensland government commissioned the University of Queensland to create a 'material library' providing "data and tools to inform competent fire safety engineers" using currently available fire testing methods.[9]

Currently, large-scale testing methods test external wall *systems*, not products. Results from system tests can only be used to make claims about the safety of as-built (or proposed) construction when a practitioner is convinced that the real system is sufficiently similar to the tested condition. This presents a problem for anybody hoping to understand the hazard presented by a single product. That is, the hazard of a product is (at least in part) a function of its context. The relative significance of an individual product's performance within a system test can only be evaluated using multiple trials. This would become extremely expensive and time consuming to perform, therefore there is a desire to find a way to better understand the potential hazard that an individual product may present within an external wall.

The strength of large-scale testing of systems is in evaluating the influence of system configurations, fixings, and mounting mechanisms. Whilst losing more of the information on individual product contribution, large-scale testing can be very useful for helping engineers to make an evaluation of the hazard of the system as a whole and showing behaviours that may not be observed in small-scale testing due to component interactions. The advantage of using product testing is in evaluating the individual product fire behaviour and hazard. This allows for the assessment of the individual contribution of each component within a larger system so that hazardous components can be identified. This then provides the knowledge for engineers to design external wall assemblies with some understanding of the influence of each chosen product.

The currently available regime for product testing for external walls is that of the Euroclasses. The process of creating the Euroclasses began in the 1980s, and is detailed more by Law et al.[10] Central to the new classification method was the Single Burning Item test (SBI). This, along with four other tests would form the basis on which products could be classified for sale within the EU.

The use of the SBI test, as discussed by Messerschmidt,[11] was based on the hypothesis that the hazard a product may present in a real fire scenario can be inferred from the results of controlled and repeatable standardised tests.

For the Euroclass system, the real fire scenario that was considered was the growth of a room fire to flashover. This, in the context of the built environment is clearly a relevant hazard—as any people close to this fire would be endangered by its growth. Of course, the real fire scenario could start in an infinite variety of ways, and the fuel and geometry in a real room could be of any configuration. To reduce the complexity presented by the variety of 'real life', it was necessary to define a more controlled test that could serve as a 'large-scale reference'. The room corner test (developed by ASTM[12]) was chosen as the reference scenario. This represented a proxy for the real fire—being of a representative scale and with an ignition scenario that might be representative of a developing room fire that has not yet involved the construction products. However, the reference scenario was also standardised—to allow a degree of repeatability. A particularly important feature of the large-scale reference test was that the developing fire should be measurable. The ASTM room corner test was provided with calorimetry, and allowed for time to flashover, and a Fire Growth Rate Index (FIGRA), to be defined.

Once the reference scenario had been established, a challenge for researchers in the 1990s was to test the hypothesis. Was it possible to develop a small-scale test, the results of which could be used to infer (or predict) the behaviours that would be observed when the same products were placed in the large-scale reference test?

The conclusion drawn by the EUREFIC project,[13] and the European Regulators Group in the 1990s was that the answer to this question was 'yes'. Some proposed the use of the cone calorimeter as the small-scale test, but ultimately a new test, the Single Burning Item test was proposed. Equipped with oxygen consumption calorimetry, the rate of a fire's growth could be quantified (as a Fire Growth Rate Index—FIGRA[14]). It was found that when a product was tested in the SBI, the resulting FIGRA was a relatively good proxy for the equivalent FIGRA in the room corner test. The SBI was therefore adopted as the small-scale test that would be incorporated into the future European classification method. Ultimately, the SBI was bound into a compound classification scheme—with the resulting classifications given in BS EN 13501.[15]

Of particular importance in relation to the use of this new classification system was that the system allowed the classification of products, rather than building systems. Once a product had been classified, it could be certified as 'conforming' to the construction product directive—and then sold across Europe. This system was self-evidently problematic for some products. For example, how could one test a loose-fill insulation product in the absence of a container? Similarly, if the manner in which the product was fixed could change the FIGRA—how should it be tested? Implicit within the SBI test was the fact that, although notionally a product test, the SBI's scale and fixing conditions made it a system test.

This classification framework has now been in operation for 20 years, and has arguably been highly successful in allowing trade between European neighbours. However, at its origination, it was recognised that the European classification system had limitations for some product categories. Similarly, it was recognised that a 'one size fits all' testing regime might not be suitable for all product categories, or for all hazard situations. Regulators therefore left room within the system for classification results to be challenged—should the need arise.

The background to this method raises the question of whether the chosen reference scenario is applicable to, or is representative of, fires in external walls. The Euroclass method was designed for products with respect to fire growth to flashover in a compartment, so the application of the method for representing external fire spread may not be appropriate. The SBI utilises a burner imposing a heat flux of, on average, 44 kW/m^2 close to the burner[16], representative of a bin fire in the corner of a room. This is lower than what would be

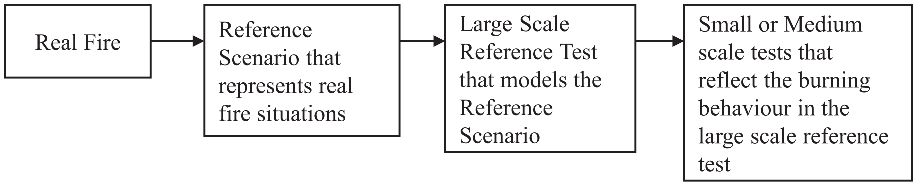

FIGURE 1 The conceptual framework for the SBI—extracted from Messerschmidt.[11]

expected of a spill plume from a compartment under flashover, which is a likely worst-case scenario for cladding products. As discussed by Agarwal,[17] lower heat flux exposures can show thermoplastic core aluminium composite materials (ACMs) perform favourably, unlike in severe fire scenarios where they present a much greater hazard than limited combustibility core ACMs. Therefore, it could be contested that the Euroclass method is not appropriate in determining the fire performance of a product used on an external wall, as the fire reference scenario is not representative.

The purpose of this paper is to report on an investigation into whether a 'Euroclass' type approach can be used for the classification of products that form part of an external wall. The motivation for this is rooted in the recognition of the potential limitations of the existing methods, and the need to establish a tool for evaluating the fire spread hazard of external wall products. This is distinct from the previously identified knowledge-based assessments and large-scale testing methods, as this work provides a small-scale classification methodology that is pinned to the performance in large-scale tests.

2 | METHOD

To develop a small-scale test for external walls, the framework outlined by Messerschmidt[11] is proposed. This concept is the logic that underpins the Single Burning Item test whereby the SBI represents a 'model' of a large-scale reference test which in turn is a 'model' of a reference scenario that represents a real fire situation. This framework is illustrated in Figure 1.

Following this approach requires:

- Reference fire scenario, relevant to the real fire scenario for external walls
- Large-scale reference test, and a metric that can be used to rank the fire performance of various products.
- Candidate small-scale test that interrogates the relevant phenomena appropriate to the reference fire scenario, and a metric that can be used to rank the fire performance of various products, which can be compared to the large-scale reference test.

When these are obtained, a series of tests can be performed on a variety of external wall products. These can then be compared to the results obtained from a large-scale reference test. The correlation of these results can be used to determine the applicability of the small-scale test.

3 | REFERENCE SCENARIO

There are many different scenarios where an external wall could be subjected to fire. For vertical fire spread on an external wall, the expected worst case fire scenario is that of an external plume from a post-flashover compartment. This spill plume will result in direct flame impingement on the face of the external wall system. Direct flame impingement could result in ignition of the external wall which, if constructed with combustible materials, could lead to vertical fire spread on the outside of a building. If the external wall allows for external fire spread, this could result in fire re-entering the building at upper floors, deeming compartmentation ineffective and causing further damage and threat to life safety. This process is shown (for example) in BR135[18] Figure 3: mechanisms for external fire spread by way of the external cladding system.

To define this reference scenario, quantification of the fire is required. The externally applied heat flux can be measured and serves as a useful determinant of the severity of the fire impinging upon the external wall system from the spill plume. Various studies show that a post-flashover compartment fire will impose an incident heat flux on an external wall assembly on the order of 60–100 kW/m^2.[19–24] This would therefore be an appropriate range of heat flux for any reference test that is intended to represent an external plume from a post-flashover compartment fire impinging on an external wall system.

4 | REFERENCE TEST

In the context of external wall systems, many jurisdictions limit the degree to which flammable products can be used in the external walls of buildings. There has been though, a recognition that external wall systems could potentially deliver acceptable fire safety outcomes—even where the product classifications were not so tightly controlled. As a result, a large number of organisations began developing large-scale system tests. The purpose of these tests was to subject a relatively realistic external wall system to a fire that was akin to a fire plume venting from a compartment in which flashover had occurred. By 1996 there were at least 15 such tests and work had started to create an ISO standard for such a large-scale test.

In relation to the key severity characteristic of these tests (i.e., heat flux) current large-scale testing methods utilise applied external heat fluxes varying from 40 to 110 kW/m^2.[25] This is illustrated for seven different tests in Figure 2. What is particularly notable about this is that several of the candidate reference tests show an applied heat flux outwith the literature values that would be suggested by the reference scenario.

Similarly, another limitation of these tests with respect to use as a reference is that, unlike the reference for the European reaction-to-fire classification method, these tests are not product tests. They are tests of entire systems. This calls into question the degree to which any system test could be used to create a classification for a product. Notwithstanding this limitation, the key characteristics of various large-scale tests are worthy of a more detailed review.

4.1 | Large-scale external wall tests

Most standard large-scale external wall tests are variations on the same theme. They comprise of an external wall assembly of over 3 m height, with a burner located at its foot. Some of the variations include wing walls, and upper floors, both with and without openings, to allow for investigation of fire breakthrough into an above compartment. Failure metrics are typically; temperature measurements above the fire source to determine whether the fire has reached a certain threshold height; or flaming above the test rig. Additional visual observations are also commonly made of flaming droplets and smoke production. More detailed descriptions of each test method are provided by White & Delichatsios.[25]

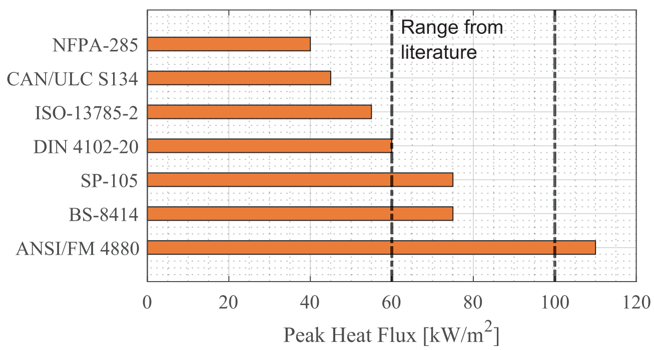

FIGURE 2 Peak heat flux comparison of various large-scale external wall tests, adapted from Agarwal.[17] Indicative lines showing 60–100 kW/m^2 range from the literature.

In recent years there has been a desire to consolidate all these national large-scale tests into one European test. This European harmonisation project echoes its predecessor by reviewing current regimes and aims to create a singular test method that is endorsed by the European Commission.[26] The two most prominent candidate tests for consideration were BS-8414 and DIN 4102-20.

A substantially different test method is the FM Global 16-ft parallel plate test. This test involves two 16-ft tall (∼5 m) panels set parallel to each other. A burner is placed underneath, between the panels, and measurements of heat release rate are made. What is particularly notable about this test is that it is a product test, where individual products are tested regardless of the intended as-built construction. A summary of these tests is shown in Figure 3 and Table 1.

From this review emerges two key problems with using the existing (and future) large-scale test as a potential reference test. First, the heat flux on some of these scenarios is insufficient to adequately represent the reference scenario; second, since all of these (with the exception of the FM parallel plate test) are system tests, they do not necessarily yield information that can be used to classify products. A further barrier to researchers using these tests as a reference scenario is the relative paucity of data. Due to the cost and commercial nature of these large-scale tests, a wide range of experimental results on a variety of external wall products were not readily available—albeit since 2017, there has been a relatively large amount of data released into the public domain concerning ACM type products.

The FM parallel plate test is therefore the only one of these large-scale tests that might be suitable as a candidate reference test. It is large, applies sufficient heat flux, and is a product test. It is noted, however, that whilst the parallel plate test is a product test, it is inevitably also influenced by the fixings, edges, and gaps that are part of any test.

FIGURE 3 Large-scale test setups; (A) Example BS 8414 setup prior to test.[32] (B) DIN 4102-20.[33] (C) NFPA 285.[34] (D) Example 16-ft parallel plate test setup.[35]

TABLE 1 Large-scale external wall standard test details.

United Kingdom	Germany	United States	United States
BS 8414[27,28]	DIN 4102-20[29]	NFPA-285[30]	FM 16-ft PPT[31]
Main wall and wing wall	Main wall and wing wall	Main wall	Two parallel plates
Wooden crib	Wooden crib	Burner	Burner

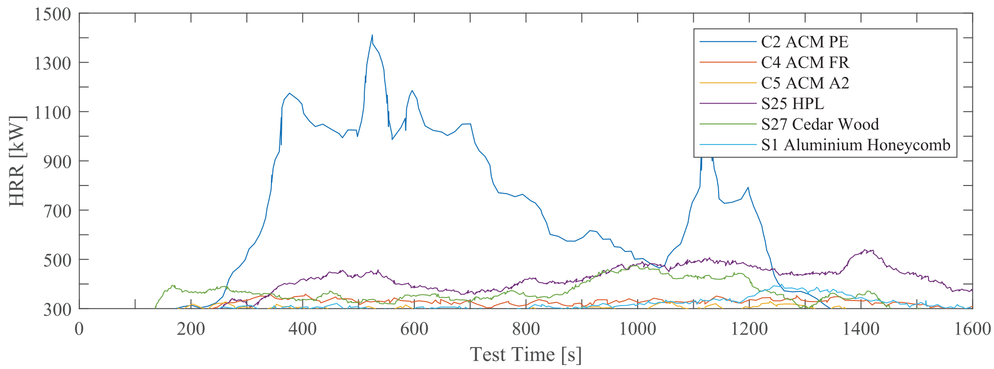

FIGURE 4 Experimental results from the UK government (undertaken by BRE) large-scale tests on the fire performance of cladding materials.[36]

TABLE 2 Summary of experimental results from the UK government (undertaken by BRE) tests.[36]

Product	Experiment no.	Peak HRR with timber crib subtracted (kW)	Time to peak HRR (s)	THR (MJ)
ACM PE	6	1192	1236	1158
	2	1125	522	964
ACM FR	4	64	342	549
	1	38	606	497
ACM A2	5	36	1044	494
	3	33	1164	504
High-pressure laminate (HPL)	S25	242	1380	699
Cedar wood	s27	179	1020	581
	s28	183	1260	674
Aluminium honeycomb	s1	104.3	1257	528.7
	s2	46.8	510	504.1
	s4	96.1	1458	544.3

4.2 | UK government cladding tests

In 2020, the UK government commissioned BRE to undertake a series of investigative tests on the fire performance of cladding products.[36] The data from these tests are publicly available and cover a wide range of external wall products. This included more than just ACM materials and therefore a comparison of a wider range of products can be made. This project was commissioned to examine the "potential performance in the event of a fire exposure representative of direct flame impingement from a fully developed fire breaking out of a compartment through a window opening on the materials/products forming the external panels of a cladding system".

The tests were designed to investigate the "burning behaviour of selected types of non-ACM cladding products using physical testing at intermediate scale in a laboratory setting to identify materials/products of potential concern so that MHCLG can consider the risk of their contribution to external fire spread when used as part of a system".

The experiments used a wooden crib designed to provide an heat release rate (HRR) of 300 kW, imposing an incident heat flux at 1.5 m above ground level, in the range of 45–75 kW/m^2, onto the face of a 3 × 2 m external wall build-up. The experimental results from this series of tests are shown in Figure 4 and Table 2.

4.3 | Other studies

Others have previously studied various large-scale tests to understand their similarities and differences. Bonner et al.[37] created a database of commercial large-scale test data to develop a statistical approach to analyse the fire performance of products used in external walls. This has provided useful insight into big datasets of large-scale tests and their variation. Agarwal[35] performed a series of experiments in the ANSI/FM 4880, BS 8414 and NFPA-285 test methods to determine how comparable the test results are. These were performed with ACM panels with differing levels of combustible cores to determine whether the tests similarly represent the changing fire hazard presented by these panels. They found the results from the ANSI/FM 4880 16-ft PPT and the BS-8414 test methods to be comparable, and more conservative than NFPA-285. Agarwal[17] suggests that the reason for this was due to the higher and more representative heat flux exposure than in NFPA-285. This emphasises the importance of the reference fire scenario used, where a lower applied heat flux can result in a favourable outcome that is not accurate in representing the true hazard posed by the product.

4.4 | Summary

The key issue inherent in these candidate reference tests is that they are system tests. With tests involving more than one product, and certain fixing and mountings, how does one isolate the individual product behaviour from the interaction between the whole system? The 16-ft parallel plate test however deals with this issue, as it comprises two parallel layers of the *same* product. The UK government's recent research project, whilst not a 'full scale' test, also deals with this issue by testing a different product in notionally the same configuration.

Either of these two test methods would meet the criteria necessary to make them candidate reference tests. It is acknowledged that the FM method is more formalised than the BRE research test—in that it is already standardised. However, the wide range of products for which there is publicly available data make the BRE's testing programme a potentially useful reference test.

5 | SMALL-SCALE TEST

In developing the small-scale test, the authors identified a series of requirements for the test such that it should be practical, test the key phenomena, and expose potential weaknesses associated with edges. The criterion, were as follows:

1. Minimal cost and required material. A small-scale test must be cheap and easy to perform with a minimal amount of material used so that material can be taken from existing buildings to ascertain its relevant hazard. This prevents the need for large amounts of material to be taken off an existing building, or for new material to be procured and assembled for the test.
2. Relevant applied heat flux. Representative of the relevant reference fire scenario of an external plume from a post-flashover compartment.
3. Product test, not a system test. The test must not be reliant on the fixings, mountings and backings of the test setup.

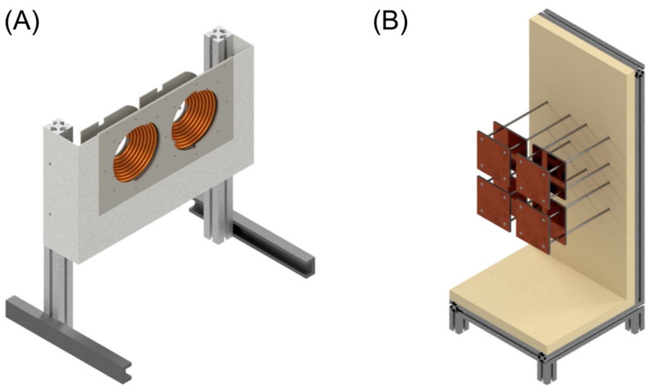

FIGURE 5 Proposed layout of small-scale testing apparatus. (A) Dual conical setup illustration. (B) Sample holder illustration.

4. Exposed edges/joints. To represent the panel-to-panel spread in products with encapsulation, especially layered composites, the panel edges must be exposed and at the same location.
5. Results are measurements of the vertical fire spread on and between panels.

5.1 | Candidate small-scale test

A candidate small-scale test was created, and the configuration of the apparatus is illustrated in Figure 5.

The test comprised a 2×2 panel array with a 20 mm gap between the edges. A secondary layer of panels was set 50 mm behind the front array to control the re-radiative heat transfer at the rear of the front array. Panels were cut to 100×100 mm squares from a larger panel. The panels were held on steel rods with bolts.

The heat exposure was by a dual conical setup, comprising two cone heaters side by side to provide a distributed heat flux across the bottom row of panels. The heat flux of each singular cone was set to 82.5 kW/m^2 at 25 mm from the centre, as is typical for cone heater calibrations, however to provide a more uniform heat flux distribution, the heaters were set at a stand-off of 40 mm from the sample assembly. The heat flux distribution from this setup ranged from 40 to 73 kW/m^2 at a standoff distance of 40 mm.

To provide a pilot source, two pencil torches were adapted into symmetrical pilots located parallel to the panels, and between the first and second row of panels. This allowed for the pilots to be within the flow of pyrolysis gases whilst not be imposing onto the panels. The pilots were set at a 20 mm standoff from the panels. Two pilots were used so that there was a pilot source for both bottom panels.

Measurements of mass loss were taken for the entire panel assembly to allow the observation of the burning rate of the assembly. The mass loss rate was therefore used as a proxy for the vertical fire spread on and between these panels.

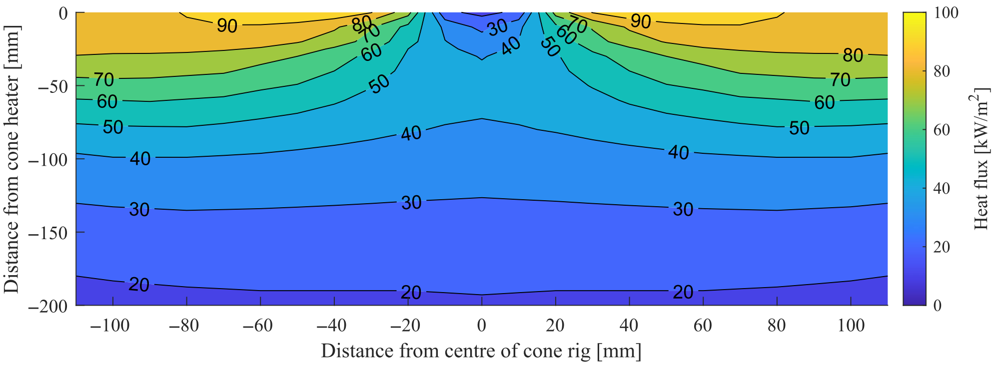

FIGURE 6 Heat flux mapping for dual conical setup along the vertical centreline of the cone heaters.

It should be acknowledged that there would be (innumerable) other ways to meet the test requirements as set out above. For example, samples could be smaller or larger, gaps could be smaller or larger, and the cones could be set to a different heat flux. As always with *tests*, rather than experiments there is no 'right' way to configure the arrangement, simply a chosen way.

5.2 | Meeting the requirements

To meet the requirements set out earlier, the following conditions were employed within the test:

5.2.1 | Minimal cost and required material

To keep the cost of performing a test and material usage to a minimum, panels of 100 × 100 mm were used, therefore, a total of 0.08 m^2 per test was required.

5.2.2 | Representative applied heat flux

From various studies, it is assumed a heat flux of 75 kW/m^2 would be representative of this reference scenario. To provide this, a dual conical setup was created to provide a peak radiant heat flux of 75 kW/m^2 across the bottom row of panels.

To fully characterise the heating applied onto the samples, the heat flux distribution that would be applied across the front panels was characterised as a function of horizontal distance along the face of the cone heaters, and of horizontal distance away from the cone heaters. This allowed for the investigation of where the most uniform heating location would be, to avoid localised 'cold spots'. All measurements were taken along the vertical centreline of the cone heaters, with the heat flux of each singular cone set to 82.5 kW/m^2 at 25 mm from the centre. The heat flux distribution observed from this setup provided minimum heating in the centre 'cold spot' of 40 kW/m^2, and a maximum of 73 kW/m^2 at a stand-off distance of 40 mm (Figure 6). The heat flux being imposed on the top row of panels is less than 35 kW/m^2 at the bottom and less than 5 kW/m^2 at the top.

5.2.3 | Product test, not a system test

To avoid the interaction of a backing material, two layers of the same product were used, in a similar approach to that used for the FM Global 16-ft parallel plate test.[35] This ensured that the heat transfer at the rear face of the front panel was controlled by the same product, not an additional system backing material.

5.2.4 | Exposed edges/joints

To make a test representative for layered products, it must present the failure (or the absence) of encapsulation, and exposure of protected internal combustible layers due to outer skin melting, buckling, delamination or physical damage. To do this, samples were cut from a larger panel and arranged in a 2 × 2 array with a 20 mm gap between edges so that edge effects and heating at joints between panels could be observed. This was identified to be a point of importance by Agarwal[17] and the BRE cladding tests.[36]

The panels were mechanically fixed using a threaded bar and nuts at the four corners of each panel. This same fixing mechanism was used for all products regardless of type. This was intended to allow for independent comparison of products, without placing reliance on its system interaction with other used materials and fixings.

5.2.5 | Results

Results were intended to quantify the vertical fire spread on and between panels. There are many ways in which this can be measured, all with benefits and limitations. Potential measurements that could be made were mass loss rate (MLR), HRR, video analysis and temperature. The mass loss rate was chosen as a proxy for spread as it allowed for the observation of the burning rate of the panels and is a relatively simple and cost-effective measurement to make as opposed to heat release which requires substantial gas analysis equipment.

5.2.6 | Test procedure

Tests were commenced by igniting the pilot flames and sliding the cone heater assembly forwards into place imposing onto the bottom

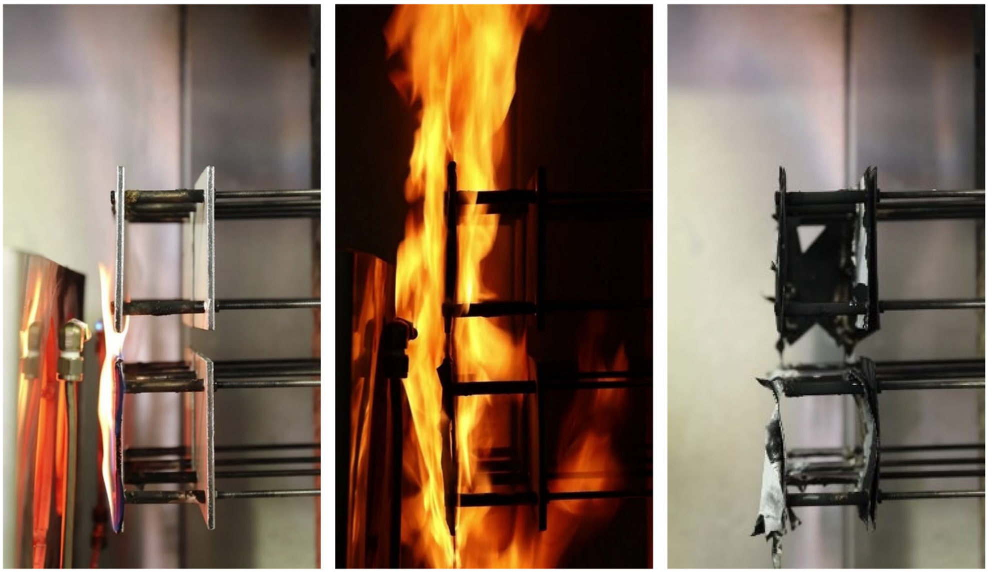

FIGURE 7 Video still captures of ACM PE experiment showing various stages in fire development; (A) ACM PE at 2 min 9 s with bottom panel burning, (B) ACM PE at 3 min 5 s with upper panel involvement, and (C) ACM PE at 9 min 24 s after burnout.

row of panels, 40 mm from the surface of the samples. Tests would be run until the samples had burned out, or until 10 min had elapsed. Mass measurements and video recordings would be made throughout the tests, after which, mass loss rate calculations would be made.

5.2.7 | Test products

A range of common external wall products were chosen to assess the applicability of the proposed test. A variety of ACMs with differing levels of flame retardants were chosen—polyethylene (PE), fire retardant (FR) and A2, which have roughly 0%, 70%–90% and 90%+ fire retardant mineral filler content respectively. The exact content of the mineral filler was not known due to manufacturer confidentiality. The tested ACM panels were 4 mm thick. These products were used within the MHCLG cladding programme as calibration tests as they provide a wide range of fire performance. Additionally, timber, high pressure laminate (HPL), and aluminium honeycomb panels were also chosen to provide a more thorough range of products. The timber panels were 22 mm thick and the other panels were 6 mm thick.

5.2.8 | Validation parameters

To assess the ability of the candidate test inreflect the behaviour in a large-scale test, the results between tests need to be compared. A series of parameters will be assessed to evaluate their applicability. The candidate parameters are the *peak MLR*, which characterises the maximum burning rate of a product; the *time to peak MLR*, which shows how quickly a product grows to peak burning and the *total mass loss*, which reflects how much of a material burns in the event of fire. Finally, a *fire growth index*, akin to that created by Björn Sundström during the development of the Euroclass SBI test, was used as a parameter for comparison. This was created as a ratio of the first two parameters, which indicates how quickly the fire develops to peak burning.

$$\text{Index} = \frac{\text{MLR}_{\text{peak}}}{t_{\text{peak}}} \quad (1)$$

5.3 | Test results

As the samples began to be heated, the bottom row of samples would begin to pyrolyse. If there was enough pyrolysis product generation, the samples would then ignite and the fire would then grow until the bottom row of panels became fully involved.

The flaming from the bottom row of panels would then impinge on the upper row of panels, and if the heat impingement was significant enough, the upper row of panels would then ignite and the fire grow until these panels were also fully involved. This way, the ability of the product to promote vertical fire spread could be measured. This process is illustrated in Figure 7.

Tests were performed on various external wall products also used within the large-scale reference test. This allowed for the comparison of results across a range of fire performance. A spline method was used to fit a function through the mass data, which was then differentiated to determine the MLR. The results are shown in Figure 8 and Table 3.

The test results show that for the ACM, mass loss rates are lower when more fire retardant is present. ACM A2 was the only ACM to not ignite.

For the other products tested, it was notable that timber gave a second peak in mass loss rate; this was due to the ignition of the rear array of panels. This second peak resulted in a mass loss rate similar in magnitude to that of the ACM PE—albeit at a much later time. This raises the question about which peak best represents the hazard—which will be discussed in the following section.

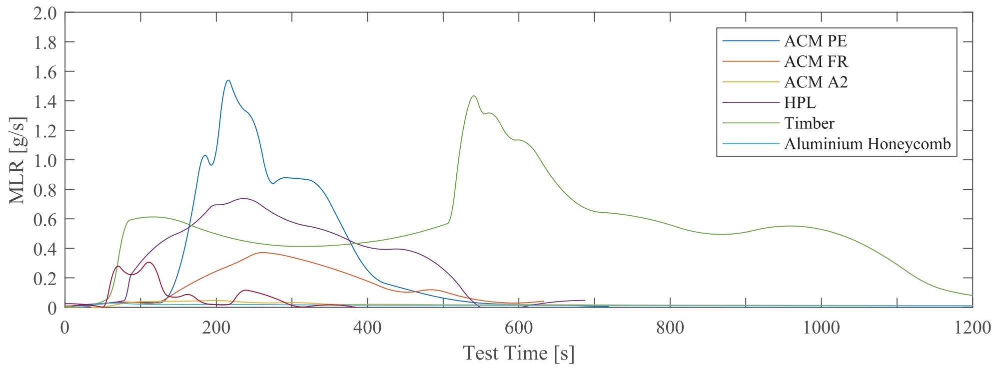

FIGURE 8 Experimental MLR results from candidate small-scale test.

TABLE 3 Summary of experimental results from candidate small-scale test.

Product	MLR (g/s)	Time to peak (s)	Total ML (g)	Index (g/s/s)
ACM PE	1.6795	208	2358	0.0081
	1.5399	216	1663	0.0071
ACM FR	0.3717	262	868	0.0014
	0.2982	337	179	0.0009
ACM A2	0.04620	197	198	0.0002
	0.0539	179	290	0.0003
HPL	0.7372	236	2008	0.0031
Timber	1.4335	540	1270	0.0027
Timber (front panel ignition)	0.6128	116		0.0053
Aluminium honeycomb	0.0283	67	151	0.0004

6 | CROSS-CORRELATION

To test the hypothesis of whether a small-scale test on external wall products can be created to reflect the behaviour in a large-scale test, the experimental results from both small and large must be compared. To allow this, a parameter for comparison must be chosen. The four candidate parameters set out earlier are examined to determine the degree to which there is any correlation between the small and large-scale tests. The candidate parameters are the peak MLR; the time to peak MLR; the total mass loss and a fire growth index.

In this study, no large-scale tests were performed. Therefore, to examine the relationship between the small-scale and large-scale tests, parameters from the candidate small-scale test are plotted on the *x*-axis against the parameters from the BRE Fire Performance of Cladding Materials Research intermediate scale test found in literature plotted on the *y*-axis. An illustration of this process is shown in Figure 9.

The statistical test performed to investigate the relationship between the test methods is the Pearson correlation. This allows for the determination of the statistical capability of the candidate small-scale test in representing the behaviour in the large-scale test (Figure 10).

The statistical investigation of the results, calculated using Pearson's linear correlation coefficient, shows that the *time to peak* parameter has no correlation between the small scale and the large scale (ρ of -0.08), and so this parameter is disregarded. The other parameters all show a more positive correlation between 0.83 and 0.90.

6.1 | Critiquing the correlation

The statistical test shows that, for certain parameters, the candidate small-scale test performs well as a proxy for the behaviour in a large-scale test. However, do the results actually reflect the fire hazard of these products?

The timber test is worthy of further examination. If peak values from the test are used, then the MLR implies timber is similarly hazardous as ACM PE, but the index shows it as much less hazardous due to the time to peak component of the calculation. If the initial peak were used for the calculation (i.e., before the rear panels were involved) the peak MLR would be lower, but the index would be higher due to the relatively quick ignition (Figure 11). So, assessment of the test results requires a level of understanding of the fundamental behaviour and test setup to understand the limitations of the method.

It was also observed that the aluminium honeycomb experiments did little by any metric; there were no visible pyrolysis gasses or visible degradation. Aluminium honeycomb, however, is bonded together using a blue adhesive, of unknown composition, around the joints between the honeycomb core and outer skins. It was therefore

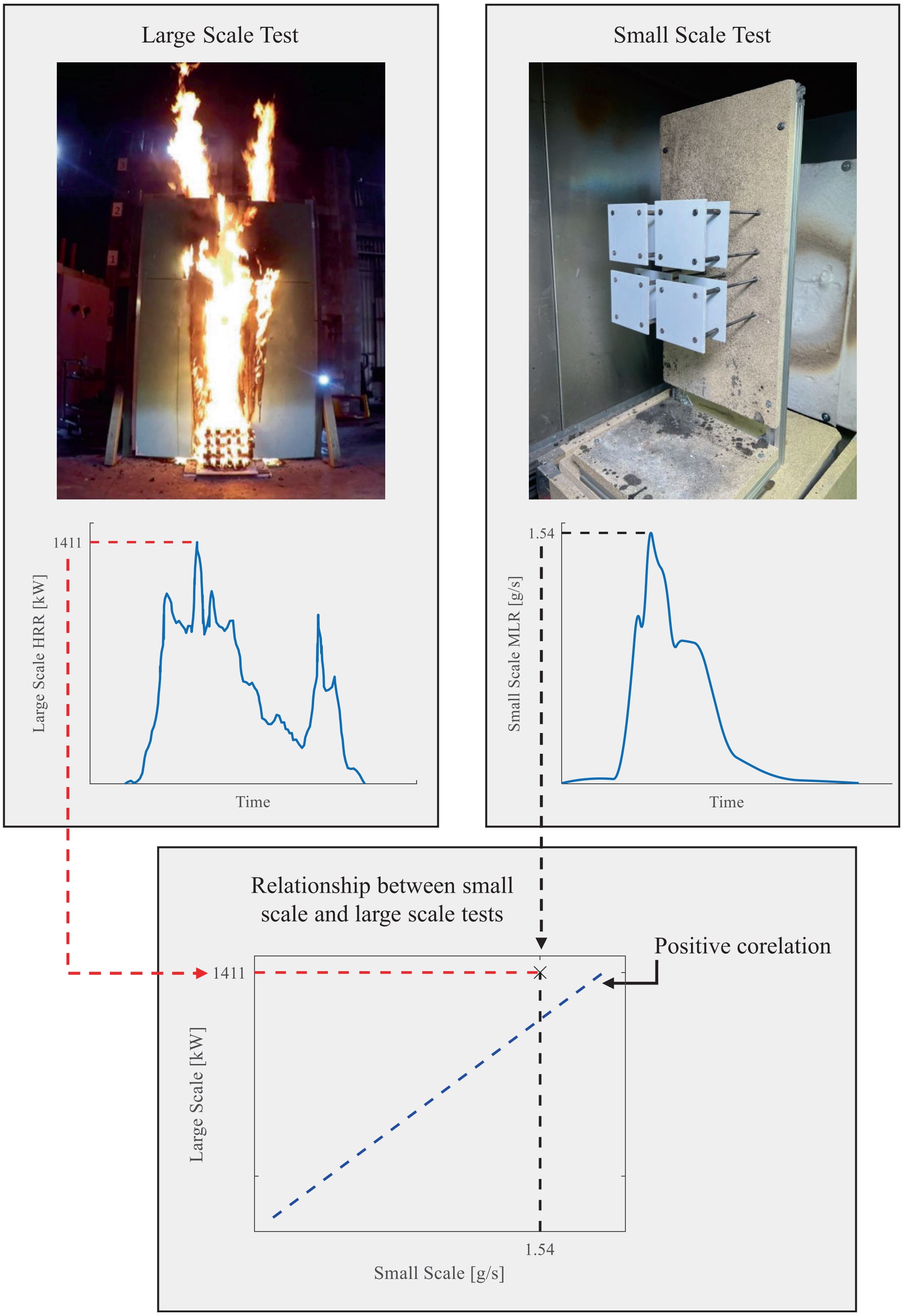

FIGURE 9 Illustration of the process of comparison between small-scale and large-scale tests.

expected that some pyrolysis should occur, and in the BRE large-scale tests some localised flaming and heat release was observed from the panels. To investigate this further, after the experiment was terminated, localised flame impingement was introduced in the form of a propane blowtorch held horizontally at the bottom corner of the bottom row of panels. This localised flame impingement caused a rapid flame spread through the honeycomb core of the bottom panel, fully involving the impinged panel within 10 s and spreading to the panel above and the panel to the side after 20 s. After 30 s, the propane torch was removed, and the fire grew to involve the upper panels and burned for 80 s before flaming ceased. Whilst this rapid flame spread was observed, it is noted that this was after 1200 s of pre-heating of the panels, and the peak MLR was only 0.30 g/s due to the low mass of adhesive in the panel with the majority of the mass being aluminium.

This does indicate, however, that even with a large applied heat flux, the panels had large enough heat losses so as to prevent significant heating. The large amounts of aluminium acted as an effective heat diffuser, and the structure of the honeycomb provided a large surface area exposed to air which resulted in large heat losses. It was

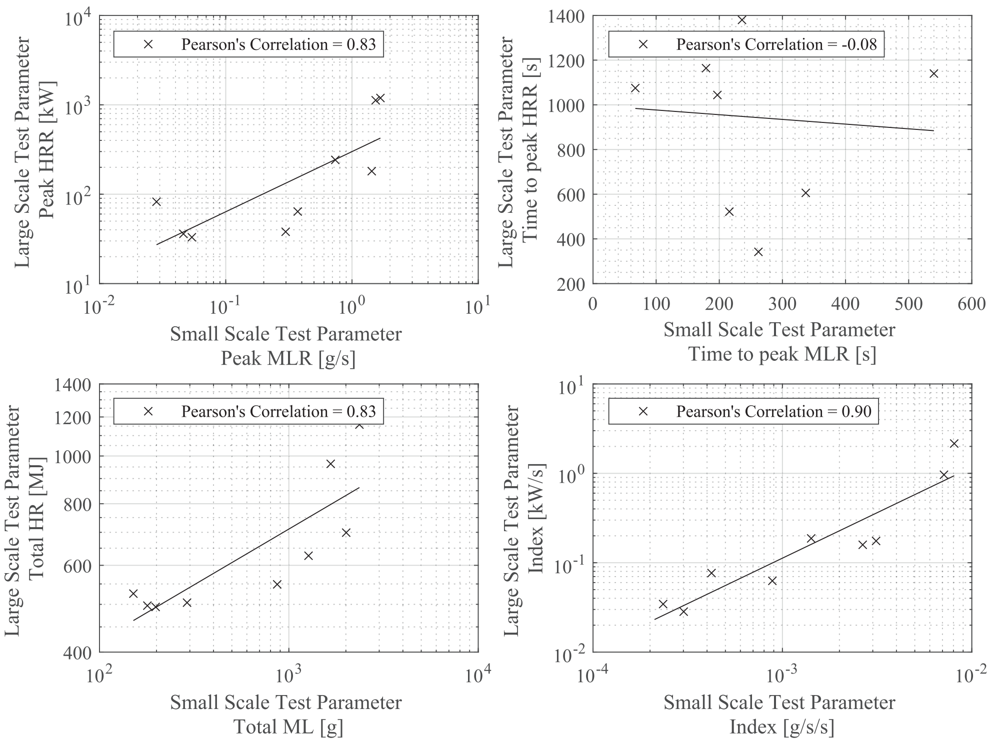

FIGURE 10 Comparison of product fire performance in large-scale MHCLG test versus candidate small-scale test for different parameters; (A) peak MLR, (B) time to peak MLR, (C) total mass loss, and (D) index.

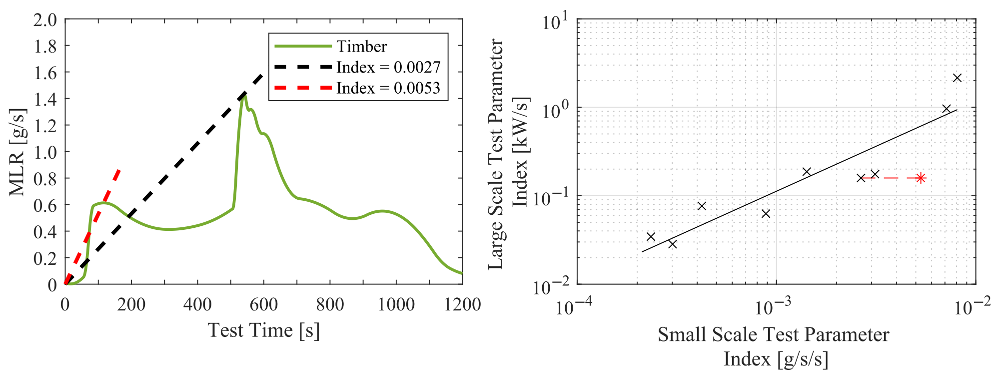

FIGURE 11 Comparison of product fire performance in large-scale MHCLG tests versus candidate small-scale tests for different parameters with the visual representation of the effect of using the different timber peaks: (A) timber MLR and (B) index.

only after locally overcoming the heat losses with a blowtorch that the panel ignited, and then promoted fire spread. This presents a further problem with materials that have very high heat losses—particularly when they are heated by radiation only.

7 | DISCUSSION

The investigation described in this paper shows that small-scale test may be created that achieves a somewhat remarkable level of correlation between the small and large-scale test results for a product. Clearly, though, there are significant limitations. Some of these simply relate to the size of the study—there are only nine data points on each plot—so a 'successful' correlation should only be declared with caution.

However, there are also questions about the degree to which the test (and its metrics) were adequately able to represent the hazard of each of the products. This was particularly the case with the timber and the aluminium honeycomb. The large amount of exposed surfaces of the timber led the rear panels to readily ignite—and therefore resulted in a high mass loss rate. Similarly, the nature of the heating (and losses) from the honeycomb panel meant that it was only with additional, ad-hoc experimentation, that it was possible to ignite the panel.

These observations clearly reveal the issues inherent within any test method for complex products. That is, a test may work for many scenarios (that the test designers had anticipated) but it is very challenging to develop a test that adequately captures the hazard associated with a product. This observation—for the process followed within this paper—echoes the conclusion of those who developed the Euroclasses in the mid-1990s.[38] Brannigan[39] also discussed that there is a constant commercial incentive to create new and innovative products to fit a specific use case, with better performance, in a more cost-effective manner. By definition, these new complex products cannot be designed for when creating a regulatory test, as they do not exist yet. Therefore, any test that is created cannot be designed to be 100% effective. There will always be products for which a test will not 'work'.

This leaves various possible options for future test designers and regulators to consider. For example, one approach could be to accept that innovation is inhibited to prevent the use of products that are not fully understood, and which do not fit the regulatory framework. Such an approach might be implemented by adopting conservative thresholds for acceptance—even where it is believed that many products that exceed these thresholds are not inherently problematic.

Another approach could be to accept that some products will not respond appropriately to small-scale testing and that this is an inherent feature of any standardised testing method. Such an approach would require a vigilant regulator—willing to withdraw test standards for use on a product when there is a suspicion that there might be an unassessed hazard.

An alternative could be to dispense with small-scale testing altogether and rely on large-scale testing in all cases. However, this approach utilises system tests and therefore requires judgements to be made about whether the tested situation is sufficiently similar to the real-world application—and also brings with it the issues of cost and practicality that were central to the motivation for the work described in this paper.

A final option (although no doubt there are more) is to couple the use of test metrics with user competence requirements and professional liability. This approach would allow the advantages of small-scale testing but would ensure that users of the test were cognisant of both the intent of the testing regime, and provide an incentive to address any shortcomings by further engineering analysis.

8 | CONCLUSION

A small-scale test for cladding products was developed in an attempt to create a simple and (relatively) inexpensive way of evaluating the hazard presented by different external wall products. The conceptual framework of the Euroclasses was used as the basis of this approach, whereby the reference scenario was selected as an external plume venting from a compartment; the reference test as intermediate scale testing by BRE; and the small-scale test was a double cone heater with an array of cladding specimens.

Six products were tested and remarkable agreement was found between the small-scale test and reference test. A Pearson's correlation of 0.9 suggests very strong agreement between the two datasets. However, the strength of this correlation is caveated by the (relatively) small number of products that were tested, and the fundamental uncertainties about which metrics should be selected. Furthermore, it was observed that for particularly complex products (in this case aluminium honeycomb panels) there was uncertainty about whether the small-scale test was capable of fully assessing the product's hazard.

Overall, the authors are left with uncertainty (and doubt) about whether the observed behaviours accurately capture the full picture of the complex products due to the complexities of the system interactions and encapsulation effects.

This observation hints at the fundamental value of retaining knowledge-based assessment (as opposed to compliance testing) within any regulatory regime. For example, the approach presented by Hidalgo[9,40] and the UQ cladding library allows a complex product to be investigated by evaluating its constituent parts individually. This approach ensures that no individual component can be concealed, and provides a more clear and comprehensive description of the fire performance of the product. This approach can therefore provide a more informative classification method, where the fire performance of all the constituent materials is shown.

The strong correlations found show that there is an intuitive appeal to such testing, and that it may serve as a rapid and inexpensive way of evaluating the fire spread hazard of a product. By this measure, the research has achieved its intended aim. However, the vulnerabilities of such a testing method to product innovation are clear—and therefore declaring a product 'safe' on the basis of a classification or pass-fail test is fraught with difficulty. Perhaps, such an approach is useful—but only when used to inform a competent fire engineering analysis in an outcomes and competency-based regulatory framework. A framework where tests are utilised by a competent engineer with an understanding of the limitations and nuances of the method, and when the results of the test may (or may not) be valid.

AUTHOR CONTRIBUTIONS

Cameron MacLeod: Methodology; investigation; validation; formal analysis; writing—original draft. **Neal Butterworth**: Writing—review and editing. **Angus Law**: Conceptualization; writing—review and editing; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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