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FLAME SPREAD CLASSIFICATION METHOD FOR EXTERIOR WALL CLADDINGS

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ABSTRACT

This paper describes a cone calorimeter fire test program and the application of a vertical flame spread model, developed for internal wall linings, to flame spread on exterior wall claddings. It outlines performance criteria for the design of building facades to ensure that exterior cladding materials are unlikely to accelerate the vertical spread of fire and endanger the safety of building occupants.

INTRODUCTION

In New Zealand, surface finishes of exterior wall claddings are regulated within the Acceptable Solutions [1], to limit their contribution to fire spread, depending on the building occupancy, building height, and distance of the wall to the boundary. Currently the two different test methods specified, a *non-combustibility* test and a *radiant heating* test, have shortcomings in their ability to classify fire hazard for this type of application. Some of the prescriptive requirements are unnecessarily restrictive, eg. irrespective of the distance to another building, timber weatherboards are not permitted on a single-storey block of flats or motel block. Wade [2] identified potential hazards posed by exterior wall claddings and measured the rate of heat release behaviour for ten different cladding materials. At that time it was recognised that, in order to develop performance criteria that had a sound scientific basis, further work was required to describe the flame spread characteristics that were necessary for a cladding material to propagate flame vertically.

The intention of this study has been to apply an existing analytical vertical-flame-spread model, developed for use in room fire modelling to vertical flame spread on exterior wall claddings. The aim was to develop improved methods for determining whether combustible exterior wall claddings exposed to window fire plumes are likely to propagate flame spread on a building facade. We have used an analytical solution for concurrent flow flame spread on a vertical surface to determine whether the flame front is expected to accelerate or decelerate under external heat flux conditions representative of window fire plumes. The cone calorimeter test method was used to measure time to ignition, peak rate of heat release and total heat released for 15 types of exterior wall claddings.

Performance criteria based on heat release or 'degree of combustibility' are proposed as they are considered to provide an improved classification scheme for exterior wall cladding materials.

NEW ZEALAND FIRE REGULATIONS

The New Zealand Building Act [3] permits buildings to be constructed provided they meet the performance requirements of the Building Code [4]. This can be met by either meeting the prescriptive requirements of the Acceptable Solutions or providing an Alternative Solution which may use fire engineering methods.

Wade [2] gives a more detailed account of the New Zealand Building Code (NZBC) and its implications for designers of exterior claddings to resist fire spread.

REGULATING THE FIRE PERFORMANCE OF EXTERIOR WALL CLADDINGS

The NZBC Acceptable Solution [1] provides one approved means of complying with the Code. Distances and areas of openings are controlled to limit radiation, and fire resistance requirements are also identified. A further requirement seeks to reduce the likelihood of fire propagating vertically up a combustible facade.

Clause 3.3.5 of C3 of the Building Code [4] provides the following objective when designing for fire performance of external wall claddings: "*External walls and roofs shall have fire resistance to the spread of fire, appropriate to the fire load within the building and to the proximity of other household units and other property*." Specifically, C3 seeks to reduce the likelihood of fire propagating vertically up a combustible facade, as a result of either direct flame impingement from an adjacent building on fire or from flames projecting through openings at a lower level in the same building and igniting the facade in the vicinity of the opening. The Acceptable Solution seeks to control either the ignitability or the contribution of the cladding to fire development (ie combustibility) and thereby directly influence the rate of vertical flame spread.

CURRENT FIRE TESTING METHODS FOR EXTERIOR WALL CLADDINGS

The test methods specified are: AS 1530 Methods for Fire Tests on Building Materials, Components and Structures-Part 1: Combustibility test for materials [5] and Part 3: Simultaneous determination of ignitability, flame propagation, heat release and smoke release [6]. Wade [2] gives a detailed critique of the test methods and describes how the non-combustibility test is considered to be overly restrictive towards some materials, such as cellulose fibre-cement sheets which, although deemed combustible by the combustibility test, do not contribute significantly to fire development.

AS 1530 Part 3 exposes a vertical specimen to a gradually increasing heat flux up to a maximum of about 30 kW/m² by moving the specimen closer to a radiant panel over a period of 20 minutes. The Ignitability Index = 0 requirement of Acceptable Solution C3/AS1 requires that no ignition occurs under these conditions. Although ignitability is an important factor influencing vertical flame spread, in this case, the heat flux level and the gradual heating conditions may be considered not severe enough to represent a window fire plume.

The combustibility test, AS 1530 Part 1 (and its equivalent around the world, BS 476 Part 4, ISO 1182, ASTM E136) is considered to be overly restrictive toward some materials, such as cellulose fibre-cement sheets, which do not contribute significantly to fire development but are deemed to be combustible under the conditions of this test.

Note that these test methods only evaluate the ignitability/combustibility of a product. They do not evaluate flame spread directly or the magnitude of a cladding material's contribution to fire development.

DEGREES OF COMBUSTIBILITY

The concept of degrees of combustibility has also been proposed [7, 8, 9] where it is suggested that rate of heat release could be used to rank building materials according to their degree of combustibility. Test methods using a cone calorimeter to measure heat release have now been published by ASTM [10] and ISO [11], and a joint Australian New Zealand Standard is also in preparation (AS/NZS 3837). Richardson and Brooks [8] have indicated a preferred exposure of 50 kW/m² for 15 minutes in the presence of an external spark igniter. Richardson and Brooks have also suggested criteria for classifying materials according to their degree of combustibility by utilising two performance parameters. The first is the peak rate of heat release and the second the total heat released after 15 minutes from commencement of the test. Thus, depending on the end use of the material and its location within the building, appropriate levels of performance in terms of peak rate of heat release and total heat release may be specified.

WINDOW FIRE PLUMES AND VERTICAL FIRE SPREAD

The severity of an external wall's exposure resulting from a window fire plume will vary depending on the burning contents of the room, the size of the fire and the geometry of the window opening. The exposure will decrease with an increase in vertical distance above the window and increase with the burning rate of the cladding material. Babrauskas [12] suggests that a heat flux of 50 kW/m² may be a reasonable condition for many applications involving heat fluxes to the building facade from a window fire plume, and that, while higher fluxes are certainly possible, they require both very large fires and very large openings.

The study of concurrent flame spread is well advanced, with many authors contributing to the field. James Quintiere provides a comprehensive summary in the SFPE Handbook of Fire Protection Engineering 2nd Edition [13]. A study of wind-aided flame spread on a thermally thick material (or thermally thin material with a backing board) by Saito, Quintiere and Williams [14] provided an integral equation for the velocity of flame spread. Thomas and Karlsson [15] then derived an analytical solution for the integral equation for certain conditions which depended on flame length correlations, initial burner output, and the heat release rate history of the burning material. The significance of this work is that it identified limits of propagation and non-propagation for concurrent flow flame spread, as described in the following section. It is this work that provides us with a method for determining how a cladding material exposed to window fire plumes could be expected to propagate flame spread.

ANALYTICAL SOLUTION FOR FLAME SPREAD

Karlsson's [16, 17] model for flame spread over internal wall linings has been used to observe flame acceleration and deceleration characteristics for the range of materials tested in the cone calorimeter. Karlsson provides details on the contribution of lining materials to flashover in a room fire and outlines a model for upward flame spread over solids. He also provides a lists of models and theories of varying levels of complexity for vertical upward flame spread on large surfaces [17].

It was unclear, before Karlsson's work, that any models could be used to predict flame spread over materials based on parameters derived from small scale tests. Karlsson developed a theory, which is presented here, for upward flame spread that only requires results from cone calorimetry testing and that builds on the work of Parker [18] and Saito [14]. He describes the thermal theory for upward flame spread on thick solids which leads to an integral equation for the velocity spread and gives a complete description of the method used in this experimental program.

Velocity of flame spread (m²/s) can be written as:

$$V(t) = \frac{A_f - A_p}{\tau} \qquad [1]$$

where A_f represents the flame area, A_p the pyrolysing area and τ is the time to ignition, written as

$$\tau = \left[\frac{4\dot{q}_f''^2}{\pi k\rho c\left(T_{ig} - T_0\right)^2} \right]^{-1} \qquad [2]$$

$\dot{q}_f''$ is the heat flux from the flame to the unburnt material, $k\rho c$ is the material thermal inertia, T_{ig} is the material ignition temperature and T_0 is the surface temperature of the material ahead of the flame front.

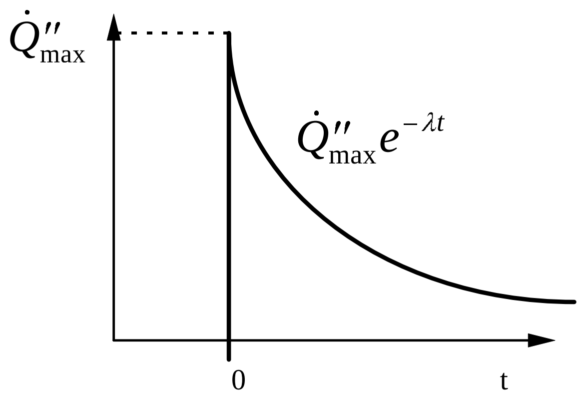
The following assumptions allow the problem to be solved analytically.

1) The method requires the heat release rate history for a material be approximated to an exponential decay function for the heat release rate, $\dot{Q}'' = \dot{Q}''_{\max} e^{-\lambda t}$. Where $\dot{Q}''_{\max}$ is the maximum heat release rate from the cone calorimeter test and λ is the decay coefficient of the heat release curve, as in Figure 1 .

2) Flame area is linearly dependent upon the total heat released and is written as $A_f = k\dot{Q}$ where k is a constant (in m²/kW) and $\dot{Q}$ is the total heat release rate.

3) The initial pyrolysing area, A_0, depends on the strength of the ignition source and the energy released from the material directly adjacent to the ignition source.

Figure 1. Mathematical representation of the material heat release rate



The resulting integral equation then becomes,

with $V(t) = \frac{dA_p}{dt}$ (in m²/s):

$$V(t) = \frac{1}{\tau}\left[A_0 + k\left(A_0 \dot{Q}''_{\max} e^{-\lambda t} + \int_0^t \dot{Q}''_{\max} e^{-\lambda (t - t_p)} V(t_p) dt_p \right) - \left(A_0 + \int_0^t V(t_p) dt_p \right) \right] \qquad [3]$$

where the first two terms on the r.h.s represent A_f and the last bracketed term represents A_p. The dummy variable of integration is given by t_p. The solution can be described graphically in terms of τ, λ and a (see Figure 2), with $a = k\dot{Q}''_{\max}$, τ is ignition time and λ is the decay coefficient from Figure 1.

The characteristic behaviour of the solution for different parameters $a = k\dot{Q}''_{max}$ and $\lambda\tau$ are shown in Figure 2. The solutions are only valid for a positive velocity since the flame height is always considered to be positive. Figure 2 is valid for other configurations too. The values of *k* and the flame length or flame area coefficient change in each configuration (flame spread up a corner, on a wall or under a ceiling) and so does the initial pyrolysis area or pyrolysis length, X_p. Also, τ, the time to ignition, will be dependent on the configuration.

Karlsson [16] presents the analytical solution for the concurrent flow flame-spread equation. These apparently crude engineering attempts to model a physically very complex reality show us that more detailed modelling is feasible and will improve predictive capabilities and enhance applicability under various situations. The equations can be set up in somewhat more complex terms and solved numerically and this is proposed for the next stage of this research work. The advantages of a numerical solution are that material heat release rates are available directly from the cone calorimeter test results.

CONE CALORIMETER TEST PROGRAM

In order to examine the concept of rate of heat release for evaluating fire performance of external wall claddings it was decided to test a range of exterior cladding materials and products (available within New Zealand) using the cone calorimeter method of ISO 5660 [11]. Each 100 mm x 100 mm sample of the cladding product was tested, at least twice, at 50 kW/m² in the cone calorimeter for at least 15 minutes. Heat release rates (kW/m²) were recorded, along with other test data from the start of the test until 15 minutes had passed. The time to ignition (sec), total heat release (MJ/m²) and the peak heat release rate (kW/m²) were measured.

A series of 15 products were tested (Table 1), five of which were selected for testing at the much higher irradiance of 75 kW/m². The results for these five products are presented in Table 2. A detailed description of each product is given at the end of this paper.

Test preparations

The following procedures of the standard test method were followed.

1) All samples were conditioned to moisture equilibrium in the constant climate room at 23°C and 50% r.h. prior to testing.

2) The unexposed sides of all samples were wrapped with aluminium foil.

3) Samples were protected by the retainer frame (and when necessary the wire grid).

4) Tests were conducted at 50 kW/m² irradiance for 15 minutes from the start of the test.

5) The spark igniter was used until continuous flaming (ignition) was noted.

6) At least two replicate samples of each cladding system were tested.

Measured parameters for analytical test method

The analytical method described above requires the following parameters from the cone calorimeter test.

1) Time to ignition , τ , *secs*.

2) Peak heat release rate, $\dot{Q}''_{max}$, *kW/m²*.

3) Total heat released, $\dot{Q}_{tot}$, *MJ/m²*.

Data derived from the tests results are:

4) Decay coefficient, λ, s^{-1}.

5) Modified $\dot{Q}''_{\max}$, a, *kW/m²*.

The decay coefficient, λ, is estimated from the actual rate of heat release decay curve achieved in the tests and $a = k\dot{Q}''_{\max}$ where k = 0.015 for external wall geometry.

Table 1. Summary of Test Results, at 50 kW/m².

ID	Generic Description	$\dot{Q}''_{\max}$ kW/m^2	$\dot{Q}_{tot}$ MJ/m^2	τ s	λ s^{-1}	a	λτ
1	EIFS	88	3	77	0.0562	1.314	4.293
2	Fibre-cement board	58	2	86	0.0078	0.870	6.676
3	Fibre-cement board	53	6	82	0.0770	0.794	6.290
4	Metal sheet	98	3	98	0.1300	1.465	12.700
5	Plaster	51	3	130	0.0633	0.765	8.197
6	Plaster	76	6	84	0.0313	1.140	2.629
7	PVC	151	46	28	0.0133	2.195	0.372
8	Timber	177	106	15	0.0190	2.648	0.277
9	Timber	229	67	18	0.0139	3.428	0.230
10	Hardboard WB	332	96	23	0.0220	4.973	0.508
11	Fibre-cement board	64	6	134	0.0735	0.953	9.853
12	Fibre-cement board	21	5	66	0.0290	0.308	3.799
13	Timber	273	77	15	0.0373	4.100	0.565
14	Hardboard WB	419	106	65	0.0343	6.291	2.214
15	Metal sheet	0	0	0	0.0000	0.000	0.000

Notes to Table 1. See appendix to this report for complete product description.

Table 2. Summary of Test Results, at 75 kW/m².

ID	Generic Description	Peak HRR kW/m^2	Total HR MJ/m^2	τ	λ	a	λτ
9	Timber	322	79	4.5	0.0192	4.84	0.082
7	PVC	190	44	17	0.0077	2.85	0.13
11	Hardboard WB	389	111	13	0.0105	5.84	0.138
6	Plaster	110	10	37	0.0509	1.65	1.881
2	Fibre-cement board	80	7	33	0.0749	1.21	2.505

Figure 2. Regions of flame front acceleration and deceleration.

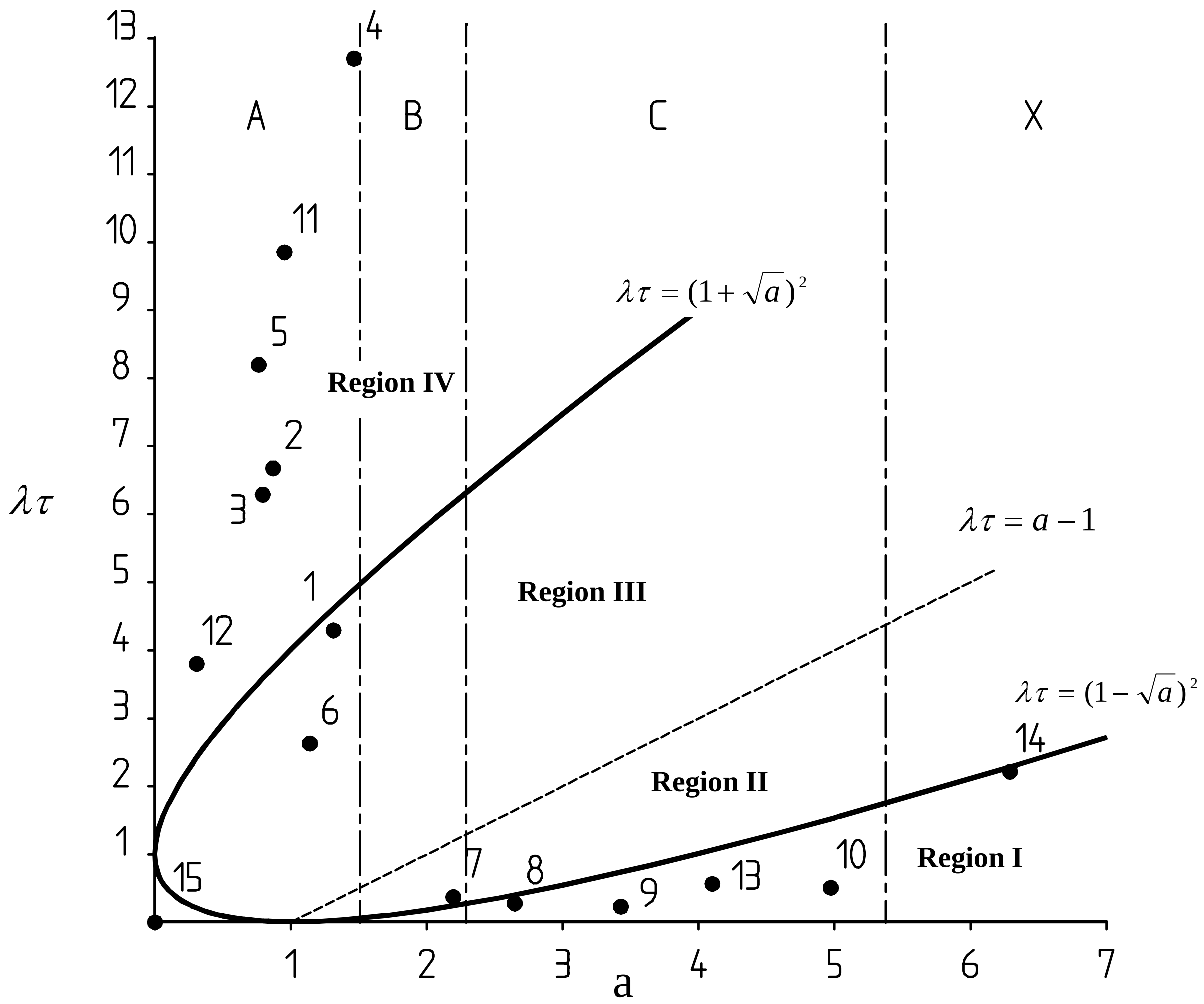


Figure 2 presents the results for each exterior wall cladding material tested as they are classified in terms of the regions of flame front acceleration.

Region I Below the line $\lambda\tau = (1-\sqrt{a})^2$ materials will normally exhibit **exponentially accelerating flame spread** characteristics**.**

In **Region II** the flame exhibits **initial accelerating** but then decelerates and stops at a finite time.

For **Region III** the solution to the equation shows an **initial deceleration**. There is no acceleration until the velocity has been negative for some time.

Materials in **Region IV** exhibit flame spread velocities that **decelerate for all time**.

The classifications based on the Flame Spread Performance Criteria are also illustrated as A, B, C and X.

FLAME SPREAD PERFORMANCE CRITERIA

External claddings play an important role in preventing fire spread from one building to another and between floors of the burning building. In the case of a single-storey building it is suggested that in most instances the combustibility of the external cladding has little effect on life safety within the building. In the context of todays performance based building codes, trade-offs can be used for buildings which are sprinklered. It is therefore suggested that a less stringent degree of combustibility on external wall claddings could also be accepted as reasonable, where the building is sprinklered.

Suggested performance criteria based on rate of heat release and total heat release and the issues of boundary distances, building height, purpose groups and sprinklers are included as Table 3.

Table 3. Suggested flame spread performance criteria for exterior wall claddings.

Building Height		**Distance to Relevant Boundary**			
		< 1 m	≥ 1 m		
		All Purpose Groups	Purpose Groups SC, SD	Purpose Groups SA, SR	All Other Purpose Groups
Single-Storey		B	C	C	C [1]
≤ 7 m		B	B [2]	C	C [1]
≤ 28 m		B	B	B [2]	C
> 28 m	Sprinklered [3]	B	B	B	C
	Unsprinklered	A	A	B	B

Notes to Table 3.

Category	**Peak Rate of Heat Release [4] (kW/m^2)**	**Total Heat Release [4] (MJ/m^2)**
A	≤ 100	≤ 25
B	≤ 150	≤ 50
C	≤ 350	≤ 125

A. Intended to apply to products which will not propagate vertical flame spread, and is indicative of regions III and IV in Figure 2. This corresponds to materials which can be used where non-combustible materials would otherwise be specified. It is less stringent than a non-combustibility requirement but it is expected that flame spread will not occur over the material. Typical materials are fibre-cement board and concretes with combustible aggregates.

B. Some initial flame spread, but later deceleration such as in regions II and III. This is less onerous than A and represents materials which will not produce uncontrolled flame spread but may have local damage. Typical materials are timber claddings with intumescent coatings, and some EIFS systems.

C. Vertical flame spread possible, but extremely rapid spread unlikely, such as regions I and II. This category excludes materials which could result in very rapid flame spread. Typical materials are PVC claddings and coated or bare timber.

1. External wall cladding systems in buildings with a building height not greater than 7m, and which do not contain SC, SD, SA or SR purpose groups need not comply with the above table provided the external wall is permitted to have 100% unprotected area.

2. Where the building is sprinklered in accordance with NZS 4541 [19] or NZS 4515 [20] (as applicable), may be reduced to a "C".

3. Sprinklered means the building is fully protected in accordance with NZS 4541.

4. Determined by testing in a cone calorimeter at an irradiance of 50 kW/m² for a duration of 15 minutes.

5. Purpose groups from New Zealand Building Code [4].

   SC Sleeping Care, hospitals, rest homes etc.

   SD Sleeping Detention, prisons, psychiatric hospitals etc.

   SA Sleeping accommodation, hotels, motels etc.

   SR Sleeping Residential, apartments etc.

This table is based as on a similar one in C3/AS1 Spread of Fire, Clause 4.9.2 of the New Zealand Building Code Approved Documents [1] where criteria based on non-combustibility and radiant panel tests are used.

Table 4. Flame spread performance of selected exterior wall claddings.

ID	Generic Description	Peak HRR *kW/m²*	Total HR *MJ/m²*	Category	Region at 50	Region at 75
15	Metal sheet	0	0	A	IV	
2	Fibre-cement board	58	2	A	IV	III
5	Plaster	51	3	A	IV	
1	EIFS	88	3	A	III	III
4	Metal sheet	98	3	A	IV	
12	Fibre-cement board	21	5	A	IV	
11	Fibre-cement board	64	6	A	IV	
6	Plaster	76	6	A	III	III
3	Fibre-cement board	53	6	A	IV	
7	PVC	182	39	C	II	I
9	Timber	229	67	C	I	I
13	Timber	273	77	C	I	
10	Hardboard WB	332	96	C	I	I
8	Timber	177	106	C	I	
14	Hardboard WB	419	106	X	I	

DISCUSSION AND CONCLUSIONS

It has been shown by Wade [2] that classifying exterior wall claddings on the basis of performance in the 'combustibility' test has proved overly stringent where some cladding materials are concerned.

A number of limitations are also apparent with the proposed test method, including the performance of large sheet products in the restricted space of a small-scale test method. The classification method is not able to evaluate performance of joints/connections nor any other large-scale effects which are not apparent from small-scale tests. The same criticism can be applied to the existing test methods AS 1530 Parts 1 and 3, used in New Zealand. Large-scale tests are expensive and there is a need for simpler, cheaper, bench-scale methods such as the cone calorimeter, even if it is not a perfect solution.

Observation of the performance of an analytical solution to the concurrent flow flame spread equations developed for flame spread on internal wall configurations, in combination with material flammability parameters, indicates that the method can be used to rank combustible cladding materials according to their flame spread propensities. It is also possible to develop performance criteria based on the *peak* *rate of heat release* and the *total heat release* in 15 minutes from the start of the test. In general terms the A, B and C categories seem to achieve intentions of providing a better classification of external wall cladding systems than the non-combustibility criterion of AS 1530 Part 1. The relative performance of each sample tested in the flame spread classification system compared with the analytical flame spread model shows good agreement, with both methods successfully ranking the flame spread characteristics of the tested materials.

An intended future outcome of this work will be to develop a numerical model for predicting flame spread via external walls. Fire engineers will then have available a methodology for the specific design of exterior wall cladding systems that will aid in the provision of life safety.

Further research work is planned which will involve exposing a series of exterior cladding systems to a full-scale fire testing method, and the development of a computer-based software model for vertical flame spread on wall claddings.

ACKNOWLEDGMENTS

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SAMPLE LIST

The following table lists the products selected for assessment.

1 EIFS
45 mm thick.
Proprietary Exterior Insulation and Finish System (EIFS). Polystyrene foam insulation board finished with a Portland cement-based plaster, reinforced with fibreglass mesh. Finished with two coats of acrylic paint.

2 Fibre-cement board
6.5 mm thick.
Proprietary cellulose fibre-cement board. Finished with two coats brown acrylic paint.

3 Fibre-cement board
10 mm thick.
Proprietary compressed cellulose fibre-cement sheet. Pre-finished with primer coats and a two-part-polyurethane top coat. Colour white.

4 Metal sheet
14 mm thick.
Aluminium cladding system. Pre-finished in white.

5 Plaster
9.7 mm thick.
Consists of a proprietary cellulose fibre-cement board, covered with a skim coat of cementitious plaster and a proprietary polymer-modified, cement-based plaster. Acrylic paint finish.

6 Plaster
12 mm thick.
Plaster coatings applied to a cellulose fibre-cement, glass fibre mesh finishing plaster. Two-coat acrylic paint system.

7 PVC
13 mm thick.
Proprietary extruded twin-wall uPVC weatherboard. Colour white.

8 Timber
20.4 mm thick.
Radiata pine treated with copper-chrome-arsenate (CCA) to H3 (resists above ground decay). Finished with three-coat acrylic paint system. Colour brown.

9 Timber
12 mm thick.
Phenol formaldehyde bonded Radiata Pine veneers, treated to H3. One coat brown decking stain on rough sawn plywood face.

10 Hardboard weatherboard
9.4 mm thick.
Shiplap cladding. Two coat brown acrylic paint.

11 Fibre-cement board
6.3 mm thick.
Proprietary cellulose fibre-cement board. Finished with two coats white acrylic paint.

12 Fibre-cement board
9 mm thick. Similar to product 31.
Proprietary compressed cellulose fibre-cement sheet. Finished with primer and an acrylic top coat. Colour white.

13 Timber
19 mm thick.
Radiata pine treated with copper-chrome-arsenate (CCA) to H3 Finished with three-coat acrylic paint system. Colour brown.

14 Hardboard weatherboard
9.5 mm thick.
Shiplap cladding Two coat white acrylic paint.

15 Metal sheet
0.5 mm thick.
A coil-coated galvanised steel sheet. Oven-dried finishing paint coat, colour titania.