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Ministry of Housing, Communities and Local Government Final Research Report

Fire Performance of Cladding Materials Research – Appendix A Literature review

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A1 Introduction

The authors of this report are employed by BRE Global. The work reported herein was carried out under a Contract placed by the Ministry of Housing, Communities and Local Government. Any views expressed are not necessarily those of the Ministry of Housing, Communities and Local Government.

This Appendix is part of a Main report and Appendices and should be read in conjunction with these.

Note: This report was completed in April 2018 and as such relates to the state of knowledge at that time. Since April 2018, the Building (Amendment) Regulations 2018 SI 2018/1230 have been introduced and Approved Document B (Fire Safety) 2019 edition has been published. Clause A2.5 has not been updated and so must be considered within this context.

This Appendix contains a literature review to establish the current state of knowledge concerning the fire performance of cladding materials/products.

The contents list of this literature review was presented to the Project Steering Group at the first meeting. Steering Group representatives were asked to provide any relevant information for the literature review.

A2 Literature review

A2.1 Introduction

The review covers a number of specific areas related to the fire performance of cladding materials/products and cladding systems, including a description of the principal materials/products and systems used in the construction of cladding to the external facades of buildings, examples of fire spread from real fire incidents, a description of the regulatory framework with regard to external fire spread (with particular reference to UK practice), a description of the test and assessment procedures used to determine the compliance of cladding materials/products and systems in fire and a summary of relevant research in this area.

A great deal of work has been carried out in recent years on the fire performance of cladding materials/products and systems and, in particular, on developing methods of test and assessment which take into account the likely behaviour of the products and systems in a realistic fire exposure. The literature survey is focused on the overall objectives of the project.

Issues arising directly from the Grenfell Tower fire are being addressed through the Independent Review of Building Regulations and Fire Safety [1] and the incident is the focus of an on-going police investigation. For this reason no specific reference is made to the Grenfell Tower fire. Similarly, the use of aluminium composite panels (ACM) has been the focus of a series of fire tests commissioned by the Department for Communities and Local Government (now MHCLG) [2] and is not considered further in this report.

Note that references to national and international standards are not dated. The latest edition of the document referred to applies.

A2.2 Background

External cladding systems are widely used for new buildings and as a means of upgrading existing buildings. The primary function of external cladding systems is to insulate the building envelope from environmental impacts. The typical section of a cladding system includes an impermeable (external) surface membrane, a cavity (in the case of ventilated rain screen systems) and an internal insulation layer.

Over recent years, there has been an increasing demand to improve the thermal insulation and energy efficiency of buildings to save energy and reduce greenhouse gas emissions. This has resulted in an increasing use of thermal insulation products both within the fabric of the building and as an integral part of the external cladding.

Figure A1 shows the heat losses (through construction elements) for a typical home.

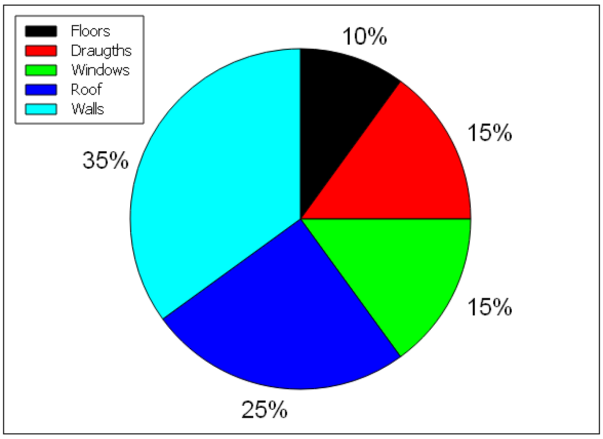

Figure A1 – Typical heat losses for a house [3]

Many of the thermal insulation products used in the external cladding are formed from products which are combustible and may, in the event of a fire, contribute to fire spread both vertically and horizontally.

In recent years, there have been a large number of high profile fires both within the UK and internationally where the external cladding systems have contributed to rapid fire spread leading to extensive damage and loss of life and injury. As the construction market has changed, with new products being developed to achieve the required levels of thermal performance, often at reduced cost, the existing system of test and assessment to demonstrate compliance with the requirements of the regulations has also has been adapted. This has led to the development of large-scale cladding fire tests. The method of test and assessment required varies from jurisdiction to jurisdiction reflecting the different national building regulation requirements. This has hindered the development of any form of harmonised international or European test standard for cladding products or systems. Depending on the risk profile of the building in a specific Country (generally related to height, occupancy type and expectations related to fire service intervention) compliance may be through small-scale national or European reaction to fire tests, intermediate-scale tests, performance based fire engineering design or large-scale fire tests.

The current situation in relation to the assessment of the performance of cladding materials/products and systems is extremely complex, with different geometries, fuel sources, heat output and thermal attack used in various national and international test methods. Part of the purpose of this review is to highlight the variations that currently exist internationally in relation to regulations, types of product and system and means of test and assessment.

Although the title of the project is “Fire performance of cladding materials”, it is important to realise that a knowledge of the material properties (at elevated temperature) alone is insufficient to determine or predict the likely performance of the system in a real fire scenario or in a large-scale test. Performance is dependent on construction details as much as material behaviour and issues such as the type of substrate and method of supporting the load of the cladding components, presence or otherwise of air gaps, the presence, location and nature of any fire barriers and vapour barriers, window frames and the detailing around joints and selection and frequency of fixings may have a significant impact on the fire performance.

The scope of the current project has been discussed with MHCLG and the focus is very much on material rather than system behaviour and on performance, related specifically to the UK regulatory framework. Of particular interest is the performance of materials/products (particularly the external panels forming the outer component of ventilated rain screen systems) where performance is typically assessed/controlled by classification of performance in small-scale reaction to fire tests.

This literature survey goes beyond this narrower scope to provide an overview of the current state of knowledge with regard to the performance in fire of cladding materials/products and systems and the means by which performance is assessed.

A2.3 Types of cladding systems

A description of some types of cladding systems can be found in a Fire Protection Research Foundation report by White and Delichatsios which focused on the fire hazards of exterior wall assemblies containing combustible components [4]. There are complications in defining systems as some systems, such as metal composite systems or external timber panelling, could also be categorised as rain screen facades or ventilated facades.

Cladding systems can be categorised into two general types: either a) external wall insulated render systems or b) rain screen or ventilated façade systems. These systems can be used to over-clad existing buildings or for new build. An illustration of each of these systems is shown in Figure A2 and Figure A3. A third type would be infill systems where the cladding, whether in the form of a decorative panel, metal faced sandwich panels, masonry or timber is built between the structural frame without any form of cavity. Curtain walling is an example of an infill system which consists of vertical and horizontal structural members (mullions and transoms) connected together and anchored to the supporting structure to form a continuous skin, which provides, by itself or in conjunction with the building construction, all the normal functions of an external wall, without performing a loadbearing function [5]. Curtain walling is constructed principally of glazed units and is often used for office buildings.

Based on the method of installation, curtain walls can be classified in two general categories: *stick systems* and *unitized (modular) systems*. In the stick system, the curtain wall frame (mullions) and glass or opaque panels are installed and connected together piece by piece. In the unitized system, the curtain wall is composed of large units that are assembled and glazed in the factory, shipped to the site and installed on the building.

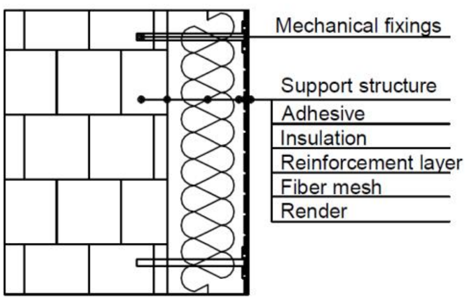

Figure A2 – Rendered systems (External Thermal Insulation Composite Systems (ETICS))

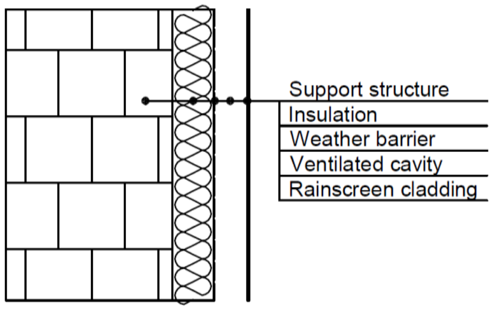

Figure A3 – Ventilated (rain screen) cladding

A2.3.1 Materials/products used in cladding systems

Cladding assemblies are complex systems that are made up of multiple products and materials, some of which are combustible or incorporate combustible components within them. Two of the key components of a cladding system are the external finish which may be formed from render or some form of external panel or tile and the insulation material.

The following materials/products have been identified by the Project Steering Group as typical external components used in rainscreen or ventilated or infill facades:

- Clay tiles
- Pre-cast concrete panels
- Stone panels
- Composite stone panels
- Metal faced panels either as profiled of flat sheets including sandwich panels
- High pressure laminate panels (HPL)
- Masonry
- Glazing
- Timber.

The following is a list of insulating materials/products that are available for purchase in the UK market. However, whilst these are included here for completeness, it should be noted that there is no evidence or information to indicate the current use of some of these in façade construction in the UK:

- Expanded polystyrene (EPS), supplied in different grades
- Extruded polystyrene (XPS)
- Polyurethane (PUR)
- Polyisocyanurate (PIR)
- Modified phenolic foam (MPHEN)
- Stone wool (MWRF)
- Cellular glass insulation (CG)
- Natural fibres – e.g. wood fibre, cork, sheep wool, cellulose and hemp
- Recycled material – e.g. recycled paper, shredded rubber.

A2.3.2 Cavity barriers and fire stopping

If fire enters a void in the cladding system, whether the void is created by the fire (for example due to melting of polystyrene insulation (thermoplastic)) or is part of the existing design, and a combustible insulant is exposed to fire, there is a potential for the fire to propagate through the system unless it is prevented by the use of fire barriers. Guidance on the use of fire barriers, fire stopping and cavity barriers are set out in regulatory guidance. There is often confusion as to the difference between **fire stopping** (which requires the same level of fire resistance as that of the element to which it applies) and **cavity barriers** which are intended to inhibit the spread of fire within (unseen) voids and cavities. An example of an intumescent cavity barrier is shown in Figure A4.

Figure A4 – Intumescent cavity barrier during installation in a ventilated cladding system [1]

Cavity barriers are generally tested as linear gap seals in a standard fire resistance test [8] but the large-scale fire tests described in this review may provide a more realistic assessment of performance for cavity barriers and fire breaks installed as part of an external wall cladding system in that the actual movement between the different components of the cladding system during a fire will be more closely replicated.

The principal materials/products used to provide cavity barriers are: stonewool, timber and intumescent products.

A2.4 Fire incidents

A number of high profile fires involving combustible exterior wall assemblies have occurred internationally and have been reported in technical literature and in the media. Many of these fires have occurred in the last twenty years and a number have occurred over the last ten years. Appendix A1 contains a summary of some of these significant fires with a reference to sources for further information.

The 2014 report by White and Delichatsios [4] provides a summary of observations based on a number of case studies of real fires. These are summarised as follows:

- Although fires involving combustible material on exterior walls are low frequency events, the resulting consequences in terms of extent of fire spread and property loss are often very high. Many of the incidents can be classified as causing disproportionate damage relative to the initiating event.
- For most (although not all) of the incidents reviewed the impact on life safety in terms of deaths has been relatively low with the main impacts being due to smoke exposure rather than direct flame or heat exposure. However, a large number of occupants are usually displaced for significant periods after the fire incident due to damage.

- Fire incidents appear to predominantly have occurred in countries with poor (or no) regulatory controls on combustible exterior walls at the time or where construction has not been in accordance with regulatory controls.

- Internal fires which spread to the exterior wall are the most common ignition scenario for the incidents reviewed.

- Falling burning debris and burning droplets can be a significant hazard relating to these fires and may cause downward fire spread.

- Re-entrant corners and channels that form “chimneys” has led to more extensive flame spread than flat walls. The effect of balconies forming partial vertical “channels” or alternatively, acting as a barrier to mitigate fire spread requires further investigation.

- Combustible exterior wall systems may present an increased fire hazard during installation and construction prior to completion and commissioning of all fire protection systems.

- The two types of construction that feature prominently among the large-scale fires reported in the media and elsewhere are ETICS systems (specifically those incorporating polystyrene insulation) and aluminium composite materials (ACM) with combustible material within the core of the rain screen panel.

A2.5 Regulatory framework

BEFORE READING THIS CLAUSE PLEASE REFER TO SECTION A1 - INTRODUCTION

Regulations with respect to external wall construction vary from country to country, ranging from no effective controls to a complete ban on the use of combustible materials for those buildings classified as high risk [4]. The focus in this report is on the measures adopted to comply with the mandatory requirement B4 of the UK (England) Building Regulations 2010, which states:

The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building.

Information on the UK regulatory requirements has been produced [9]. Regulatory guidance for the UK (Approved Document B [10]) recommends restrictions on the combustibility of external walls to reduce the danger from fire spread via the building’s external façade and to reduce the susceptibility of the surface to ignition from an external source. It is considered that the use of combustible materials and/or extensive cavities in cladding systems (in tall buildings) can pose a route for fire spread and hence a danger to life safety, as shown by the case studies. Hence, the recommendation is to limit both the combustibility of materials used on the external face of the building and the extent of cavities in cladding systems [9].

Diagram 40 of AD B shown in Figure A5, sets out the provisions for external surfaces relative to the relevant boundary, height and use of the building. The reaction to fire classification of the external surface of a building depends upon the distance to the relevant boundary; any external surface less than 1000mm from the relevant boundary, regardless of its height, must be European Class B-s3,d2 (BS EN 13501-1 [11]) or National Class 0 or better.

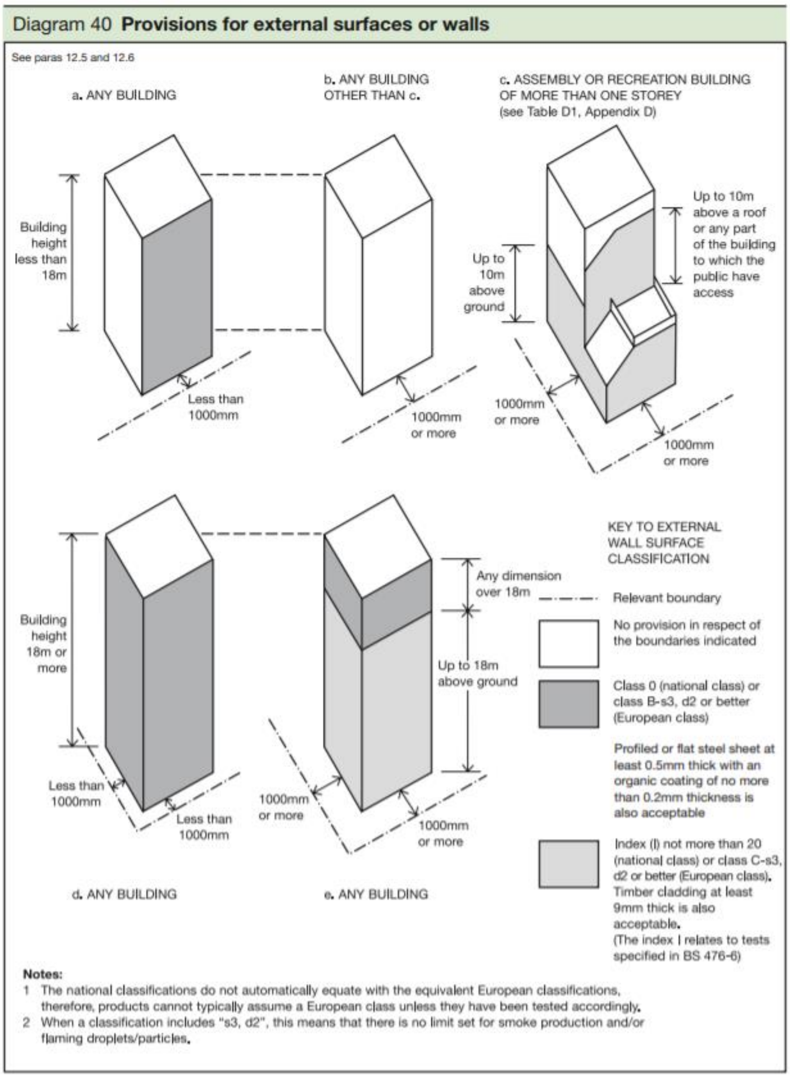

Figure A5 – Provisions for external surfaces of walls (Diagram 40 of AD B) [10]

This increased level of protection for surfaces close to the relevant boundary is provided to mitigate building to building fire spread, rather than fire spread across the surface of one building.

Should the construction (rather than the external surface of the walls) incorporate combustible materials (usually in the form of insulation) for a building with a storey at 18 m or above, then it should meet the performance criteria set out in BR 135 [14] using the full-scale test methods BS 8414-1: 2015 [16] or BS 8414-2: 2015 [17] which involves testing the entire cladding system including the insulation along with all other components including framing system/fixings, breather membranes, cavities, cavity barriers and/or fire breaks. A more detailed description of the large-scale test methodology is provided in section A2.7.3.1 of this report.

With regards to insulation materials/products paragraph 12.7 of AD B states [10]:

In a building with a storey 18m or more above ground level any insulation product, filler, material (not including gaskets, sealants and similar) etc. used in the external wall construction should be of limited combustibility. This restriction does not apply to masonry cavity wall construction which complies with diagram 44 in section 9.

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A2.6 Fire scenarios

The key initiating events, based on a review of real fire incidents [4], are:

- A compartment fire (pre or post flashover) spreading to the external wall system via external openings (windows). The initial fire spread could be as a consequence of fire spread through an open window or following glazing failure.
- A compartment fire (pre or post flashover) spreading to the external wall system via internal openings including cavities or other concealed spaces.
- Exterior fire directly adjacent to the external wall system igniting the wall due to radiant heat and/or direct flame impingement.
- Exterior fire at a distance from the external wall system causing ignition through for example, radiation from a fire in an adjacent building and/or burning brands.

Vertical fire spread from one compartment to another via the exterior of the building is a very complex mechanism which is shown schematically in Figure A6.

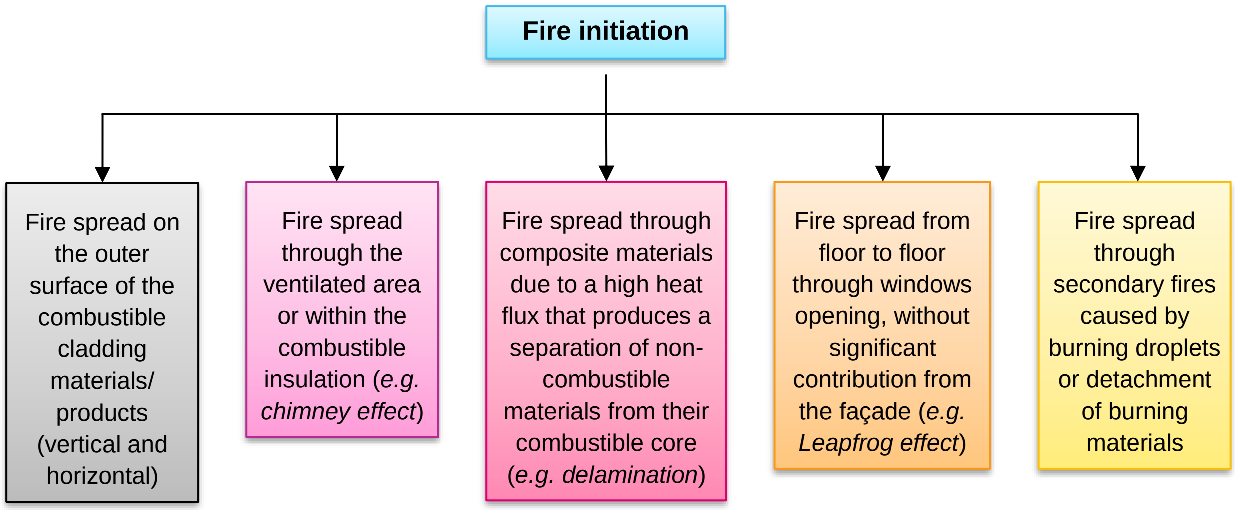

Figure A6 – Mechanism of external fire spread [3]

The key initiating event may be summarised as one of two possible types of fire exposure (initiation) scenarios shown in Figure A7:

- Fires external to the building or
- Fires internal to the building.

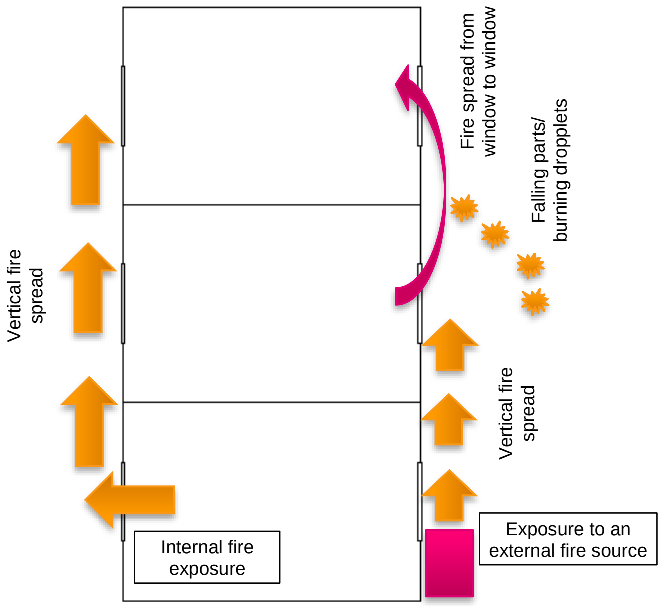

Figure A7 – Mechanisms for external fire spread by way of the external cladding system [14]

Previous research [4] has identified that exposure to the exterior wall system is generally (although not always) more severe for an internal post-flashover fire exposure with flames projecting from windows than for an external fire source. For this reason, most existing large-scale cladding tests simulate an internal post-flashover fire. Based on large-scale testing a series of typical parameters including total heat release, flame length and fire duration have been identified in order to understand the severity of an internal and an external fire [15].

Table A1 – Typical range of parameters characterising fire exposure from an external and internal source [15]

Fire exposure	Fire exposure from an external source	Fire exposure from a compartment below	
	Façade	Internal	External
Heat release	1.2 - 1.5 MW	2.0 - 5.0 MW	1.5 - 2.5 MW
Average height of flames	2.5 - 3.0 m	2.8 - 3.0 m	
Maximum height of flames	3.8 m	3.0 - 6.0 m	
Fire duration on façade	20 - 35 minutes	15 - 25 minutes	
Time to flames on the façade, after ignition	3 - 7 minutes	12 - 13 minutes	

A2.7 Test procedures

A number of different test methods are available to determine the compliance of materials/products and systems used for external walls. These range from small-scale reaction to fire tests generally related to material and component behaviour, through intermediate-scale tests to large or full-scale fire tests that evaluate the performance of the system including joints, fixings and ancillary products.

The small-scale reaction to fire tests are generally designed to evaluate the classification of internal linings rather than external cladding systems or materials/products but results from such tests are often used as an indication of performance or to demonstrate compliance with regulatory requirements. A recent report for the Scottish Government [18] considers the suitability of standard reaction to fire test methods in relation to fire spread on external walls. It concludes that the small-scale reaction to fire standards are inappropriate for assessing the potential fire spread on external walls, except where the construction is composed of non-combustible materials. The conclusion is based on the opinion that adequate testing of complex systems and assemblies, such as exterior insulated wall systems and cladding systems, require large-scale tests with suitably representative initiation fire sources, which are not present in small and intermediate-scale fire tests. Other studies have similar findings and highlight that the burning behaviour in the Single Burning Item (SBI) test (BS EN 13823) can be different for products with external applications [1], [6], [7].

A number of large-scale and a smaller number of intermediate-scale tests have been developed with the intention to predict and assess the performance of external cladding systems. For the purpose of this report, large-scale tests are defined as those where the height of the test rig is greater than 5.5 m and intermediate-scale tests are defined where the height of the test rig is less than this value. Although this definition takes no account of the heat flux to the specimen, it will provide a useful basis for further discussion.

Appendix A2 provides a summary of intermediate and large-scale cladding test methods and sets out the principal parameters associated with each test.

A2.7.1 Small-scale test methods

A2.7.1.1 Combustibility tests

Various standard test methods exist including BS 476 Part 4 [19], BS 476 Part 11 [20], ISO 1182 [21], ASTM E136 [22], ASTM E2652 [23] and AS 1530.1 [24].

In all such tests, small specimens are exposed to high temperatures (typically 750-850 °C) within a small conical tube furnace. Criteria for non-combustibility are typically:

- No sustained flaming
- Mean furnace temperature rise not to exceed set value (typically 50 °C)
- Mean surface temperature rise not to exceed set value (typically 50 °C)
- Limited mass loss.

A2.7.1.2 European classification system

The European classification system based on data from (harmonised) European reaction to fire tests is set out in EN 13501-1 [11]. The classification system was designed to allow the EU Member states to have a common set of metrics which they could use in their building rergulations to control the fire performance of internal linings (excluding flooring materials). The basis for this is the Construction Products Regulation which aims to permit free movement of construction products throughout the EU. As such, within EU Member States, classification in accordance with EN 13501-1 is often applied to exterior wall systems sometimes in conjunction with a national large-scale cladding test.

Classification is based on the results from a range of small-scale reaction to fire tests. Products are assessed on the basis of contribution to fire development where the fire scenario is a localised ignition source representative of a waste paper bin located in the corner of a small room. Products are classified as:

- Class A1 – products are essentially non-combustible and will not contribute to fire growth
- Class A2 – products are not easily ignited and will not contribute significantly to fire growth or fuel load in a fully developed fire
- Class B – products are combustible and will contribute to a fully developed fire but will not, in the absence of other materials, result in flashover in the specific fire scenario of a small room lined with the product
- Class C-E – products may lead to flashover in a set of explicitly defined scenarios related to the small room.

Reaction to fire class F was originally for products which had not been tested and therefore had no performance determined. However, since 2016, class F is defined as the class for products tested with the small flame test EN 11925-2 and which fail the criteria i.e. have a surface flame spread more than 150 mm within 20 seconds (no flaming droplets or particles are recorded) [12].

Table A2 – Tests used to determine the European reaction to fire class

Reaction to fire class	Smoke released	Burning droplets	Test methods used			
			Non-combustibility [21] EN 1182	Bomb calorimetry [26] EN 1716	Single Burning Item [28] EN 13823	Small flame [27] EN 11925-2
A1	-	-	x	X	-	-
A2	s1-s3	d0-d2	x	X	X	-
B	s1-s3	d0-d2	-	-	X	X
C	s1-s3	d0-d2	-	-	X	X
D	s1-s3	d0-d2	-	-	X	X
E	-	d2	-	-	-	X
F	-	-	-	-		X

The European classification system includes an evaluation in relation to smoke production (s) and flaming droplets/particles (d) when products are tested in the SBI test (EN 13823). When a classification includes s3, d2 there is no limit set for smoke production and/or flaming droplets/particles. Class s1 is the highest smoke class and d0 the highest flaming droplets/particles class.

The test methods used to determine the reaction to fire characteristics for materials and construction products are briefly described below. It should be noted that all of these methods are not used for classification purposes, some are used to support fire engineering approaches to building design.

A2.7.1.3 Cone calorimeter

The cone calorimeter is a small-scale oxygen consumption calorimeter shown in Figure A8. Specimens, 100 mm square, are supported horizontally on a load cell and exposed to a set external radiant heat flux in ambient air conditions. The radiant heat source is a conically shaped radiator set to impose any specified heat flux in the range 0 – 100 kW/m² on the specimen surface. Combustion gases are extracted and analysed to determine exhaust gas flow, temperature, oxygen, carbon monoxide and carbon dioxide concentrations and optical smoke density.

From the measured values heat release rate, mass loss rate, effective heat of combustion and smoke production are calculated. The cone calorimeter apparatus and procedure are described in ISO 5660 [25] and other national test standards [18], [19], [21], [22], [23].

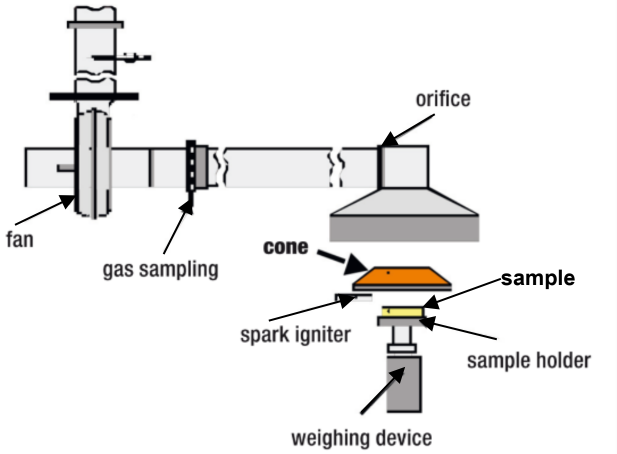

Figure A8 – ISO 5660 cone calorimeter test [25]

The cone calorimeter is intended to be used for characterising the behaviour of single materials when exposed to a range of thermal radiations up to a maximum of 100 kW/m². The configuration of the sample in the horizontal orientation means that it is not subject to convective heat transfer which is an important consideration when seeking to derive input parameters to mathematical models of material fire behaviour. However, the small-scale performance that is measured in the apparatus is dependent on the surface layer of the material especially in the case of laminated and/or multi-layered products. For complex composite products and systems (such as external wall cladding systems), it is not possible to include a representative make up of system on such a small scale that can replicate the typical modes of failure seen on a larger scale such as edge effects, interactions between different component parts of the system and opening up of joints [25].

A2.7.1.4 EN ISO 1182 Non-combustibility test [21]

The test apparatus is illustrated in Figure A9. This test method is used to determine the combustible content of materials and products and the contribution that they would make in the event of a fire.

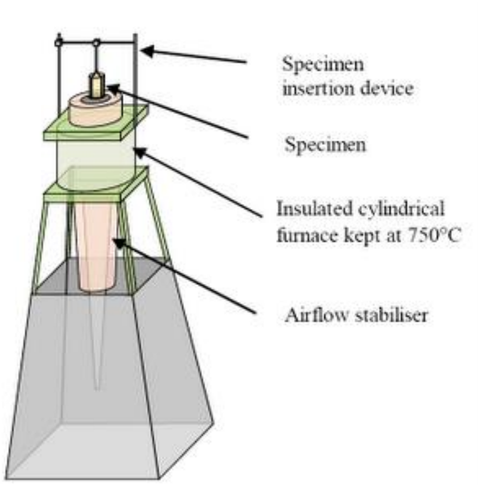

Figure A9 – Test apparatus for the non-combustibility test [21]

A2.7.1.5 EN ISO 1716 Gross Calorific Value [26]

A specified mass of material is burnt under standardised conditions in a bomb calorimeter in an oxygen atmosphere. The gross heat of combustion which is an inherent property of the material is determined based on the measured temperature rise of the combustion chamber which is immersed in a water bath of known temperature. This uses a fundamental test methodology that has been in widespread use for many decades to determine the calorific content of materials and products (not just construction related) and is based on fundamental chemistry principles. A photograph of an example of a proprietary test apparatus is shown in Figure A10.

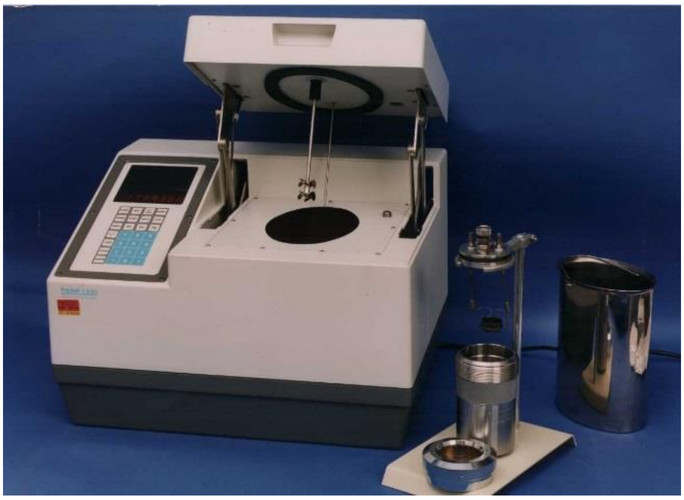

Figure A10 – Test apparatus for bomb calorimetry [26]

A2.7.1.6 EN ISO 11925-2 Small flame test [27]

Specimens are exposed to a 20 mm high propane gas flame for a specified period of time in a controlled manner. The time to ignition (if it occurs) is recorded along with the height of the flame tip as a function of time and the occurrence of burning droplets or particles. The test apparatus is shown in Figure A11.

Figure A11 – Small flame test apparatus [27]

The flame is applied to the front face of the material or product and additionally, if is is intended to be used with the edges exposed, then the edge of the material or product is also subjected to test.

A2.7.1.7 EN 13823 Single Burning Item (SBI) test [28]

The SBI test is an intermediate-scale corner test conducted under an exhaust hood fitted with oxygen consumption calorimetry and smoke meters. Heat release rate, total heat release, smoke production rate, total smoke produced and production of burning droplets/debris are measured. The extent of flame spread is observed as spread across the full width of the sample is one of the classification criteria. A photograph of the test set up is shown in Figure A12.

Figure A12 – Single Burning Item test – external view [28]

Existing research [29] has shown that for an ETICS system with EPS insulation and a fire barrier, a classification of B-s2, d0 can be achieved. This means that no burning droplets were observed or recorded during the SBI test. However, there is some reported evidence from large-scale tests that this might not be typical. In addition, as already reported, the modes of failure in large-scale tests and real fire incidents tend to be such that they are not replicated in the intermediate scale. This is because the structural make up and loadings on the samples are very different which means that some details including joints and fixings can behave very differently.

A2.7.1.8 Room corner test methods

A number of room corner test methods exist to simulate the scenario of an interior localised fire in one corner of a room with a ventilation opening. They are designed to quantify fire spread on interior wall and ceiling linings and evaluate performance in relation to contribution to flashover. Such tests are not designed to assess the fire performance of external walls and facades. Test methods include NFPA 286 [30], UBC 26-3 [31], ISO 13784-1 [32], ISO 13784-2 [33], LPS 1181-1 [34] and LPS 1181-2 [35]. The most widely known room corner fire test is the ISO 9705 [36] which utilises a gas burner in the corner of a room with output of 100 kW from 0 - 10 minutes and 300 kW from 10 - 20 minutes in a room with dimensions of 2.4 m (wide) by 2.4 m (high) by 3.6 m (long) based on the refence scenario set out in BS EN 14390 [37]. The test produces data on heat release rate, smoke optical density, temperatures at the ceiling and opening and heat flux at floor level. As with all ISO fire test methods, they do not provide any criteria for classifying products, this is left to the national fire regulator in any given country to specify.

An example of an ISO 9705 test is shown in Figure A13.

Figure A13 – ISO 9705 Room corner fire test [36]

A2.7.2 Intermediate-scale façade fire test methods

A number of intermediate-scale (i.e. rig height less than 5.5 m) cladding test methods have been developed and proposed. In general, the purpose of the intermediate-scale tests is to provide an indication of performance in the large-scale tests at a reduced cost to manufacturers and/or contractors. This idea of an "indicative" test is the basis of this current project and therefore requires investigation. A summary of current intermediate-scale test methods is included in Appendix A2.

Some indicative tests such as the proposed ASTM vertical channel test [38] designed to provide a less costly alternative to the large-scale CAN/ULC S134 [39] are actually large-scale tests when using the definition in this report. BRANZ developed a modified version of the vertical channel test using a test rig which uses a wall height of 5.5m [40]. FM Global have developed a parallel panel test [41] as an intermediate test to predict results from the larger FM tests. Some tests generally considered large-scale would, on the basis of the current definition adopted for the purposes of this project, actually be classified as intermediate-scale. This would include the proposed Japanese façade test [42].

The two intermediate test methods of most interest in terms of the current project are those developed by the International Standards Organisation and the European Organisation for Technical Approvals (EOTA).

A2.7.2.1 ISO 13785 Part 1 [43]

The intermediate test is based on a re-entrant L shaped arrangement with a total specimen height of 2.4 m, a rear wall width of 1.2 m and a side wall width of 0.6 m. The set-up is based on a full-scale test with a timber cladding system [44], [45]. The cladding system is installed with all relevant insulation, cavities, air gaps and fixings as for the end use condition. The fire source is a propane burner located 0.25 m below the bottom edge of the rear wall. The test rig is illustrated in Figure A14.

Forest and Wood Products Australia [46] has produced a document which specifies modifications to the ISO 13785-1 standard to incorporate two specific changes:

- To replace the propane burner with a timber crib fire source
- To introduce an imposed radiant heat flux of at least 10 kW/m^2 but not greater than 12 kW/m^2.

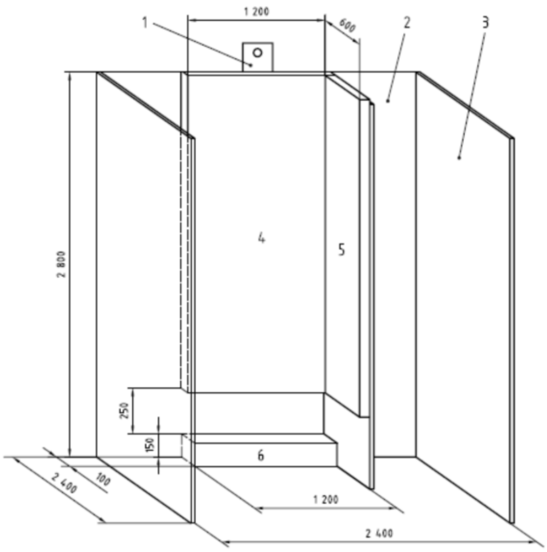

Figure A14 – ISO 13785 Part 1 test rig [43]

A2.7.2.2 Draft EOTA Technical Report 73 [47]

A draft Technical Report "Large-scale fire performance testing of external wall cladding systems" was produced by an EOTA Task Group in 2013 [47]. The report describes a test approach containing two different levels of exposure. The height of the test rig varies depending on the exposure level used for testing. For exposure level 1 (intermediate-scale test) the height of the test rig is 5.5 m, shown in Figure A15.

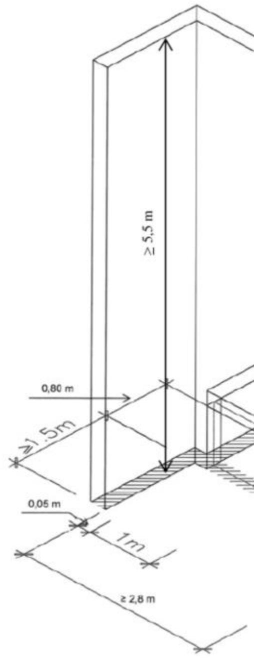

Figure A15 – EOTA draft TR073 test rig for exposure level 1 [47]

The principal parameters for the test standards and methods are included in Appendix A2.

A2.7.3 Large-scale test methods

The principal parameters for all large and intermediate-scale cladding test methods reviewed are included in Appendix A2. This section describes some of the main large-scale test methods used in various parts of the world.

A2.7.3.1 BS 8414 Parts 1 and 2 [16], [17]

The BS 8414 tests are large-scale fire tests for non-loadbearing external cladding systems. The test rig allows external cladding systems to be installed as close to typical end-use conditions as possible. The test faces consist of either a masonry or steel framed vertical main test face, into which the combustion chamber is located, and a masonry or steel framed return wing wall set at 90° to the main wall. The test specimen is installed with all relevant components to manufacturer's installation instructions.

The main test face is at least 8 m high and 2.6 m wide and the return wing is 8 m high and 1.5 m wide. A wooden crib is typically used as the heat source for the test although a gas burner can be used as an alternative. The combustion characteristics of the crib give a total nominal heat output of 4,500 MJ over a 30 minute period at a peak heat release rate of 3 ± 0.5 MW. A schematic of the test rig is shown in Figure A16 while Figure A17 shows the location of the thermocouples at level 1 and level 2.

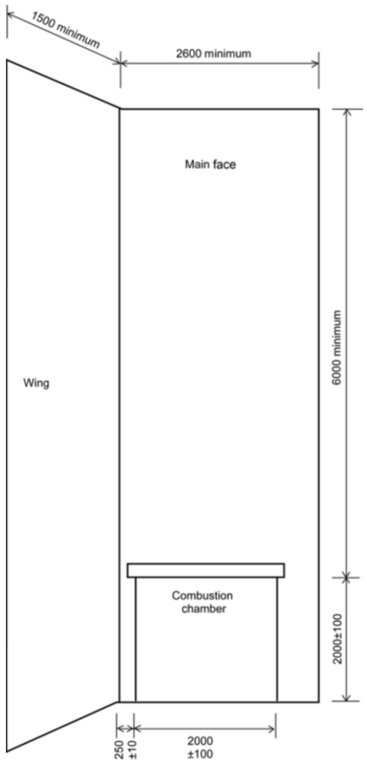

Figure A16 – Schematic of the test rig (all dimensions in mm) [14]

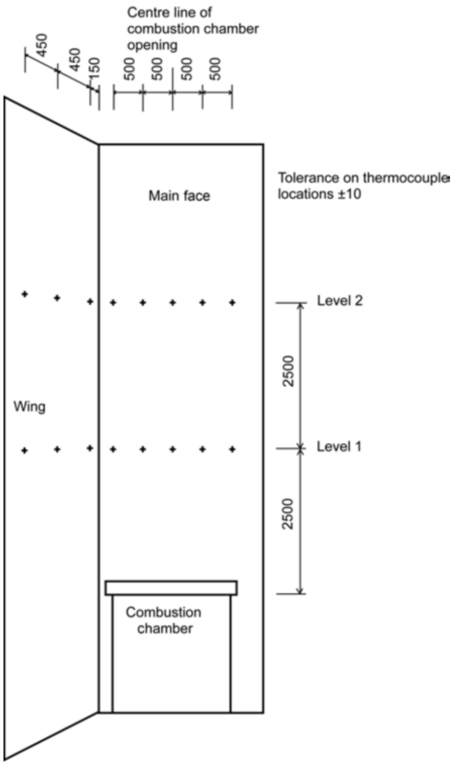

Figure A17 – Location of thermocouples (all dimensions in mm) [14]

The primary purpose of the test method is to determine the propensity for the cladding system to spread fire beyond the location of the ignition source (i.e. self propagate) both across the surface of the system and within the system within a 1 hour duration.

There are additional requirements set out in the insurers' versions of BS 8414 parts 1 and 2 which relate to damaged area within the cladding system and propensity for smouldering. These are the basis for certification of cladding systems and are published as LPS 1581 [48] and LPS 1582 [49] for approval and listing of non-loadbearing external cladding systems.

A2.7.3.2 ISO 13785 Part 2 [50]

The test assembly is installed as a re-entrant corner L arrangement with a main wall and a wing wall. The height of the tested façade is at least 4 m above the lintel of the window opening. The main façade is at least 3 m wide and the wing wall is at least 1.2 m wide. The opening is on the main wall with a height of 1.2 m and a width of 2 m, the façade is installed representative of the end use condition including all insulation and fixings.

The standard fire source is a series of propane burners, although alternative fire sources are permitted. The fire source is calibrated to give an average total heat flux of 55 ± 5 kW/m² at 0.6 m above the window and an average total heat flux of 35 ± 5 kW/m² at 1.6 m above the window. Recently the method was discussed in ISO TC 92 with respect to repeatability of the calibration and possibilities to achieve the flux levels with different heat sources. This led to the start of the revision of the standard.

Temperature and heat flux are recorded and fire spread is observed and noted. A schematic of the test rig is shown in Figure A18.

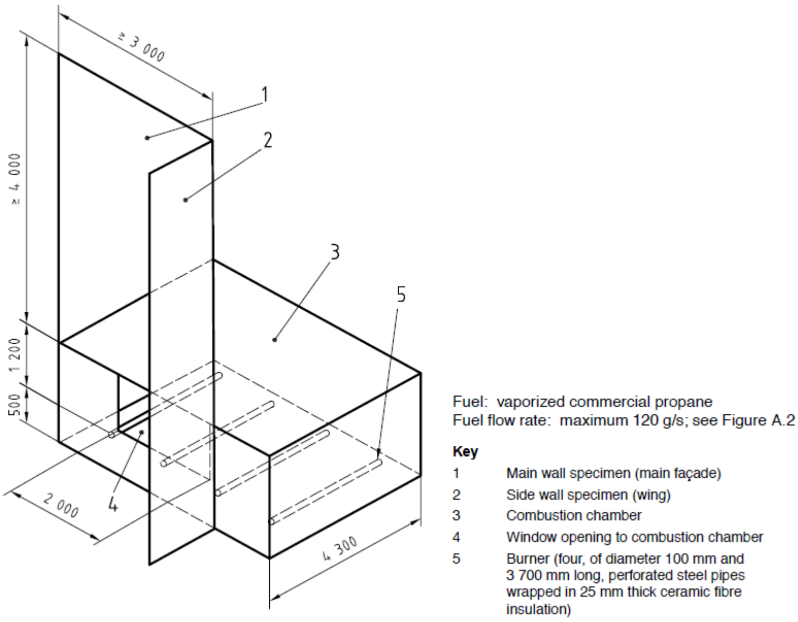

Figure A18 – ISO 13785 Part 2 test rig with standard fire source [50]

A2.7.3.3 DIN 4102-20 [51]

A description of the German large-scale test method is provided in a BRE client report [52] published on the Eurima (client) website.

The German test simulates a scenario of flames emerging from a compartment fire and is installed as a re-entrant corner L shape. The substrate is constructed from lightweight concrete.

The test wall extends at least 5.5 m high. The main wall is at least 2 m wide (burner) or 1.8 m wide (crib) and the wing wall is at least 1.4 m wide (burner) or 1.2 m wide (crib). The fire enclosure opening is located at the base of the main wall. The façade is installed to represent the in use condition including all relevant components and insulation materials.

The fire source is a 320 kW constant HRR gas burner or a 25 kg timber crib. Figure A19 shows a test sample following a test to the then draft DIN 4102-20 taken from [52].

Figure A19 – External façade following test to DIN 4102-20 [52]

A2.7.3.4 NFPA 285 [53]

The test wall is installed as a single flat surface with no re-entrant corners. The rig is a two-storey steel framed structure with an open fronted test room on each storey constructed form concrete slabs and walls. The bottom test room contains the fire source with a single opening. The test apparatus is shown schematically in Figure A20.

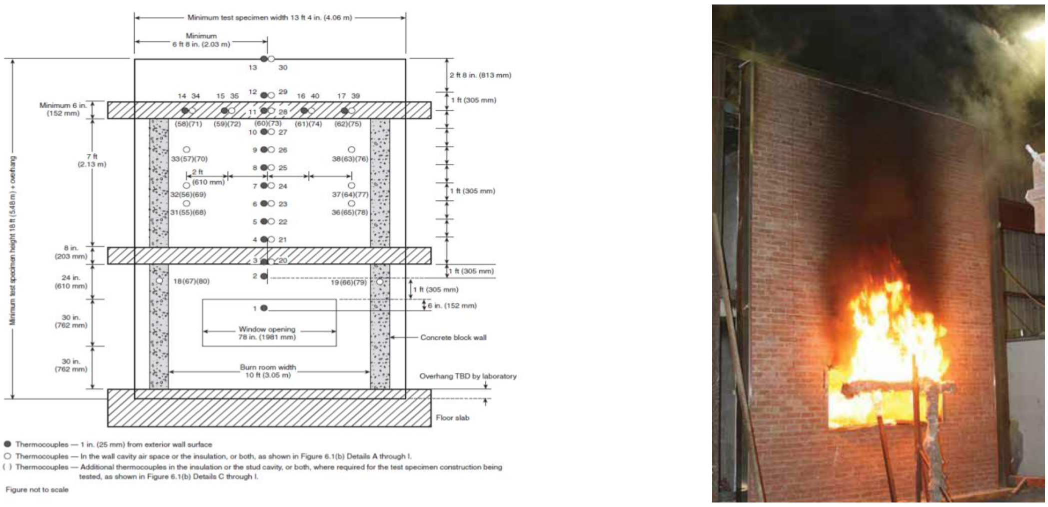

Figure A20 – NFPA 285 test apparatus front view without test wall (left) and during a test (right) [53]

The fire source consists of propane burners, one in the fire room and one at the window soffit. The initial fuel source is from the burner in the room. Five minutes into the test, the window burner is ignited. The burners are calibrated to give average heat fluxes at the surface of a non-combustible test wall of approximately 40 kW/m² at 0.6 m above the opening.

A2.7.3.5 SP Fire 105 [54]

This method tests the performance of façade claddings or complete external wall systems. The test specimen is installed as a single wall 6 m (high) by 4 m (wide) with no re-entrant corners. The fire source is flames emerging from a fire room beneath the specimen and the fuel source is heptane. The test rig is illustrated in Figure A21.

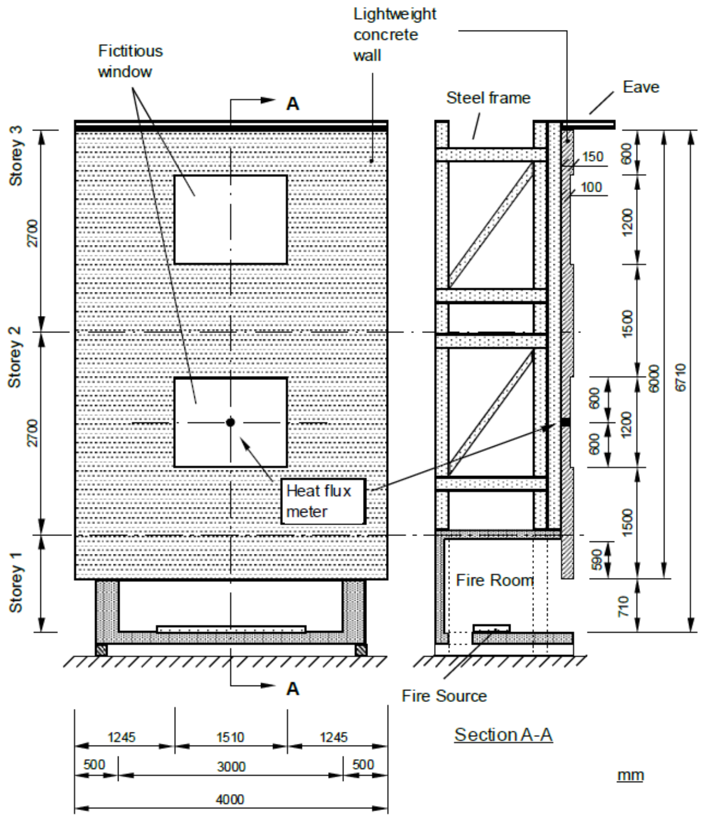

Figure A21 – SP105 test rig [54]

A2.8 Research

A large amount of research has been undertaken in recent years motivated by the nature and extent of the large-scale fires involving combustible materials in external walls. Much of this work has provided the input and rationale for the use of specific test methods such as those described above and detailed in Appendix A2.

Previous studies [55] have provided a detailed background to research projects in this area focussed specifically on cladding fire behaviour, the development of test methods, performance of insulated sandwich panels, curtain walling, ETICS systems, the impact of balconies and projections on fire spread, façade fire calculation tools and modelling. The review of previous research is very thorough and provides a database for research undertaken in different countries up to 2000, the time of publication. White and Delichatsios [4] have updated this work to cover the period from 2000 to the publication of their report in 2013.

In addition to the references identified so far, which have largely been focussed on the development of test and assessment methodologies for façade systems, there has been a great deal of research focused on specific aspects of the fire performance of cladding systems.

Anderson et al [57] carried out a simulation study of three large-scale façade test methods (SP Fire 105, BS 8414-1 and ISO 13785-2). Generally good correlations between simulations and experimental data were achieved provided that thermal properties of the façade material and heat release rates are known.

In a Romanian study, Lalu et al [58] present the behaviour of proposed solutions for systems to improve the energy performance of existing buildings which were designed to use polystyrene as the insulation. The solution aims to provide an optimal width of the non-combustible barrier system to achieve the required level of performance in the event of a fire. Three laboratory tests for different design parameters were presented based on testing to the standard fire resistance time-temperature curve.

Hofmann [59] presents an overview of different large-scale test methods and the means by which they are implemented in building regulations in various countries. Challenges in the fire safety of facades regarding testing, weathering, ageing and damage to systems and their potential impact on fire safety are discussed.

Nilsson et al [60] investigated the impact of horizontal projections on external fire spread using the numerical software FDS. The numerical study incorporated a validation study and a comparative analysis. The validation was undertaken using experimental results from the SP Fire 105 test. The comparative analysis considered the impact of different configurations of horizontal projections and spandrels on the outside of the building on the development and spread of a fire. The analysis showed that a horizontal projection at least 600 mm deep resulted in a lower impact on the façade compared to scenarios composed of different heights of spandrels.

Weghorst et al [61] describe how a project in France has been approached in order to create an assessment range from bench-scale tests in combination with the results from large-scale LEPIR2 experiments. The authors looked at a combustible foam insulation covered with a variety of different cladding materials/products in a ventilated system both with and without gap and joints and incorporating wood cladding.

Kolaitis et al [62] present the results from a large-scale test on a ventilated façade system. The fire source was from a fully developed fire in a compartment. No thermal insulation was used, the aim being to investigate the main aerodynamic and thermal phenomena affecting the flow of hot gases and flames in the air cavity. The ventilated façade did not incorporate any fire barriers. Analysis of the experimental data suggests that even though gaseous combustion products may penetrate the air cavity no consistent flaming conditions were established. In addition, wall surface temperatures on the unexposed side of the system remained below 180 °C for the entire duration of the test.

Kolbrecki [63] focused on a fire originating in a compartment of a building which spreads outwards through the windows. Fire spread of different types of facades are discussed including glazed facades, double skin facades, facades with structural barriers, facades with side walls at the opening and facades covered by ETICS. Additional information on radiation from compartment fires to adjacent buildings is included.

Hofmann and Kaudelka [64] considered fire scenarios originating on the outside of buildings with a specific focus on fires originating in waste containers. The situation where buildings remain in use while repairs are undertaken to upgrade the thermal performance were discussed. At several stages of the construction process, large amounts of unprotected polystyrene are stored in the immediate proximity of the occupied building and such material may be on site for several weeks. As a consequence of the investigations possible measures to enhance the fire safety of ETICS systems both during and post installation are discussed.

Oleszkiewicz [65] describes full-scale experimental studies of heat flow to building facades caused by fires venting through window openings. The experiments were conducted using two burn facilities and two different fuels. A mathematical model of heat flow to facades is described and its applicability is discussed in the light of the data collected.

Lund University and the University of Edinburgh have been involved in research projects looking at the fire performance of façade systems.

Lund University has been involved in the development of the ISO 13785 test standards (intermediate and large-scale tests) through ISO TC92 SC1 WG7 [56]. They have recently started a new project (HOLIFAS), An HOLIstic approach for fire safety requirements and design of FACade Systems. This project was approved by the Swedish Board of Fire Research (Brandforsk) at the end of March 2018. The main tasks of the project are:

- WP1 Collection of different façade systems in Sweden
- WP2 Determination of technical requirements and criteria for external façade systems
- WP3 Social technical system considerations and regulatory system comparisons
- WP4 Reporting, dissemination and management.

The project is a collaborative research programme with the involvement of experts from Swedish universities with expertise in different aspects of façade design and engineering covering structural, thermal and material performance as well as fire safety issues.

Other current research projects involving Lund University include two post-doctoral projects in collaboration with the Danish Building Institute covering screening methods for façade systems and fire development of façade systems (for rendered systems). Lund University is also involved in collaboration with Key State Laboratory in Hefei (China) looking at the effects of wind on the flame spread of facades. They are also involved in a project named FIRETOOLS (a Marie Curie PhD project in collaboration with DBI Denmark) dealing with research into ventilated cavities looking specifically at flame heights and heat transfer in the cavities of ventilated systems.

The University of Edinburgh is currently involved in an EPSRC-funded research project Grenfell Tower Response: Urgent Research on Cladding Fires (EPSRC grant EP/R023875/1) where the fundamental objective is to conduct research to systematically quantify the links between fundamental material characteristics, medium (intermediate)-scale system behaviour and large-scale system performance. The methodology consists of three distinct phases:

- Phase 1 Small-scale characterisation of the relevant materials' burning behaviour
- Phase 2 Medium-scale characterisation of the governing parameters for fire spread in vertical systems
- Phase 3 Large-scale characterisation of the complex interactions that can take place in a full-scale building.

A3 Interim conclusions of the literature review

The following interim conclusions may be drawn from the literature review undertaken:

- Regulations vary considerably from country to country. Currently there is no EU (harmonised) test standard specifically for cladding systems. Recourse is often made to standard reaction to fire tests and classification procedures which have been developed based on the scenario of a relatively small ignition source within an internal environment and may not be directly applicable to an external fire scenario.

- There is a wide range of different cladding systems in common use. Many of these systems incorporate some form of combustible material either within the insulation layer, the external face or in the cavity in the form of breather membranes. Exterior wall assemblies are generally complex composite systems incorporating many components which interact with each other in the event of a fire. The two main types of system are rendered insulation systems and rainscreen or ventilated façade systems. Typically render systems are fixed directly to the external face of the building such as an existing masonry or concrete panel. Most common types of rain screen cladding or ventilated façade systems incorporate a cavity between the insulation layer and the external rainscreen component and can be found both masonry backed or on structural-framed systems.

- Based on a study of real fire incidents, the key initiating event resulting in fire spread on the external cladding is either:
  - A fire external to the building for example a waste skip or stored materials left alongside an existing building, or
  - A fire internal to the building often characterised in the later post-flashover phase by flames emerging from an opening (such as a window) following failure of the glazing or through an open window.

- The latter generally (although not always) results in a thermal exposure that is more severe for an external wall cladding system and is the basis for the heat source in the majority of large-scale and intermediate test methods. Many also incorporate a return wall to provide a realistic worst case in terms of thermal heat transfer (radiative, convective and conductive) between the walls that increases the fire severity for a given fire load and ventilation condition.

- A range of different small, intermediate and large-scale test methods have been reviewed. Significant parameters such as overall geometry and severity of fire source vary significantly from country to country and from test to test. Large-scale cladding tests incorporating a wing wall and an ignition source representing an internal fully developed fire impinging directly on the external cladding are currently the most commonly used method for determining the fire performance of complete assemblies. This is because performance in a real fire scenario will be influenced not only by material behaviour of the individual components but also the nature, location and presence of any cavities (ventilated or not), joints, methods of support and fixings and the presence and nature of any fire stopping or cavity barriers. Small and intermediate-scale tests may not correctly predict behaviour in a real fire scenario due to the inability to reproduce the build-up of the system, the true structural loadings and the interaction of the components. In addition, the thermal exposure levels in the small and intermediate-scale tests are typically substantianally lower.

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Appendix A1 International fire incidents

Country/Year	Comments	Images
Manitoba, Canada, 1990 [4]	The building had an external insulation finished system with combustible insulation (unidentified). No horizontal fire breaks (fire barriers) were included.	
Knowsley Height tower, UK, 1991 [3]	The building was exposed to an external fire scenario. The fire spread was through (unstopped) cavity.	
Munich, Germany, 1996 [4]	An external fire source was present from a rubbish container. The façade system consisted of an ETICS system with ≈100 mm polystyrene insulation.	

Country/Year	Comments	Images
Magdeburg, Germany, 2000 [3]	The building was exposed to an internal fire scenario. An incombustible insulation with a render system was present on the building. Thermal and smoke damage is visible on the external surface of the façade system.	
Berlin, Germany, 2005 [4]	The building was exposed to an internal fire scenario. The façade system consisted of a combustible insulation (EPS-80 mm flame retardant) fixed on 25 mm chipboard and an external render.	
Rin Grand Hotel, Bucharest, 2007 [1]	The hotel had a ventilated façade system with combustible insulation. The fire was initiated during construction works, potentially from welding. Rain screen was not present when the fire started.	

Country/Year	Comments	Images
MGM Hotel, Las Vegas, USA, 2008 [4]	Ignition of the exterior wall assembly was attributed to welding on the catwalk on the roof parapet side. The decorative architectural details consisted of EPS foam with polyurethane resin encapsulant.	
Miskolc, Hungary, 2009 [3]	This block of flats was refurbished with an ETICS system with polystyrene thermal insulation. Post fire investigations revealed that the system was not installed in accordance with the manufacturer's guidance. No fire barriers were present.	
Millennium Business Centre, Bucharest, Romania, 2009 [3]	The office building had a façade system built with curtain wall and ventilated façade system. The fire started from an advertising panel situated at the very top of the building fixed into the outer skin of the façade. The cladding material was metal composite panel built with polyethylene core between two aluminium sheets. Incombustible insulation was used without cavity barriers.	

Country/Year	Comments	Images
CCTV Tower, Beijing, China, 2009 [4], [75]	Central Television headquarters (CCTV Tower) was nearly completed when the fire started. The façade at the top of the building was ignited by illegal fireworks. The fire spread to involve the majority of the facade over the entire height of building. The façade is believed to have included a polystyrene insulation.	
Dijon, France, 2010 [4]	The fire started from an external rubbish container at the base of the building resulting in vertical spread on the façade system. The façade is believed to be an ETICS system with polystyrene insulation. Wind was reported to be blowing the flames against the wall.	
Wooshin Golden Suites, Busan South Korea, 2010 [4]	The building was constructed with metal composite panels consisting of aluminium with a 3 mm polyethylene core with incombustible insulation. The fire is reported to have started on the fourth floor. The fire spread was concentred around a vertical "U" shaped channel in the external profile of the building. This appeared to enhance the fire spread through re-radiation and chimney effect.	

Country/Year	Comments	Images
Shanghai, China, 2010 [4], [3]	This fire was believed to be caused by welding resulting in fire spread on polyurethane insulation to external walls. No other information was available regarding the façade system.	
Bucharest, Romania, 2011 [3]	The office building had a façade system built with curtain wall and ventilated façade system. The fire started from an air conditioning unit, inside the top floor compartment and spread outside igniting the ventilated façade system composed from metal composite panel with polyethylene core between two aluminium sheets. Incombustible insulation was used without cavity barriers.	
Mermoz Tower, Roubaix France, 2012 [4]	The building was refurbished in 2003 by installing a metal composite cladding rainscreen. The metal composite panel consisted of a 3 mm thick polyethylene core sandwiched between two 0.5 mm thick aluminium sheets.	

Country/Year	Comments	Images
Al Tayer Tower, Sharjah, 2012 [4], [3]	The exterior of the building was clad with metal composite panels consisting of aluminium with a polyethylene core. The fire is believed to have started from a discarded cigarette landing on the balcony which contained cardboard boxes and plastics.	
Tamweel Tower, Dubai, 2012 [4], [3]	The building was clad with metal composite panels consisting of aluminium with a polyethylene core. Downwards spread of fire across the façade system was observed.	
Saif Belhasa Building, Tecom, Dubai 2012 [4]	The building was clad with metal composite panels consisting of aluminium with a polyethylene core. The fire started on the fourth floor and rapidly spread to reach the top of the building. The image appears to show that vertical spread was centred on vertical channel profiles created by balconies.	

Country/Year	Comments	Images
Tirgu Mures, Romania, 2012 [3]	The block of flats was refurbished with polystyrene insulation and external render. The fire started outside the building from an adjacent warehouse spreading over the entire height of the building in less than 12 minutes. Post-fire investigations reported that the system was not installed in accordance with the manufacturer's guidance. No fire barriers were present.	
Polat Tower, Turkey, 2012 [3]	The building was a mixture of offices, residential and shopping areas. The cladding system was a combination of curtain wall and ventilated façade system. The rainscreen consisted from metal composite panel with unknown type of core. The insulation type is not known.	
Grozny City Tower, Chechenia, Russia, 2013 [3]	The tower was not in use when the fire occurred. It was reported that the fire started from an air conditioning unit and the fire spread rapidly to the ventilated façade system. The rainscreen consisted from metal composite panel with unknown type of core. The insulation type and if cavity barriers were used was not reported.	

Country/Year	Comments	Images
Karlstad, Sweden, 2013 [3]	The building was in the process of thermal refurbishment. The fire started during the construction phase. The EPS insulation was ignited during work on the façade system and the fire rapidly spread to the entire height of the building.	
Krasnoyarsk, Russia, 2014 [3], [74]	The residential building was built incorporating a ventilated façade system, with the outer panels built from metal composite panel with unknown type of core. Incombustible insulation was used. It was not reported if cavity barriers were used.	
Seoul, South Korea, 2015 [3]	The fire started in a car park situated at the ground floor of the residential assembly and spread to the entire height of the building. The façade consisted of a rendered system with combustible insulation (unknown type or thickness). It was not reported if cavity barriers were have been used.	

Country/Year	Comments	Images
Baku, Azerbaijan, 2015 [3]	The rainscreen consisted of metal composite panel with unknown type of core. It was reported that polyurethane based insulation was used (unknown type).	
Ream Island – Abu Dhabi, 2015 [3]	The fire started from the upper floors of the building spreading downward on the ventilated façade system. The outer panels were built from metal composite panel with unknown type of core. The type of insulation used or if cavity barriers were used was not reported.	
Address Downtown Hotel, Dubai, 2016 [3], [76]	It was reported that this cladding consisted of panels with plastic infill between aluminium sheets and may have contributed to the rapid fire spread. The insulation type and if cavity barriers were used was not reported.	

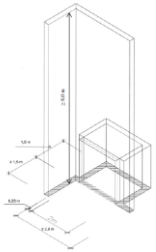
Country/Year	Comments	Images
Torch Tower, Marina, Dubai 2015 [3], [77]	It is understood that the fire started from a grill located on one of the building's balconies. The tower had a combination of curtain wall and ventilated façade system. The panel type, the insulation type or if cavity barriers were used was not reported.	
Torch Tower, Marina, Dubai 2017 [3], [77]	Is not clear what caused the fire in the 79-storey skyscraper. It was the second involvement in a façade fire after a full refurbishment of the cladding system. The panel type, the insulation type or if cavity barriers were used was not reported.	
Hospital in Istanbul, Turkey, 2018 [78]	A ventilated façade system was installed. The fire started from the roof area but the cause has not been identified. The panel type, the insulation type or if cavity barriers were used was not reported.	

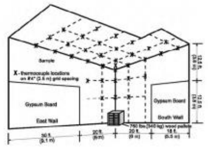
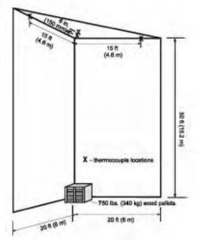
Appendix A2 Large and intermediate-scale façade testing methods

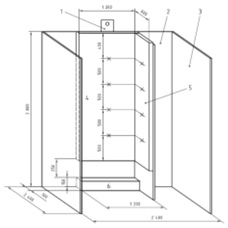
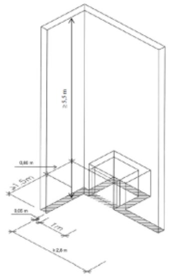
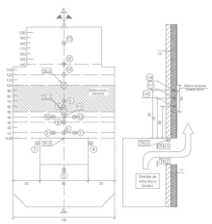
Test standard (large scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m^2]	Photograph
BS 8414-1/2, UK Fire from inside [16], [17]	Wood crib, 315 kg (based on 420 kg/m^3), peak heat released 3 ± 0.5 MW	> 600 °C in the compartment and > 500 °C at 2.5 m above the opening	Between 45-95 kW/m^2, Mean peak 75 kW/m^2, at 1.0 m above the opening	30	≥ 8.0	≥ 6.0	2.0	2.0	2.0 x 2.0	Exterior and interior < 600°C, at Level 2 (5.0 m above the opening) over 30 sec (within first 15 min of the test)	-	
ISO 13785-2, International Fire from inside [33]	Wood cribs 25 kg/m^2, 400 kg or gas, peak heat released 5.0 ± 0.5 MW	> 800 °C at 50mm over the window opening	55 ± 5 kW/m^2 at 0.6 m above the opening 35 ± 5 kW/m^2 at 1.6 m above the window opening	30	≥ 5.7	≥ 4.0	1.2	2.0	2.0 × 2.0 H=2.0	Exterior and interior	-	

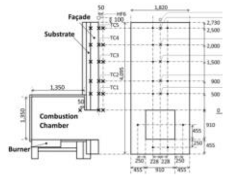
Test standard (large scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m²]	Photograph
MSZ14800-6, Hungary Fire from inside [68]	Wood cribs 32.6 kg/m², 600 kg, peak heat released 3.25 MW	ISO 834 exposure, ±10% deviation after 10 min	-	45	≥ 6.3	≥ 4.1	1.2	1.2	4.0 × 4.6 H = 2.65	Exterior	-	
Draft test method, Romania Fire from inside [3]	Wood cribs 48 kg/m², 720 kg, peak heat released 5.5±0.5 MW	> 900 °C above the window opening	-	> 30	≥ 6.35	≥ 4.25	1.2	3.0	5.0 × 3.0 H = 2.30	Exterior and interior	-	
SP FIRE 105, Sweden Fire from inside [54]	Liquid fuel (heptane), 60 l, peak heat released 2.5 MW	-	15 kW/m² at 4.8 m above the opening at least 7 min 35 kW/m² at 4.8 m above the opening at least 1.5 min < 75 kW/m² at 4.8 m above the opening during test	15	6.71	6.0	0.71	3.0	1.6×3.0 H=1.3	Exterior < 450 °C	2.1 m above the opening (centre of 1st storey window)	

Test standard (large scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m^2]	Photograph
LEPIR II, France Fire from inside [67]	600 kg wood cribs, peak heat released ≈ 4.8 MW	500 °C (average) and 800 °C (max) at 150 mm from surface	-	30	6.6		1.5	1.0	30 m^2	Exterior and interior and floor interface	Heat flux measured level 1	
DIN 4102-20, Germany Fire from inside [51]	Gas burner (320 kW) or 25 kg wood crib	< 800 °C at 1.0m above the opening	60 kW/m^2 at 0.5 m above the opening, 35 kW/m^2 at 1.0 m above the opening, 25 kW/m^2 at 1.5 m above the opening	20 (gas) 30 (crib)	≥ 6.3	4.5	1.0	1.0	1.0 × 1.0 H = 1.0	Exterior and interior, < 500°C at 3.5 m (or higher) above the combustion chamber	-	
NFPA 285, USA Fire from inside and near the opening soffit [30]	Gas burner inside compartment (increases from 690 kW to 900 kW over 30 sec) Window burner (increases from 160 kW to 400 kW) ignited 5 min after main burner	Average 712 °C at 0.91 m above the opening, average 543 °C at 1.83 m above the opening	38 ± 8 kW/m^2 at 0.6 m above window opening, 40±8 kW/m^2 at 0.9 m above opening, 34±7 kW/m^2 at 1.2 m above opening (at peak fire growth)	30	≥ 5.33	4.5	0.762	1.98	3.05 × 3.05 H = 2.13	Exterior < 538 °C at 3.05 m above the window opening and < 278 °C at the rear of test wall in 2nd storey room	-	

Test standard (large scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m^2]	Photograph
GOST 31251, Russia Fire from inside [69]	Wood cribs, 700 MJ/m^2	750 °C, at lintel position	12.5 kW/m^2 at 2 m height	35	≥ 5.1	3.6	0.75	1.6	3.05 × 1.55 H = 1.7	Exterior	-	
CAN/ULC S134, Canada [39]	Gas burners (120 g/s), peak heat release 5.5 MW or wood cribs 675 kg total mass	-	45±5 kW/m^2 at 0.5 m above the opening, 27±3 kW/m^2 at 1.5 m above the opening (15 min average on steady state duration)	25	9.5	6.6	1.44	2.69	6.6 × 4.4 H = 2.75	Exterior and interior	< 35 kW/m^2, 3.5 m above the opening	
EOTA draft TR073 [47]	Wood crib 382.5 kg	-	-	30	≥8.0	≥6.0	2.0	2.0	2.0×1.0 H=2.0	Exterior and interior	-	

Test standard (large scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m^2]	Photograph
ANSI FM 4880 25FT [70]	Wood pallets, 340 kg, 1.5 m × 1.065 m × 1.065 m	-	-	15	7.54	-	-	-	15.7 m (wide) × 11.96 m (wide) × 7.54 m (high)	2.5 m grid spacings on the walls	-	
ANSI FM 4880 50FT [70]	Wood pallets, 340 kg, 1.5 m × 1.065 m × 1.065 m	-	-	15	15.2	-	-	-	6.2 m (wide) × 6.2 m (wide) × 15.2 m (high)	External	-	

Test Standard (intermediate scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m^2]	Photograph
ISO 13785-1, international Fire below test specimen [43]	Gas burner (100 kW) 1.2 m (long) x 0.1 m (wide)	-	-	30	2.8	2.4 above the burner	-	-	-	Exterior	2.8 m height	
EOTA draft TR073 Fire from inside [47]	30 kg wood crib	-	-	30	≥ 5.5	4.7	0.8	1.0	1.0×1.0 H = 0.8	-	-	
Draft test method, Romania Fire from inside [3], [58]	Gas burner (ISO 834 exposure)	-	-	50	≥ 3.4	2	0.5	0.9	1.9×0.8 H = 1.5	Exterior and interior	-	

Test Standard (intermediate scale)	Fire load	Temperature limits (calibration)	Heat flux limits (calibration)	Ignition source burning duration [min]	Total height [m]	Height above the window opening [m]	Window opening height [m]	Window opening width [m]	Compartment size [m]	Temp. measured [°C]	HF measured [kW/m²]	Photograph
Önorm B3800-5, Germany Fire from inside [71]	Wood crib 25 kg or gas burner (320 kW)	-	-	30	6.0	-	-	-	-	Exterior	-	
PN-90/B-02867, Poland Fire in front of the specimen [72]	Wood crib 20 kg Wind is applied towards the specimen 2 m/s	800 °C, at lintel position	-	30	2.3	-	-	-	-	Exterior	-	
JIS A 1310 [73]	Gas burner (≥ 600 kW)	-	-	20	4.1	2.7	0.91	0.91	1.35×1.82 H = 1.35	Exterior	-	

Report Ends