Development of a Fire Safety Assessment Test for External Cladding Systems

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A thesis submitted in partial fulfilment for the requirements for the degree of MSc (by Research) at the University of Central Lancashire

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Student Declaration

I declare this thesis is the result of my own original research work. No part of this thesis has been submitted for any other academic award and I do not have concurrent registrations for two or more academic awards.

I acknowledge that I received financial support from the Fire Protection Association (FPA) as I am an FPA employee. However, the views expressed and conclusions drawn in this thesis are my own.

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Abstract

In the context of increasing façade fires, especially in the UK, where combustible cladding systems are approved for high-rise buildings, this study addresses concerns related to fire testing cladding systems. Key developments include:

1. **Comprehensive Database of BS 8414 Tests**: A database was compiled, analysing various cladding systems and their subsequent fire performance. It highlights certain systems' unrealistic construction methods, which aren't replicated in real buildings. It also raises concerns around thermocouple criteria and placement relative to the fuel load. Test results were analysed to estimate the impact of changing the evaluation criteria.
2. **Material Fingerprinting**: A method for characterising cladding products was developed, using microscale combustion calorimetry and infrared spectroscopy to assess chemical composition and properties relating to fire performance.
3. **RISC 501 Development**: This study proposes a new fire test method and assessment criteria for external cladding systems, called RISC 501, which can be conducted alongside the existing BS 8414 test method, allowing conference with the BR 135 performance criteria. While BR 135 is focused on life safety, RISC 501 specifies enhanced performance criteria to focus on property protection. It incorporates revised requirements for the test construction, material characterisation, temperature criteria, and mechanical performance criteria. It also includes gas sampling methods to assess potential smoke toxicity produced by a burning cladding system.
4. **Validation Tests**: Validation tests confirm RISC 501's effectiveness in distinguishing between combustible and non-combustible cladding systems, offering a clearer performance differentiation compared to the BR 135 criteria. The proposed gas sampling method effectively distinguishes between combustible and non-combustible systems and provides insights into predicting the Fractional Effective Dose for incapacitation.

In summary, this study produces research to aid the development of a fire test and assessment for external cladding systems and then uses that research to develop RISC 501 – Fire Safety Assessment Test for External Cladding Systems.

Contents

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Lastly, I wish to acknowledge a passing in my own family. During the early stages of this research, my beloved mother passed away. She was a driving force behind my work and my main source of encouragement. It is to her memory that I dedicate this work.

List of Tables

List of Figures

Glossary of Terms and Abbreviations

ACM – Aluminium composite material

ADB – Approved Document B

BR 135 – Fire performance of external thermal insulation for walls of multistorey buildings

BS 8414 – British Standard 8414 - Fire performance of external cladding systems parts 1 and 2. *For undated references, the latest edition of the referenced document (including amendments) apply. Where the part is not referenced, all relevant parts apply.*

CHNS – Carbon Hydrogen Nitrogen and Sulphur

Cladding – Non-loadbearing external cladding system

D-ATR-FTIR - Diamond-Attenuated Total Reflectance-Fourier Transform Infra-Red spectroscopy.

EIFS – Exterior insulation and finishing system(s)

EPS – Expanded polystyrene

ETICS – External thermally insulated cladding system(s)

Euro classification system – BS EN 13501-1:2018 Fire classification of construction products and building elements. Classification using data from reaction to fire tests.

Façade – Principal front of the structure that faces on to an open space

FED – Fractional effective dose

FTIR - Fourier Transform Infra-Red spectroscopy

Gaming - Deliberate attempt to interpret a test standard in a way that increases the chance of passing or failing while deviating from the intended spirit of the test standard

HCN – Hydrogen cyanide

HPL – High pressure laminate (panels)

LPS 1581/2 – Refers to both of the following Loss Prevention Standards:

- LPS 1581: Issue 2.1 – Requirements and tests for LPCB approval of non-load bearing external cladding systems applied to the masonry face of a building.
- LPS 1582: Issues 1.1 Requirements and tests for LPCB approval of non-load bearing external cladding systems fixed to and supported by a structural steel frame.

MCC – Microscale combustion calorimetry

MCM – Metal composite material

MW – Mineral wool insulation

PIR – Polyisocyanurate insulation

PHEN – Phenolic insulation

Phenolic – Phenolic insulation

PUR – Polyurethane insulation

PVC – Polyvinylchloride

RISC 501 - Fire Safety Assessment Test for External Cladding Systems – Version 0.2 (Draft copy)

TCPP - Tris(chloropropyl) phosphate

Validation Test - A validation test involves comparing the results of predicted performance with experimental data to verify the accuracy and validity of the prediction

1 Introduction

1.1 Background

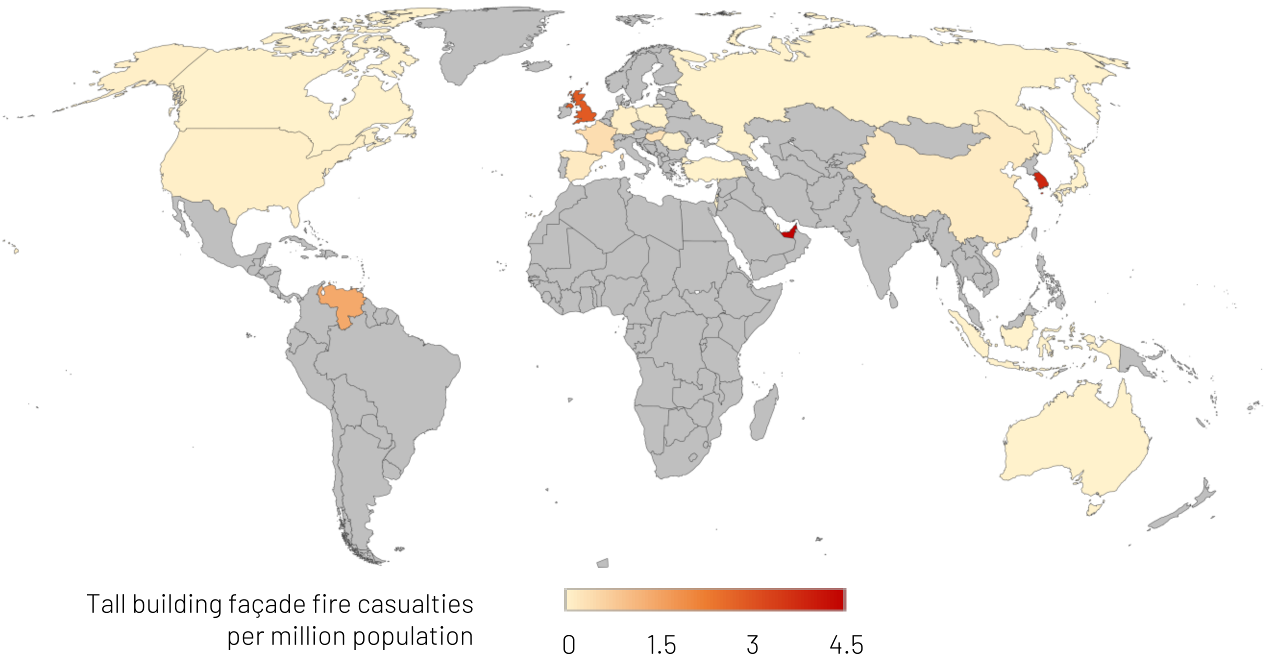
External cladding refers to the protective and decorative layers applied to the external surfaces of structures. They can be integral to a buildings design, or installed retrospectively to improve a buildings insulation and aesthetics [1].

The occurrence of large cladding system fires has been increasing, globally, since 1990 [2, 3]. This is of particular concern as a building's cladding system has the potential to spread fire around a building, bypassing the internal fire compartments. Fire can spread via the external material and penetrate the building through void connections such as windows and ducts, as seen with the tragic events of the 2017 Grenfell Tower fire [4].

These fires are particularly devastating in tall buildings. Most tall building fires have occurred in buildings constructed or refurbished within the last 15 years. In fact before 2000, there were no reported façade fires in buildings higher than 30 stories [5]. This correlates with the increase in tall buildings, with the number of buildings over 200 meters high increasing by a factor of four from 2000 until the end of 2016. That number grew another 26.5% between 2016 and 2018 [6].

Since 1990, the United Kingdom (UK) has reported the second most façade fires of any country and the third most casualties per population [3]:

Figure 1 – Tall building fire casualties, per million population, created using data extracted from the OFR Consultants External Wall Fire Incidents database [3]



It should be noted that the data for Figure 1 was extracted from newspaper reports at the time of the incident. The database was populated in the UK and may be biased towards the English-speaking countries. It may also be biased towards countries with editorially independent media.

1.2 Aim

The principal aim of this research is to enhance the safety of tall buildings by preventing fire spread through external cladding systems. The objective was to develop a new fire safety test and assessment method for external cladding systems that meets the following insurance industry requirements:

- The test standard should support both property protection and life safety in buildings where compliant cladding systems are installed.
- The test should be capable of conferring compliance with the criteria of BR 135 – Fire performance of external thermal insulation for walls of multistorey buildings – Third edition [7].
- It should be resilient to 'gaming' by the test sponsor (deliberate attempt to interpret the standard in a way that increases the chance of passing or failing and deviating from the intended spirit of the standard).
- It should not result in a non-combustible system failing to meet the fire spread or temperature requirements. This is defined as any system where the relevant materials and products, have achieved European Classification A2-s1, d0 or better, when assessed against BS EN 13501-1:2018 – Fire classification of construction products and building elements. Classification using data from reaction to fire tests [8].

2 Regulatory Route to Compliance

2.1 Current Routes to Compliance for External Cladding Systems in England

Most building work being carried out in England must comply with the Building Regulations 2010. The building regulations require the external walls of a building to adequately resist the spread of fire over the walls and from one building to another, this is described in paragraph B4 of Schedule 1 [9].

Regulation 7 of the Building Regulations 2010 specifies additional requirements, banning the use of most combustible components on most buildings over 18 m tall, with some exceptions:

- Regulation 7(2) specifies that materials which become part of an external wall, or specified attachment, of a relevant building, should be of European Classification A2-S1, d0 or Class A1 in accordance with BS EN 13501-1 [8, 10].
- Regulation 7(3) specifies which materials and components this doesn't apply to, for example it doesn't apply to membranes, seals or gaskets.
- Regulation 7(4) specifies what a relevant building is, which covers most buildings over 18 m with sleeping accommodation.

Metal composite material with a highly combustible core is also banned on the external wall of any building of any height by Regulation 7(1).

Other than the banned materials in specific scenarios, the regulations are not prescriptive and do not specify how the requirement for adequately resisting fire spread must be met. To assist with this, the government publishes statutory guidance, which provides more specific details on how compliance could be achieved, such as Approved Document B (ADB), volumes 1 and 2 [11, 12]. It should be noted that compliance with ADB does not guarantee compliance with the building regulations.

ADB recommends two routes to compliance for external cladding systems. A linear route to compliance, where all components must individually meet a certain requirement. And a performance based route to compliance, where all components must be tested as a system and that system must meet certain requirements.

Although not explicitly stated, other routes are possible to satisfy the requirements of Regulation B(4). PAS 9980:2021 summarises the various options as four different routes to compliance :

1. Linear Route to Compliance: Small-scale tests of each relevant cladding system component via BS EN 13501-1 [8] reaction to fire testing. Each component must meet the required performance level for the system to comply. The linear route to compliance is now the only option for relevant buildings over 18 m.
2. Performance Based Route to Compliance: Large-scale test of the whole cladding system. Tested against the BS 8414 test method [13, 14] and assessed against the BR 135 [7] performance criteria.
3. Assessment in Lieu of Test: A desktop study by a suitably qualified fire specialist to assess whether a system would meet the requirements of the BR 135 [7] performance criteria. This is done by assessing the reaction to fire properties of the materials [15] and comparing the fire performance of similar systems which have been tested to BS 8414 [13, 14]. This can be assessed using the criteria in BS 9414 [16].
4. Holistic Fire Engineered Approach: This involves adopting a comprehensive fire-engineered approach that considers various factors such as building geometry, ignition risk, and limitations on fire spread. This approach is expected to incorporate established fire engineering principles and methods that are applicable to the specific context. Additionally, quantitative analyses should be utilised when necessary to support the decision-making process.

This research focuses on testing via the performance based route to compliance. The results of which may be used as part of an assessment in lieu of test or a holistic fire engineered approach.

2.2 Current Performance Based Route to Compliance

The current performance based route to compliance is a large scale fire test over 9.7 m tall [11, 12]. This follows either the BS 8414-1 or the BS 8414-2 test method [13, 14]. The performance is then classified against the BR 135 [7] performance criteria.

The test involves subjecting a cladding system to a nominally 3 MW, wood fuelled fire, that could represent a post-flashover burning room venting out of a window. This is inherently a test for combustible systems as non-combustible systems can demonstrate compliance on a smaller scale, using BS EN 13501-1 [8] (the linear route to compliance).

Despite the 2018 ban on combustible components of cladding systems for relevant buildings over 18 m [17], the BS 8414 and BR 135 approval process remains an important route for assessing cladding system fire performance in England, Wales, Northern Ireland and Scotland, with the number of UKAS (United Kingdom Accreditation Service) certified test facilities doubling between 2017 and 2020 [18-22], and the number of test rigs increasing by a factor of 4.

Discussion of the criteria specified in BS 8414 and BR 135 has raised questions regarding the appropriateness of the fuel source, test construction, construction detailing, assessment criteria and availability of test results [23, 24].

2.3 BS 8414 Test Method

2.3.1 Test Summary

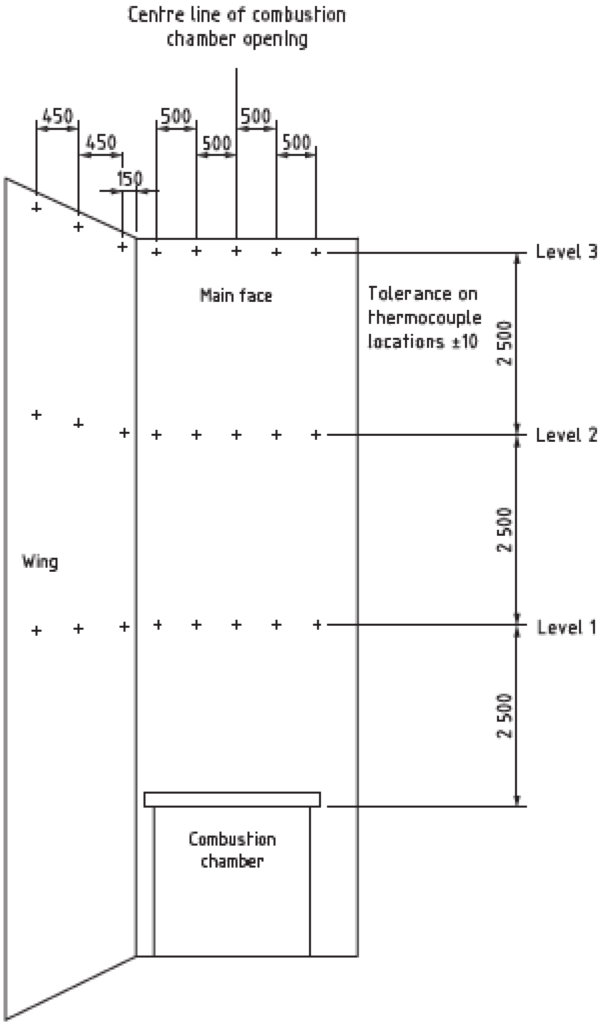
A 9.7 m high cladding system is installed onto the test rig. A wooden crib is placed at the bottom of the test rig, inside a burn chamber, recessed beneath the test rig. The crib is ignited and allowed to burn for 30 minutes, imparting a heatflux between 45-95 kW/m^2 [25] onto the front face of the cladding system. After 30 minutes the crib fire is manually extinguished, while the cladding system is allowed to continue burning. The test runs for a total of 60 minutes.

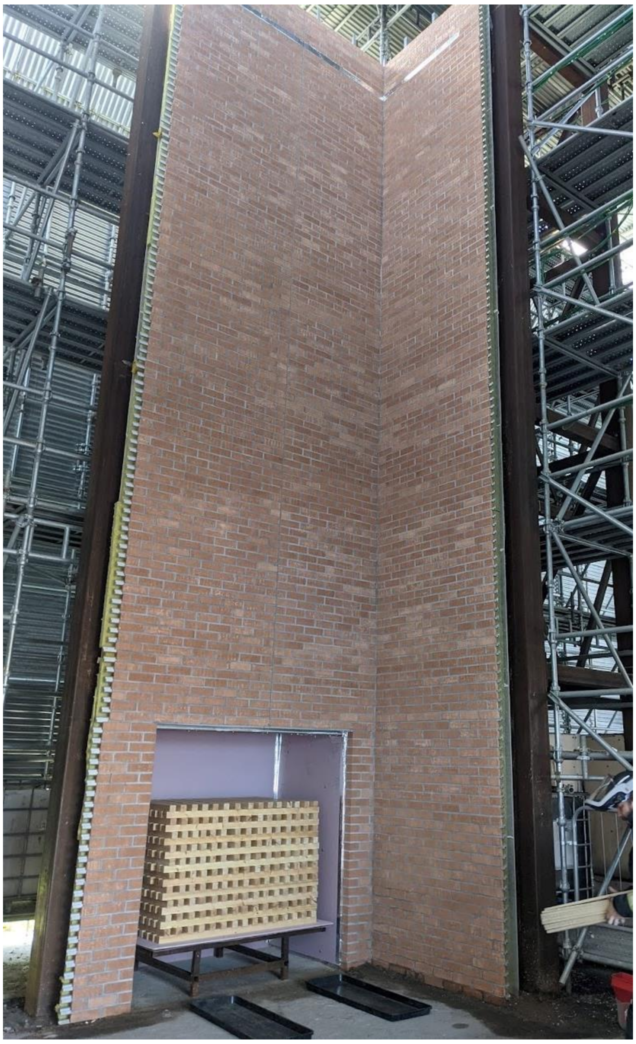
Thermocouples are installed at three levels, 2.5 m, 5 m and 7.5 m above the combustion chamber opening as shown in Figure 2 below.

- The level one thermocouples are used to determine the test start time, once the wooden crib has reached a certain level of involvement.
- The level two thermocouples are used by BR 135 to determine the performance criteria for fire spread.
- The level three thermocouples do not have a specified purpose, but may be used by the test house to assist with determining if a test should be terminated, as a test should be terminated if flame spread extends above level three.

Figure 2 – Figure 2 from BS 8414-2:2020 showing a diagram of the test rig with the thermocouple locations relative to the combustion chamber [14]

Figure 3 – Photograph of an example of test setup in accordance with BS 8414-2:2020





2.3.2 Fuel Source

The fuel source consists of wooden crib, nominally 1 m x 1 .5 m x 1 m (length x width x height), placed inside the combustion chamber.

There has been debate over the suitability of wood cribs as a fire source due to the variability in material [26]. When combined, all the tolerances specified in BS 8414 [13, 14] allow for the total heat release to vary by a factor of 2 [23]. A significant difference in potential fuel load between tests. It has been argued that the crib is ventilation controlled, so additional wood may not lead to a greater peak heat release rate and only lead to a longer burn time, as shown by some indicative tests [27]. As the wooden crib is extinguished after 30 minutes, the longer burn time may not be relevant if it exceeds the duration of the test fire burn time.

The initial rate of thermal exposure on the façade is limited by the fire growth rate of the crib. A fully involved fire from a room in flashover suddenly breaking out of a window may present a faster thermal exposure to the façade. Fuel loads in modern buildings are reported to contain 20% plastic-based fuel [28]. A plastic fuel can result in an increase in fire acceleration compared to a wooden fuel with the same total heat output. It can also result in an increase in peak temperature and 20% larger flame heights [29]. The rate of thermal exposure is relevant because cladding system components, such as cavity barriers, can perform differently when heated rapidly, compared to when heated gradually. This could be resolved by replacing a portion of the wooden crib with a plastic component. Another proposed solution is to use a gas burner that is capable of following a specified fire growth curve [30].

2.3.3 Construction Detailing

The BS 8414 standard states that the system shall be representative of the intended end-use design [13, 14]. However, it is rarely possible to install a system exactly as it would be on a real building, for example real buildings have windows in place of the burn chamber. BS 8414 does not stipulate how features such as the burn chamber opening, lintel detailing, floor heights and edge sealing around the test rig should be accommodated. For test results to be meaningful, there should only be one consistent way of doing anything that may affect the outcome of the test. This would also prevent cladding system manufacturers from having the option for overadjustment to meet the specified test criteria. For example the acceptance criteria include specified temperature rises in locations which could be above or below the fire barriers, depending on decisions that are up to the test system designer.

2.3.3.1 Burn Chamber Opening

The wooden crib is placed inside a 'burn chamber' at the base of the test rig. BS 8414 states that the fire exposure is intended to be representative of an "external fire source or fully developed fire in a room venting from an aperture" [13, 14]. Representing multiple potential options introduces ambiguity. The design guidance for the cladding system subjected to test may have different detailing solutions for an opening depending on its assumed role. For example, the series of seven publicly available tests conducted for the then Ministry for Housing, Communities, and Local Government (MHCLG) used a 5 mm thick, welded aluminium window pod to surround the burn chamber [31]. This is not representative of the intended end design, and it may have prevented the fire from entering the rainscreen cavity.

It has also been shown that the width the cladding system protrudes out from the burn chamber opening can also have a significant impact on the flame height by increasing the flame path length [32].

2.3.3.2 Cavity Barriers

A fire break is anything which separates combustible components to restrict the spread of fire. This is usually in the form of a non-combustible barrier. When a fire break is used in a cavity, it is called a cavity barrier. There are two main types of cavity barrier, referred to as open state and closed state. A closed state cavity barrier is a non-combustible barrier which always blocks off the cavity. An open state cavity barrier will leave the cavity open during normal operation, to allow ventilation, but will expand and close off the cavity during a fire.

Cavity barriers are typically made from mineral wool to meet the insulation and integrity requirements from fire resistance tests such as TGD 19 - Fire resistance test for 'open-state' cavity barriers used in the external envelope or fabric of buildings [33]. But they can also be made from fire resistant boards, solid metal plates or metal gauze. Most open state cavity barriers use an intumescent material to expand and fill the air gap when exposed to heat. Some cavity barriers rely on the thermal expansion of metal components [34].

The proximity of cavity barriers installed on a test rig is not always representative of a real-world installation [35]. The ambiguity with the burn chamber opening can also lead to ambiguity with the location of cavity barriers. If the installer interprets the opening to represent a window, they may surround the opening with cavity barriers in accordance with ADB [11, 12]. However, other installers may leave the opening unprotected, leading to cavity barriers located 3 m above the burn chamber. A comparison of different façade tests, conducted by the Building Research Establishment (BRE), demonstrated that placing a fire barrier immediately above the burn chamber opening can improve the fire performance during the test [36].

2.4 BR 135 Performance Criteria

2.4.1 Assessment Criteria and Classification Method.

BR 135 specifies performance criteria based on the results of a completed BS 8414 test. The fire performance of the system under investigation is evaluated against the following three criteria:

1. External fire spread
2. Internal fire spread
3. Mechanical performance

2.4.2 Internal and External fire spread

The current acceptance criteria in BR 135 state that both the internal and external temperatures must remain within 600°C of ambient at a specific height on the test rig for a 15-minute period, once the fire is sufficiently involved [7]. The scientific origin of this requirement and the criteria are not publicly available and it may not be sufficient to ensure life safety [23].

It is also worth noting that in 2018, a BS 8414-2 test [14] was conducted at Exova in Dubai, commissioned by Kingspan. The system comprised of non-combustible products (European Classification A1 and A2 based on BS EN 13501-1:2018 [8]) which would comply with the guidance in ADB [11, 12]) but when tested did not meet the criteria set out in BR 135 [7]. Such a system would not normally be considered to present a fire hazard and would not support flame spread. It failed due to excessive temperature in the cavity, despite there being no fire spread through the façade or insulation materials [37]. This could be considered a flaw of the measurement criteria specified for BS 8414 as the standard is "solely intended to give an indication of fire spread across or within an external cladding system" [13, 14]. The Grenfell Tower Inquiry heard how Kingspan's technical team had modified the façade designed to maximise the chance of failure. This raises two important points. The first is that the test does not adequately discriminate between combustible (which can support fire spread up a façade) and non-combustible (which cannot). The second is that the standard is insufficiently specified, so that it is possible to modify the façade, not only to achieve a pass, but also to achieve a failure.

Within the science community, thermal radiation is often considered a more useful measure of flame intensity than temperature. Radiation is a significant component of the heat transfer from a flame, which is not present at the same levels from a hot gas [38]. Other studies have attempted to use plate thermocouples or heat flux sensors to quantify the fire exposure received by the façade to address these concerns [30, 39, 40]. Plate thermocouples and heat flux sensors both measure the rate of temperature change of a thermal mass, which effectively measures the rate of energy transfer [41]. This enables them to provide a clearer distinction between a hot gas and a flame, than just measuring temperature.

2.4.3 Mechanical Performance

It is regularly reported, during external cladding system fires, that fallen material has interfered with firefighting operations [5]. Despite this, there are no mechanical performance pass/fail criteria specified in BR 135 [7], there is only a requirment to observe and record mechanical performance.

2.4.4 Smoke Toxicity

Testing at the BS 8414 scale is expensive and rarely repeated on a system. When all factors such as the installation and test laboratory fee are combined, it can cost the client over £100,000 per test. The test could also be used as an opportunity to measure additional features that might not necessarily contribute directly to a pass or failure but could form part of the selection and risk assessment process. This could be done through a more detailed classification, similar to the European Classification smoke and droplet ratings [8]. For example, an emerging issue is the smoke toxicity from a burning cladding system, particularly when the cladding system is linked to windows, and service penetrations via the cavity [42].

2.5 Availability of Test Information

2.5.1 Publicly Available Test Results

There is currently no requirement to make either the BS 8414 test or the BR 135 classification report publicly available. In Dr Lane's report to the Grenfell Tower Inquiry, she observed that "The absence of a body of relevant fire test evidence for rainscreen cladding systems, and the components of rainscreen cladding systems, based on the current submissions to the Public Inquiry, show a serious failing in the testing and certification regime." [43].

Valuable information is lost from both hiding failed test results and not fully disclosing successful test reports. By hiding failed test results, there is the possibility that a cladding system could be repeatedly subjected to the BS 8414 test [13, 14] until it achieves a successful BR 135 [7] classification through test variance. Multiple test failures would indicate that the expected result is a test failure, which is disguised when only the singular test pass is reported.

Conversely, by not fully disclosing successful test reports, features which are relevant to installers and risk assessors become unavailable. For example, mechanical performance must be included in any BR 135 report and "should be considered as part of the overall risk assessment" [7] but it cannot be considered as part of the building's overall risk assessment, without the assessor having access to the test report.

2.5.2 Material Identification

A BS 8414 test report must include details of all products and components used in the construction of the test specimen, together with identification marks and trade names [13, 14]. However, identification marks and trade names do not guarantee that the product supplied for test is representative of the product supplied for market and does not appear to report manufacturing variations and changes as described in module 2 of phase 2 of the Grenfell Tower Inquiry [44].

2.6 Obstacles to Regulatory Compliance

At the time of writing (2024) there are two obstacles for complying with the performance based route, both related to the fact that the test method and assessment criteria are different documents, managed by different organisations.

1. The British Standards Institution (BSI) released a new version of BS 8414 in 2020 [13, 14], which superseded all previous versions. It notably included changes to the required height of the test specimen and an additional row of temperature sensors. However, the BRE announced [7] that they will not be updating BR 135 to recognise BS 8414:2020. Therefore, BR 135 is only valid for the 2015 version of BS 8414, which has been withdrawn.
2. Approved Document B (ADB) requires that test laboratories are third party accredited by the United Kingdom Accreditation Service (UKAS). However in February 2022, UKAS stopped accrediting BR 135 [7] against ISO 17025 - Testing and calibration laboratories [45, 46]. They determined that BR 135 should be accredited against ISO 17065 instead (Conformity Assessment — Requirements for bodies certifying products, processes and services) [47]. As of January 2024, there are no test facilities accredited by UKAS to conduct BR 135 assessments in accordance with ISO 17065. Therefore new products cannot conform with clause B5 in Appendix B of ADB [11, 12].

3 Research Programme

The following research programme was created to develop a new fire safety test and assessment method for external cladding systems that meets the insurance industry requirements and addresses the current concerns identified with BS 8414 and BR 135 where possible. The remainder of the work has been subdivided into the following chapters:

- Chapter 4 – Analysis of BS 8414 test results
- Chapter 5 – Identification and characterisation of fire rated insulation products
- Chapter 6 – Development of fire test method and assessment method
- Chapter 7 – Large scale validation testing
- Chapter 8 – Review of proposed test and assessment method

Chapter 4 – Analysis of BS 8414 test results

This study involved the creation of a database comprising data from fire tests of external cladding systems conducted according to the BS 8414 test method and evaluated against the BR 135 performance criteria. This database was created using test reports from the Fire Protection Association (FPA) archive and publicly available reports from the Building Research Establishment (BRE). The database was populated with standardised fields to examine a variety of test specimens, the corresponding testing conditions, and their influence on performance criteria.

The primary objective was to generate data that would serve as a foundation for critically evaluating the BS 8414 test methodology by exploring the strategies and interpretations employed to meet the BR 135 criteria. The investigation extended to analysing test outcomes under more stringent evaluation criteria, utilising the fire performance standards LPS 1581 and LPS 1582 (LPS 1581/2) for this purpose. Although closely resembling the BS 8414 test method, LPS 1581/2 diverges in its assessment criteria.

Chapter 5 – Identification and characterisation of cladding products

To address the concern of manufacturers using superior performing products in fire tests, compared to those actually installed on buildings, a method for material characterisation was developed.

Products can differ between fire tests and real-world applications for a variety of reasons:

- Continuous improvement: Products are constantly being changed and improved to keep up with changes in the market. Minor changes do not constitute the need for re-evaluation of fire ratings. However, cumulative alterations can eventually amass into significant changes. Although significant changes should prompt re-testing, this may not be conducted.
- Test specials: Manufacturers could employ chemically enhanced products to deceive a fire test house. These enhanced products might be too expensive to mass produce, leading to cheaper, worse performing products sold to market.
- Insufficient test specification: The test standard might lack precise specifications, allowing a product used in a fire test to differ substantially from the real-world application, while still complying within the defined parameters.

A method was therefore developed to produce a representative 'chemical fingerprint' of the products tested. Using small scale tests, designed to identify significant chemical variations between products submitted for testing and those supplied to market.

Chapter 6 – Development of fire test method and assessment method

The findings of the literature review, analysis of BS 8414 tests and material characterisation testing where collated and analysed.

A new test standard was developed which specified improved requirements for the test construction, fire load, instrumentation, test conditions, reporting requirements and performance criteria. The development was constrained by a requirement to ensure the test could be conducted in accordance with BS 8414 and would still be eligible for a BR 135 assessment.

Chapter 7 – Large scale validation testing

A validation test involves comparing the results of predicted performance with experimental data to verify the accuracy and validity of the prediction. Validation tests were run on two different cladding systems against the proposed test standard. The results were analysed with the aim of critically appraising the proposed standard and amending it if necessary. A baseline non-combustible system was compared against a similar combustible system with the aim of identifying:

- Any physical impossibilities with the implementation of the prescribed test setup, including construction detailing and sensor locations.
- The test's ability to identify flame spread through known combustible cladding systems.
- The test's ability to identify a lack of flame spread through known non-combustible cladding systems.
- The test's ability to identify mechanical failures.
- The test's ability to measure a significant difference in the smoke toxicity between a combustible and non-combustible system.

The hypothesis was that the test method would be able to differentiate between the combustible and non-combustible system, in terms of both fire spread and smoke toxicity.

Chapter 8 – Review of proposed test and assessment method

The findings of the validation tests were used to review and update the test standard considering changes to the following parameters:

- Ambient test conditions, such as the range of permitted ambient temperatures a test can be conducted in.
- Test specimen, considering clauses such as the floor heights which dictate the cavity barrier locations.
- Temperature criteria, considering the type of sensors used, their location, the maximum permitted temperature and the duration under consideration.
- Mechanical performance, considering the quantity and type of measurements conducted to determine mechanical performance.
- Gas sampling, considering the type of sensors used, the gas extraction methods used and the location of the sensors on the test specimen.

The findings were also used to identify areas of further research.

4 Analysis of BS 8414 Test Data

4.1 Introduction

A database was populated with test results from cladding systems fire tested according to BS 8414 [13, 14] and assessed against the BR 135 [7] performance criteria. BS 8414 test reports and BR 135 classification reports were gathered from the Fire Protection Association's (FPA) archive and from publicly available reports from the Building Research Establishment (BRE). The full list of reports examined is provided in Appendix A. A redacted version of the database has been provided separately with commercially sensitive information removed (Database of BS 8414 Test Reports – Redacted Copy).

The database was populated with common fields to investigate the range of specimens submitted for test, the conditions they are tested under and the impact this has on classification performance. The aim was to produce data that could underpin a critical appraisal of the BS 8414 test method by investigating the options and interpretations employed for achieving the BR 135 classification criteria.

Test results were analysed for the impact of changing the evaluation criteria to discriminate better between safe and unsafe cladding systems. The fire performance standards LPS 1581 and LPS 1582 (LPS 1581/2) were used for this purpose [48, 49]. LPS 1581/2 uses an almost identical test method to BS 8414, the only notable difference being a result of the height change to BS 8414 in 2020 [13, 14]. It uses a different set of criteria for assessing performance, designed to provide users with third-party approved external cladding systems for the purposes of property protection.

Babrauskas suggested that each fire disaster should be used to evaluate the suitability of the test regime that permitted it [50]. The performance of cladding systems in BS 8414 tests was therefore compared against real-world performance in tall building façade fires around the world.

4.2 Method

61 BS 8414 reports for tests undertaken between 2010 and 2022 were analysed. The tests were based on four different versions of the BS 8414 test standard (2002, 2015, 2015 + A1 2017 and 2020).

Test details were collated for the test construction, test conditions and classification criteria. The full list of data fields and how they were collected is available in Appendix A. The fields were chosen to capture pertinent factors that could possibly influence fire outcomes. These include combustible components that could propagate fire spread, like insulation and non-combustible components that could prevent fire spread, like cavity barriers.

The fire ratings based on BS EN 13501-1 reaction to fire testing [8] for all insulation and façade materials was recorded where possible. Materials were placed into two fire classification categories: combustible and non-combustible. This was defined using the 2018 amendment to 2010 building regulations, restricting the use of combustible materials in external walls of certain buildings over 18 m in height [9]. It defined non-combustible cladding components as either an A1 or A2 s1 d0 classification from BS EN 13501-1 [8]. The smoke and droplet ratings were not regularly provided for materials supplied for testing, so this definition was simplified further to incorporate all A2 products for this study.

Vapour barriers, otherwise known as breather membranes, were commonly used to protect the insulation from moisture and ultraviolet radiation, while still allowing air movement. These had a variety of claimed fire performances, however no correlation was found with the overall system performance. More data would be required to appropriately assess these. This was the same for other light components, that were investigated, such as the fixing material.

The test data, visual observations and test photographs reported in BS 8414 and BR 135 reports were used to retrospectively assess systems against the LPS 1581/2 criteria. Both methods use 600°C + ambient as the maximum temperature criteria for determining external and internal fire spread. The main differences between the criteria are:

- BR 135 specifies temperature criteria over a 15-minute period. Mechanical damage must be reported, but there are no criteria set [7].
- LPS 1581/2 uses the same temperature criteria, but over a longer 30 minute period
- LPS 1581/2 sets additional performance criteria set for mechanical damage, visible flaming, burning debris, pool fires and glowing combustion [48, 49]. See Table 37, Appendix A for definitions of each criterion and how they are interpreted.

As LPS 1581/2 incorporates all of the BR 135 criteria, all tests that meet the LPS 1581/2 criteria will always meet the BR 135 criteria. Cladding systems could therefore be placed into one of 3 categories:

- Systems that met neither test criteria
- Systems that only met BR 135 test criteria
- Systems that met both BR 135 and LPS 1581/2 test criteria

The colours are consistent with the relevant graphs from Figure 4 to Figure 31.

4.3 Test Specimens

The BS 8414 and BR 135 test reports for 61 unique cladding systems were submitted for analysis. All systems comprised of insulation behind an external façade and could be broken down into two common types shown in Table 1.

Table 1 – Types of cladding systems submitted for analysis

Cladding System	Number	Typical Composition
Rainscreen cladding systems	57	Weather defence board, thermal insulation, breather membrane, empty cavity and a solid external façade.
External thermally insulated cladding systems (ETICS)	4	Weather defence board, thermal insulation, breather membrane, reinforcing mesh and an external render.

Not all systems comprised of all layers described in Table 1

13 of these systems were considered non-combustible systems, with all significant components achieving class A2 or better when tested to BS EN 13501-1.

19 of the systems were tested to assess the cladding system on an existing building. The rest were conducted to either gain approval for new cladding systems, for research purposes or unconfirmed.

No glass curtain wall systems were analysed as these are outside the scope of BS 8414.

Composite panel systems and living green wall systems are types of cladding system within the scope of BS 8414, but no test results were available for analysis from the reports considered.

4.4 Findings

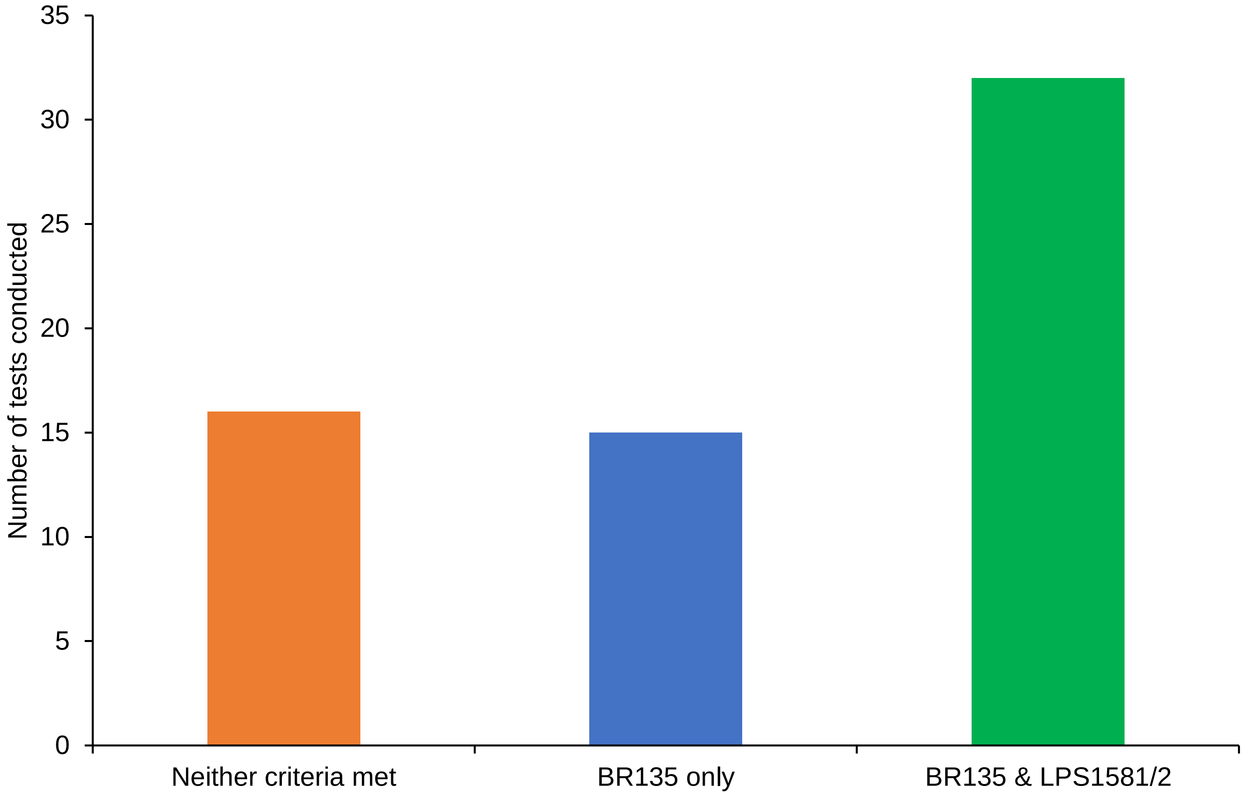
4.4.1 Note on Findings

In order to visualise the data, it has been summarised in a series of graphs showing the proportion of passes and fails for the different parameters investigated. It is important to recognise that no causative relationship is being claimed and the choice of the parameters will be a function of the cladding system being tested. For example, a combustible system for which the client wanted to demonstrate compliance is likely to be more heavily protected with e.g. cavity barriers than a non-combustible system.

4.4.2 General System Performance

61 BS 8414 tests were included in the database, conducted between 2010 and 2022. Figure 4 shows that most of the cladding systems in most of the tests analysed met both the BR 135 criteria and LPS 1581/2 criteria (32), with around half that number only meeting the BR 135 criteria or meeting neither criteria. Of the tests that met the BR 135 criteria, 68% of those also met the LPS 1581/2 criteria as shown below.

Figure 4 – General system performance (n = 61)

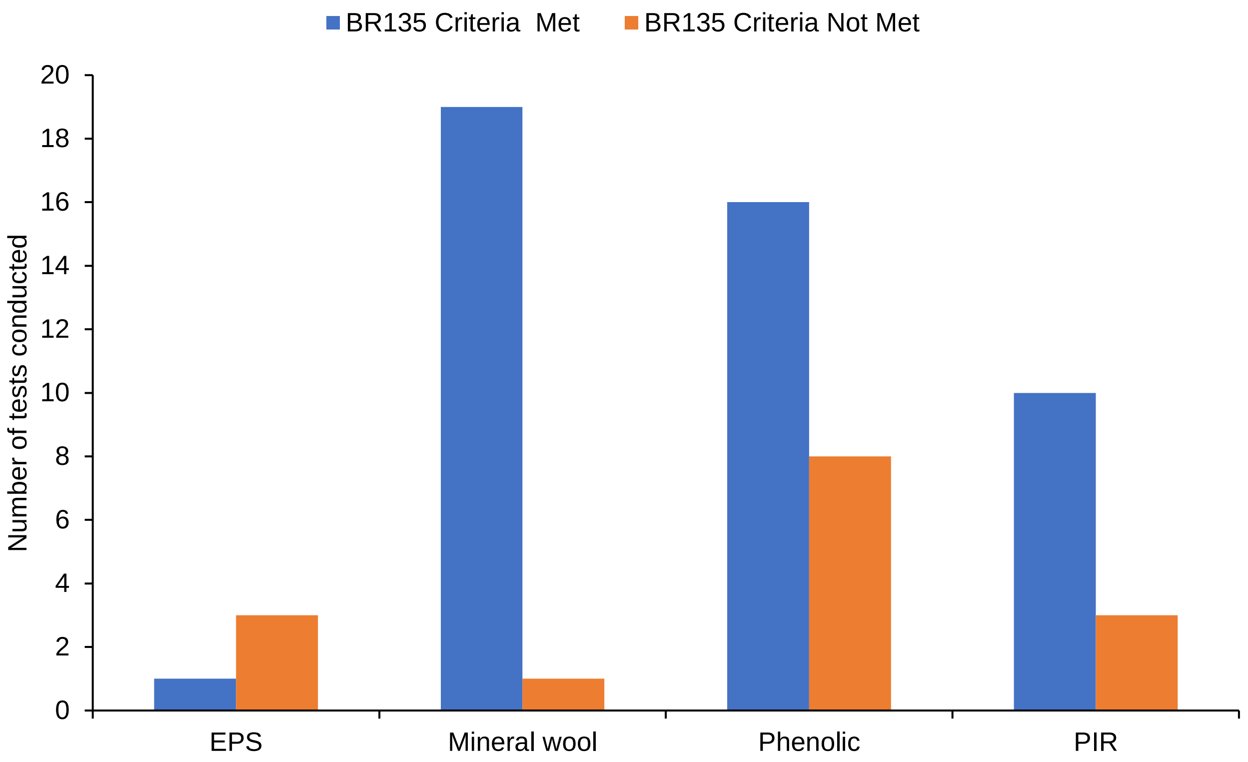


4.4.3 Test Construction

4.4.3.1 Insulation Materials

First, the effect of the cladding insulation materials on the test outcome was investigated. All cladding systems tested used some form of insulation material for purposes such as thermal and sound insulation. Figure 5 shows that the insulation materials for all systems fell into four categories: expanded polystyrene (EPS), mineral wool, phenolic foam (phenolic), and polyisocyanurate foam (PIR).

Figure 5 – Frequency of meeting BR 135 criteria as a function of insulation material (n = 61)



Mineral wool insulation was found to meet the requirements of BR 135 in 95% of tests conducted. It was unable to meet the requirements during one test, when combined with a polyethylene filled ACM façade panel.

4.4.3.2 Insulation and Façade Combinations

Insulation is not weatherproof or aesthetically attractive and was always protected by an external façade. The façade was considered to be the principal front of the structure that faces on to an open space, such as an Aluminium Cladding Material (ACM) panel. The following façade materials were found to be used:

Table 2 – Façade materials tested

Façade Material	Definition used for database entry
Render	The render material refers to a coating applied to the insulation layer. It's categorised as either inorganic or organic render depending on whether it consists of mineral-based components or organic compounds.
Metal panels	These are metal panels, recorded as the metal reported by the manufacturer. These can be solid panels, or composite panels with a core material sandwiched between two layers of metal. This core material can sometimes be combustible.
Brick	This refers to non-loadbearing brick façades, which means that the bricks are used for decorative purposes rather than structural support.
Brick slip	A brick slip system involves attaching brick-like tiles to a metal rail system.
Blockwork	Blockwork refers to a non-loadbearing façade constructed using masonry blocks. These blocks are made from materials like concrete, clay, or other aggregates and provide a solid structure.
Cement board	A cement board façade uses sheets of cement-based material.
Concrete	This refers to concrete panels. Often the insulation is sandwiched between two layers of concrete panels.
HPL	High pressure laminate (HPL) refers to façade panel consisting of compressed layers of cellulose fibres, bound with a phenolic resin.
Ceramic tiles	Ceramic tiles refer to any flat, thin, rigid, non-brick, ceramic façade.

Figure 6 below shows that metal façade panels were the most common type of façade tested. Non-combustible mineral wool performed better than the combustible phenolic and PIR insulation when combined with a metal façade. These panels could either melt away and expose the combustible insulation or contribute to the fire themselves. These metal panels could contain a combustible core material, with sufficient combustible content to fail to meet the BR 135 criteria, on their own, without any additional fuel from the rest of the cladding system. This was seen during one test, when combined with a non-combustible mineral wool insulation.

Aluminium was the most common metal used in metal panel systems. Figure 7 illustrates the influence of a combustible Aluminium Cladding Material (ACM) vs a non-combustible ACM. It shows how significant this can be for meeting the BR 135 criteria. The composition of panels was not always reported so the analysis is only available for a small dataset. Non-combustibility was defined as either an A1 or A2 classification from BS EN 13501-1 [8].

Figure 6 – Frequency of meeting BR 135 criteria as a function of façade and insulation material combinations (n = 60)

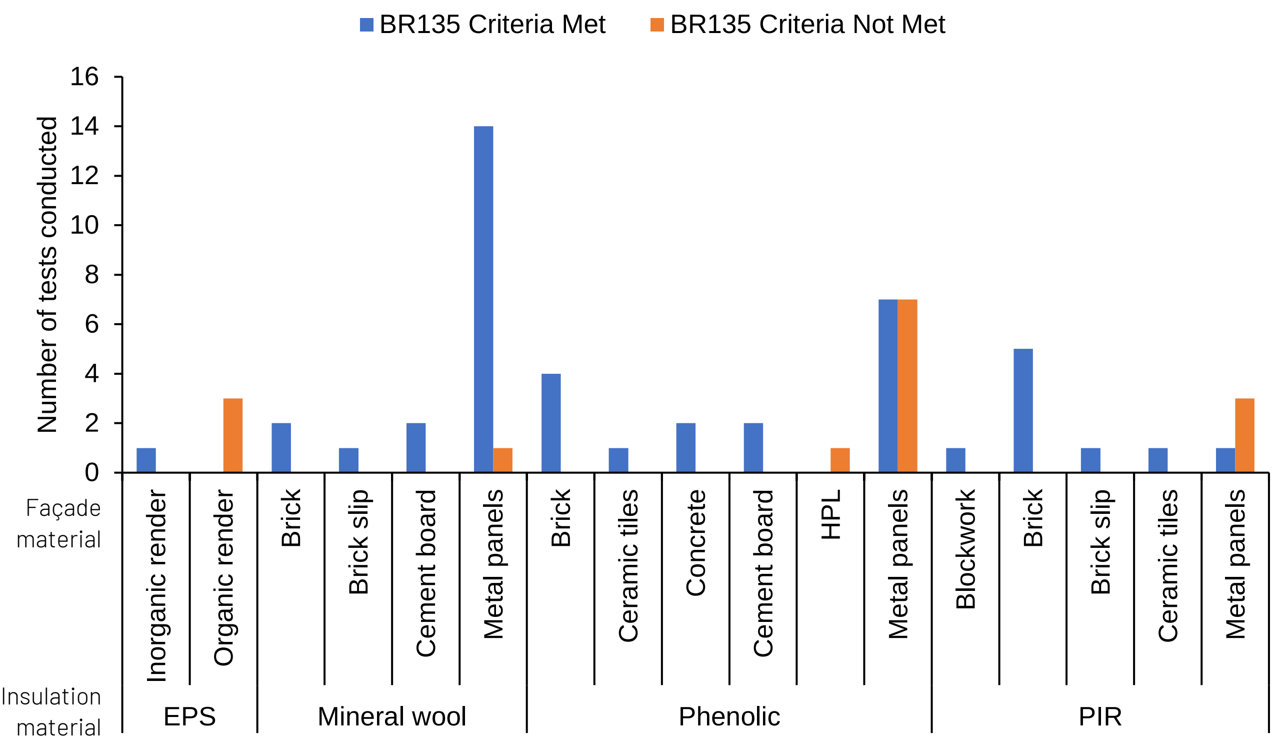
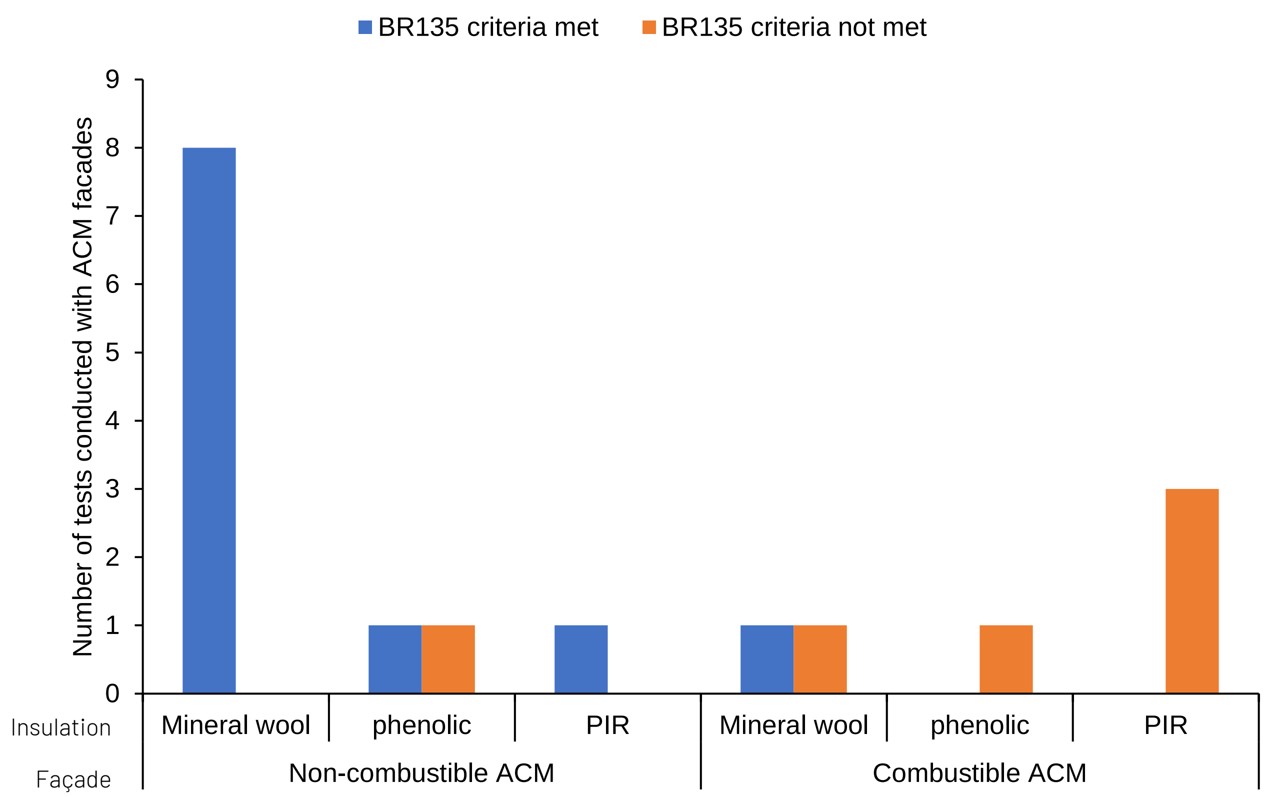


Figure 7 – Frequency of meeting BR 135 criteria as a function of façade and insulation material combinations for ACM facades only (n = 17)



4.4.3.3 Material Fire Classifications

To simplify the dataset, the insulation and façade materials were placed into two fire classification categories: combustible and non-combustible. This was only possible for 39 systems where the fire classification was reported, or obtainable from the manufacturer.

Figure 8 shows that a combustible insulation combined with a combustible façade was never found to meet the requirements of BR 135, while a non-combustible insulation combined with a non-combustible façade was always found to meet the requirements.

As mentioned in section 2.4.2, it is possible for a system comprising of products classified as non-combustible to fail to meet the BR 135 criteria, as Kingspan demonstrated in 2018 [37].

Figure 9 shows the percentage of these tests meeting the LPS 1581 criteria. No systems with a combustible façade were able to meet the LPS 1581/2 criteria.

Notably, 5 out of 13 non-combustible systems failed to achieve the LPS 1581/2 criteria. This was due to either the mechanical performance (n = 3), internal fire spread (n = 1) or visible flaming (n = 1):

- Two of these tests did not meet the mechanical performance criteria due to the aluminium panels and aluminium brackets collapsing under the heat from the crib. The other mechanical performance non-conformance was a cement board system with plastic bracketry which spalled and collapsed during the test.
- The internal fire spread requirement was exceeded by a system with mineral wool insulation, a 67 mm cavity and a non-combustible ACM panel. There were no significant combustible products of note, and no visual evidence of fire spread was observed. This suggests that the assessment criteria might be overly sensitive, failing to approve some systems that it was designed to approve. This test was conducted during normal ambient conditions (12.6°C), with three horizontal cavity barriers in place. It is believed that flames from the wooden crib entered the cavity between the façade panel and the insulation. These extended up the cavity, gradually heating it until the LPS 1581/2 temperature criteria was exceeded.
- For the visible flaming non-conformance, flames were observed protruding via the cavity at the vertical edges of the test rig, which were not enclosed. This criteria is not relevant to BS 8414 and would not result in early test termination.

Figure 8 – Frequency of meeting the BR 135 criteria as a function of insulation and façade combustibility (n = 39)

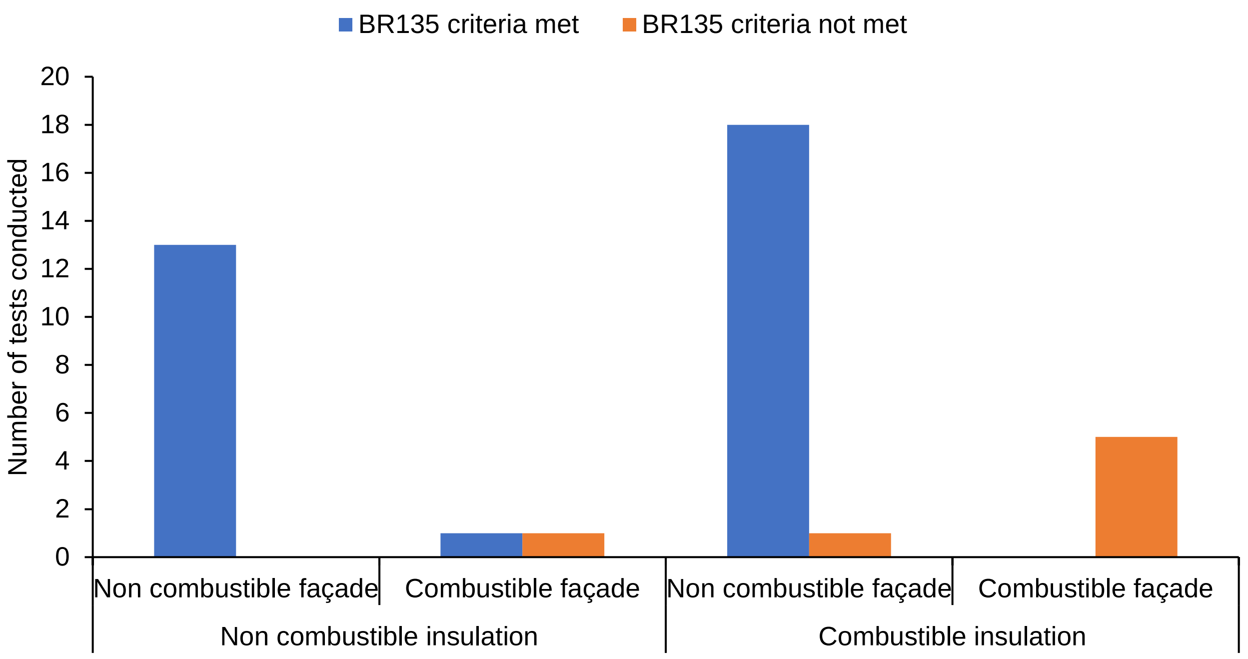
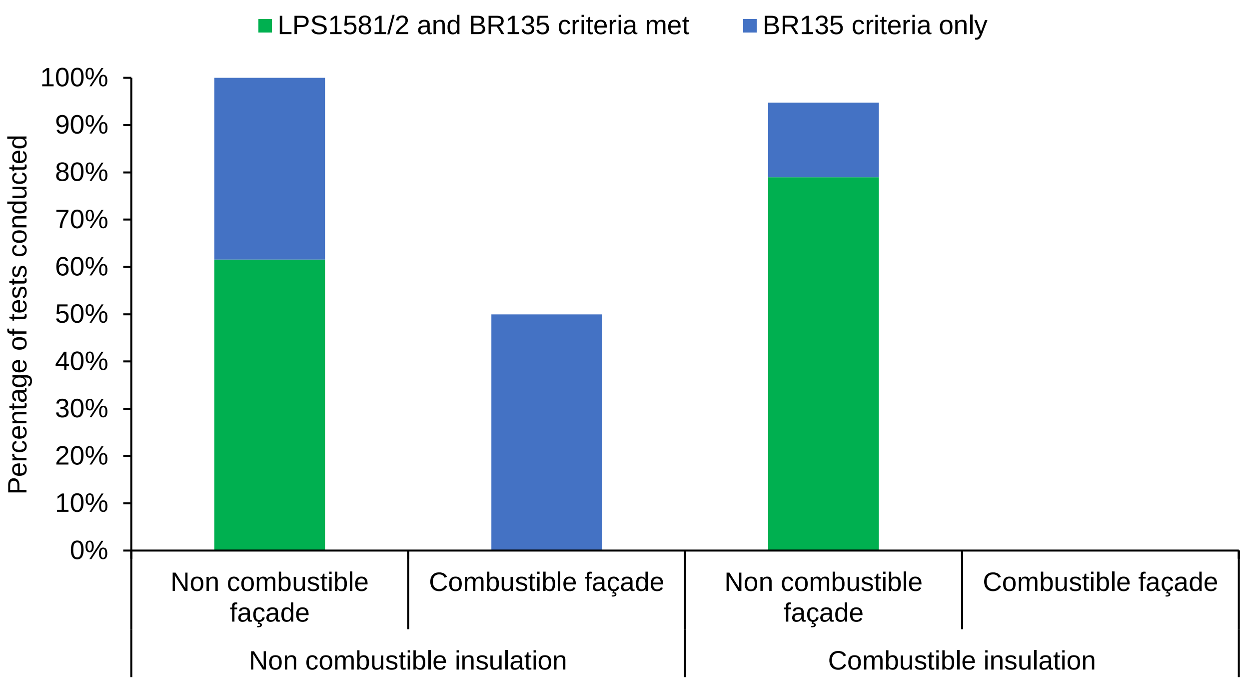


Figure 9 – Bar graph showing the percentage of tests meeting BR 135 and LPS 1581/2 criteria as a function of insulation and façade combustibility (n = 39)



4.4.3.4 Real World Cladding System Fire Performance

Façade fire incidents in tall buildings have most commonly been reported with systems with combustible insulation and rendered Exterior Insulation and Finishing Systems (EIFS) [5] as shown below. These systems are otherwise known as External Thermal Insulation Composite Systems (ETICS).

This is concerning because this is a system type that appears to be rarely subjected to a BS 8414 test. Only four EIFS systems exist in the BS 8414 database and these were all conducted for research purposes and not for system approval. So there is little test data available to analyse the most common system involved in external façade fires.

Table 3 – Tall building façade fire incidents - recreated from the OFR database of external wall fire incidents [3]

Façade Type	Insulation	Number of tall building façade fire incidents	Total Casualties	Casualties per incident
EIFS – Exterior Insulation and Finishing Systems	Non-combustible insulation	3	0	0
	Combustible insulation	15	189	13
	Unknown insulation	3	0	0
HPL – High Pressure Laminate	Unknown insulation	1	1	1
MCM – Metal Composite Material	Non-combustible insulation	2	0	0
	Combustible insulation	5	150	30
	Unknown insulation	21	71	3
Unknown	Combustible insulation	3	178	59
	Unknown insulation	49	301	6

Where a casualty is either an injury or a fatality.

While the majority of incidents involved rendered (EIFS) systems, the most hazardous systems were found to be rainscreen systems, when a combustible insulation was combined with an MCM façade, averaging 30 casualties per incident.

This is influenced by the 72 deaths that occurred during the Grenfell Tower fire in 2017 [4], recorded as 71 in Table 3 above because all data in the OFR database was taken from newspaper reports at the time of the incident.

One of the factors which makes rainscreen systems particularly devastating is the presence of a cavity between the insulation and the façade panel. This can intensify the fire due to the chimney effect, which draws flames upwards and reradiates heat [51]. Studies have shown the significant impact of the chimney effect, increasing the mass burning rate by 3-6 times [52] and how cavity barriers need to be installed to prevent fire spread [53].

The façade panels on rainscreen systems can also be highly combustible, with a higher potential heat release (per metre squared of cladding) than the plastic insulation behind it [54]. If the outer façade disappears, either through melting or combustion, then there is nothing for the cavity barrier to seal against and it becomes ineffective [35, 55].

It should be noted that the data for Table 3 was extracted from newspaper reports at the time of the incident. The database was populated in the UK and may be biased towards the English-speaking countries. It may also be biased towards countries with editorially independent media.

4.4.3.5 Insulation thickness

The data suggest that the thicker the insulation, the less likely it is to meet the requirements of BR 135. It follows for combustible insulation, that the thicker it is, the more of it is available for combustion as shown in Figure 10 below.

Figure 11 shows that as insulation thickness increases, fewer systems that met the BR 135 criteria were able to also meet the LPS 1581/2 criteria.

Figure 10 – Frequency of meeting the BR 135 criteria as a function of insulation thickness for combustible insulations only (n = 41)

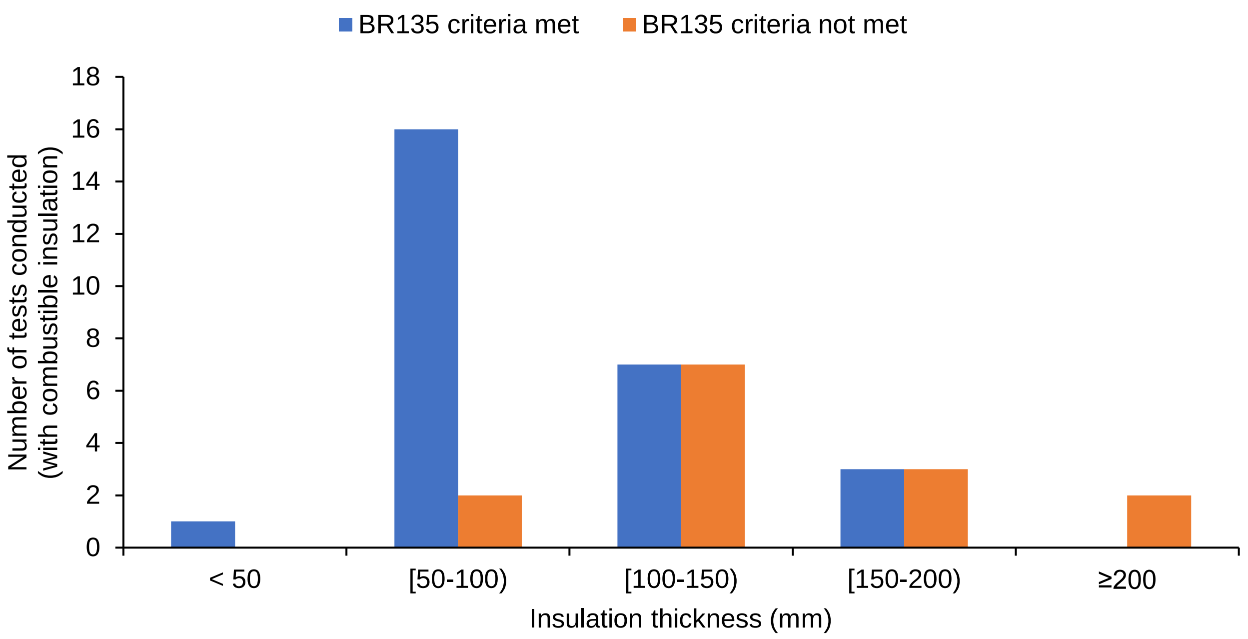
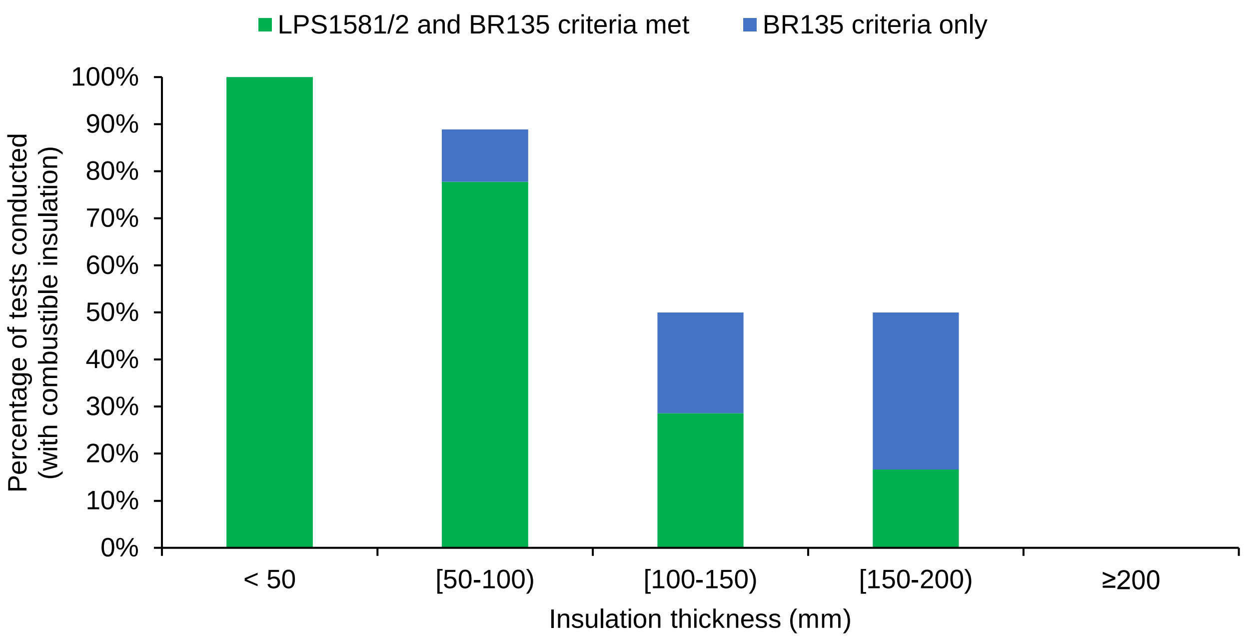


Figure 11 – Stacked bar graph showing the frequency of meeting the BR 135 criteria as a function of insulation thickness for combustible insulations only (n = 41)



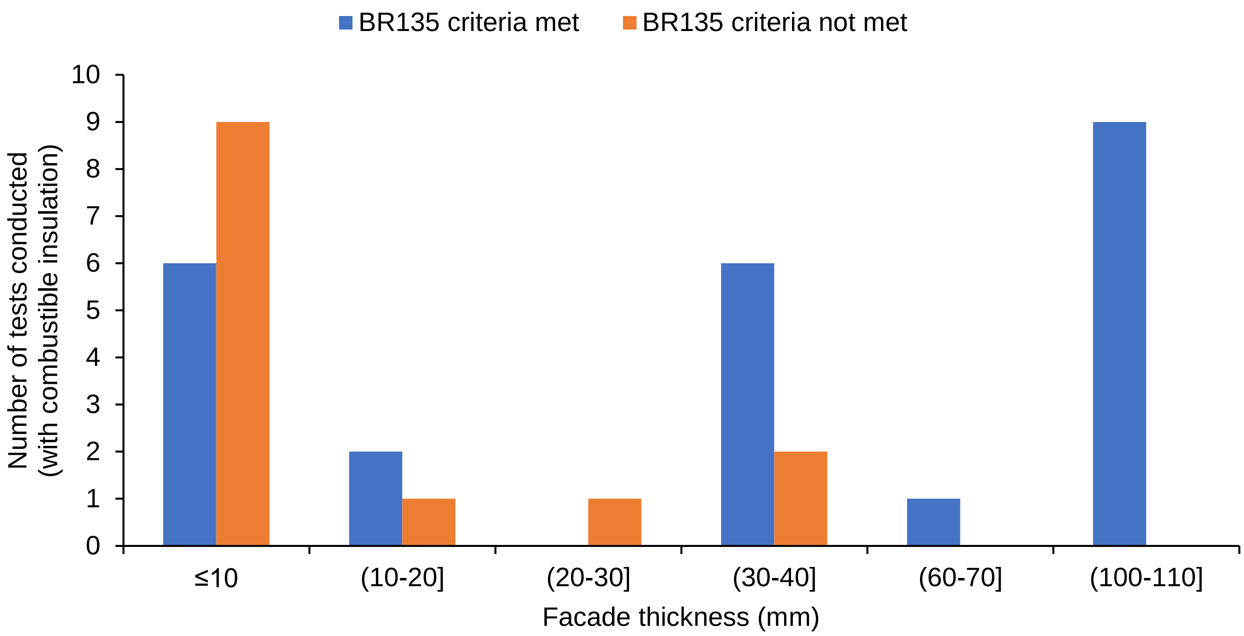
4.4.3.6 Façade thickness

Combustible façades frequently failed to meet the BR 135 classification. Seven confirmed combustible façades were tested, all less than 10 mm thick, with only one successfully meeting the BR 135 criteria. This was with non-combustible mineral wool insulation and a combustible ACM façade, with the core having a calorific value of 13.5 MJ/kg when tested to BS EN ISO 1716:2010 [56]. This would be considered to be the intermediate ACM with fire retardant filling. A polyethylene filling would have a calorific value around 43 MJ/kg [54].

Non-combustible façades almost always met the BR 135 criteria, with only one system out of 32 failing. This was a combustible phenolic insulation with a non-combustible, 4 mm thick, aluminium façade. The façade panel was observed to melt away, exposing the combustible insulation behind.

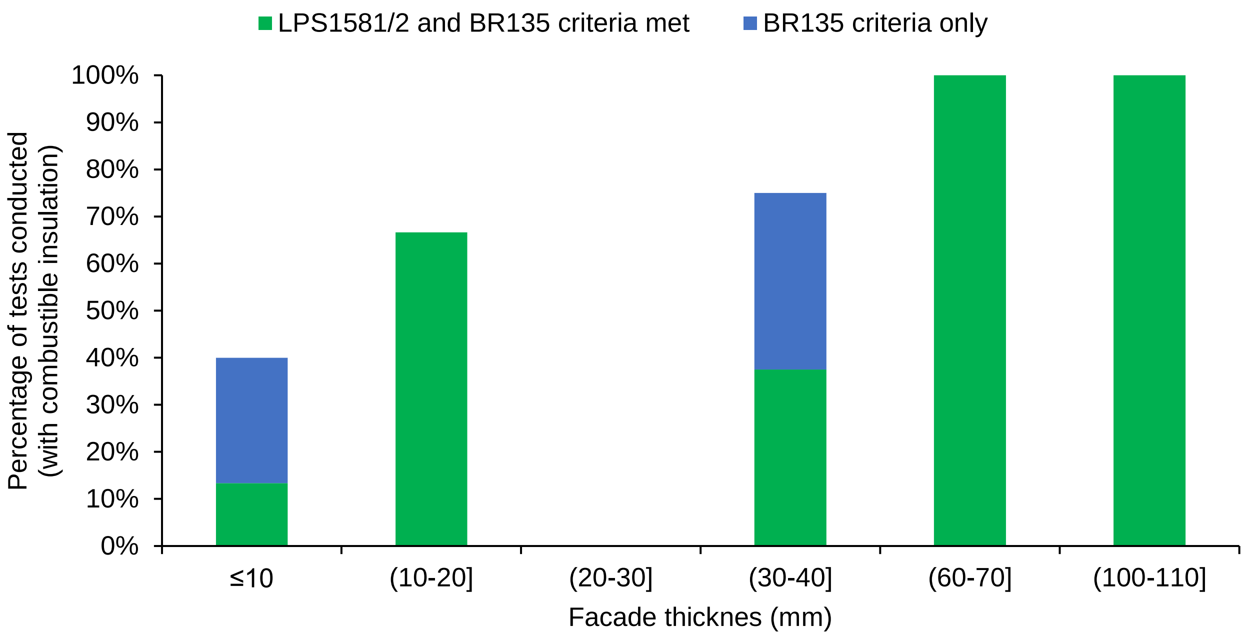
Figure 12 shows, in general, how thicker façades were found to protect combustible insulation during a BS 8414 test. It follows that if the façade is non-combustible, the thicker it is, the more likely it is to protect any combustible components behind. However, it should be noted that thinner façades tend to be more likely to be combustible, for example the thinnest façade is typically ACM, which can contain a highly combustible polyethylene core. Meanwhile the thicker façades, around 100mm thick, tend to be non-combustible brick systems.

Figure 12 – Frequency of meeting the BR 135 criteria as a function of façade thickness for combustible insulations only (n = 37)



All masonry systems, over 50 mm thick, met both BR 135 and LPS 1581/2 criteria in all tests conducted.

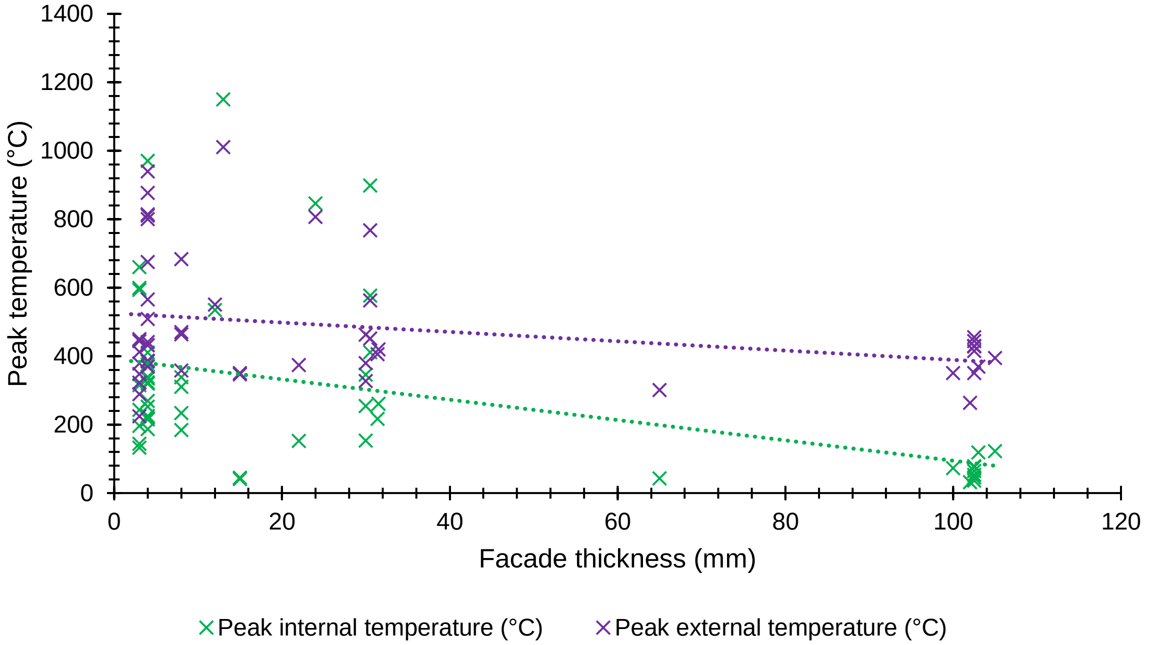
Figure 13 – Stacked bar graph showing the frequency of meeting the BR 135 criteria as a function of façade thickness for combustible insulation only (n = 37)



Thicker masonry façades are less likely than thinner aluminium façades to deteriorate in a fire, exposing the potentially combustible insulation behind. The thicker a non-combustible façade the more it will insulate and protect the insulation. This is especially true with brick systems over 50 mm thick and Figure 14 shows how peak internal temperature tended to decrease with façade thickness.

Peak external temperature also slightly decreases with façade thickness. Again, the thinner façades tended to be more combustible. Also, the thicker the cladding system as a whole, the more it protrudes from the test rig, increasing the flame path length. This has been shown in simulations to reduce the intensity on the front face of the façade [32].

Figure 14 – Peak temperature as a function of façade thickness (n = 61)



4.4.3.7 Cavity thickness

80% of systems incorporated a cavity between the insulation and the façade. Figure 15 shows the likelihood of achieving BR 135 classification appeared to decrease as cavity thickness increased.

Figure 16 shows that as cavity thickness increased, the number of tests found to meet both BR 135 and LPS 1581/2 criteria decreased. Most tests with a cavity over 100 mm thick were only able to meet the BR 135 criteria. Internal temperature, mechanical performance and visible flaming were the reasons for failing to meet the LPS criteria for cavities over 100 mm thick. This data suggests that performance deteriorates with cavity thickness, despite Schlyter demonstrating in 1939 that 50 mm was the "optimum spacing in his test to promote upward flame spread in a cavity" [50].

Figure 15 – Frequency of meeting the BR 135 criteria as a function of cavity thickness (n = 58)

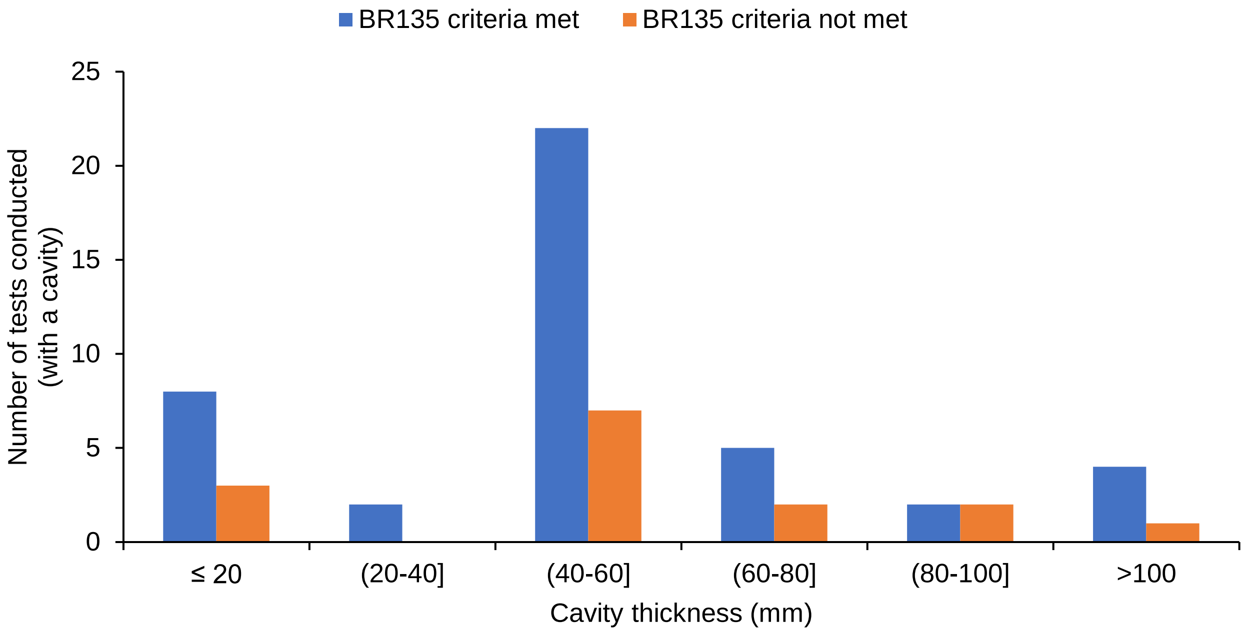
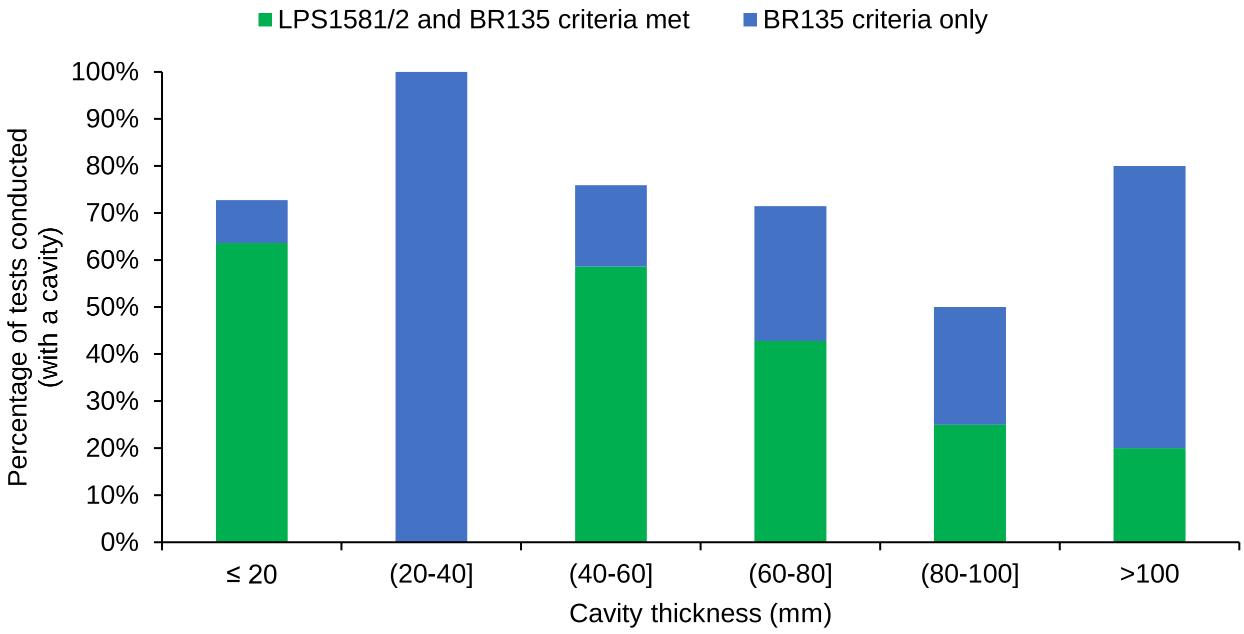


Figure 16 – Stacked bar graph showing the frequency of meeting the BR 135 criteria as a function of cavity thickness (n = 58)



4.4.3.8 System Build-up

Both combustible and non-combustible systems used a variety of insulation thicknesses, cavity thicknesses and façade thicknesses. Generally, the thicker (better performing) façades were more commonly used with the more combustible (worse performing) insulations, while the non-combustible insulations were generally tested with the larger cavities and thinner façades.

Figure 17 – Average system build-up as a function of thickness, for the most common insulation types, for systems ***found*** *to meet the BR 135 criteria (n = 45)*

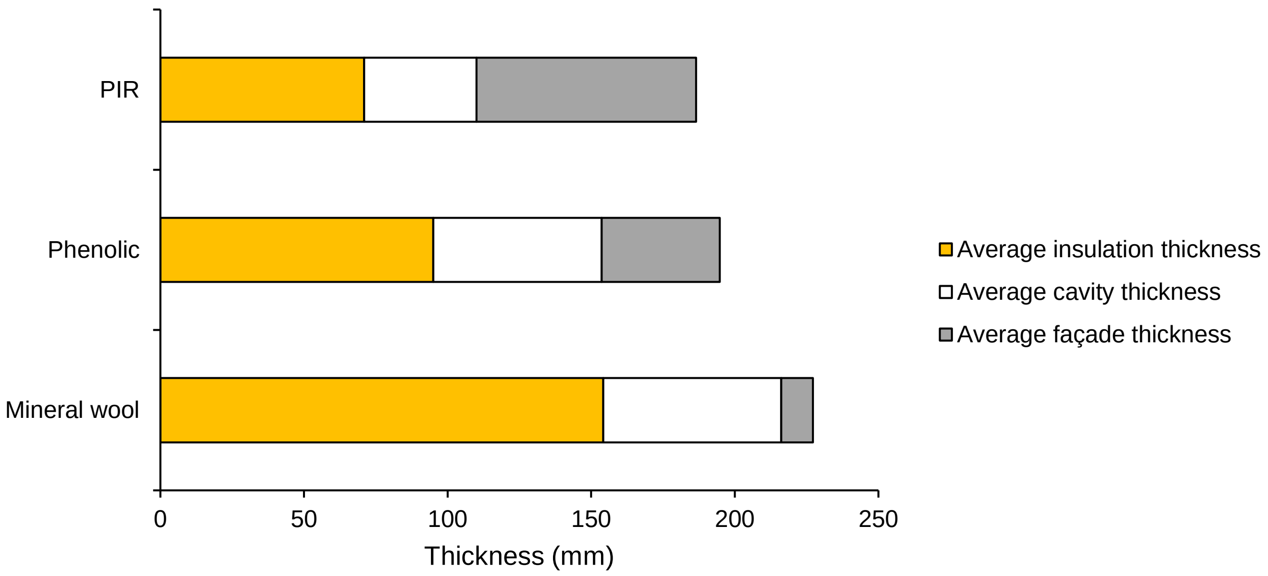
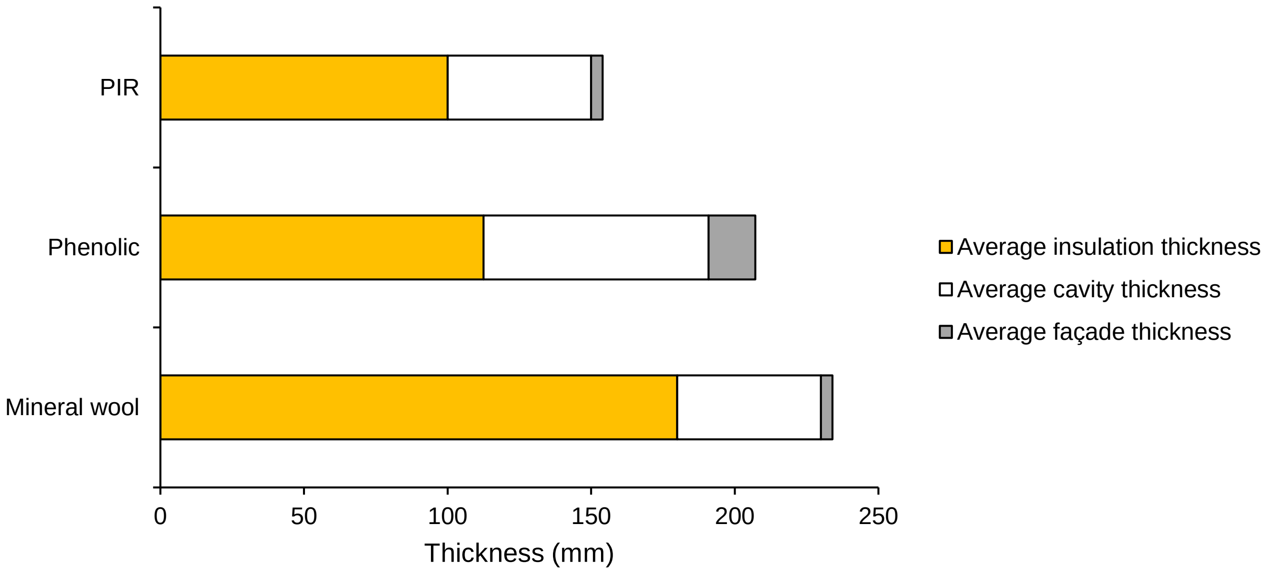


Figure 18 – Average system build-up as a function of thickness, for the most common insulation types, for systems ***found to not*** *meet the BR 135 criteria (n = 12)*

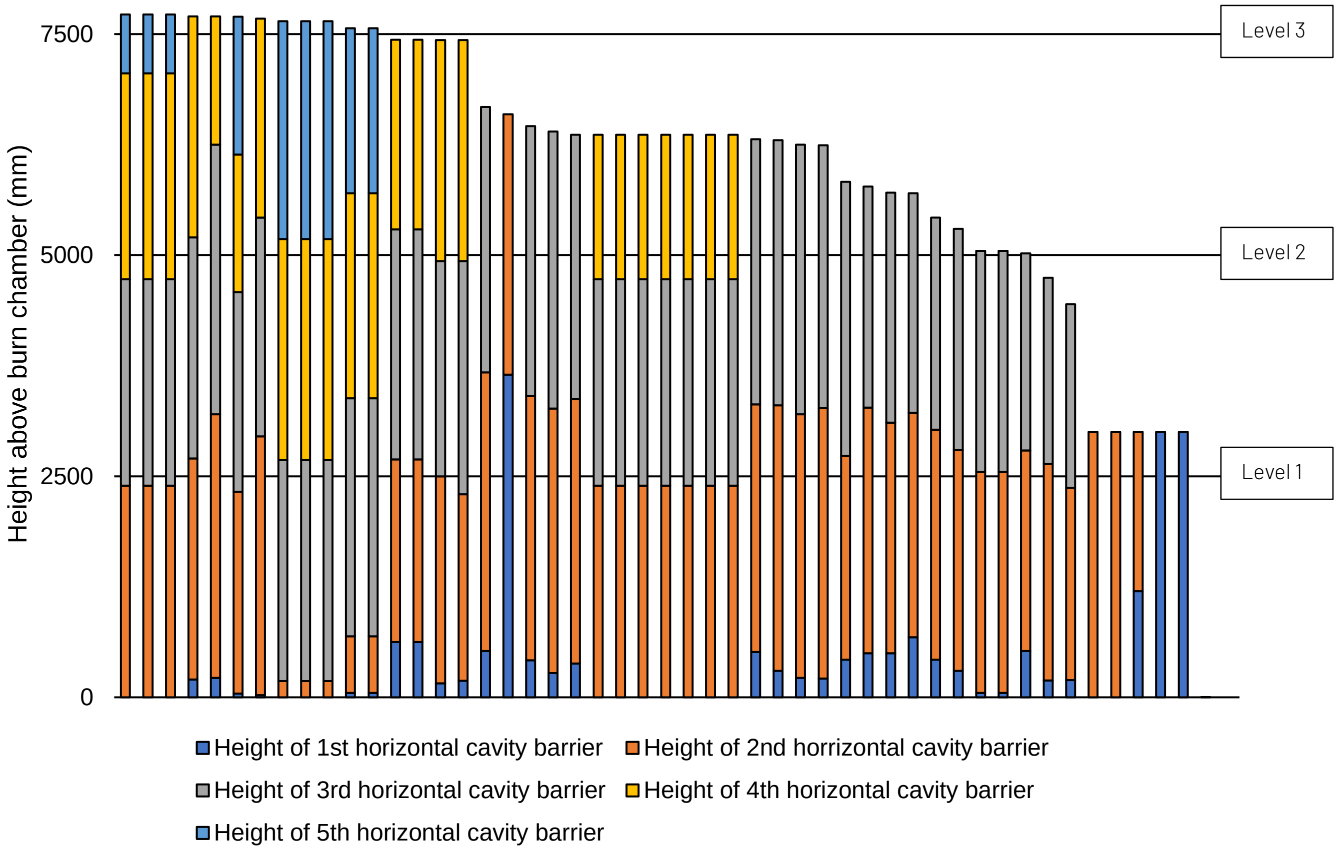


4.4.3.9 Horizontal Cavity Barriers

The average number of horizontal cavity barriers used was 3.14, with 3 being the most common. A previous study suggests that combustible insulation, combined with a ventilated cavity, cannot meet the BR 135 criteria with fewer than 4 horizontal cavity barriers [35].

Horizontal cavity barriers were used at a variety of different locations between tests as shown in Figure 19:

Figure 19 – Graph of horizonal cavity barrier locations with each bar representing a single cladding system (n = 45)



It should be noted that BR 135 uses the level 2 thermocouples, 5000 mm above the burn chamber, for its temperature criteria. The relative position of the thermocouples and cavity barrier has a significant impact on the test outcome.

Most systems are designed to use one cavity barrier per floor. BS 8414:2020 states that the thermocouple levels, 2500 mm, 5000 mm and 7500 mm above the burn chamber are meant to represent floor spacing in a building [13, 14]. Most installers interpret this to mean that the floors are located at each thermocouple level. BS 8414 states that internal thermocouples should be clear of any cavity barriers. Therefore, cavity barriers are normally located either slightly above or slightly below the thermocouples, a choice provided to the installer, which can have a significant impact on the temperatures recorded.

The peak internal temperature, at level 2, for systems with cavity barriers just above and just below the critical level 2 thermocouples was investigated. This was done for all non-combustible systems with a cavity barrier within 1000 mm of the level 2 thermocouples.

Table 4 – Average temperature for non-combustible systems with a horizontal cavity barrier just above or just below the level 2 thermocouples

	Number of tests	Average of the peak internal temperature at level 2 thermocouples	Standard deviation of the peak internal temperature at level 2 thermocouples
Non-combustible systems with a cavity barrier just below level 2 thermocouples	7	278.3°C	±60.2°C
Non-combustible systems with a cavity barrier just above level 2 thermocouples	2	383.8°C	±98.0°C

Table 4 suggests that placing a cavity barrier directly below the level 2 thermocouples can result in a 100°C reduction in internal temperature, albeit over a small sample size as it only considers non-combustible systems with a cavity barrier near the level 2 thermocouples.

The majority of horizontal cavity barriers used were open state and made mostly from mineral wool.

A closed state cavity barrier is a non-combustible barrier which always blocks off the cavity. An open state cavity barrier will leave the cavity open during normal operation, to allow ventilation, but will expand and close off the cavity during a fire.

Cavity barrier insulation and integrity values were often recorded, but there wasn't sufficient data to assess their impact on fire performance. It is noted that:

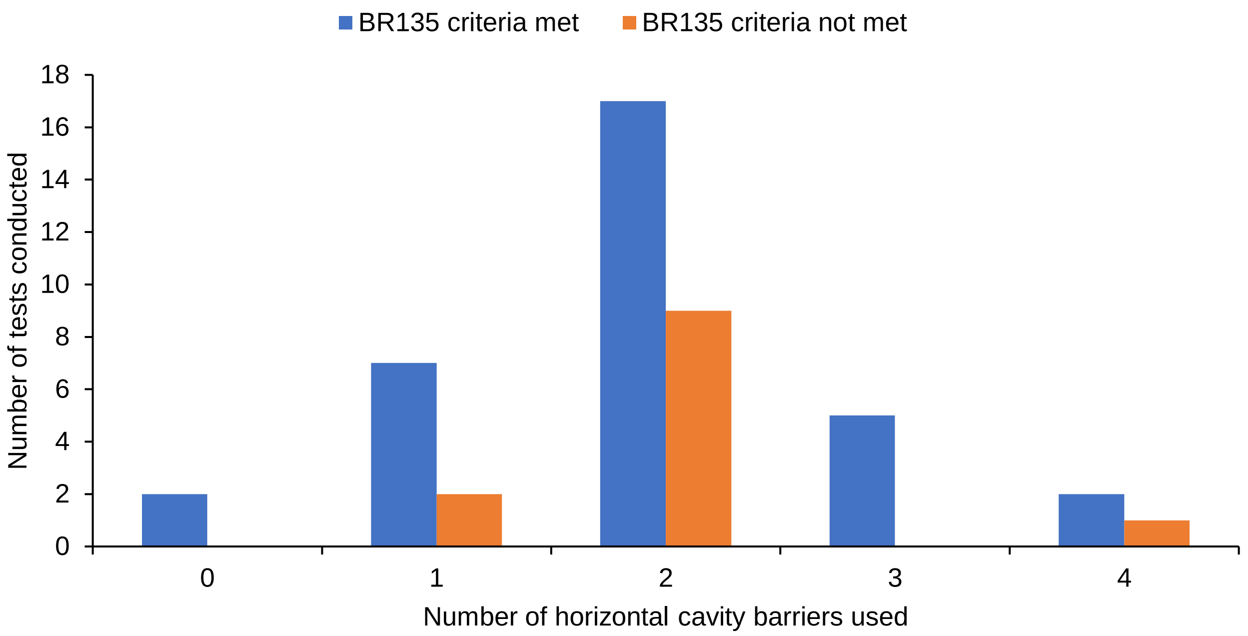
- A steel L-bracket was used as a closed state cavity barrier successfully during another test with non-combustible mineral wool insulation.
- A reflective aluminium open state cavity barrier was used successfully, with combustible insulation, on two occasions, once with an ACM façade and once with a ceramic tile façade.

Metal cavity barriers are anticipated to offer relatively poor insulation compared to mineral wool cavity barriers. Insulation is one of the performance criteria required for new cavity barriers when tested to ASFP TGD 19. The above results suggest that further research should be conducted on the impact of cavity barrier insulation and whether it should remain a relevant metric for external cladding systems. ADB currently recommends that cavity barriers should provide sufficient insulation for 15 minutes when tested to ASFP TGD 19 [11, 12, 33]. A metal cavity barrier would be unlikely to achieve this 15 minute requirement, yet the above results suggest that it can still reduce fire spread in some systems without providing any significant insulation.

4.4.3.10 Vertical Cavity Barriers
All tests with vertical cavity barriers used closed state, mineral wool, vertical cavity barriers.

Figure 20 shows that the majority of tests used two vertical cavity barriers, these were placed either side of the burn chamber and extended the entire way up the test rig. Two tests were found to meet the BR 135 and LPS 1581/2 criteria without any vertical cavity barriers. Both with a non-combustible ACM façade, one with a combustible phenolic insulation and the other with a non-combustible mineral wool insulation.

Figure 20 – Frequency of meeting the BR 135 criteria as a function of the number of vertical cavity barriers (n = 45)



4.4.3.11 Impact of Cavity Barriers in Real-World Cladding Fire Incidents
Several real-world incidents demonstrate the significance of cavity barriers in external cladding systems. For instance, in the Knowsley Heights fire [57] that occurred in Liverpool, UK, in 1991, there were no fire barriers installed in the air cavity behind the cladding and the fire spread the entire way up the building.

Similarly, the TVCC tower fire [58] in Beijing, China, in 2009 was exacerbated by the absence of barriers, coupled with the use of combustible insulation and cladding materials. This incident prompted Chinese regulations to be revised, necessitating the inclusion of spandrels and horizontal fire stops at the floor perimeter [59].

In the case of the Lacrosse building fire in Melbourne, Australia, in 2014, the installation of aluminium composite panels with a polyethylene core on the balcony sidewall did not incorporate cavity barriers and the fire spread rapidly up the building away from the floor of origin [35].

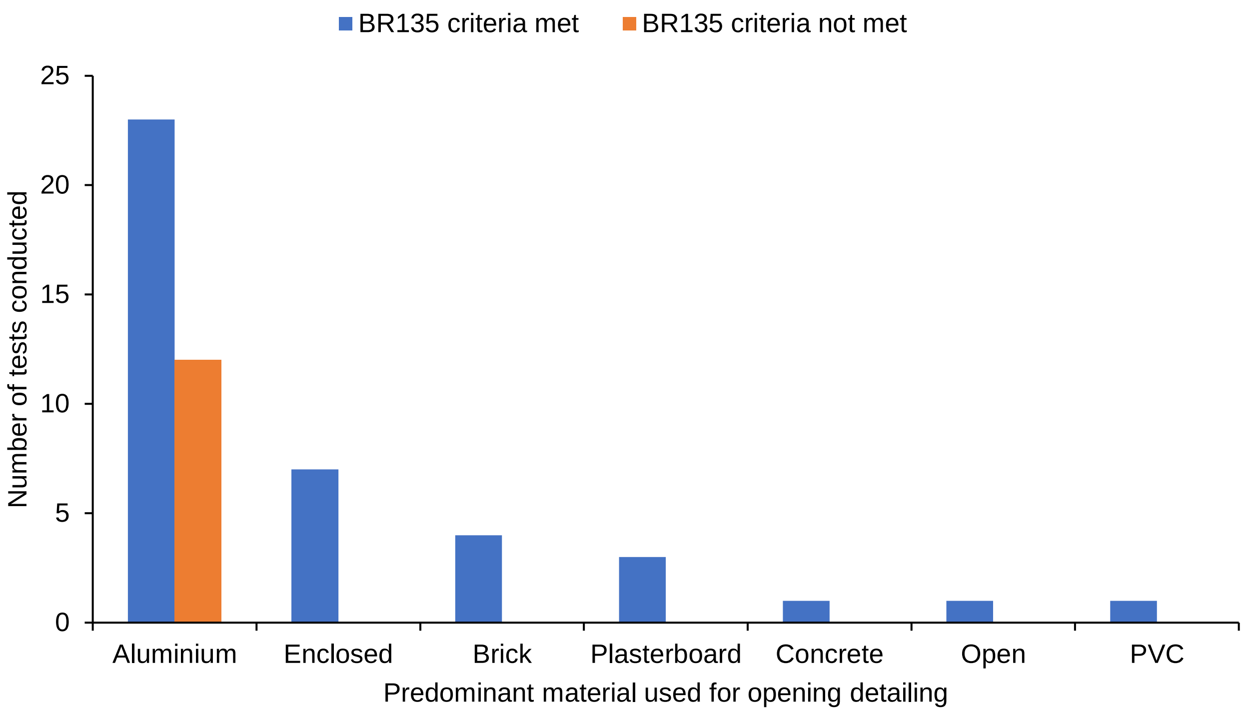
Another notable example is the Grenfell Tower fire in London, UK, in 2017. In this example cavity barriers were installed, but they were clearly ineffective. Professor Jose Torero determined in his expert report to the Grenfell Inquiry that no matter how well or badly the cavity barriers were designed and/or implemented, they would not have prevented flame spread due to the combustible façade [4]. The combustible ACM façade provided the fire with a route on the external face of the building, avoiding the cavity barriers. The aluminium also melted, preventing the cavity barriers from having anything to seal against.

4.4.3.12 Opening Detailing

The opening detailing was not always reported or able to be inferred from the system drawings or test photographs. Almost all installations sealed around the opening, with only one test found to not use any detailing around the opening. This system was found to meet the BR 135 criteria. The system used both a non-combustible façade and non-combustible insulation and would have been compliant via the linear route.

Figure 21 shows that one test was conducted with polyvinyl chloride (PVC) around the burn chamber opening, replicating a window frame. This was found to meet the BR 135 criteria, it is unknown if there was additional fire protection behind the window frame.

Figure 21 – Frequency of meeting the BR 135 criteria as a function of opening detailing material (n = 52)

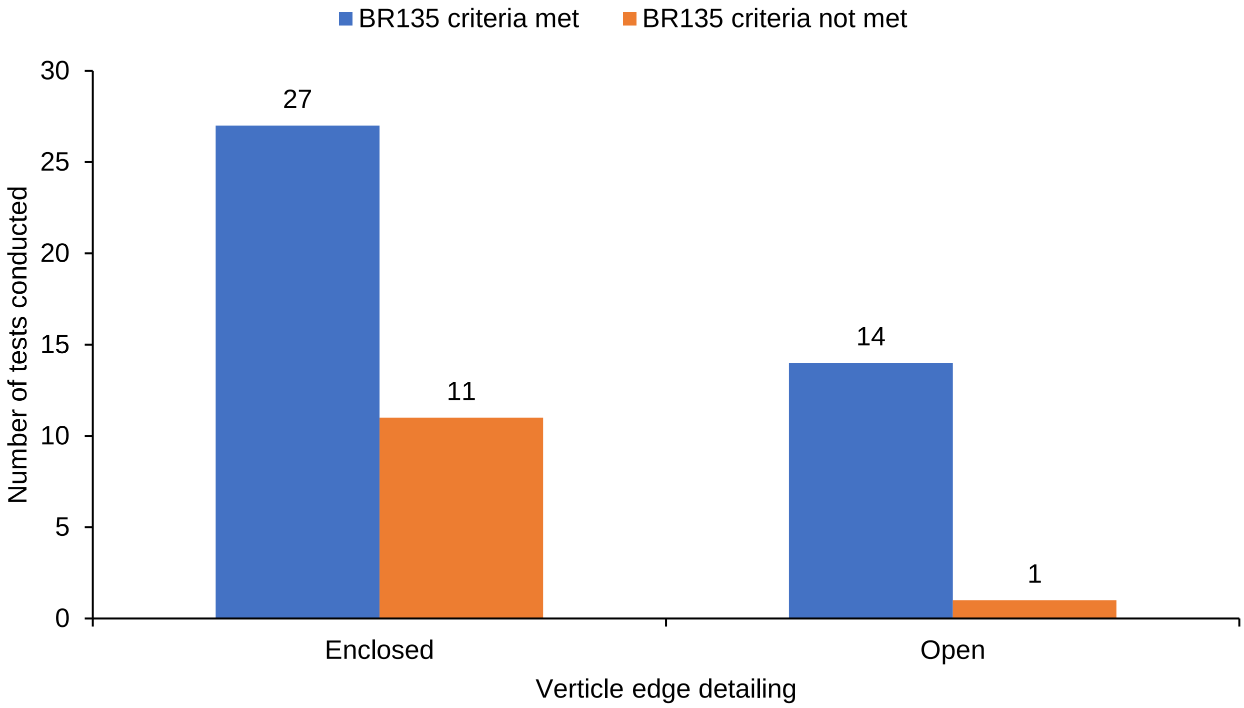


4.4.3.13 Edge Detailing

The majority of tests enclosed the vertical edges of the test rig. It should be noted that the majority of tests used two closed state vertical cavity barriers, either side of the burn chamber, the entire way up the test rig, reducing the impact of any edge detailing.

Figure 22 shows how systems which left the vertical edges open successfully met the BR 135 criteria more often than systems which enclosed the edges. 60% of those were found to be non-combustible systems compared with 13% of systems with enclosed edges. This suggests that the more combustible systems were more likely to include additional protection features, such as sealing the edges of the test rig to increase the chance of the system meeting the BR 135 criteria.

Figure 22 – Frequency of meeting the BR 135 criteria as a function of vertical edge detailing material (n = 53)



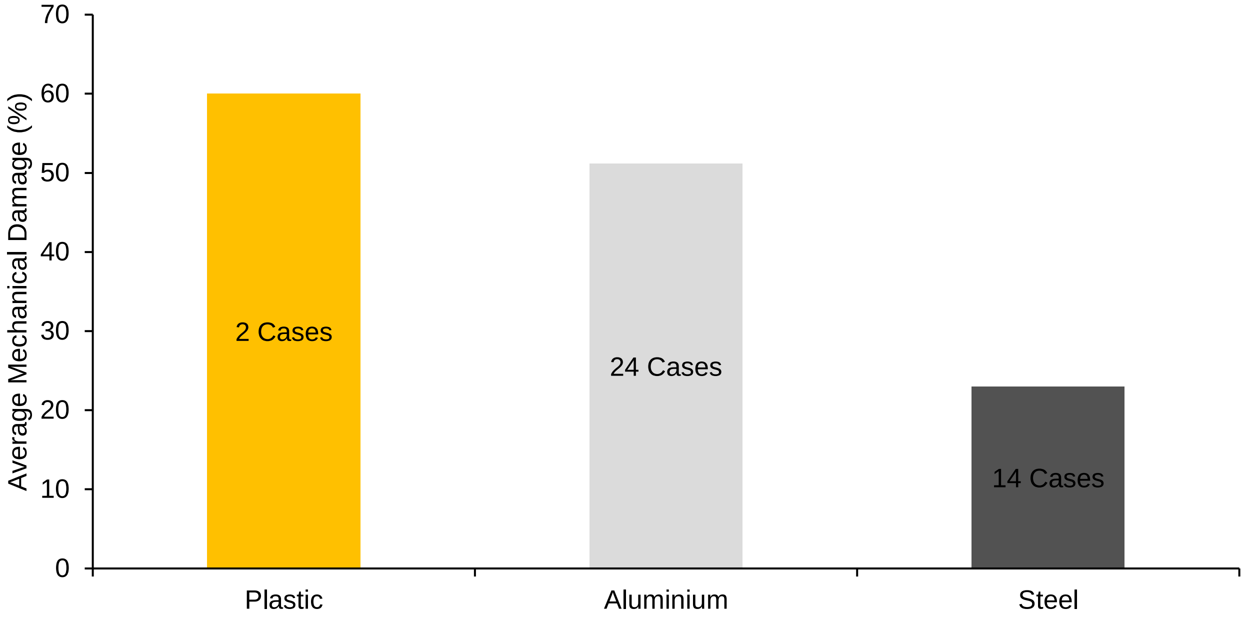
4.4.3.14 Bracketry

There was no general correlation between bracketry material and the BR 135 failure criteria. It should be noted that mechanical damage doesn't form part of the failure criteria. A correlation was identified between bracketry material and mechanical damage as shown in Figure 23. The lower the melting point and the more combustible the bracketry, the greater the observed levels of mechanical damage.

One particular system failed to meet the BR 135 temperature criteria when tested with aluminium bracketry. It was retested, with the only change of note being the use of steel bracketry and it was then found to meet the BR 135 criteria.

Two tests were conducted with plastic bracketry, they both used non-combustible insulation and non-combustible façades and met the BR 135 criteria. However, the levels of mechanical damage prevented either of them from meeting the LPS criteria.

Figure 23 – Mechanical damage as a function of bracketry material (n = 40)



4.4.4 Test Conditions

4.4.4.1 Ambient Temperature

Figure 24 – Frequency of meeting the BR 135 criteria as a function of ambient temperature (n = 57)

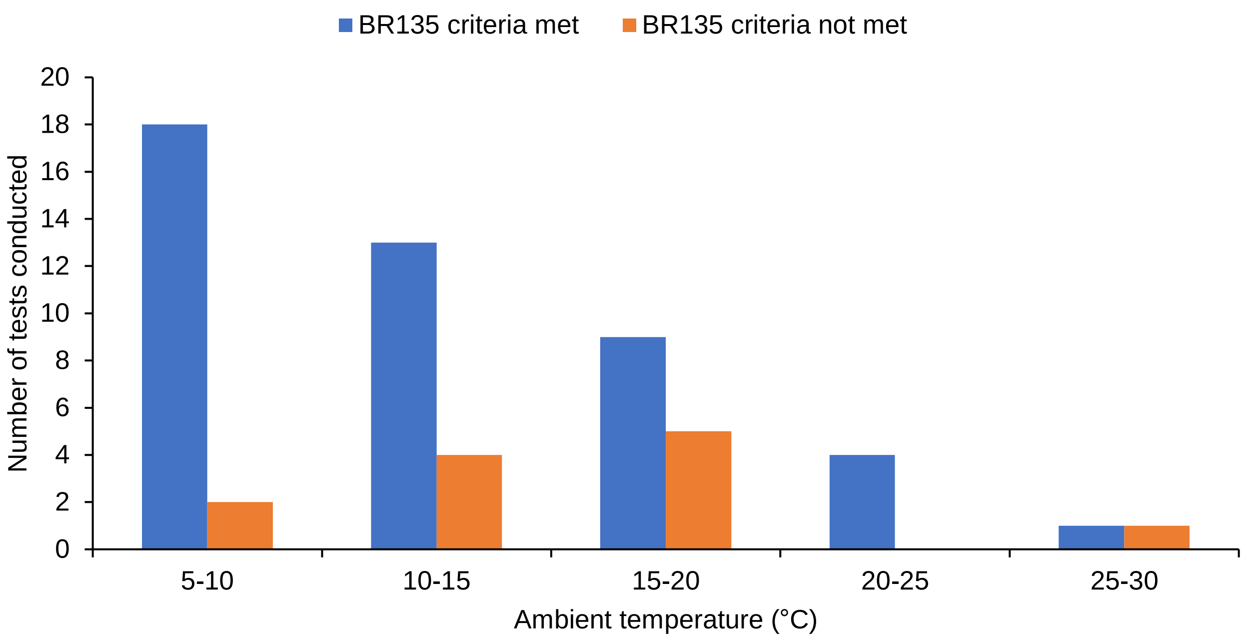
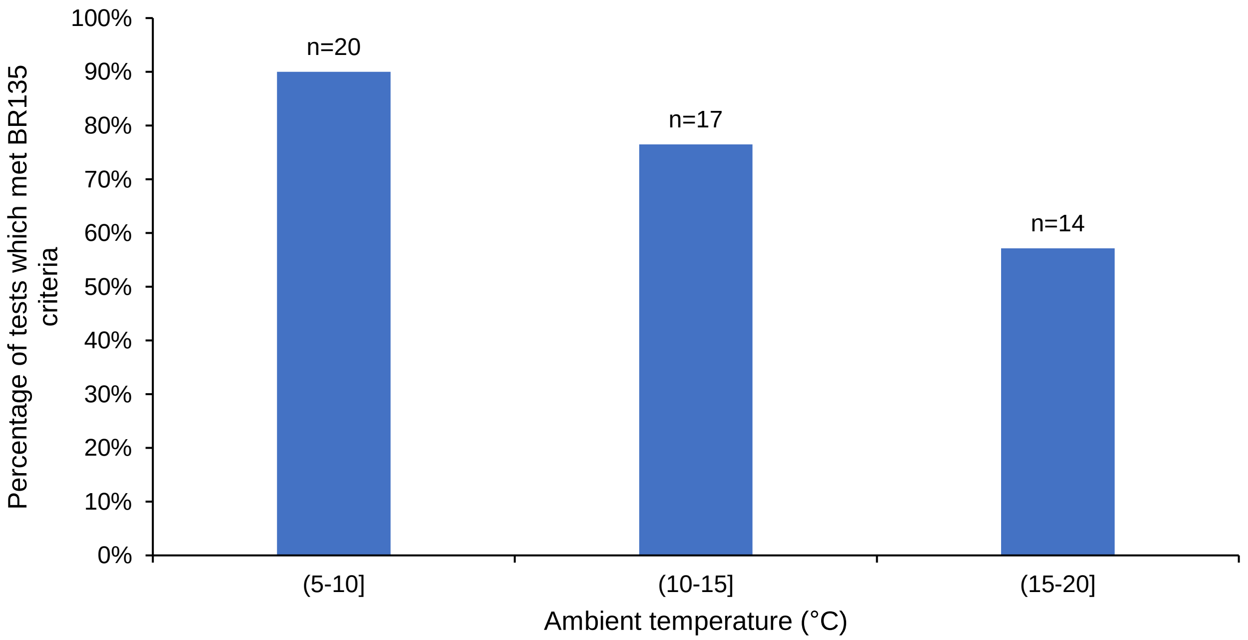


Figure 24 suggests that as the ambient temperature increases, the likelihood of a system failing to meet the BR 135 criteria significantly increases. This suggests that the warmer the cladding system is, the less energy is required for drying and heating each component to its activation energy for ignition.

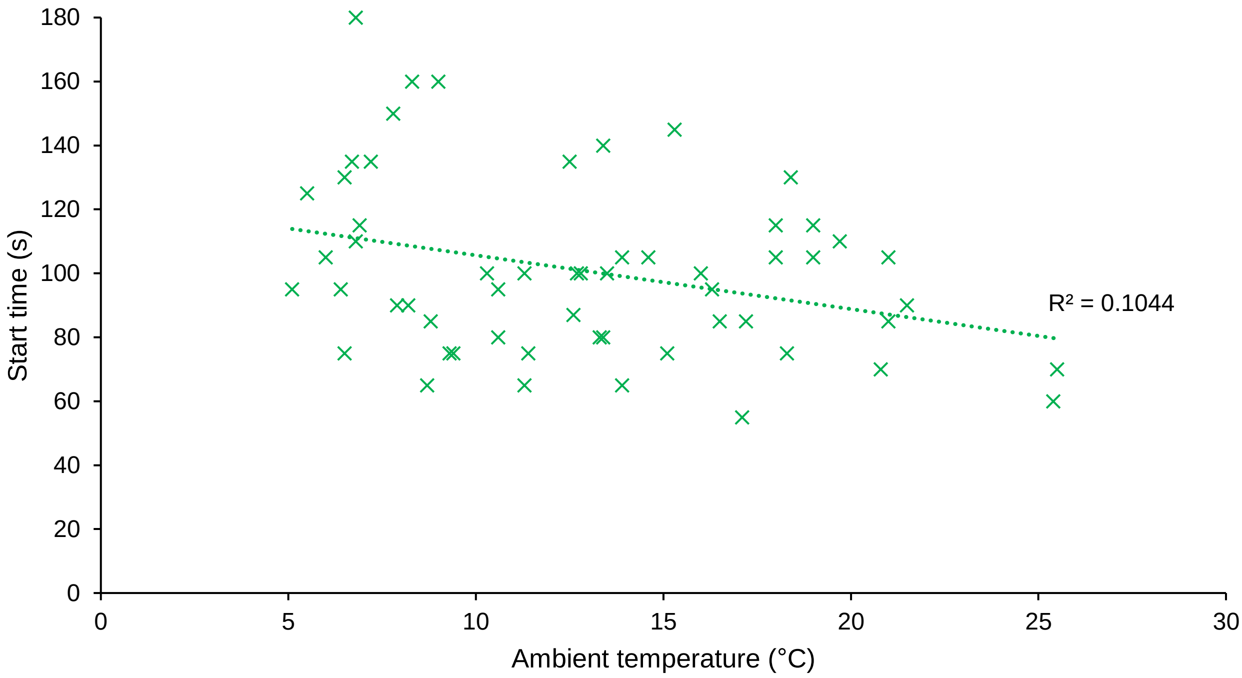
Figure 25 below shows the percentage of tests which met the BR135 criteria between 5°C and 20°C. It should be noted that this is based on a relatively small dataset and will be influenced by other factors, such as the cladding system construction.

Figure 25 - – Bar graph showing the percentage of tests meeting BR 135 criteria as a function of ambient temperature (n = 51)



The influence of ambient temperature can be somewhat seen from the 'test start time' data in Figure 26 below. The start time is the time between ignition and when the temperature recorded by any external thermocouple at level 1 equals or exceeds a 200°C temperature rise above ambient and remains above this temperature for at least 30 seconds [13, 14].

Figure 26 – Scatter graph showing the influence of ambient temperature on test start time (n = 61)



Start time was chosen as a metric because it is mostly independent of the system tested, although factors like the thickness of the system will have a slight impact. Thicker systems will protrude further from the burn chamber, increasing the flame path length from the wood crib to the level 1 thermocouples.

BR 135 already attempts to compensate for the influence of ambient temperature by assessing the temperature rise above ambient. The maximum temperature criteria is effectively 600°C + ambient (°C) [7].

Figure 24 above implies that an additive compensation is insufficient for counteracting the influence of ambient temperature. A study was conducted to identify a more appropriate compensation, using the following equation [60] to estimate flame temperatures at different ambient temperature conditions:

$$T_{p(centerline)} - T_a = 9.1 (T_a / g \, c_p^2 \, r_a^2)^{1/3} \, Q_c^{2/3} (z - z_0)^{-5/3}$$ *Equation 1*

Where:

- Tp(centerline) = plume centerline temperature (°C)
- Qc = convective portion of the heat release rate (kW)
- Ta = ambient air temperature (K)
- g = acceleration of gravity (m/s^2)
- cp = specific heat of air (kJ/kg-K)
- ra = ambient air density (kg/m^3)
- z = distance from the top of the fuel package to Tp (m)
- z_0 = hypothetical virtual origin of the fire (m)

Using the following values to calculate Tp:

- Qc = 2100 kW (based on the nominal 3000 kW heat release rate of a BS 8414 crib with an assumed 70% convective portion of the heat release rate)
- Ta = Varied between 5°C and 35°C based on the ambient temperature requirements of BS 8414
- g = Simplified to 9.81 m/s^{-2}
- Cp = Simplified to 1 kJ/kg-K
- ra = Varied between 1.27 kg/m^3 and 1.15 kg/m^3 based on the ambient temperature
- z = 5.6 m based on the height of the level thermocouples above the top of the wooden crib
- z_0 = 0.63 m based on Equation 2 below

To calculate z_0, the top surface area of the crib (1.5 m^2), which is a rectangle, was converted to a circle for the purposes of the equation and the diameter of that hypothetical circle was calculated to be 1.38 m. The following equation was then used [60]:

$$z_0/D = -1.02 + 0.083\,(Q^{2/5})/D$$

Equation 2

Where:

- D = diameter (1.38 m)
- Q = Heat release rate (3000 kW)

Equation 1 was then used to estimate the following temperatures at level 2 between 5°C and 35°C:

Table 5 – Flame temperatures at BS 8414 level 1 and level 2 at different ambient temperature conditions

Ambient (°C)	Tp at Level 2 (5.6 m above the fuel load) (°C)
5	273.2
10	283.0
15	292.9
20	302.7
25	312.5
30	322.3
35	332.2

An equation for estimating the temperature at level 2, based on ambient temperature, would therefore be:

$$y = 1.965x + 263.4$$

Equation 3

Where:

- y = level 2 thermocouple temperature
- x = ambient temperature

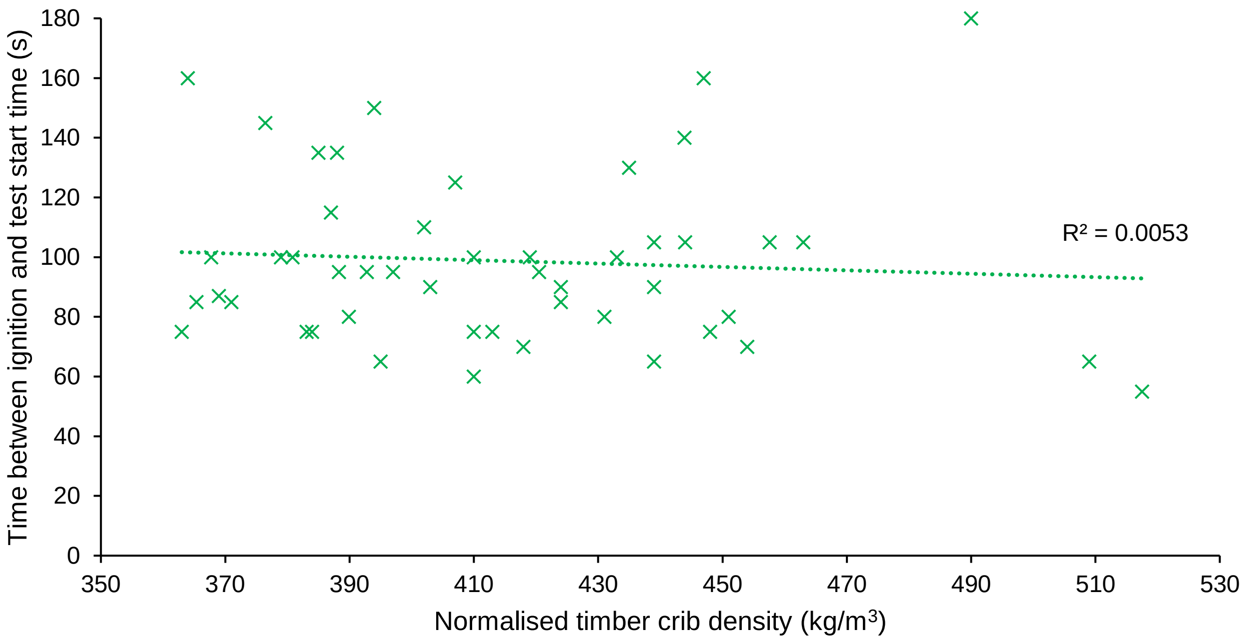
Equation 3 suggests that if ambient temperature were to be incorporated into the failure criteria, it would be more appropriate to include it as a factor of two times ambient, as 1.966 is approximately 2.

4.4.4.2 Timber Crib

BS 8414 uses a timber crib heat source to represent a fully developed fire in a room venting from an aperture that exposes the cladding system to the effects of external flames. The timber crib is conditioned prior to the test so that the moisture content is between 10-15% by mass. This is typically done by placing it in a controlled environment and adjusting the ambient temperature and/or the relative humidity.

The timber crib's moisture content is recorded. No correlation was found between the moisture content and the test start time. The timber density is also recorded, this was normalised by subtracting the mass of the moisture content, as this is not combustible content. Again, no correlation could be identified with the test start time as shown in Figure 27.

Figure 27 – Scatter graph showing no correlation between normalised fuel load density and test start time (n = 61)



Theoretically, wood density should be the most influential factor in terms of available fuel load. BS 8414 mandates the following tolerances for factors which can affect the available fuel load:

Table 6 – BS 8414 fuel load tolerances

	Nominal value in BS 8414	Tolerance permitted in BS 8414
Width of the wood	50 mm	± 2 mm
Length of the short wood	1000 mm	± 5 mm
Length of the long wood	1500 mm	± 5 mm
Density of the wood	0.525 kg/dm^3	± 0.125 kg/dm^3
Moisture content of the wood	12.5%	± 2.5%

The tolerance permitted for the density of the wood, allow for the largest variation in fuel load. Assuming a heat release of 19.31 MJ/kg for dry pinus sylvestrus (the wood used for BS 8414 tests) and taking into account the energy required to heat and vaporise the water content allows the creation of the following uncertainty budget:

Table 7 – BS 8414 fuel load type B uncertainty budget

#	Source of Uncertainty	Uncertainty value (MJ)	Probability Distribution Function	Divisor	U (MJ)
1	Width of wood	521.3	Normal	2	260.6
2	Length of short wood	16.3	Normal	2	8.1
3	Length of long wood	10.9	Normal	2	5.4
4	Density of the wood	1551.4	Normal	2	775.7
5	Moisture content	217.5	Normal	2	108.8

Where U = the standard uncertainty (the uncertainty value divided by the divisor based on the probability distribution function)

Table 7 was created using the UKAS type B method for the expression of uncertainty and confidence in measurement [61]. This estimates an average total heat release of 6515.8 MJ, with a combined uncertainty of 825.6 MJ.

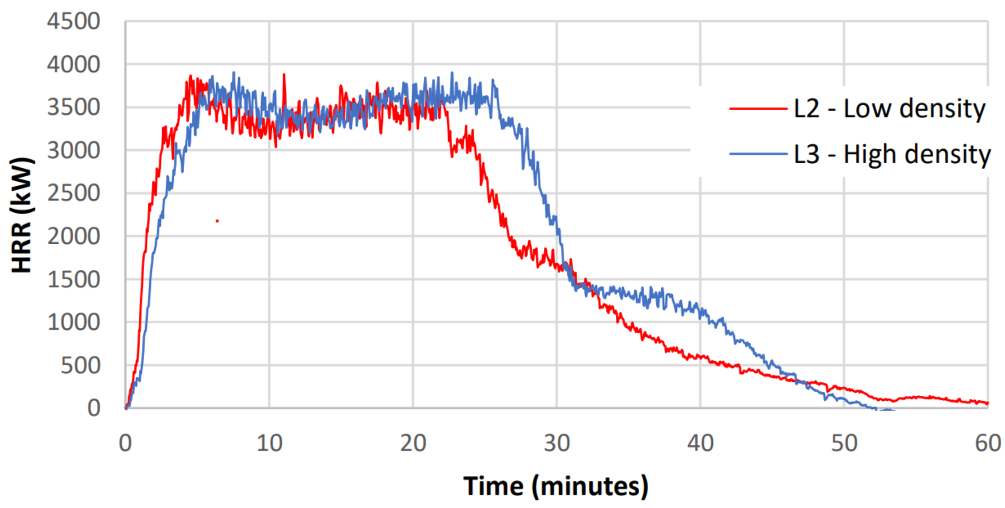
It is industry practice to double the uncertainty for a 95% confidence level. Using a coverage factor k = 2 expands the uncertainty to 1651.1 MJ. This predicts that 95% of the time the potential fuel load heat release will fall between 4865 MJ and 8167 MJ. This is ±25% of the mean.

It's worth noting that intentional manipulation of the fuel load is possible. It has been argued that the fuel load in BS 8414 can be adjusted between 4500 MJ and 9000 MJ [23], representing a variation of ±35% from the mean.

Table 7 suggests that the width of the wood is significantly more critical than the length of the wood. It also shows how the density of the wood is more critical than all other factors combined.

It should be noted that the wooden crib is extinguished after 30 minutes, and the entire fuel load is never consumed. BS 8414 estimates that around 4500 MJ is released in that period [13], so additional fuel load may not correlate with additional heat release. Research by RISE (Research Institutes of Sweden) demonstrates that additional fuel only correlates with a longer burn time and does not increase the heat release rate [27], suggesting the fire is oxygen controlled as shown in Figure 28. They produced similar results when experimenting with the length and width of the wood, which effectively changes the surface area, suggesting it is the geometry of the burn chamber restricting the available oxygen and not the presented surface area of the wood.

Figure 28 – Effect of wood density on a BS 8414 crib's heat release rate [27]



4.4.4.3 Flame Height

BS 8414 test reports were analysed to estimate the natural flame height from the wooden crib. The flame height from the floor of the test facility was estimated and compared to a computational study. It was estimated to the nearest 0.5 m based on reported panel heights and the test rig height. This was only estimated for non-combustible systems to avoid measuring the influence of a combustible system. Only systems with sufficient reference points were considered. Peak flame height was measured considering the methods and eddy shedding principles described in 'Enclosure Fire Dynamics' [62].

Table 8 shows the following flame heights were recorded:

Table 8 – Flame heights from BS 8414 wooden cribs

Insulation material	Façade material	Ambient temperature (°C)	System thickness (mm)	Wood density (kg/m^3)	Fuel load moisture content (%)	Flame height from floor (m)
Mineral wool	ACM	12.6	210	510	14.1	5.5
Mineral wool	ACM	6.5	224	508	12.5	6.5
Mineral wool	ACM	5.5	392	530	12.3	5
Mineral wool	ACM	13.9	288	586	12.3	6
Mineral wool	ACM	14.6	488	565	12.1	6
Mineral wool	ACM	8.8	224	500	13.5	5.5
Mineral wool	Brick	13.4	118	545	9.4	6.5
Mineral wool	Brick	10.6	173	574	14.3	5
Mineral wool	Brick slip	11.4	194	540	12.7	6.5

The average flame height was 5.83 m, which corresponds with a computational study on the Influencing Factors of Rapid Fire Spread of Flammable Cladding in a High-Rise Building [53] which estimated the flame height would be 6 m from the floor, when no wind is considered, approximately above the centre of the opening, with a slight tilt in the direction of the corner.

The tallest flame measured was 6.5 m, which is noteworthy because the level 2 thermocouples are located 7 m above the floor. The flame height is affected by many factors such as the thickness of the test specimen, the crib condition and the ambient conditions. It is theoretically possible for all factors to combine and result in a non-combustible system failing to meet the BR 135 criteria, because the flames from the crib have naturally reached the level 2 external thermocouples.

Because of the close proximity between the level 2 thermocouples (at 7 m) and the flame height from the wooden crib (6 m), vertical flame spread up the system is effectively only measured over a 1 m distance, between 6 m and 7 m from the ignition source to the thermocouples. This makes BR 135 more an assessment of whether the cladding system ignites and contributes to the total heat release rate and less an assessment of whether the cladding system supports vertical flame spread. Increasing the distance between the wooden crib fire and the thermocouples would help determine if the cladding system has the potential to spread fire to multiple floors, past cavity barriers, away from the source of ignition.

4.4.4.4 Wind Speed

Wind speed must be less than 2 m/s before a BS 8414 test begins. The exact wind speed value is rarely reported, and no correlation with classification performance was found from the available data.

Several computational studies predict that wind from any direction, on a façade fire, will decrease flame height [63-69].

Wind has been reported, by journalists, in nine tall building fires to increase fire growth. In the majority of cases, it was because the wind encouraged lateral fire growth, spreading to adjacent buildings. Conversely, it was reported in five tall building fires to reduce fire growth [5].

A series of BS 8414 fire tests, conducted outdoors in Croatia, identified that wind can cause variations at the level 2 BS 8414 thermocouples in the order of 100°C [30]. It does not state whether higher wind speeds resulted in higher or lower temperatures and only comments on the impact on test variability.

In general, there is little evidence to suggest that higher wind speeds increase vertical fire spread, but there is evidence to suggest that higher wind speeds can negatively impact the consistency of a fire test.

4.4.5 Classification Criteria

4.4.5.1 LPS 1581/2 Criteria

Test results were analysed for the effect of varying the assessment criteria. The fire performance standards LPS 1581 and LPS 1582 (LPS 1581/2) were used for this purpose. 47 tests were found to meet the BR 135 criteria, only 32 of them were able to meet the LPS181/2 criteria.

LPS 1581/2 has seven criteria that must all be met, see Table 37, Appendix A for definitions of each.

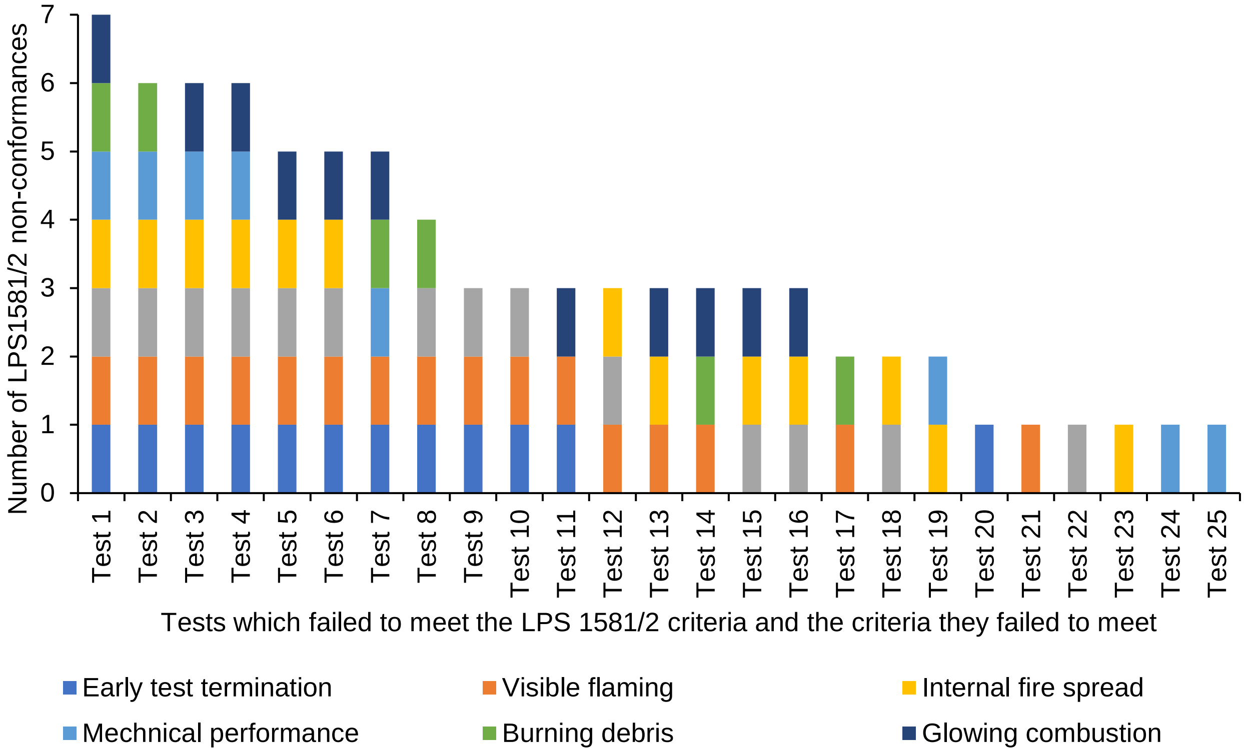
- Early test termination
- Visible flaming
- External fire spread
- Internal fire spread
- Mechanical performance
- Burning debris
- Glowing combustion

Four tests out of the 61 studied, were unable to be assessed against these criteria due to insufficient information in the test reports.

Figure 29 shows the 25 tests which failed to meet the LPS 1581/2 criteria, showing all the criteria that was failed to be met for each test.

The seven different LPS 1581/2 criterion for failure were encountered in at least one of the cases examined in this study. The failure criteria 'burning debris' and 'glowing combustion' were never the sole reason for failing to achieve the LPS 1581/2 classification, in the cases studied here. It should be noted that all LPS 1581/2 assessments were conducted retrospectively based on the data and observations available in the BS 8414 reports and it is possible that observations critical to the LPS 1581/2 assessment, such as glowing combustion weren't appropriately collected or reported.

Figure 29 – Reasons for LPS 1581/2 non-conformances (n = 25)



One non-combustible system failed to meet the LPS1581/2 internal fire spread criteria, despite not contributing to combustion and no visual fire spread being recorded. It is assumed that this was due to the extended flame height from the crib through the wider than average cavity (185 mm wide). This system did meet the BR 135 criteria, which is only valid for the first 15 minutes of the fire test. This suggests that the LPS 1581/2 criteria may be too onerous if they are incorrectly determining fire spread through systems which are incapable of supporting fire spread.

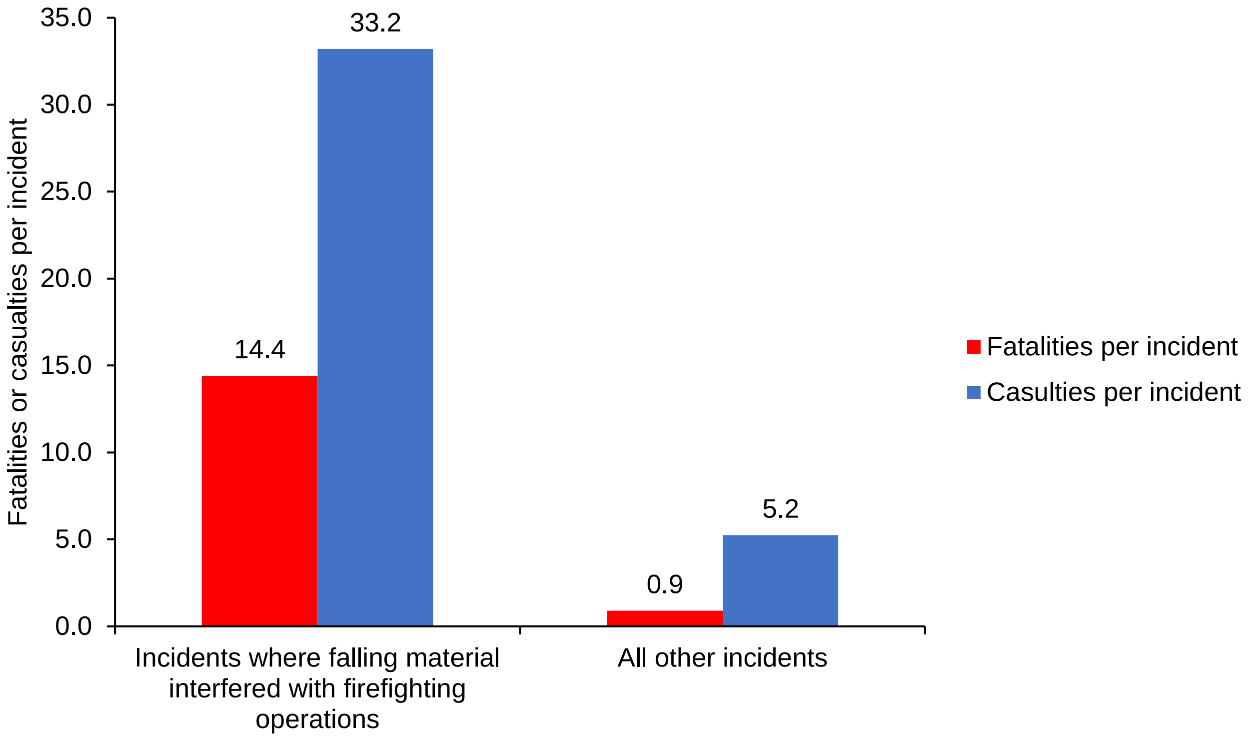
The mechanical performance criteria were generally not met by systems with a combustible insulation and a non-combustible façade. The insulation would burn and structurally damage the system so that large façade components could detach and fall from the system.

4.4.5.2 Mechanical Performance

There are currently no criteria for mechanical performance in BR 135 despite being reported as a relevant factor in real-world scenarios, often hindering firefighting operations. Figure 29 above shows how components were identified to fall from systems which didn't promote fire spread as there were two systems which were not found to meet the LPS 1581/2 criteria for mechanical performance, but did meet the criteria for internal and external fire spread.

Figure 30 shows data from real world incidents. Where falling material was reported to interfere with firefighting operations there were 6 times more casualties, with a much higher fatality rate, resulting in 16 times more fatalities per incident [5].

Figure 30 – Number of casualties and fatalities per incident for tall building façade fire incidents where falling material was reported to interfere with firefighting operations [5]



However, falling material is also indication of fire severity.

There were no direct links reported between falling material and loss of life. The following indirect links for falling material interfering with firefighting operations were reported, which could all theoretically lead to loss of life [5]:

- "Burning debris fell on evacuating occupants"
- "Firefighters had to be protected from falling debris"
- "Falling burning debris limited fire service access"
- "Cladding fell onto at least one fire appliance"
- "Large falling debris endangered fire-fighters"

Falling material was also reported to damage property in 5 other incidents, all in the form of damage to cars [5]:

- "Around 5 cars destroyed by falling material"
- "Burning debris destroyed several cars"
- "Damage to cars"
- "Destruction of cars"
- "Small pieces of burning debris drifted to the ground damaging seven cars."

4.4.5.3 Level 3 thermocouples

The level 3 thermocouples, located 7500 mm above the burn chamber and are used for determining whether flames have reached the top of the test rig, for confirming if the early test termination criteria from BS 8414 have been met [13, 14]. Any test which is terminated early automatically fails to meet the BR 135 criteria. Peak level 3 temperature is only available for the tests conducted to the 2020 version of the BS 8414 standard.

20 tests are available in the database for analysis. Four of the available tests failed to meet the BR 135 criteria, all being terminated early, with flames visually observed above the level 3 reference line. Three of these tests would have failed to meet the BR 135 temperature requirements at the level 2 thermocouples. The remaining test did meet the level 2 temperature requirements but was terminated after 52 minutes due to flames being visually observed over the top of the test rig. Data from the level 3 thermocouples did not directly form part of the failure criteria in any of the test conducted.

BR 135 has not yet been updated to incorporate the 2020 version of the BS 8414 standard. As such there is currently no failure criteria for the level 3 thermocouples and there is no early termination temperature criteria specified in BS 8414. In the absence of any criteria, most test houses use the 600°C + ambient criteria specified in BR 135 for confirming the presence of a flame. However, the data shows this criterion could not always correctly identify flames at the level 3 location in all tests.

Figure 31 – Frequency of meeting the BR 135 criteria as a function of peak level 3 temperature (n = 20)

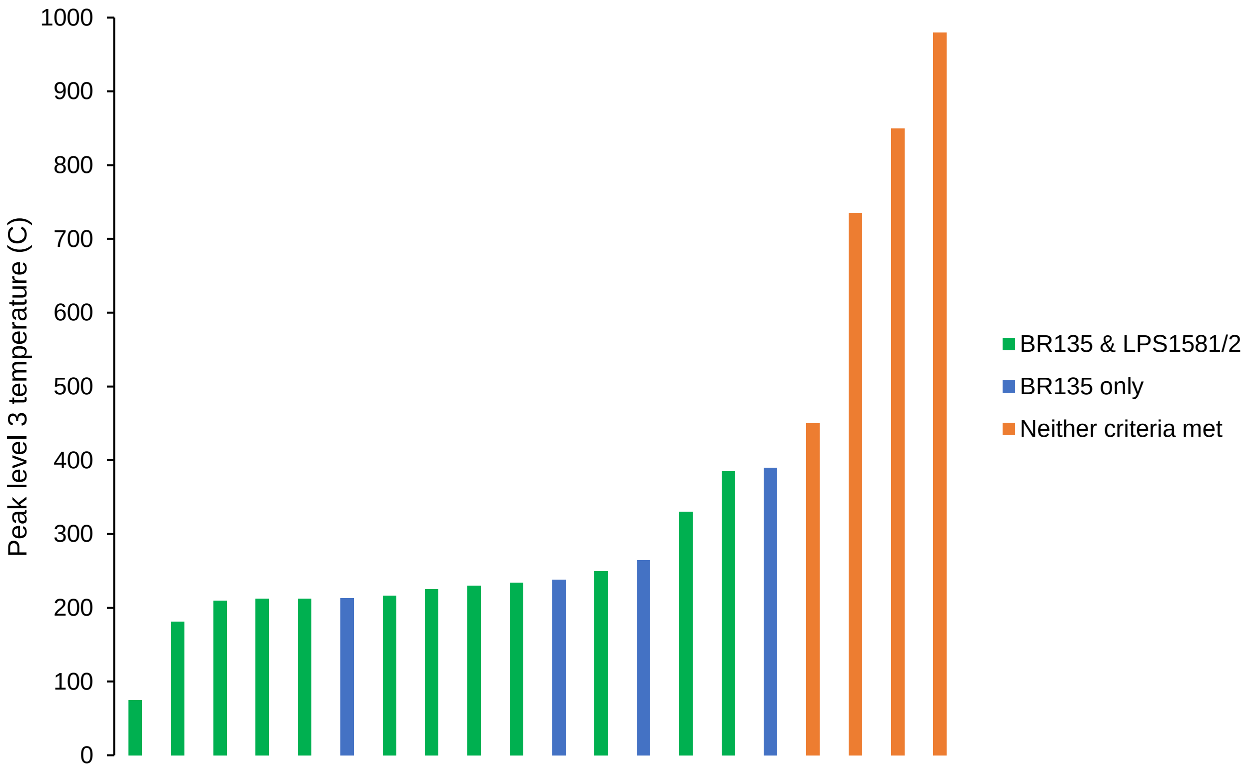


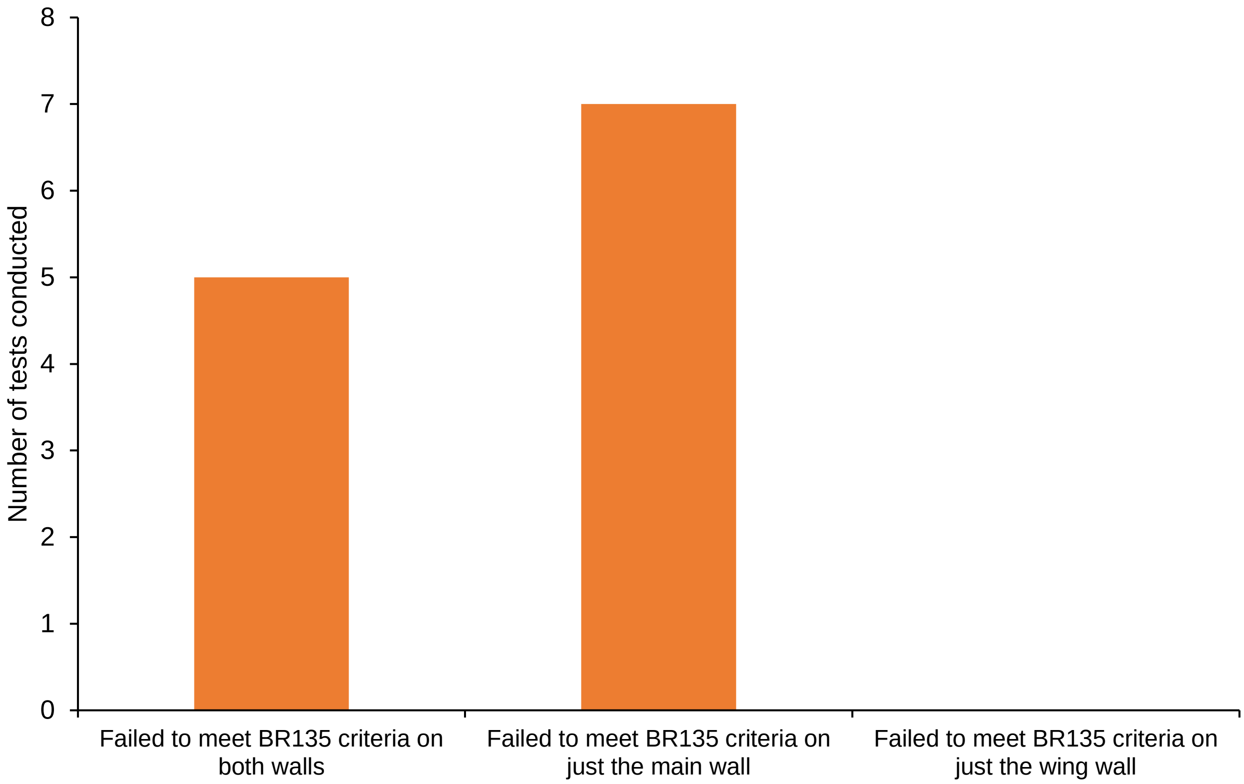
Figure 31 shows that four tests failed to meet the BR 135 criteria, all four of these were terminated early due to flames visually extending beyond the test rig. For one of these tests, the level 3 thermocouples recorded a peak temperature of 450°C, significantly lower than the 600°C + ambient criteria used by most test houses. It should be noted that all successful tests displayed lower temperatures at level 3 than those where flaming was visible out the top of the rig.

In all tests with non-combustible systems the level 3 temperatures were always below 270°C.

4.4.5.4 Wing wall

No tests failed to meet the BR 135 criteria only on the wing wall as shown by Figure 32. It could be argued that the wing wall does not provide a significant contribution to assessing the fire performance of the system. While it may not be necessary to instrument the wing wall, it may still have significant involvement in the test, contributing to fire growth and it is known that fires located in a corner wall setup can result in flame heights two times higher than fires in open air [70] with four times the energy release rate [71]. This is double the energy release rate from a single wall setup [71]. Fire can also spread up the wing wall and radiate onto the main wall increasing the chance or rate of fire growth on the main wall. The argument for excluding the wing wall therefore appears inconclusive.

Figure 32 – Frequency of failing to meet the BR 135 criteria as a function of the main wall and wing wall (n = 12)



4.5 Discussion

A database was populated with 4880 data entries from 61 fire tests conducted to BS 8414, parts 1 or 2 [13, 14] and assessed against the BR 135 performance criteria [7], between the years 2010 to 2022. The data were analysed for commonalities of features to investigate the spectrum of specimens submitted for test, the conditions they are tested to and the impact this has on meeting the BR 135 criteria. Test results were also analysed for the effect of varying the assessment criteria. The fire performance standards LPS 1581 and LPS 1582 (LPS 1581/2) [48, 49] were used for this purpose.

The study is limited by the sample size and selection. 50% of these tests were conducted to assess cladding on existing buildings. The rest were conducted to either gain approval for new cladding systems or for research purposes.

The main potential routes for fire spread were driven by the main combustible components, the insulation and the façade. The façade being the principal front of the structure that faces on to an open space. If the façade and insulation were both non-combustible, the system would not support flame spread and the criteria for BR 135 were always met. However, when both the insulation and façade components were combustible, the BR 135 criteria were never met. Kingspan demonstrated that it is possible for a system comprising of products classified as non-combustible to fail to meet the BR 135 criteria [37].

Combustible insulation products were installed with thicker, less combustible façades on average. Presumably because the thinner façades were not expected to pass the test. These façades would insulate and protect the combustible insulation from the fire. The test simulates the fire performance of a newly built construction against an external fire attack, with few imperfections or complex detailing. The system may perform differently with more imperfections, as seen on real buildings, particularly if the fire is able to break into the cavity through holes, vents, weaknesses in the façade or around a window.

BR 135 does not set any mechanical performance criteria, although any mechanical damage must be reported. Systems with poor mechanical performance in a fire may fail to meet the BR 135 temperature requirements, one specific system was found to meet the temperature criteria with steel bracketry but fail with aluminium bracketry. Mechanical performance was found to correlate somewhat with peak internal temperature, which is part of the BR 135 criteria. Data from real world fires suggests that mechanical performance is relevant for life safety, especially if it prevents firefighters from accessing the building.

LPS 1581/2 does set mechanical performance criteria. In some cases where systems met the BR 135 criteria, but not the LPS 1581/2 criteria it was the result of poor mechanical performance. This is one of the reasons why some fully non-combustible systems were found to be capable of not meeting the LPS 1581/2 criteria.

The findings suggest that there might be a problem with the sensitivity of the LPS15181/2 temperature criteria. This was highlighted by a test where a non-combustible system exceeded the requirement for internal fire spread, despite no visual evidence of fire spread being observed. This indicates that the assessment criteria could be too strict, causing systems that should have been approved to fail. This test met the BR 135 criteria, when assessed over a 15 minute period. But when this period was extended to 30 minutes for LPS 1581/2, it no longer met the requirements. This is because the flames from the crib had entered the cavity, extended up the cavity, gradually heating it, until it exceeded the temperature criteria. This suggests that either the temperature transducer locations, or the temperature criteria defined in LPS 1581/2 are not appropriate for assessing fire spread over a 30 minute period.

It was clear that the test standard was being interpreted differently by different installers. The burn chamber opening in particular had a wide range of interpretations, with some installers leaving it open and unprotected, most installers appeared to interpret it as a window opening and surrounded it with aluminium protection and cavity barriers.

There was a variety of different detailing at the edges of the test rig with 60% of tests enclosing the edges. The majority of tests used vertical cavity barriers either side of the burn chamber. These were closed state cavity barriers running the entire way up the rig and would probably reduce the impact of any edge detailing. It is unlikely that vertical cavity barriers would be provided with the same proximity with their end use on buildings, either side of every potential opening, extending the entire way up the building. However, the narrowness of the rig enabled installers to interpret the edge of the rig as the edge of the wall and their design principles could allow them to install vertical cavity barriers unrealistically close during the test. If the test rig was wider, the vertical cavity barriers would have to be installed further apart, providing a wider cavity with more oxygen available to support fire spread.

Some systems installed a horizontal cavity barrier directly below the level 2 thermocouples, these thermocouples are used to judge the BR 135 temperature criteria, and this was found to have a significant impact on the temperatures recorded. Horizontal cavity barriers are typically installed at each floor level, but the floor levels are not defined in BS 8414. Installers are therefore required to decide where the floor levels would be, to determine where the cavity barriers should be installed. Most installers interpret the BS 8414 thermocouple levels to be the floor levels as one of the advisory notes in BS 8414:2020 states that "levels 1, 2 and 3 are meant to represent floor spacing in a building". This is only advisory and it does not state which part of the floor level these locations represent, so it's ambiguous where on each level the horizontal cavity barrier should be located. BS 8414 later suggests that the floor levels can vary between tests as the test report is required to document the floor level heights used. The result of this is that at the level 2 thermocouple location, installers are provided with a choice of installing the level 2 cavity barrier above or below the level 2 thermocouples. This decision, which is not relevant to real buildings, can have a significant impact on the temperatures recorded and the chance of meeting the BR 135 criteria.

The ambiguity on the location of floor levels provided by BS 8414 also permits horizontal cavity barriers to be installed 2.5 m apart, much closer than they would be on a real building. Some systems justified the use of 5 cavity barriers per test, with a horizontal cavity barrier installed above the burn chamber, at each of the three thermocouple levels and at the top of the rig. This is 5 cavity barriers over a span of 7.7 m, averaging one cavity barrier every 1.54 m. This is not a realistic representation of the credible worst-case scenario on a building, where cavity barriers can be installed over 3 m apart.

The test rig is constructed in an L-shape, with a main wall 2.6 m wide and a wing wall 1.5 m wide. The fire performance on the wing wall did not ultimately determine the test performance in any of the 61 tests conducted. No tests were found to fail to meet the BR 135 criteria on the wing wall that didn't also fail to meet criteria on the main wall. The wall may still contribute to fire growth as it is known that fires located in a corner wall setup can result in double the heat release rate from a single wall setup. However, it may not be necessary to install the 30 thermocouples (on average) that the test standard currently requires on the wing wall. It may also not be necessary for the full cladding system to be installed on the wing wall and similar performance might be measured with a cheaper installation such as just the façade installed on the wing wall, or a generic reflective panel in place for all tests. The level 3 thermocouples, averaging 40 per test, introduced in 2020, also did not ultimately determine the test performance against the BR 135 criteria in any of the tests conducted and may not be necessary. The number of thermocouples varies between tests depending on the number of layers in the cladding system.

In the limited range of systems studied here, most of the test conditions did not appear to have a strong correlation with fire performance, suggesting the tolerances are adequately tight enough to avoid influence. The exception being the ambient temperature, with tests at lower temperatures achieving a BR 135 classification significantly more often than those at higher temperatures.

In summary the main findings were:

- Significant inconsistencies were identified in the test setup, particularly regarding the number and placement of cavity barriers. This typically varied between three and five horizontal cavity barriers, despite the same design principle of one cavity barrier per floor being applied.
- Non-combustible facades were regularly combined with combustible insulation. When installed perfectly on a test rig, these non-combustible facades could robustly protect the combustible insulation behind. However, the fire performance of these systems may reduce when the integrity is compromised by imperfect installation, damage over time, or the installation of unprotected service penetrations. BS 8414 and BR 135 are unable to assess the resilience of cladding systems to these imperfections.
- The ambient temperature can have significant impact on the chance of meeting the BR 135 criteria.
- The location of the thermocouples relative to the fire from the wooden crib is relatively close and may not be appropriate for assessing the cladding systems ability to prevent fire spread past cavity barriers to multiple floors.
- Extending the temperature criteria to 30 minutes, as required by LPS 1581/2, might result in several non-combustible systems failing to meet the temperature criteria, despite not supporting fire spread.
- Some systems, while meeting the BR 135 criteria, generated falling debris posing a significant hazard to firefighting operations, highlighting a potential need for mechanical performance criteria.

This analysis could be taken further with the population of more data from more test reports. Increasing the sample size would reduce the uncertainty of some of the macro data analysis and enable more fields to be analysed, such as understanding of the influence of better performing cavity barriers and the influence of combustible membranes. Future studies could also incorporate more datasets on the general system makeup, considered factors such as panel sizes and panel gaps etc.

5 Identification and Characterisation of Cladding Products

5.1 Introduction

This chapter evaluates a test protocol designed for identifying cladding system components or products. Specifically, products which have been tested against the BS 8414-1:2020 or BS 8414-2:2020 (BS 8414) Fire Performance of External Cladding Systems [13, 14]. The aim is to assess the suitability of the test protocol for identifying significant differences in formulation potentially affecting performance of products supplied for fire testing and products later installed on buildings.

The BS 8414 test report must include details of all products and components used in the construction of the test specimen, together with identification marks and trade names. However, identification marks and trade names do not guarantee that the product supplied for test is representative of the product supplied for market, at present or at some point in the future, and does not appear to address manufacturing variations and changes as described in module 2 of phase 2 of the Grenfell Tower Inquiry [44].

Preliminary research by the University of Central Lancashire has shown that bench scale analysis of insulation materials can be used to identify chemical changes in a material which may affect its flammability. Using both Fourier-transform infrared spectroscopy (FTIR) [72-74] and microscale combustion calorimetry (MCC) [54, 75, 76] on samples of insulation provides a multi-point identification system [77].

While this chapter details the general material characterisation approach, specific markers employed by the FPA to identify subtle product variations are omitted. This decision aims to prevent exploitation of such knowledge for manipulating the characterisation results, thereby ensuring the integrity and reliability of results.

5.2 Materials

5.2.1 Test Samples

A review of BS 8414 tests conducted at the Fire Protection Association between (FPA) 2018 and 2022 indicated that the three most common insulation products being tested are mineral wool insulation, phenolic foam insulation (phenolics) and polyisocyanurate foam insulation (PIR). Two of each product were included for assessing the proposed test methods. An additional three PIRs were included to investigate the ability for the test procedure to identify differences between similar products across a range of manufacturers with a range of manufacturing dates. A polyurethane foam (PUR), taken from a sandwich panel, was included for comparison against PIR foams as it is known to have a similar chemical composition with worse fire performance.

Testing was conducted between March and September 2022. The products used in these small-scale tests are not the same ones that were used for the large-scale tests described in 7.

Table 9 shows the samples provided and their year of manufacture. All samples were provided by the FPA after being submitted for fire testing, except for PIR 5, which was taken from the FPA Fire Testing and Experimental Unit building.

Table 9 – Material Characterisation Test Samples

Sample ID	Material	Year of manufacture
MW 1	Mineral wool (MW)	2020
MW 2	Mineral wool (MW)	2020
PHEN 1	Phenolic foam (PHEN)	2021
PHEN 2	Phenolic foam (PHEN)	2020
PIR 1	Polyisocyanurate foam (PIR)	2022
PIR 2	Polyisocyanurate foam (PIR)	2021
PIR 3	Polyisocyanurate foam (PIR)	2021
PIR 4	Polyisocyanurate foam (PIR)	2017
PIR 5	Polyisocyanurate foam (PIR)	2011
PUR 1	Polyurethane foam (PUR)	1996

5.2.2 Mineral Wool

Mineral wool is a general name for inorganic insulation materials based on vitreous fibres. These can be made from products such as rock, glass or slag [78].

The actual fibres are considered non-combustible. The combustibility of the product could be changed by the inclusion of additives. It is typically held together with a small amount of binding agent, which can be combustible, but is generally a small proportion of the overall formulation having a limited effect on its combustibility. As the desire for cheaper, more insulating products increases, different mineral based components have become a growing focus for research [79].

5.2.3 Phenolic Foam

Phenolic foams are formed from phenolic resin, which is a synthetic thermosetting polymer produced by polycondensation between phenol and formaldehyde [80].

The flammability may be increased by the toughening process. Phenolic foams are naturally very brittle. They are typically toughened via an additional process such as fibre reinforcement, inert fillers or chemical modification, which may reduce its fire performance [81]. The fire performance of phenolic foams is frequently improved by incorporation of phosphorus-based fire retardants [82-84].

5.2.4 Polyurethane and Polyisocyanurate Foam

Polyurethane is formed by the reaction of polyol hydroxyl groups with isocyanates. Polyisocyanurate is formed from polyurethane via catalytic cyclotrimerization of excess isocyanate groups to create isocyanurate trimer rings [73, 85]. The structures are shown in Figure 33 and Figure 34 below.

Figure 33 – Urethanes

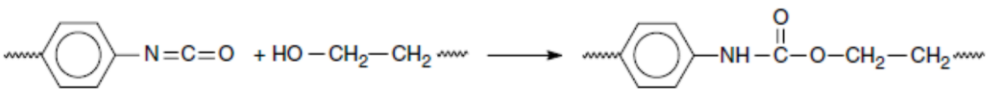
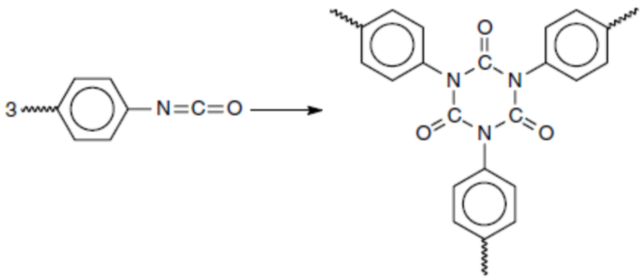


Figure 34 – Isocyanurate rings



The fire performance is strongly linked to the trimer content [86]; the more isocyanurate rings, the less flammable the product. The fire performance can also be improved by the addition of fire retardants [87, 88].

5.3 Methods

5.3.1.1 Sample Preparation

Samples were cut to a size of 100 mm x 100 mm (L x W), at the product's thickness. The cutting process removed any exposed edges, revealing a clean surface. The samples were received dry and stored in a dry place as they would be for BS 8414-1/2 testing [13, 14].

Test samples were taken from the centre of the 100 mm x 100 mm blocks as polyisocyanurate foams have been found to differ near the surface [73, 89].

5.3.1.2 FTIR Method

Infrared spectroscopy describes the resonance of certain chemical bonds based on their absorption of infra-red radiation. The intensity of the absorption is dependent on the number of bonds of a particular type and their polarity. Fourier-transform infrared spectroscopy (FTIR) allows the whole spectrum to be recorded simultaneously.

Diamond-Attenuated Total Reflectance-Fourier Transform Infra-Red spectroscopy (D-ATR-FTIR) was used in this study. In summary, an infrared beam is focused onto an optically dense diamond crystal at a specific refractive angle so that it reflects. The reflections create an evanescent wave that extends beyond the crystal. The sample is pressed onto the crystal surface and certain frequencies of the evanescent wave are absorbed, based on the sample's composition. In the parts of the spectrum where the sample absorbs energy, the wave will be attenuated. The final attenuated energy for each frequency returns back to the original infrared beam and the absorbance is quantified from Fourier transformation.

The Nicolet iS5 FTIR Spectrometer was used for this study with the ID7 ATR (AR coated) diamond crystal. Preliminary experiments at the University of Central Lancashire identified that using samples of at least 0.05 g, compressed into a flat disk (pellet) with a KBr pellet press at a pressure of at least 7 tons/cm^2 for at least two minutes can produce consistent spectra for polyurethane and polyisocyanurate foams [89].

A background spectra, with no sample, was collected before testing and subtracted from the results. 32 complete scans were run per sample, taking around one minute.

5.3.1.3 MCC – ASTM D7309 Method A – Anaerobic Pyrolysis [90]

Tests were conducted using the FTT FAA Micro Calorimeter. Microscale combustion calorimetry (MCC) measures the heat release rate of a sample by the principal of oxygen depletion calorimetry. A 2-3 mg sample is heated, at a fixed rate of 1°C per second, in an inert gas to pyrolyze it. The inert gas carries the pyrolyzate (the combustible gases) to the combustor. It is then mixed with oxygen in a furnace at 900°C. The heat release is measured from the oxygen consumption in the effluent. The results give the total heat release rate as function of temperature. The mass of the sample can be used to calculate the heat of combustion.

5.3.1.4 MCC – ASTM D7309 Method B – Aerobic Pyrolysis [90]

Method B determines the heat release as above, except that the sample is pyrolyzed in synthetic air (20% oxygen, 80% nitrogen). Typically, Method A leaves behind a char residue, but Method B will oxidise any carbonaceous char.

5.3.1.5 Elemental Analyser

A third method involving an elemental analyser was evaluated, where the Carbon, Hydrogen, Nitrogen and Sulphur (CHNS) content of a pyrolyzed sample are determined by gas chromatography.

Samples between 2.000 and 3.000 mg were ground into a fine powder and loaded into the instrument. The furnace for combusting the sample was set to 950°C with the gas chromatography column oven set to 65°C. Helium was used as the carrier gas with the carrier flow set to 140 ml/min, the reference gas flow was set to 100 ml/min. The detector level was set to auto adjust at 1000 μV. Samples were placed into the instrument, with every three samples interrupted by a bypass sample to purge the system.

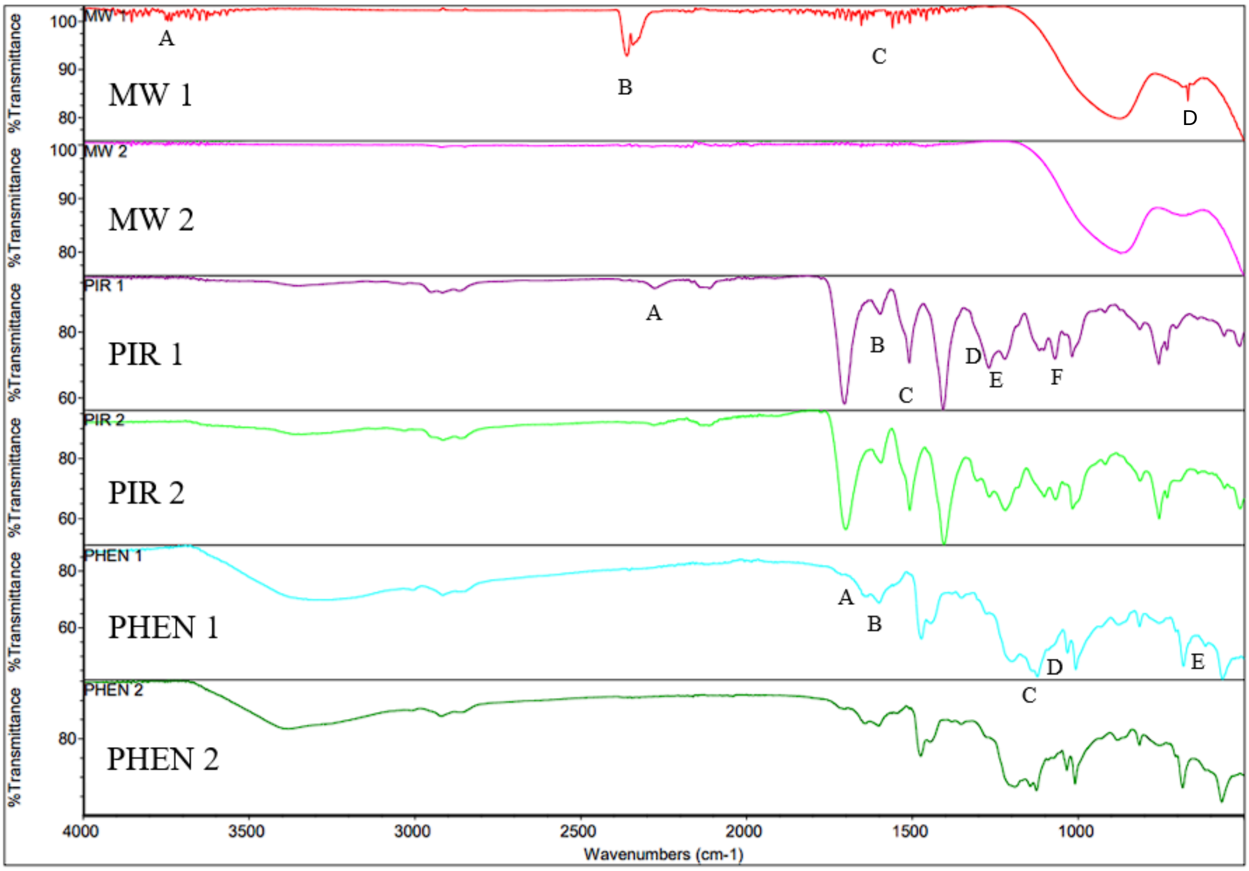
5.4 Results

5.4.1 FTIR Results

5.4.1.1 Summary FTIR Results

The spectra of 2 mineral wools, 2 PIRs and 2 phenolics from Diamond ATR FTIR spectroscopy were compared and shown in Figure 35. Each type of material followed a distinctive pattern.

Figure 35 – Mineral wool, PIR and Phenolic FTIR results



5.4.1.2 Mineral Wool FTIR Results

Both mineral wool samples could be characterised by a general lack of peaks, with notable peaks around 870 cm^{-1} and 680 cm^{-1} indicating SiO_4 and Si-O_b symmetry stretching [91, 92]. MW 1 revealed a prominent double peak at 2342 cm^{-1} and 2360 cm^{-1} (location B) and noise at locations marked A, C and D, which was not present in MW 2. This is atmospheric CO_2 and water vapour which can be removed by background correction.

5.4.1.3 PIR Foam FTIR Results

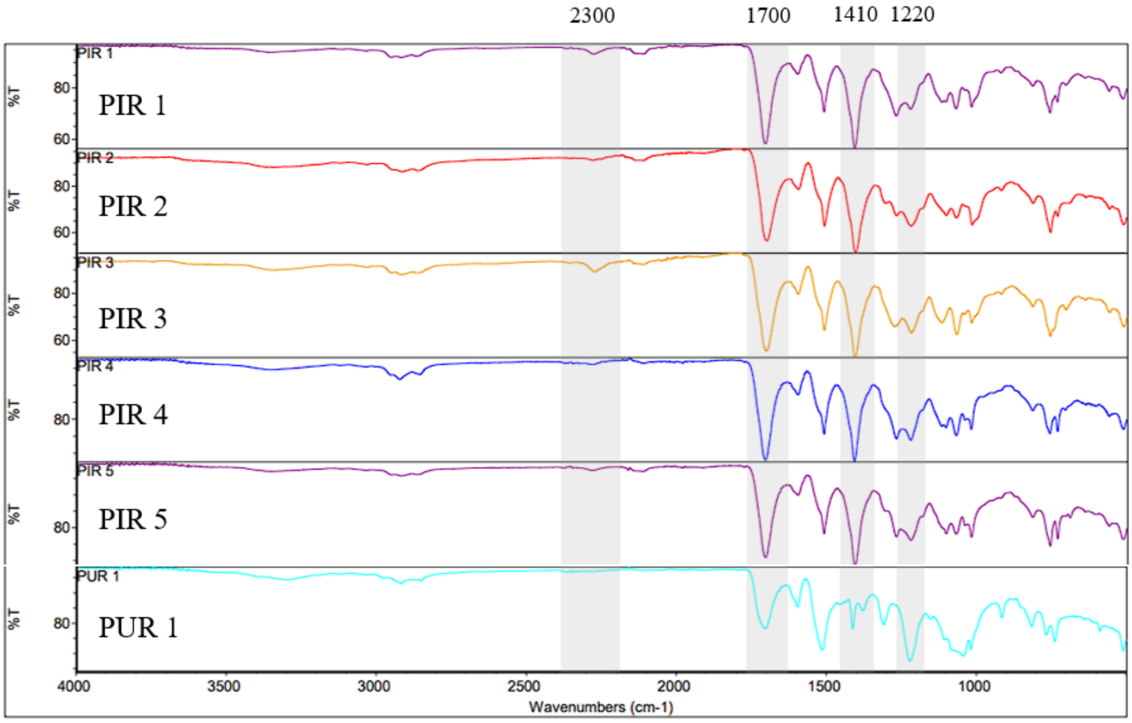
The PIR foams could be characterised by the following peaks:

Table 10 – PIR FTIR Peaks

Wavenumbers (cm^{-1})	Bond
~3500-3200	N-H vibrations
~2300	Free unreacted isocyanate groups
~1700	Isocyanurate rings
~1410	Isocyanurate rings
~1220	Urethane
~750	TCPP phosphate and chloride groups
~500	TCPP phosphate and chloride groups

Important differences could be seen at locations marked A to E. All PIR displayed a peak at 2300 cm^{-1}, indicating unreacted isocyanate, which was not present in the PUR. All PIR displayed larger isocyanurate peaks at 1700 cm^{-1} and 1410 cm^{-1} and smaller urethane peaks at 1220 cm^{-1} than the PUR as shown in Figure 36 below.

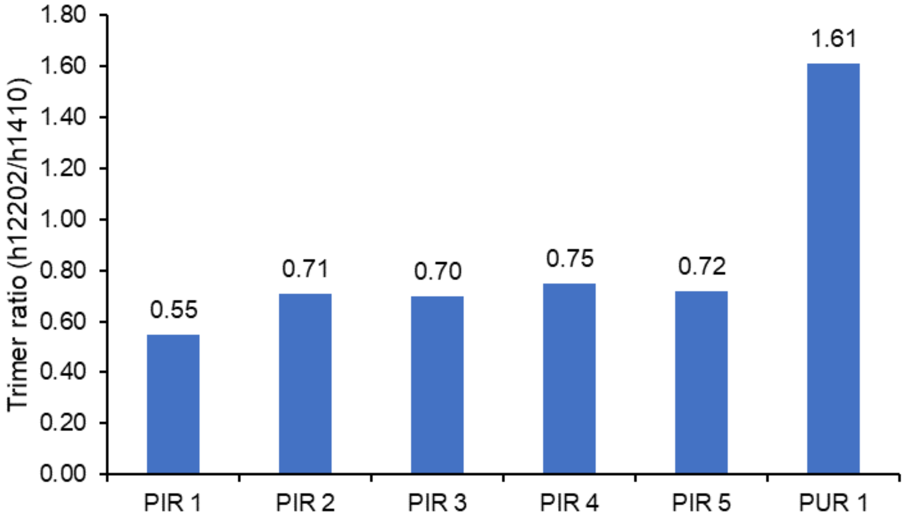
Figure 36 – Polyurethane based foams FTIR results (grey shading indicates regions of interest)



One of the ways the fire performance of PIRs can be improved is by the 'trimer ratio' [73]. This is the ratio of urethane linkages to isocyanurate rings and can be used to quantify the proportion of isocyanurate rings, the product of isocyanate trimerization. This is conventionally calculated by the ratio of the 1220 cm^{-1} urethane peak to the 1410 cm^{-1} isocyanurate peak [72]. The higher the ratio, the lower the expected fire performance (greater flammability).

The trimer ratio has been shown to maintain consistency between experiments and instrumental methods [72, 73, 89]. Figure 37 shows that PUR 1 was the only sample tested to give a urethane/isocyanurate trimer ratio over 1.

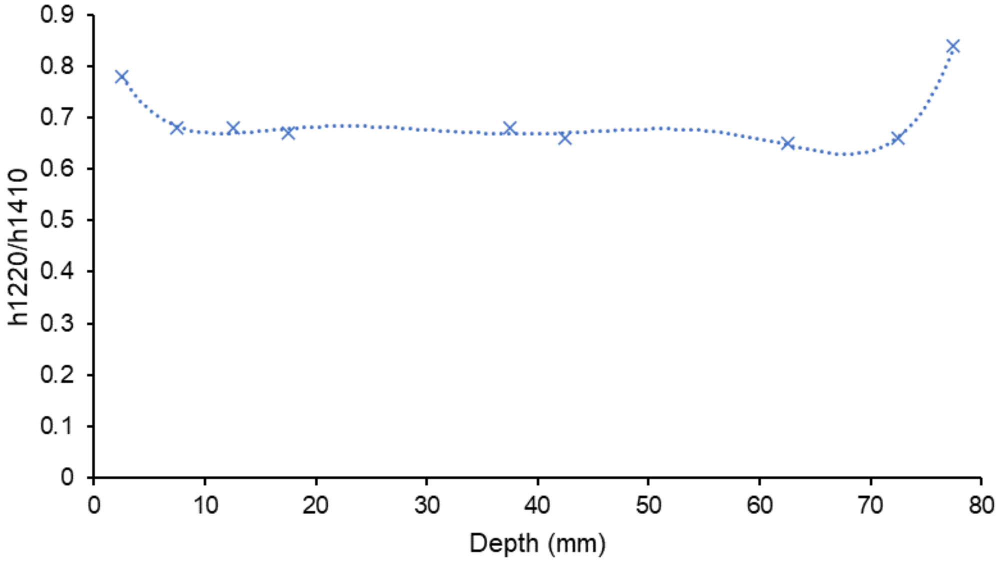
Figure 37 – Trimer ratio results for all polyurethane-based foams



Polyurethane based foams have been shown to be relatively homogenous throughout the core [89]. However, various literature reports that the urethane/isocyanurate trimer ratio differs near the surface [72, 73], shown in Figure 38 below. This is believed to be due to the trimerization process requiring longer reaction times at low temperatures. During manufacture, surfaces of the sample cool down faster than the core, so less trimerization happens near the surface.

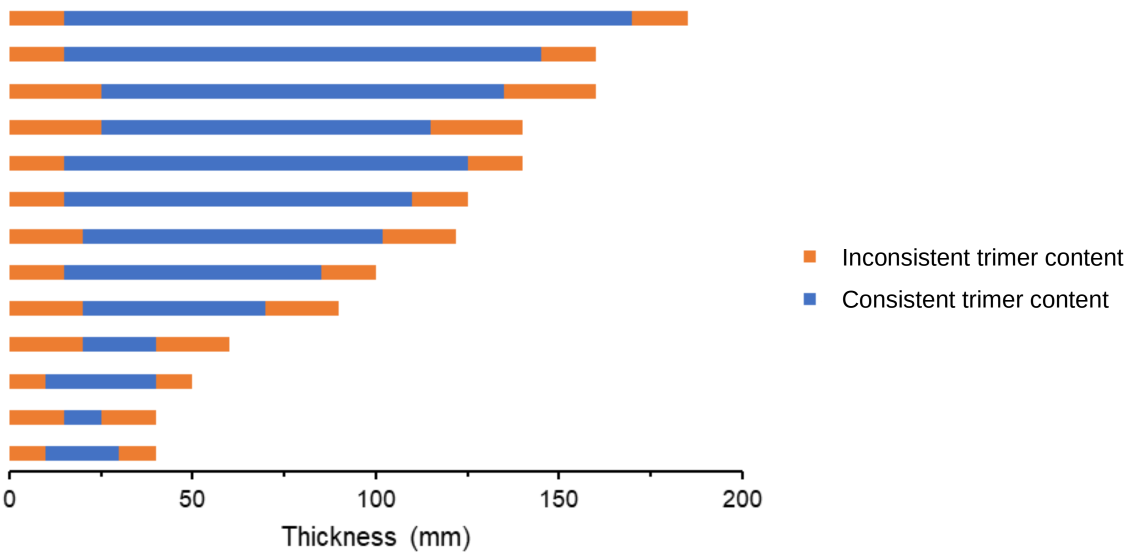
A test was conducted with samples taken at 5 mm intervals from the surface of a product, throughout the cross-section. The results are shown in Figure 38, there is consistency between all results after a depth of 5mm from the surface. This would be expected to give worse fire performance near the surface than in the core.

Figure 38 – Urethane/isocyanurate trimer ratio throughout the thickness of a PIR sample



This surface/core difference has been reported elsewhere [72, 73]. Figure 39 below shows the location of consistent trimer content and inconsistent trimer content as a function of PIR board thickness. All samples had a stable centre at least 10 mm wide. Some of the samples 60 mm thick or less could be considered inhomogeneous as there is more unstable thickness than stable thickness. This consistency within commercial products is particularly important for this individual product characterisation work and without careful understanding could lead to erroneous conclusions of product variation.

Figure 39 – Trimerization stabilisation as a function of PIR board thickness, reported elsewhere [72, 73]



Absorbance appeared to be influenced by sample thickness. The sample, in this case is a pellet after it has been compressed into a disk. Figure 40 shows this, with the absorbance decreasing with pellet thickness. This is possibly because thicker samples are harder to compress, so the pellet is less dense. Figure 41 shows how the trimer ratio is independent of the pellet thicknesses.

Figure 40 – Pellet thickness vs absorbance

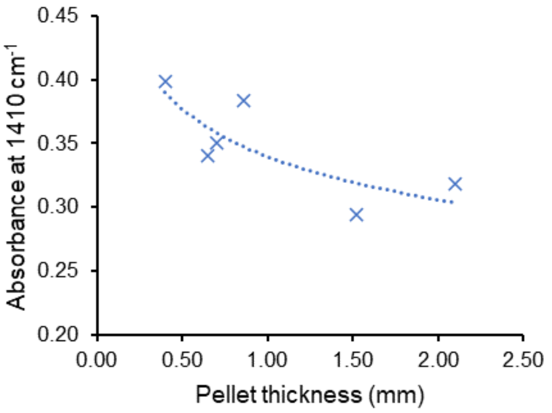
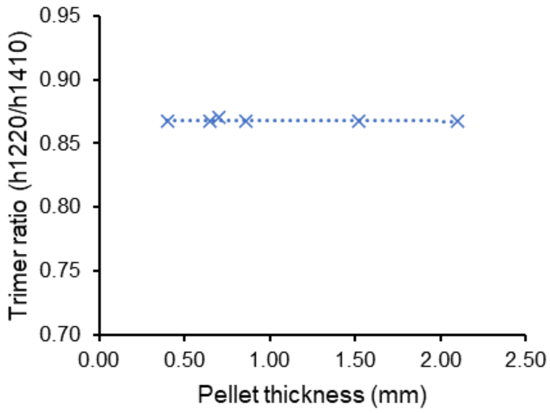


Figure 41 – Pellet thickness vs trimer ratio



5.4.1.4 Phenolic Foam FTIR Results

The phenolic foams could be characterised by the following peaks:

Table 11 – Phenolic foam FTIR peaks

Wavenumbers (cm^{-1})	Bond
~3400	O-H stretching vibration
~3070	=C-H stretching vibration of groups on aromatic ring
~2870	C-H stretching vibration of -CH2- groups
~1590	C=C skeletal vibration of aromatic ring
~1460	C=C aromatic vibrations
~1350	C-O stretching vibrations
~1000	C-H aromatic C-H in-plane benzene ring
~815	C-H out-of-plane

Important differences could be seen at locations marked A to E in Figure 35. The small peaks identified at 1290 and 950 cm^{-1} could indicate P=O and P-O-Ph stretching vibrations respectively. This could indicate the presence of phosphorus added as part of a fire retardant to improve fire performance [82].

5.4.2 FTIR matching software results

As well as manually comparing different absorption peaks, FTIR spectra can also be compared using peak matching software.

Spectra were compared using Omnic Specta 2.2.43 using the Spectral Search feature. The software uses 100 to represent the best match and 0 to equal the worst match. It uses a ranking technique which means there is always a best match, regardless of whether the test sample is represented in the database or not. Therefore, the presence of an individual match does not necessarily indicate the quality of the match.

The results were presented in the two similarity matrices below. The colour coding indicates the degree of similarity between items:

- Green represents the highest similarity, suggesting a high correlation
- Red represents the lowest similarity, indicating a low correlation
- Yellow and other intermediate colours indicate moderate similarity, with the shade progressing from red to green as similarity increases.

Table 12 - Percentage match between common insulation using Omnic Specta Spectral Search software

	MW 1	MW 2	PHEN 1	PHEN 2	PIR 1	PIR 2
MW 1	100	99	70	64	38	48
MW 2	99	100	70	65	37	48
PHEN 1	70	70	100	99	64	74
PHEN 2	64	65	99	100	65	74
PIR 1	38	38	64	65	100	97
PIR 2	48	48	74	74	97	100

Table 13 - Percentage match between polyurethane based foams using Omnic Specta Spectral Search software

	PIR 1	PIR 2	PIR 3	PIR 4	PIR 5	PUR 1	H 1
PIR 1	100.0	97.1	98.4	98.4	97.4	86.6	96.9
PIR 2	97.1	100.0	98.9	97.7	98.3	91.3	96.0
PIR 3	98.4	98.9	100.0	98.7	98.5	91.0	97.5
PIR 4	98.4	97.7	98.7	100.0	99.2	92.2	99.2
PIR 5	97.4	98.3	98.5	99.2	100.0	93.3	98.1
PUR 1	86.6	91.3	91.0	92.2	93.3	100.0	93.3

Table 12 shows the software can distinguish between different materials, with each materials closest match being to its own material. Table 13 shows the software comparing similar materials and was able to identify the difference between all PIR's from a PUR, with each PIR's least similar match being the PUR.

5.4.3 MCC Results

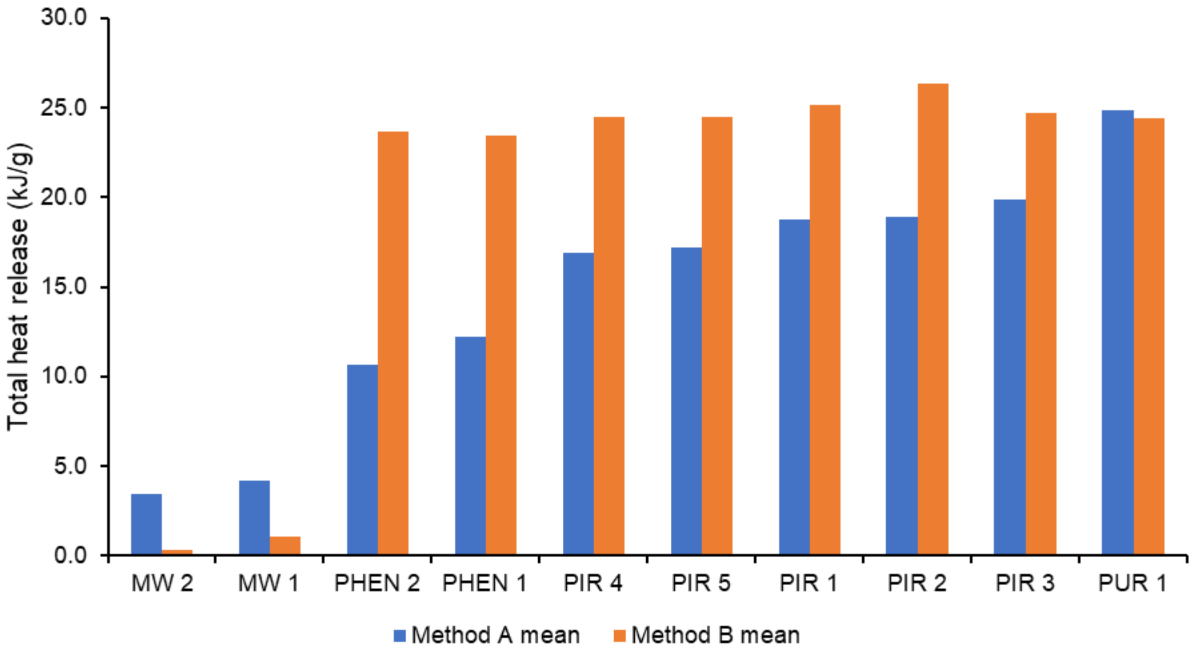
5.4.3.1 MCC Summary Results

Tests were run in triplicate, with an average taken of all 3. The heat release was calculated based on the initial sample mass to produce a value for the expected heat release per mass of product.

Figure 42 shows all polymer-based foams produced around 25 kJ/g when tested using Method B. Method A provided better differentiation between products, with individual products falling into groups. Individual manufacturers also fall into groups, with PIR 4 & PIR 5 being made by one manufacture and PIR 1 & PIR 2 being made by another manufacturer.

Method B produced slightly more consistent results than Method A. 20 tests were conducted on PIR 1, with all samples taken from the same depth. 10 to Method A and 10 to Method B. The Method A results had a standard deviation of 0.63 kJ/g, while the Method B results had a standard deviation of 0.42 kJ/g. Method A did not completely combust the sample, with some sample residue left at the end of each test, this additional factor could have increased the variance resulting in a higher deviation. Method A exhibited more sampling noise, which made baseline and low readings more inaccurate. This was noticeable with the MW samples measuring higher heat release rates with Method A than Method B. This was most probably due to an error in the flow control system, feeding oxygen to the pyrolizer rather than to the combustor. This error was found to be consistent across different samples and different devices [93]. It was considered an error because this combustible content was not observed when tested to Method B or when tested in a bomb calorimeter to ISO 1716 [56].

Figure 42 – Total heat release using microscale combustion calorimetry



5.4.3.2 MCC Repeatability and Matching Accuracy

The purpose of material characterisation is to compare a sample from a fire test with a sample from a building to determine if they are the same product or chemically different. To assess this, it's important to establish how much variation in test results would be required to confidently say the samples are different.

To achieve this, a Monte Carlo analysis was conducted to determine the level of confidence that can be attached to MCC in differentiation between samples. This is further detailed below.

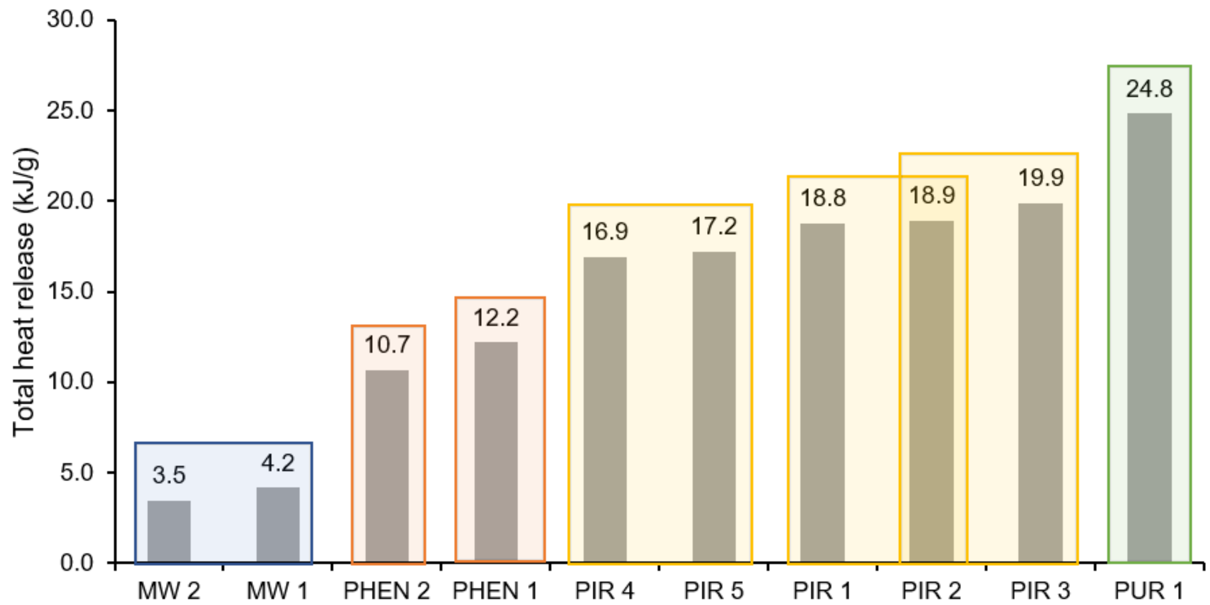
The analysis suggests that if MCC test results differ by more than 1.08 kJ/g, the samples are likely to be chemically different, approximately 95% of the time. This is based on conducting tests in triplicate and averaging the results, as recommend by ASTM D7309 [90].

If the results are within 1.08 kJ/g there is no evidence to suggest that the samples are chemically different.

This threshold of ±1.08 kJ/g can be used to group samples, as shown in Figure 43 below. For example, Method A was able to group PIR 4 and PIR 5 together, which are made by the same manufacturer. PIR 1 and PIR 2 were also grouped and are also made by the same manufacturer. It also demonstrated that this method could differentiate between materials such as PUR, PIRs, phenolics, and mineral wools with high confidence.

For Method B all the polymer-based foams produced similar results, as shown in Figure 42 above.

Figure 43 – MCC Method A results grouped within ±1.08 kJ/g



5.4.3.3 Monte Carlo Analysis

A Monte Carlo analysis is a computational technique for predicting the probability of different outcomes. It involves using a random number generator to simulate the results of a random event. The simulation is run numerous times, to leverage the law of large numbers, providing a distribution of potential outcomes.

It was used to simulate testing a sample from a building and comparing it to a sample from a fire test, to understand the likelihood that the samples were different. For example, if the results were 2 kJ/g apart, would this infer that the samples are likely to be different? How common would this outcome be if they were the same product?

This was achieved by testing the null hypothesis that there was no significant difference between the samples.

ASTM D7309-21b [90] recommends testing samples in triplicate and averaging the results. The range of outcomes from this is simple to calculate using the mean and standard deviation. Results within one standard deviation of the mean for a normal distribution occur roughly 68% of the time. Results within two standard deviations occur roughly 95% of the time.

The aim was to understand if samples were tested in triplicate and then the results were compared to the same sample, tested in triplicate, how close together would those results typically be.

A secondary aim was to understand what the benefit would be of testing samples once, twice, five, ten, or 100 times. The more times a sample is tested, the more accurate the average will be, but at the expense of more time and cost.

In order to run a simulation, the standard deviation, for MCC results, needed to be calculated first. The first step was to calculate the standard deviation of the results of the MCC method on typical insulation products. The method was assumed to produce results with a normal distribution.

80 tests were conducted in total on 11 different products using both Method A and Method B from ASTM D7309-21b [90], shown in . 20 of these tests were conducted on the same sample. All other samples were tested six times, split evenly between Method A and Method B. All standard deviations were averaged, weighted by the number of tests, to produce an average standard deviation of 0.65 kJ/g.

They were weighted by multiplying the standard deviation by the number of tests. The sum of all weighted standard deviations is then averaged by the total number of tests. This was done to provide more weight to the tests which had been conducted more.

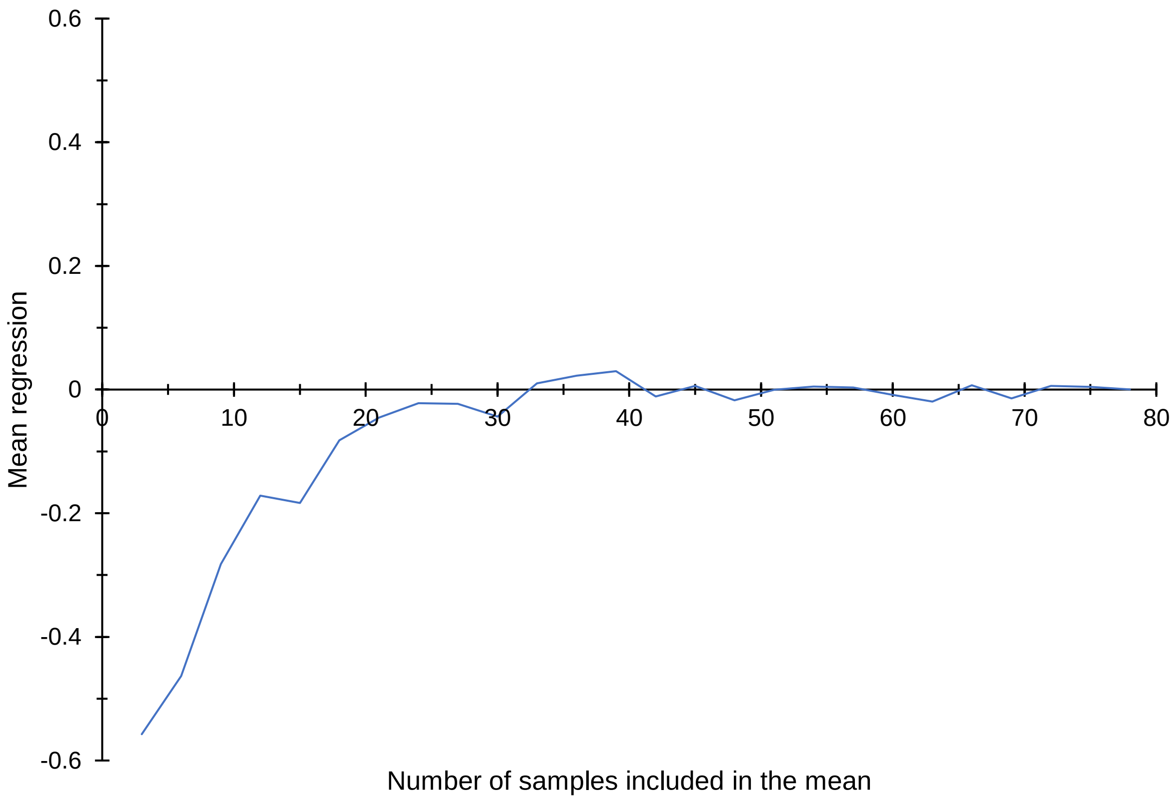
Table 14 – MCC test results used to calculate the weighted standard deviation

Sample ID	Test method	Number of tests	Mean (kJ/g)	Standard deviation (kJ/g)
MW 1	A	3	4.2	1.21
MW 1	B	3	1.1	0.17
MW 2	A	3	3.5	0.93
MW 2	B	3	0.3	0.29
PHEN 1	A	3	12.2	0.80
PHEN 1	B	3	23.5	0.29
PHEN 2	A	3	10.7	0.55
PHEN 2	B	3	23.7	0.74
PIR 1	A	10	18.8	0.63
PIR 1	B	10	25.1	0.42
PIR 2	A	3	18.9	0.83

PIR 2	B	3	26.3	0.81
PIR 3	A	3	19.9	0.82
PIR 3	B	3	24.7	0.42
PIR 4	A	3	16.9	0.75
PIR 4	B	3	24.5	0.12
PIR 5	A	3	17.2	1.08
PIR 5	B	3	24.5	0.10
PIR 6	A	3	17.6	1.22
PIR 6	B	3	25.1	0.90
PUR 1	B	3	24.4	1.13
PUR 2	A	3	24.8	0.78

This standard deviation is taken from 80 samples, but only has 58 degrees of freedom due to the averaging of multiple samples. A regression study, shown in below, implied that the mean value stabilised within ±0.1 of the expected value after 35 test results. After 58 tests, the results stabilised within ±0.02 of the expected value. This suggests that the averaging method chosen with 58 degrees of freedom was a reasonable sample size for estimating the true expected value.

Figure 44 – Mean regression as the number of samples included in the mean increases, with a standard deviation of 0.65



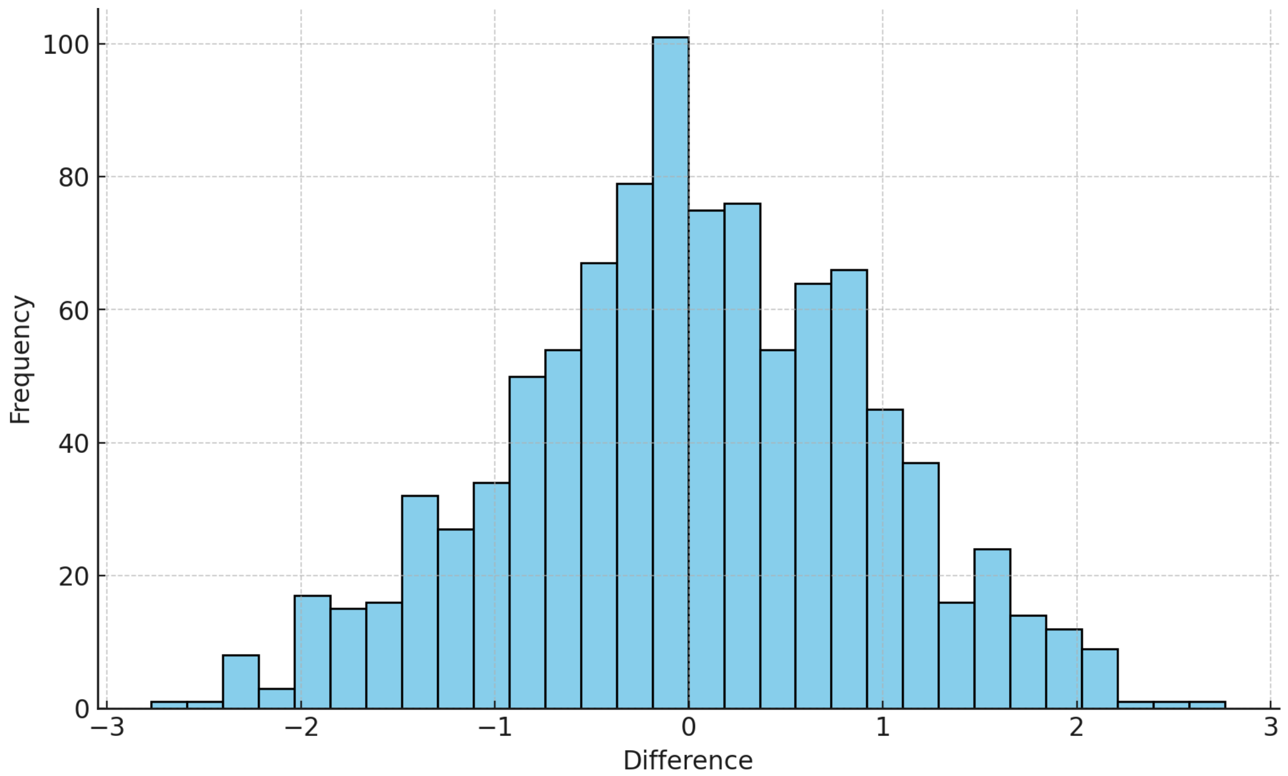
For the Monte Carlo Simulation method, data was simulated using the method specified in An Investigation of the False Discovery Rate and the Misinterpretation of P-values [94]. Where data is randomly simulated based on a given mean and standard deviation. Each data point generated is referred to as a random observation.

IBM SPSS Statistics for Windows – Version 28 was used for simulating and analysing data on mass.

For each random observation, data were drawn from a normal distribution with a mean of 0 and standard deviation of 0.65. The simulation ran tests with 1 random observation and compared the results to 1 other random observation. This was run 1000 times shown in Figure 45 below.

While the standard deviation of all random observations was 0.65, the standard deviation of the difference between two observations was 0.93. This means that roughly 68% of the time, the difference between two identical samples will be within 0.93. This is when one single measurement is compared to another single measurement.

Figure 45 – Differences between two random observations from a normal distribution with a mean = 0 and a standard deviation of 0.65



The simulation was repeated with two random observations averaged and compared to the average of two different random observations. This is simulating taking two measurements from one material, averaging the results and comparing it to the average of two measurements from an identical material.

This was repeated for 3, 4, 5, 10 and 100 random observations per group, with each grouping run 1000 times.

Table 15 – Standard deviation of the mean difference between observation groups

Number of observations per group	Standard deviation of the mean difference between observation groups
1	0.93
2	0.62
3	**0.54**
4	0.47
5	0.42
10	0.30
100	0.09

The results in Table 15 indicate that if three random tests were averaged and compared to the average of three other random tests on the same sample, the results would be within 0.54 kJ/g of each other roughly 68% of the time.

Expanding this uncertainty to within two standard deviations, the results would be within 1.08 kJ/g of each other 95% of the time, shown in Table 16. Therefore, anything outside this range could be considered likely to be a different or modified product, when testing in triplicate and compared to another sample also tested in triplicate.

Table 16 – Two standard deviations of the mean difference between observation groups

Number of observations per group	2 Standard deviations of the mean difference between observation groups
1	1.86
2	1.24
3	**1.08**
4	0.94
5	0.83
10	0.60
100	0.18

5.4.4 Elemental Analyser Results

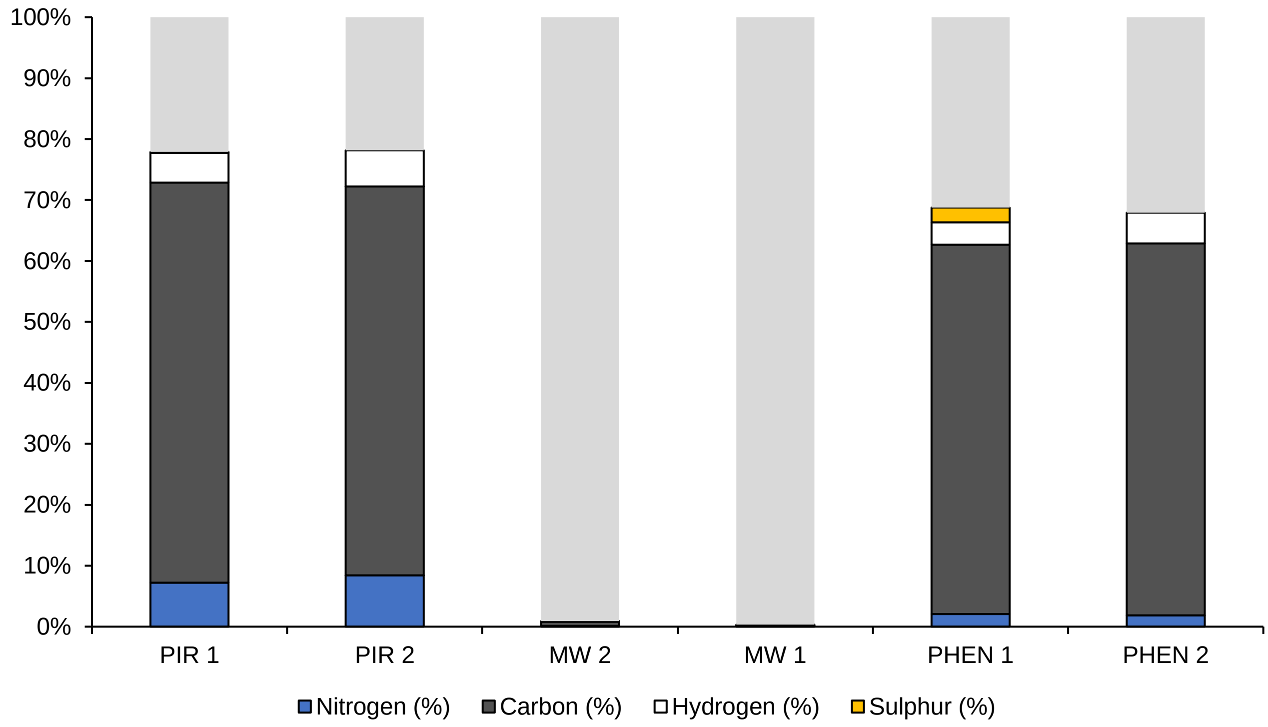
5.4.4.1 Elemental Analyser Summary Results

Tests were run in triplicate and averaged. The results of 2 PIRS, 2 mineral wools and 2 phenolics are shown below.

Table 17 - CHNS results for common insulation products

Sample	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Sulphur (%)
PIR 1	7.22	65.62	4.91	0.12
PIR 2	8.45	63.80	5.93	0.00
MW 2	0.14	0.67	0.09	0.00
MW 1	0.00	0.17	0.17	0.00
PHEN 1	2.08	60.60	3.66	2.42
PHEN 2	1.86	61.01	5.03	0.00

Figure 46 – CHNS results for common insulation products



Mineral wool fibres do not typically contain the components the CHNS analyser measures and is typically composed of calcium, magnesium and aluminium silicates [78]. There is usually a small amount of combustible product in mineral wools from the binding agent. This clearly wasn't significant enough in mass to produce sufficient gas, for the gas chromatography to detect.

Phenolic resin is typically used as the binding agent for mineral wool insulation. In the MCC tests conducted the mineral wool insulation products averaged 0.7 kJ/g and the phenolic insulation products averaged 23.6 kJ/g. If the phenolic resin has a similar combustible content to the phenolic insulation, then it could be assumed that the mineral wool products contained 3% phenolic resin by mass. The elemental analyser measured 61% content from the phenolic insulation products, so you would expect to see around 1.8% carbon content from the mineral wool insulation. From the tests conducted, it does not appear that the elemental analyser is appropriate for testing mineral wool insulation.

PHEN 1 was the only sample to contain a significant amount of sulphur. However, PHEN 2, a phenolic foam made by the same manufacturer, did not appear to contain any sulphur in any of its three tests.

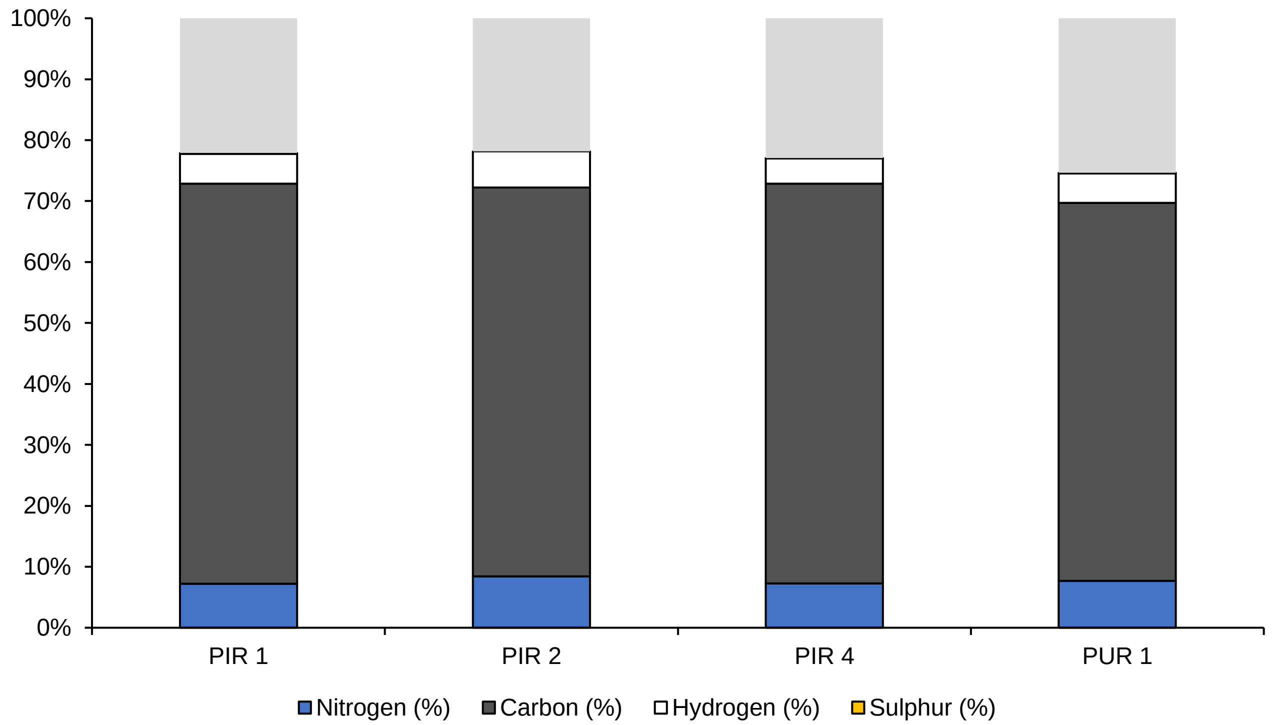
Phenolic foams are formed from phenolic resin, which is a synthetic polymer produced by polycondensation between phenol and formaldehyde [80]. These have the chemical formula C_6H_5OH and CH_2O respectively. Notably, these would not be expected to contain any sulphur or nitrogen. Flame retardants are often added to phenolic foams which can introduce nitrogen [95]. The sulphur content in PHEN 1 may have come from toluene sulphuric acid, which is used as a catalyst. Catalysts are used in phenolic foam production for increasing the reaction rate, to increase the chances of cross linking and improve the fire performance of the foam [80, 96].

The polyurethane-based foams were distinguished by their higher nitrogen content, a core element in polyurethane-isocyanurate foams [73]. The PUR contained less carbon than the PIRs but wasn't able to be easily distinguished from the PIRs.

Table 18 – CHNS results for polyurethane-based foams

Sample	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Sulphur (%)
PIR 1	7.22	65.62	4.91	0.12
PIR 2	8.45	63.80	5.93	0.00
PIR 4	7.26	65.60	4.14	0.07
PUR 1	7.72	62.01	4.82	0.11

Figure 47 – CHNS results for polyurethane-based foams



5.4.4.2 Elemental Analyser Repeatability

Trace amounts of sulphur were only detected for tests run immediately after a bypass run. This was some residue left behind from the calibration sample and not actually present in sample.

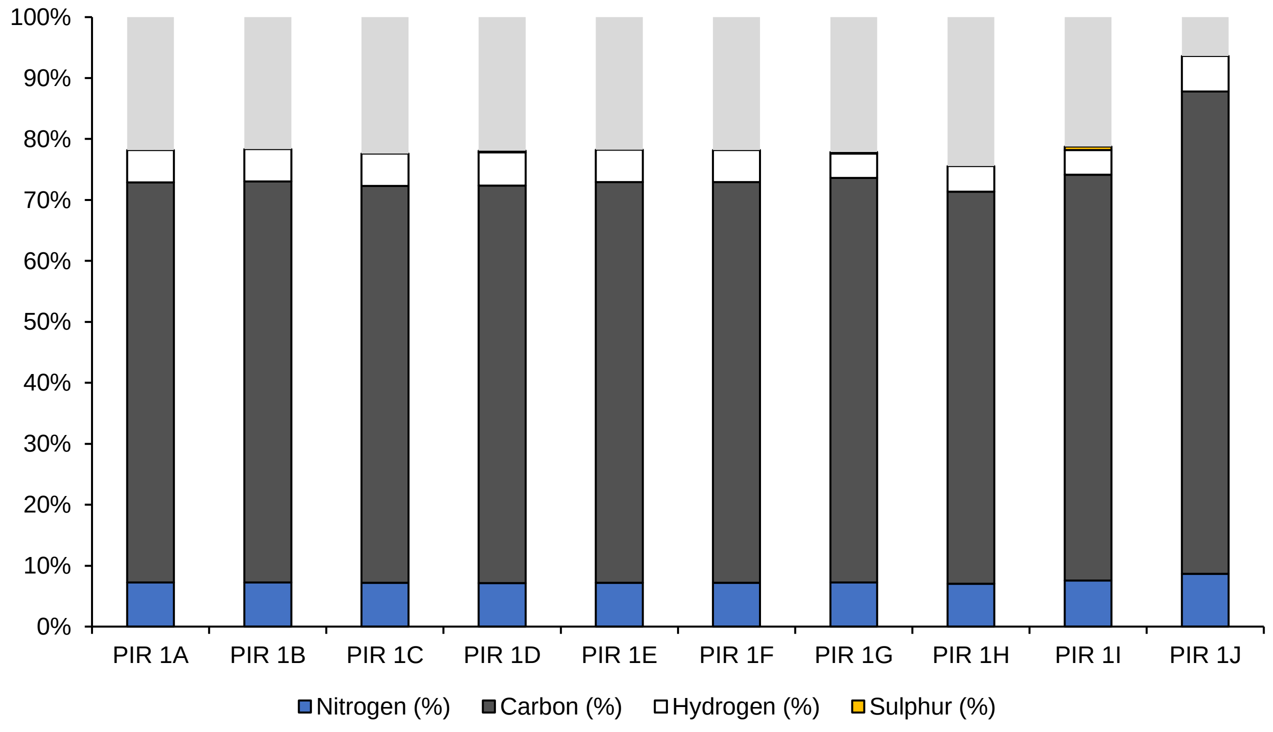
10 tests were run on PIR 1, labelled A-J, shown in Table 19. Test PIR 1J appeared to be an anomalous result, as it contained a much higher total Nitrogen, Carbon, Hydrogen and Sulphur content. PIR 1J was therefore removed from the analysis.

Table 19 – 10 CHNS tests on PIR 1

Sample	Nitrogen (%)	Carbon (%)	Hydrogen (%)	Sulphur (%)
PIR 1A	7.23	65.65	5.31	0.00
PIR 1B	7.25	65.80	5.32	0.00
PIR 1C	7.17	65.16	5.27	0.00
PIR 1D	7.13	65.20	5.51	0.25*
PIR 1E	7.20	65.72	5.32	0.00
PIR 1F	7.17	65.76	5.27	0.00
PIR 1G	7.26	66.34	3.98	0.27*
PIR 1H	7.05	64.32	4.20	0.00
PIR 1I	7.55	66.62	4.01	0.59*
PIR 1J	8.64	79.18	5.80	0.00
Average	7.37	66.98	5.0	N/A
Standard deviation	0.47	4.34	0.67	N/A

*PIR 1D, PIR 1G and PIR 1I were run immediately after a bypass sample.

Figure 48 – 10 CHNS tests on PIR 1



With the exception of sulphur, which was only measured in negligible amounts, the deviation between 9 tests on multiple products appeared similar to the deviation between 9 tests on 1 product, as shown by the PIR products in Figure 47 and Figure 48. This suggests that the elemental analyser would be unable to reliably identify a difference between products.

5.5 Conclusion

Three methods proposed for chemically fingerprinting cladding products were assessed against three common cladding products, mineral wool insulation, phenolic foam insulation (phenolics) and polyisocyanurate foam insulation (PIR). These methods were Fourier-transform infrared spectroscopy (FTIR) , microscale combustion calorimetry (MCC) and elemental analysis of Carbon, Hydrogen, Nitrogen and Sulphur content (CHNS).

FTIR is an analytical technique used to identify and quantify the chemical composition of materials. It measures the absorption of infrared radiation by a sample at different wavelengths, producing a spectrum that represents the molecular fingerprint of the sample.

Samples can be compared by analysing the position and intensity of different absorption peaks in each spectrum. The position of the peaks identifies the presence of certain chemical bonds or functional groups, while variations in peak intensity reflect differences in concentration. The overall pattern and shape of the spectra can indicate differences in material composition. FTIR matching software can assist with comparing spectra.

Using these principles, FTIR was able to distinguish between different cladding materials and different products made from the same material. This was demonstrated both manually and using matching software.

It was shown that the level of absorption at different wavelengths can vary between tests based on factors such as sample thickness. However, the ratio of certain peaks can remain consistent regardless of these factors. This was demonstrated using the trimer ratio for PIR foams, showing how absorbance ratios can be used to produce consistent values for comparing samples across different laboratories, with different ambient conditions, sample preparations, and equipment.

MCC measures the heat release rate of a sample during combustion. The sample undergoes a controlled heating process, leading to pyrolysis, where it breaks down into smaller volatile molecules. This can occur in an inert environment with nitrogen, known as anaerobic pyrolysis, or in an atmospheric environment, known as aerobic pyrolysis. The pyrolysis gases are then transferred to a combustion chamber and mixed with a known quantity of oxygen to measure the heat release rate. If the sample's mass is known, this technique can calculate the heat of combustion of a sample in kJ/g. The resulting data provides insights into the material's flammability and combustion characteristics, with the heat release rate curve helping to identify the temperatures at which significant combustion occurs and the intensity of the heat released.

For example, the PUR sample did not show a significant difference in the heat of combustion when pyrolyzed aerobically or anaerobically. However, all other samples did. When samples were tested anaerobically (pyrolyzed without oxygen), MCC was able to differentiate between common insulation products, identifying products from the same manufacturer as similar and distinguishing between similar products from different manufacturers.

MCC tests were conducted in triplicate, and the results were averaged. A Monte Carlo simulation suggested that this method was sufficient for differentiating between products with an accuracy of ±1.08 kJ/g at a 95% confidence level.

The CHNS elemental analyser measures the elemental composition of sample in terms of its carbon (C), nitrogen (N), hydrogen (H), and sulphur (S) content.

The elemental analyser could identify a difference between PIR, phenolic and mineral wool. However, it could not clearly identify between a PIR and PUR and failed to differentiate between PIRs. This method was therefore considered redundant. A recent study found that the device's recognised accuracy of

±0.4%, for pure samples, is frequently not attained [97]. The study revealed that the device's inaccuracies are greater than previously recognised.

There could be some confidence that no significant changes had been made to a product's composition or processing conditions if FTIR was unable to detect the presence of new substances, or the loss of existing substances and the MCC results were within 1.08 kJ/g of the expected value. It should be noted that minor changes to the ratio of raw materials may not be detected with confidence by the FTIR and may still fall within the accepted range of MCC values.

Further research should be conducted on the variation of results for each material over manufacturing batches and with ageing of samples, both in laboratories and on buildings. An investigation should also be conducted to identify how the heat release rate measured during both aerobic and anaerobic MCC compares to the heat release rate during a full-scale cladding system fire.

6 Development of Fire Test Method and Assessment Method

6.1 Test Standard Development

The findings of the literature review, analysis of BS 8414 tests and material characterisation testing where collated and analysed. This section explains how those findings were used to develop a new test standard which specified new requirements for the test construction, fire load, instrumentation, test conditions, reporting requirements and performance criteria. The development was constrained by a requirement to ensure the test could be conducted in accordance with BS 8414 and would still be eligible for a BR 135 assessment.

The proposed test standard was called RISC 501 – Fire Safety Assessment Test for External Cladding Systems and is presented in Appendix B. The new requirements from RISC 501 are presented and explained below.

The main differences between RISC 501 and the BS 8414 test method are:

- Additional design requirements affecting floor heights and cavity barrier locations.
- Additional design requirements affecting detailing around the burn chamber opening and edges of the test rig.
- Additional service penetration requirements.
- Additional material characterisation requirements.
- Different thermocouple locations.

The main difference between RISC 501 and the BR 135 assessment criteria are:

- Different thermocouple criteria.
- Additional gas sampling requirements.
- Additional mechanical performance requirements.

6.2 Scope of RISC 501

The scope of the test standard was dictated by the scope of the project, presented in section 1.2 of this thesis, most notably:

- The test standard should support both property protection and life safety in buildings where compliant cladding systems are installed.
- The test should be capable of conferring compliance with the criteria of BR 135

In order for the test to confer compliance with BR 135, the test must also confer compliance with BS 8414. This constrained features such as the fuel load, preventing them from being altered.

The scope is therefore similar to BS 8414's scope with additional reference to property protection.

6.3 Design Requirements

6.3.1 Virtual Building

A virtual building was created for cladding systems to be designed against, shown in RISC 501 - Appendix A. This specified locations for suspended ceilings, concrete floor slabs floor heights and a window opening.

The virtual building does not need to be physically built. It exists to provide criteria for the cladding system to be designed against. A cladding system will vary between buildings as it needs to adapt to different features like floor heights. It was decided that for test results to be comparable and repeatable, cladding systems should be designed against the same building.

This was introduced to primarily prevent the variation in the location and number of horizontal cavity barriers used, identified in section 4.4.3.9 on page 26 of this thesis. Most systems use the design principle of one horizontal cavity barrier per floor, as recommend by ADB [11, 12]. Without the floor heights being defined, this led to significant variation in the location and number of horizontal cavity barriers being used between BS 8414 tests.

The virtual building defines the floors heights, leading to consistency between horizontal cavity barrier placement between tests. The floor-to-floor height of 3150 mm was chosen for three reasons:

- It was reasonably within the range of storey-storey heights identified in a study of building height by the Westminster City Council [98].
- It allowed for multiple stair rises in compliance with Approved Document K [99] when using standard 215 mm blockwork with 10 mm of mortar. It is desirable for the blockwork to align with the stair rises between floors and 3150 mm allows for 14 blocks to align with either:
  - 21 Rises at 150.00mm
  - 20 Rises at 157.50mm
  - 19 Rises at 165.79mm
  - 18 Rises at 175.00mm
  - 17 Rises at 185.29mm
  - 16 Rises at 196.87mm
- 3150 mm positions a floor between the maximum flame height from the wooden crib and the critical thermocouples for assessing fire spread so that if cavity barriers are used their effectiveness for preventing fire spread between floors can be assessed.

6.3.2 Combustion Chamber Opening

The combustion chamber opening was defined by the virtual building as a window opening. A cladding system must consider it's detailing around openings and will have different solutions for different types of openings. By defining the opening as a window, it encourages consistency between the detailing used between tests. For example, systems complying with ADB would surround the window opening with appropriate cavity barriers [11, 12].

This criterion notably prevents the common practice of unrealistically surrounding the combustion chamber opening with a welded aluminium pod as identified in section 2.3.3 and 4.4.3.12. The protection around the combustion chamber opening must now be representative of how window openings are intended to be protected on real buildings.

6.3.3 Edges of Test Rig

No detailing is permitted at the edges of the test rig. The test rig must be modelled as a continuous flat surface and shall not be sealed around the external edges.

This criterion was included to prevent cladding systems from overprotecting around the edges, choking the cavity of fresh air and artificially influencing system fire performance. It also introduces consistency between tests as previously the edges have either been fully sealed or not sealed at all as identified in section 4.4.3.13.

6.3.4 Service Penetrations

A specific hazard was identified from section 4.4.3.2 due to the frequency of robust non-combustible façades being used to protect combustible insulation. If the façade was compromised, this would expose the combustible insulation behind, resulting in worse fire performance.

One notable hazard is the inclusion of a service penetration as Approved Document B does not require protection around penetrations through a building's façade. It was therefore decided that the influence of penetrations should be considered when assessing the fire risk presented by a cladding system.

It was decided that RISC 501 should not be a test of the protection around service penetrations as more appropriate tests for that exist such as EN 1366-3:2021 and BS 476-20:1987.

The criteria for RISC 501 therefore state that if unprotected vents are permitted in the system design, then the fire test must include a 100mm Ø PVC vent.

If the system design principles state that vents must be fire protected, then that fire protection should be tested via the appropriate test method, such as BS 476-20:1987 and a service penetration need not be included in a RISC 501 test.

The design of the service penetration in RISC 501 is intended to replicate a tumble dryer extract duct. This vent is to be located 600±100 mm above the combustion chamber opening, placing it in the void above the suspended ceiling on the virtual building, where an extract duct might be located.

BS 8414:2020 specifically states that it does not test ancillary penetrations [13, 14] and it was identified that test houses may choose not to accept any test specimens which incorporate penetrations. However, BR 135 is only valid for BS 8414:2015+A1:2017, which does not reference penetrations in this sense. Therefore RISC 501 can still confer compliance with BR 135 if a service penetration is included.

6.3.5 Cavity Barriers

If cavity barriers and fire breaks are required for system performance, they must be installed with the system's design principles applied against the virtual building in RISC 501 – Appendix A.

If the design principles require one horizontal cavity barrier per floor, then they must be installed at locations appropriate for the virtual building, 3150 mm apart as discussed in 6.3.1.

6.3.6 Material Characterisation

During Stephanie Barwise QC's opening statement to the Grenfell Inquiry on the 5th of November 2020 she accused some of the manufacturers for the products used on the Grenfell Tower's external cladding of abusing test regimes. They were accused of concealing components in a manner designed to facilitate a pass and/or using materials that were not as described in test reports, such as supplying test reports for a more fire-retardant version of the product [100].

A method for material characterisation was therefore developed to identify if any significant changes had been made to a product's composition or processing conditions. The research presented in section 5 identified that this could be achieved by taking samples of each significantly combustible component and testing them using Diamond-Attenuated Total Reflectance-Fourier Transform Infra-Red spectroscopy (D-ATR-FTIR) and Microscale Combustion Calorimetry (MCC).

RISC 501 excludes non-combustible components from material characterisation, defined as components which meet classification A1 or A2 s1 d0 when tested to BS EN 13501-1. These are excluded because the methods developed for material characterisation were intended for combustible products and do not perform as intended with non-combustible products.

This exclusion also reduces the number of samples required to be taken, so that material characterisation can be a realistic and achievable requirement. The number of samples required is further reduced by the requirement to exclude components which are exempt from regulation 7(2) as noted in Approved Document B so that only the significant combustible elements are tested, such as the insulation product.

Non-combustible products can easily be retested to elements of BS EN 13501-1 if concerns arise. For example, the bomb calorimeter test BS EN ISO 1716, which was used as screening test for combustible ACM products when concerns arose over their fire performance after the Grenfell Tower fire.

To prevent test sponsors from providing a product for material characterisation that was not used on the test rig, the samples must be selected at random by the test house.

6.4 Classification Criteria

6.4.1 Temperature Criteria

A thermal analysis study suggests that most external cladding materials decompose below 500°C. The most common combustible rainscreen insulation material for systems subjected to a BS 8414 test is PIR, as identified in section 4.4.3.1. PIR, decomposes between 280°C-590°C with no residue left after 600°C [52]. That study therefore used 500°C as the maximum permissible temperature.

'Fire behaviour of modern façade materials' demonstrated that the peak decomposition temperature of the polymeric fuel is always close to 500 °C and the peak heat release for PIR occurs between 300°C to 400°C [54].

An impact analysis was conducted on the database of 61 x BS 8414 tests to assess the impact of using 500°C as the maximum temperature criteria. It was discovered that 15 out of the 61 systems would fail to meet it, with three of these being non-combustible systems which hadn't visually supported fire spread. It would be exactly the same outcome if 500 + 2At was used as the failure criteria (At being Ambient temperature and 2At is based on the findings in section 4.4.4.1).

The aim of the temperature criteria is to identify vertical fire spread up the cladding system across multiple floors. The impact of using 500°C as the maximum temperature criteria would not comply with the aims of RISC 501 as it would result in a non-combustible system failing to meet the fire spread or temperature requirements. This would therefore be an inappropriate criterion with the current thermocouple locations used by BR 135, as it would incorrectly identify fire spread through systems which were incapable of supporting fire spread.

An impact analysis was also conducted to identify the impact of different time periods, for the temperature criteria, on system performance. BR 135 currently assesses temperatures over a 15 minute period after the test 'start time' [7]. LPS 1581/2 assess over a 30 minute period [48, 49]. The BS 8414 test is 60 minutes long [13, 14].

If temperatures were assessed over a 30-minute period from ignition, instead of 15 minutes, then seven additional systems would fail to meet the maximum temperature criteria. One of those systems being considered non-combustible and hadn't visually support fire spread. It would be the same result if temperatures were assessed over a 60-minute period, for the entire test.

Therefore, increasing the temperature duration to 30 minutes or more could result in non-combustible systems, which hadn't supported fire spread, failing to meet the temperature requirements.

The average flame height once a BS 8414 crib has become fully involved, 15 minutes after ignition, during tests on non-combustible systems was identified in Table 8, page 37. The flame height from the wooden crib averages 6 m from the test facility floor. This is relatively close to the thermocouples used for assessing the BR 135 temperature criteria, which are located 7 m above the test facility floor. The proximity led to concerns that the thermocouples might be too close to the wooden crib.

The test is not designed to assess non-combustible systems as BS EN 13501-1 already fulfils this purpose on a much smaller scale. The test is therefore designed to assess combustible systems for their ability to promote or prevent fire spread. Due to proximity of the BS 8414 thermocouple locations, BR 135 is only able to assess fire spread over a 1 m distance from the top of the flames from the wooden crib. This makes the criteria more of an assessment of whether the cladding system contributes to the total heat release rate and less an assessment of whether the cladding system supports vertical fire spread, beyond cavity barriers, to multiple floors.

The proximity also means that it is possible for a non-combustible system to fail to meet the BR 135 temperature criteria, as Kingspan demonstrated in 2018 [37].

The BS 8414 level 3 thermocouples, which are higher up, showed good correlation with fire spread as shown in section 4.4.5.3. Where no systems measuring under 400°C failed to meet BR 135 and all systems over 400°C, at the level 3 thermocouples, failed to meet BR 135.

The findings suggest that:

- To prevent systems which haven't supported fire spread from failing, the thermocouples need to be located higher.
- To correctly identify systems which promote fire spread, the temperature criteria need to be lower over a longer time period.

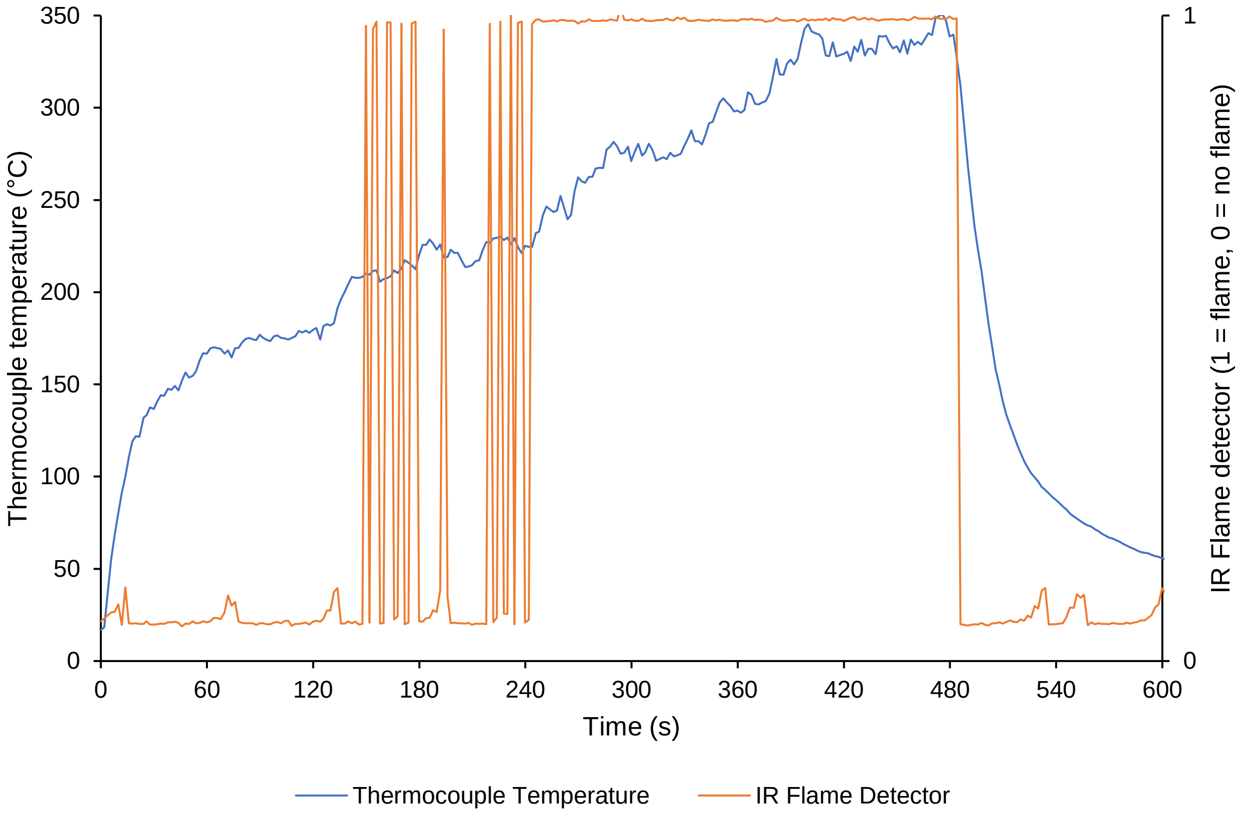
It was therefore decided to raise the thermocouple locations from 5 m above the burn chamber, to 6 m above the burn chamber for RISC 501. 6 m being the furthest thermocouples can be from the burn chamber, while still complying with the minimum test rig height requirements of the 2015 version of BS 8414.

It was also decided that thermocouples should remain below 500°C + 2 At, where At = Ambient temperature.

Different methods for measuring the temperature or rate of heat transfer were considered. Plate thermocouples and heat flux sensors are notably harder to install as they cannot be installed retrospectively and must installed with each layer of the system.

An infrared flame detector was also tested on a mineral wool system with a 50 mm cavity. It detected flames in the cavity at temperatures between 200-300°C as shown in Figure 49. This is below the ignition temperature of some cladding materials [52] and it was decided that further research outside the scope of this study was required to investigate the application of infrared flame detectors further.

Figure 49 – The correlation between thermocouple temperatures and an Infrared Flame Detector in a 50 mm cavity as the flame height is gradually increased



6.4.2 Visual Observations

An additional requirement was included in the test setup for a classification line to be marked 6000 mm above the combustion chamber opening so that it is clearly visible on the video recording. Alternatively, it is acceptable for the top of the rig to be used as the test classification line if it is located 6000 mm above the combustion chamber opening.

If flames extend beyond this point, visually, the system is not eligible for classification and the test may be terminated.

6.4.3 Mechanical Performance

There are no mechanical performance criteria specified in BR 135 [7]. LPS 1581/2 requires there to be no collapse of the system or part thereof, whether flaming or not onto the floor of the test facility outside the designated crib collapse zone, within the duration of the full 60-minute test period [48, 49].

If this criterion was used in BR 135, an additional 8% of systems would fail to meet the criteria according to the findings of section 4.4.5.2. All of those being rainscreen systems with a combustible PIR or Phenolic insulation and a metal panel façade.

One of the stakeholders for the European approach to assess the fire performance of façades highlighted the relevance of using the impact limit for firefighting helmets, for the mechanical performance criteria [101].

In the UK firefighting helmets are tested to BS EN 443:2008 where a 5 kg blunt weight and 1 kg sharp weight are effectively dropped from a height of 2 m [102]. With sharp defined as <6 mm thick.

It was not possible to conduct an impact assessment based on this criterion on all tests as the mass of fallen parts was rarely recorded. The five aforementioned tests which failed to meet the LPS 1581/2 mechanical performance criteria but did meet the BR 135 criteria were assessed and displayed in the table below, with all largest fallen parts less than 5 kg highlighted in green and all tests with parts greater than 5 kg highlighted in orange:

Table 20 – Impact Assessment of 5 kg limit for fallen parts

Fallen Part Material	Largest Fallen Part
ACM	12.28 kg
ACM	0.42 kg
ACM	Partial system collapse with no individual significant parts identified
Steel	Multiple steel panels, all in excess of 5 kg
ACM	Partial system collapse with no individual significant parts identified

If a test specimen is at risk of collapse or losing parts dangerously in a way that puts the test house at risk, then a BS 8414 test would be terminated. Any tests terminated prematurely are not eligible for a BR 135 assessment. This means there is technically a mechanical performance assessment that can affect the chance of receiving a BR 135 classification in the current performance based route to compliance. Although it is subjective, not based on the risk to real buildings and the implementation varies between test houses.

The RISC 501 criteria were therefore based on the limits for UK firefighting helmets. The largest part, for each component, which has fallen to the floor should be weighed. The largest part, for each component, which an edge ≤ 6mm, which has fallen to the floor should be weighed.

Parts should be weighed dry and if a part has been observed to break upon impact, it is acceptable to weigh an equivalent piece.

No falling parts should exceed 5 kg. No sharp falling parts should exceed 1 kg, with sharp being defined as any edges which are ≤ 6 mm.

6.4.4 Video recording

RISC 501 states that the cameras shall have a nominal framerate ≥5 frames per second. This is to ensure that the framerate for the cameras is sufficient to identify falling parts.

The Nyquist-Shannon sampling theorem states that in order to capture an event the sampling frequency should be at least twice as high as the frequency of the event [103].

The time taken for an object to fall from a façade can be estimated using the following SUVAT equation [104]:

$$S = ut + \frac{1}{2}at^2 \qquad \textit{Equation 4}$$

Where:
S = displacement (m)
u = initial velocity (ms^{-1})
a = acceleration (ms^{-2})
t = time (s)

Equation 4 estimates it would take 0.64 seconds for an object to fall 2 m, from the top of the burn chamber to the floor, when gravity is 9.81 ms^{-2} and air resistance is ignored.

A camera frame recorded every 0.32 seconds would therefore be required to capture the event. This equates to 3.2 frames per second. This was rounded up to 5 frames per second for simplicity.

It is noted that any parts below the burn chamber may be missed by the cameras.

6.4.5 Gas Sampling

A gas sampling probe should be located (3750±100) mm above the combustion chamber as shown in Appendix B.

- The tip of the probe should be positioned in line with the rear of the test sample.
- The probe should be inserted through a hole, in the rear of the test specimen, made through each internal layer. The hole should not extend through the outer layer.
- The probe should have an internal diameter 8 mm.
- The probe should be sufficiently non-reactive and capable of surviving the duration of the test.

Air should be extracted from the gas sampling probe at a rate of 1 lpm. It should be measured for O_2, CO_2 and CO concentration and they should be recorded at least every 10 seconds.

There are no criteria specified at this point. The purpose of the gas sampling is to enable a comparison between systems and to provide information to those who might need to be aware of a system's potential toxicity in a fire scenario, such as in prisons or hospitals where escape is less easy.

Specific types of gas sensors were not prescribed to avoid obsolescence and encourage competition, innovation and fairness. No criteria were set for the sensors as there are no performance criteria set by the standard at this point.

It is noted that it would not be feasible for a test house to predict and measure all potential gases produced by all potential systems during a fire test. To simplify testing and assess combustion efficiency, it was decided to measure three key gases: O_2, CO_2 and CO. These provide an insight into the combustion efficiency. Incomplete combustion, characterised by a higher CO/CO_2 ratio, increases the risk of toxic byproduct generation [42].

The location of the gas sampling probe was chosen to model a kitchen vent, as this was the chosen scenario modelled in a study of the smoke toxicity of rainscreen facades [42]. The location chosen was the floor above the combustion chamber opening. This was anticipated to be the maximum incapacitation risk from toxic byproducts, to occupants who weren't immediately at risk from the fire. It was located in the ceiling void, where a kitchen vent could be expected to be.

The study of smoke toxicity of rainscreen facades [42] used a kitchen vent with 100 mm ⌀ ducting. It was not possible to mandate a vent and ducting for RISC 501 as BS 8414:2020 specifically states that it does not test ancillary penetrations [13, 14]. Instead, the penetration for the gas sampling probe can be installed through a 10 mm diameter hole, so that it is not more intrusive than the holes typically drilled for thermocouple installation. The hole must not penetrate the outer layer of the cladding system. The hole does have to penetrate all other layers, giving it access to fire effluent from any layer.

6.5 Open Access Results

The test house should publish publicly the details of the system tested with the results of the Test. The following details should be published:

- Company name and contact details
- Unique report reference and date
- Details of the test rig structural frame
- Description of the cladding system including insulation and front panel
- If cavity barriers and/or fire breaks were used
- Classification result

This enables test houses to check if a system has undergone testing multiple times. Systems which have been tested multiple times must meet the classification criteria successfully more times than they fail to meet it, to comply with the limits of application of RISC 501.

7 Large Scale Validation Testing

7.1 Introduction

This study conducted validation tests on two distinct cladding systems according to the proposed test standard, RISC 501, shown in Appendix B. A validation test involves comparing the results of predicted performance with experimental data to verify the accuracy and validity of the prediction. The resultant data was subjected to analysis with the primary goal of critically assessing the proposed standard and making revisions where necessary.

The proposed test method simulates an external fire or a fully developed (post-flashover) fire in a room, venting through an opening such as a window aperture that exposes the cladding to the effects of external flames.

A baseline non-combustible system was compared against a similar combustible system with the aim of identifying:

- Any physical challenges with the implementation of the prescribed test setup, including construction detailing and sensor locations.
- The ability of the test thermocouples to identify flame spread through known combustible cladding systems.
- The ability of the test thermocouples to identify a lack of flame spread through known non-combustible cladding systems.
- The test laboratory's ability to identify mechanical failures.
- The ability to measure a significant difference in the smoke toxicity between a combustible and non-combustible system.

The test method describe a method of assessing the behaviour of non-load bearing external cladding systems, rainscreen over cladding systems and external wall insulation systems when applied to the face of the building and exposed to an external fire. The fire exposure is intended to be representative of an external fire source or a fully developed (post-flashover) fire in a room, venting through an opening such as a window aperture that exposes the cladding to the effects of external flames.

7.2 Deviations

No cladding system was installed on the return wing wall to speed up the installation and turnaround time between tests. While the return wall is necessary for approving cladding systems, as it may impact the fire behaviour, it was not considered necessary for the aims outlined in 7.1. A plasterboard wall was installed on the return wall instead to protect the test facility.

No test report was produced for each cladding system as the tests were not conducted for approval purposes.

No material characterisation was conducted as these tests were not conducted for approval purposes and so there is not a real building to compare the results against.

7.3 Test Setup

7.3.1 Details of the Tests Carried Out

Two tests were carried out in accordance with the proposed test standard RISC 501 – Fire Safety Assessment Test for External Cladding Systems – Draft V0.2.

The tests were conducted at the Fire Protection Association, London Road, Moreton-in-Marsh, Gloucestershire, GL56 0RH and sponsored by RISCAuthority, London Road, Moreton-in-Marsh, Gloucestershire, GL56 0RH. Test 1 was conducted on the 19th of July 2023 and test 2 was conducted on the 4th of August 2023 under the reference number 103353.004. Construction of the test specimen was carried out by FNV Ltd, Office 2, 2A Sidney Road, Beckenham, London, BR3 4QA.

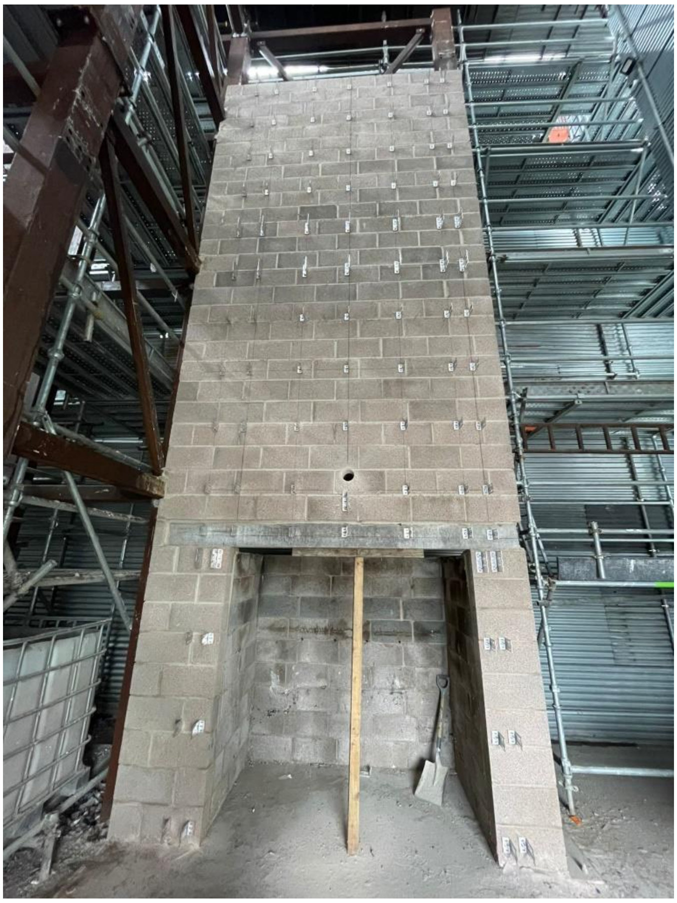
7.3.2 Details of Test Apparatus Used

The test apparatus consists of a steel frame structure that forms a vertical main test wall and vertical return wall at a 90° angle at one end of the main test wall.

A masonry blockwork wall was constructed against the main test wall from 440 mm x 225 mm x 140 mm, medium density, masonry blocks as shown in Figure 50.

The wall was over 8 m in height and over 2.6 m in width, with a 2 m x 2m opening for the burn chamber.

Figure 50 – Photograph of masonry substrate



The burn chamber was built to the following specifications:

Figure 51 – Side elevation of burn chamber

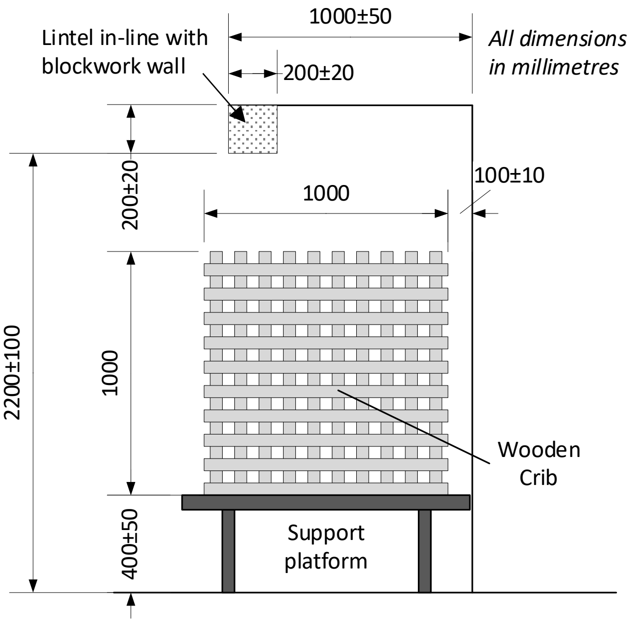
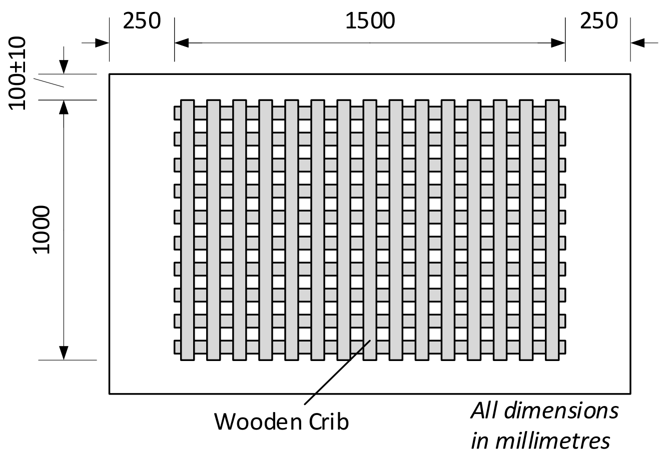


Figure 52 – Plan view of burn chamber



7.3.3 Description of the Systems Under Test

Test 1 comprised of 100 mm thick mineral wool insulation, a 50 mm cavity and a 4 mm ACM façade panel. Test 2 used the same composition with PIR insulation instead of mineral wool.

All mineral wool insulation was provided by Rockwool and all cavity barriers were provided by Siderise. All other components were procured by the test sponsor.

All components are shown in Table 21 and Table 22. All dimensions are shown in Figure 53 to Figure 57.

Photographs of the installation are shown in section 7.3.4.

Table 21 - List of components for test 1

Component	Product	Manufacturer	Product Reference
Brackets	Double Bracket	Ash & Lacy	AXL-HB120D-TP
	Single Bracket	Ash & Lacy	ACL-HB-120S-TP
Rails / Mullions	Aluminium T- Profile	Ash & Lacy	AXL-T60X80X2.2
	Aluminium L-Profile	Ash & Lacy	AXL-L60X40X2.2
Insulation	Mineral wool insulation	Rockwool	Rainscreen Duo Slab
Vertical cavity barriers	Closed state cavity barrier	Siderise	RV 90/30
Horizontal cavity barriers	Open state cavity barrier	Siderise	RH25 90/30
Façade Panels	ACM Panel	Ash & Lacy	Alucobond 4.0mm A2 Ocean (914)
Fixings	Bracket to substrate fixing	Ash & Lacy	R-FF1-N-10K080-A4
	Bracket to rail fixing	Ash & Lacy	SS-LS22
	Panel to bracket fixing	Ash & Lacy	RIV-K11-5-12

Table 22 - List of components for test 2

Component	Product	Manufacturer	Product Reference
Brackets	Double Bracket	Ash & Lacy	AXL-HB120D-TP
	Single Bracket	Ash & Lacy	ACL-HB-120S-TP
Rails / Mullions	T- Profile	Ash & Lacy	AXL-T60X80X2.2
	L-Profile	Ash & Lacy	AXL-L60X40X2.2
Insulation	PIR insulation	Celotex	GA4100
Vertical cavity barriers	Closed state cavity barrier	Siderise	RV 90/30
Horizontal cavity barriers	Open state cavity barrier	Siderise	RH25 90/30
Façade Panels	ACM Panel	Ash & Lacy	Alucobond 4.0mm A2 Ocean (914)
Fixings	Bracket to substrate fixing	Ash & Lacy	R-FF1-N-10K080-A4
	Bracket to rail fixing	Ash & Lacy	SS-LS22
	Panel to bracket fixing	Ash & Lacy	RIV-K11-5-12

The fire ratings for the components used for test 1 and test 2 are listed below, provided by the manufacturer.

Table 23 - Fire rating of components for test 1

Component	Fire Rating
Brackets	None provided. 6063T6 grade aluminium used for bracket with a Nylon P66 pad.
Rails / Mullions	Class A1 to BS EN 13501-1:2018.
Insulation	Class A1 to BS EN 13501-1:2018.
Vertical cavity barriers	90 minutes integrity (E) and 30 minutes insulation (I) when tested to EN 1366-4: 2006+A1: 2010
Horizontal cavity barriers	90 minutes integrity (E) and 30 minutes insulation (I) when tested to EN 1366-4: 2006+A1: 2010
Façade Panels	Class A2 to BS EN 13501-1:2018.
Fixings	None provided. Stainless steel construction with rubber washers.

Table 24 - Fire rating of components for test 2

Component	Fire Rating
Brackets	None provided. 6063T6 grade aluminium used for bracket with a Nylon P66 pad.
Rails / Mullions	Class A1 to BS EN 13501-1:2018.
Insulation	Class F to BS EN 13501-1:2018.
Vertical cavity barriers	90 minutes integrity (E) and 30 minutes insulation (I) when tested to EN 1366-4: 2006+A1: 2010
Horizontal cavity barriers	90 minutes integrity (E) and 30 minutes insulation (I) when tested to EN 1366-4: 2006+A1: 2010
Façade Panels	Class A2 to BS EN 13501-1:2018.
Fixings	None provided. Stainless steel construction with rubber washers.

Figure 53 – Mullion and bracket locations – Front elevation

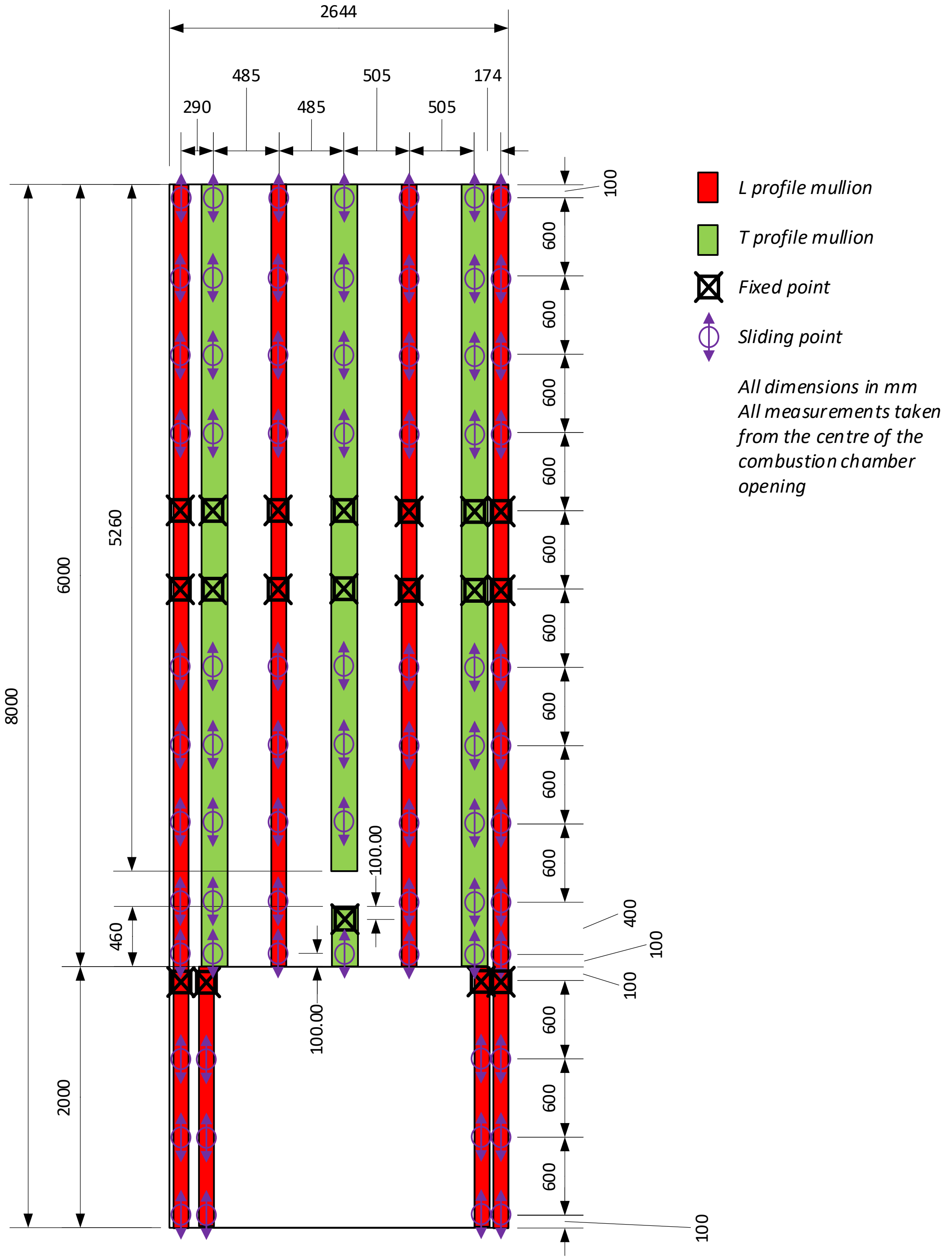


Figure 54 - Cavity Barrier Locations – Front elevation

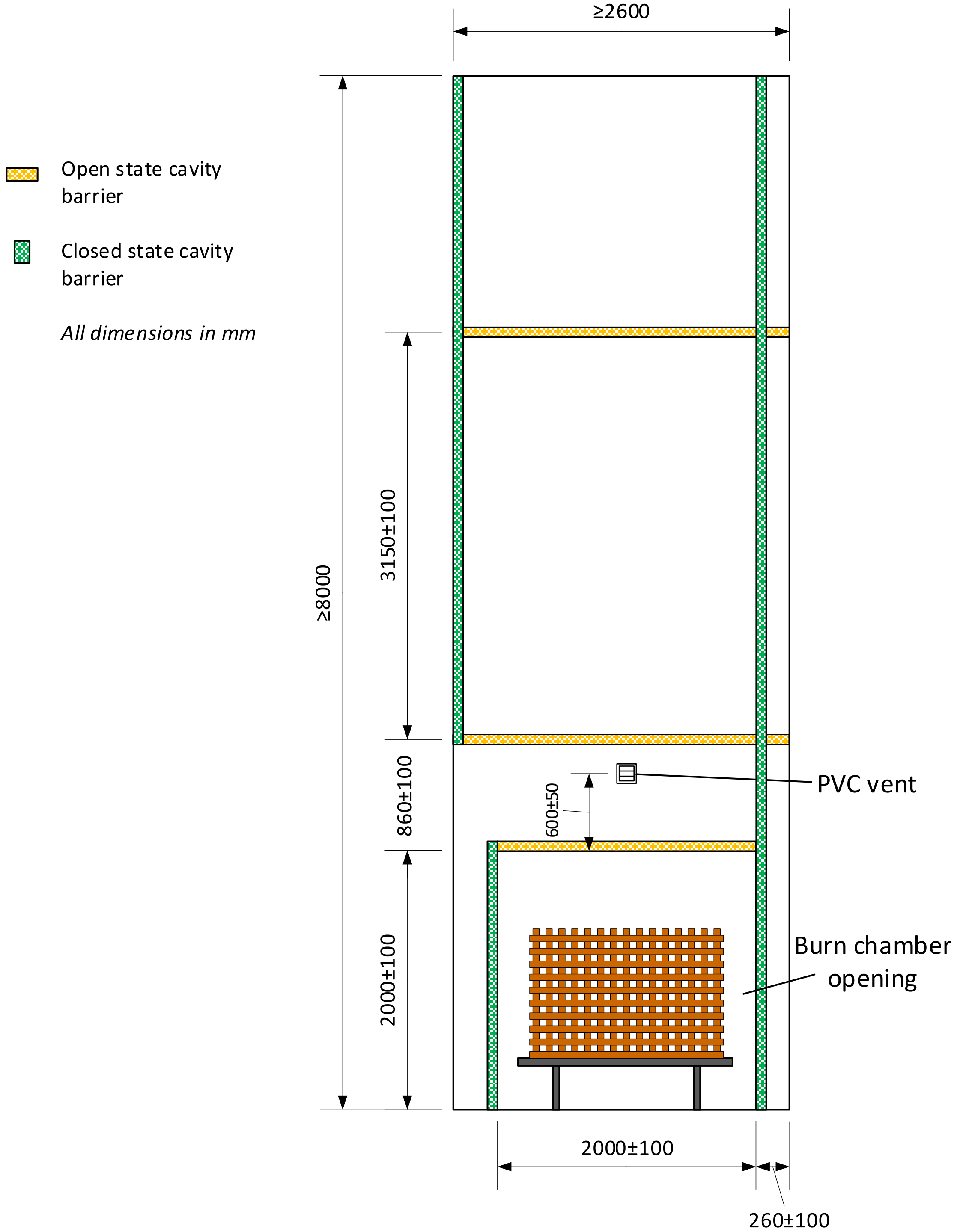


Figure 55 - Insulation and fixings locations – Front elevation

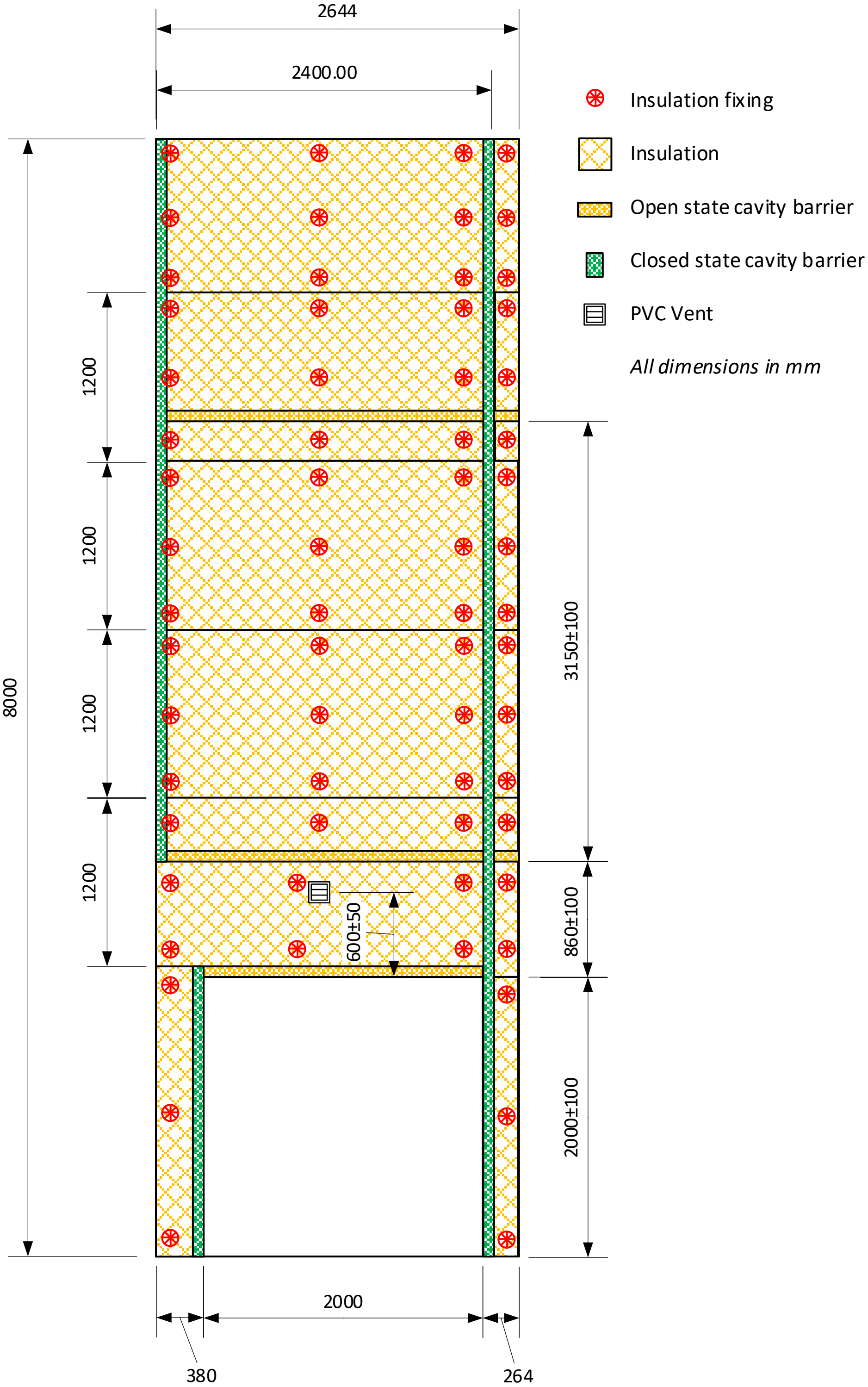


Figure 56 – Façade panel and fixing locations, with cavity barrier locations shown behind – Front elevation

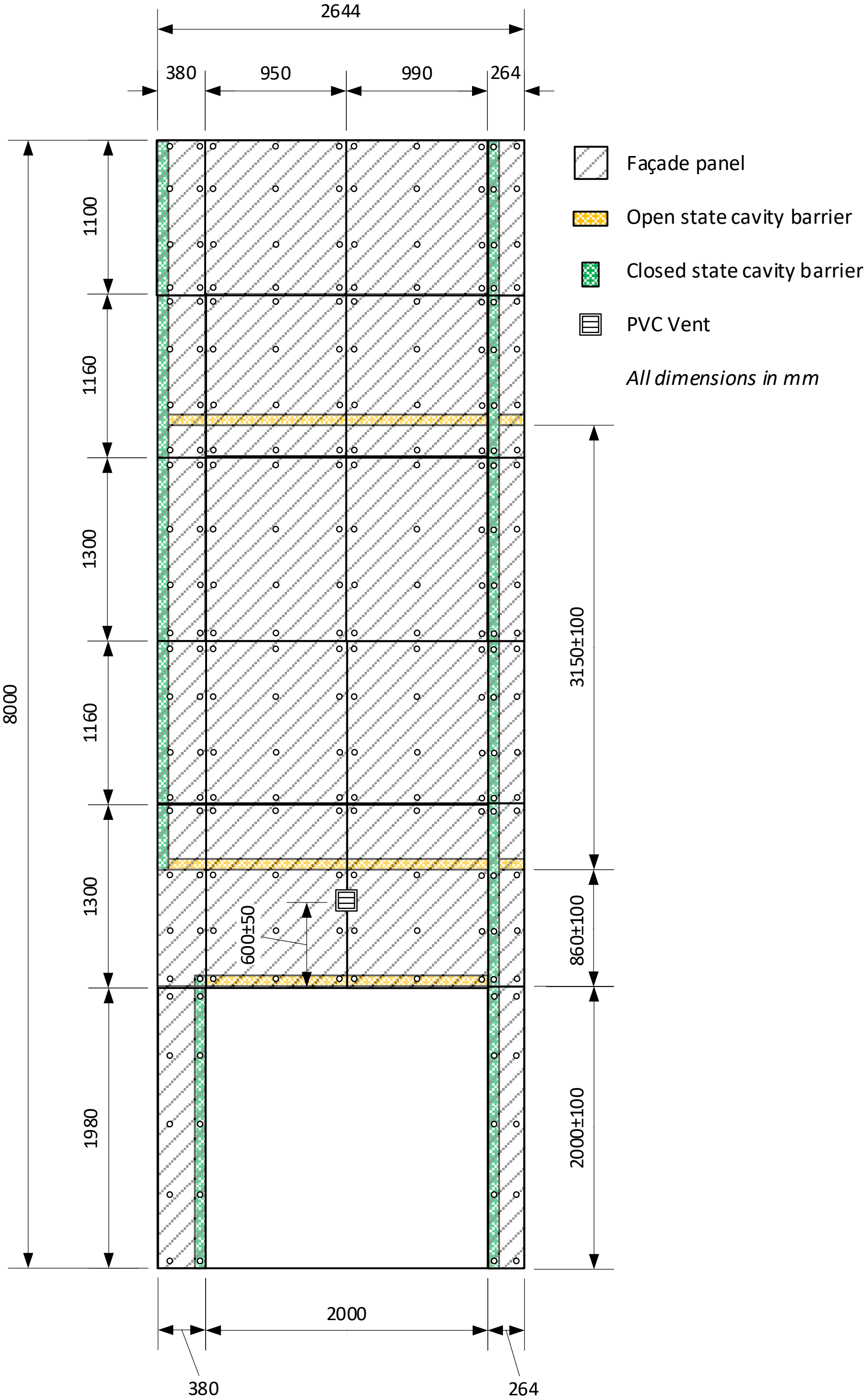
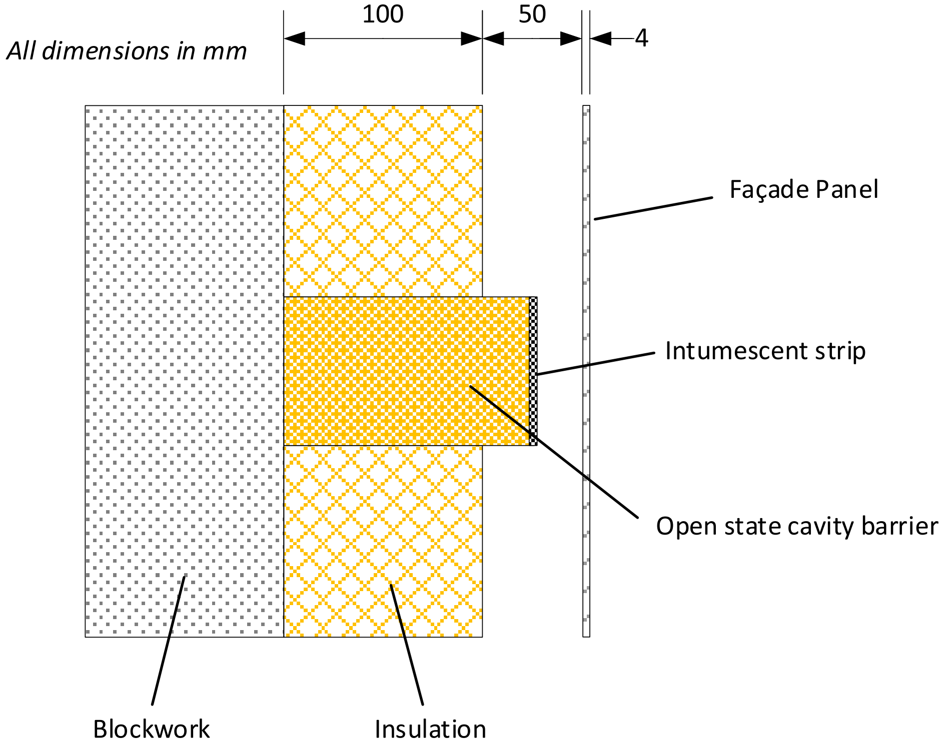


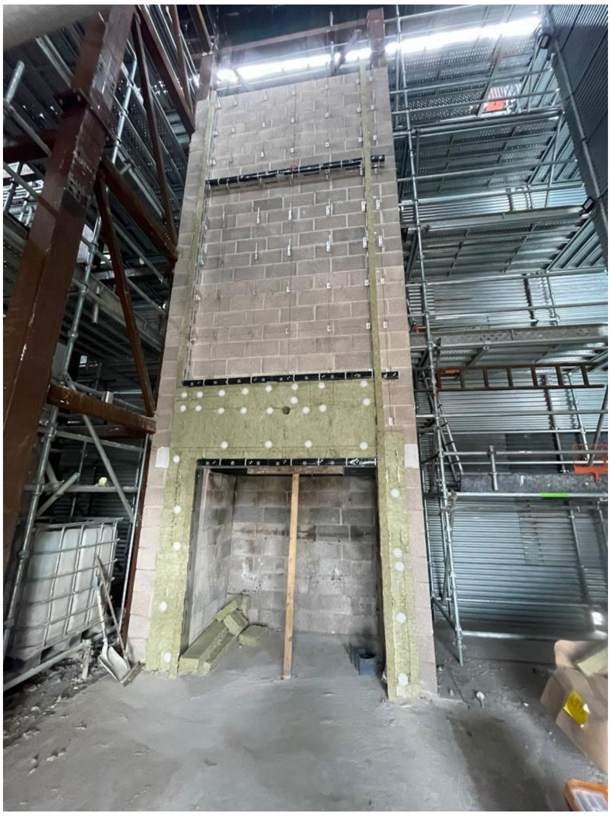
Figure 57 - Insulation, cavity barrier, cavity and façade panel locations - side elevation



7.3.4 Test Specimens

Installation photographs are shown in Figure 58 below.

Figure 58 - Installation Photographs for Test 1 (left) and Test 2 (right)



Test 1 - Horizontal cavity barriers

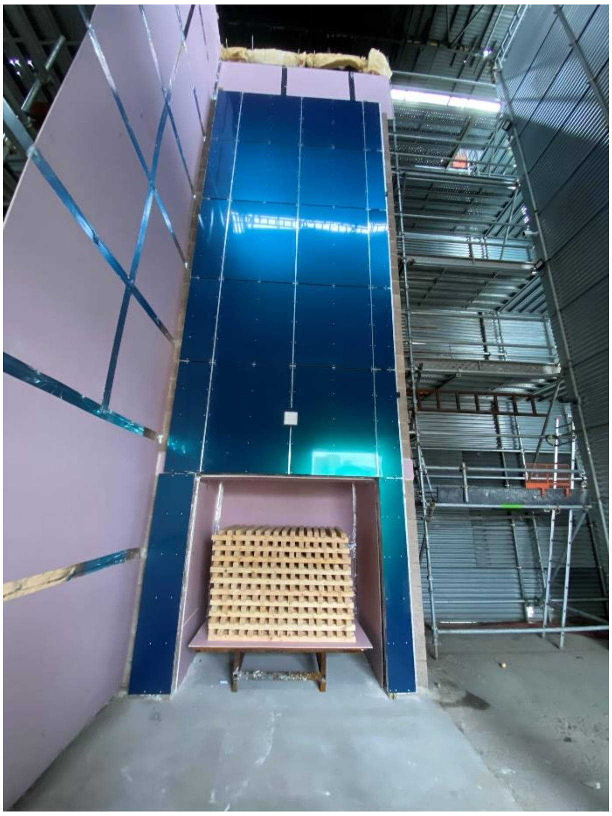
Test 2 - Horizontal cavity barriers

Test 1 - Mineral wool insulation and mullions

Test 2 - PIR insulation and mullions

Figure 59 (continued)

Test 1 - Façade Panels



Test 2 - Façade Panels

Test 1 – Side elevation

Test 2 – Side elevation

For Test 1 the cavity barriers were installed first, then the insulation, then the mullions and then the façade panel. For Test 2 the mullions had to be installed before the insulation because the insulation was too rigid to allow for the mullions to be installed afterwards.

The open state cavity barriers were installed with a 25 mm air gap between the cavity barrier and façade panel as recommended by the manufacturer and demonstrated in Figure 60. Figure 61 and Figure 62 show the detailing around the burn chamber opening, with a closed state cavity barrier on the vertical edges and an open state cavity barrier on the horizontal edge, for both tests. Figure 63 shows how the air gap is maintained from the burn chamber opening to the top of the test rig, for both tests.

Figure 60 - Open state cavity barrier installed with 25 mm gap to façade panel

Figure 61 - Closed state cavity barrier installed on vertical edges of burn chamber

Figure 62 - Open state cavity barrier installed on horizontal edge of burn chamber

Figure 63 - Photograph of cavity extending from burn chamber opening to top of test rig

The top of the test rig was left open for both tests as shown in Figure 64 and Figure 65.

Figure 64 - Test 1 - Top of test rig detailing

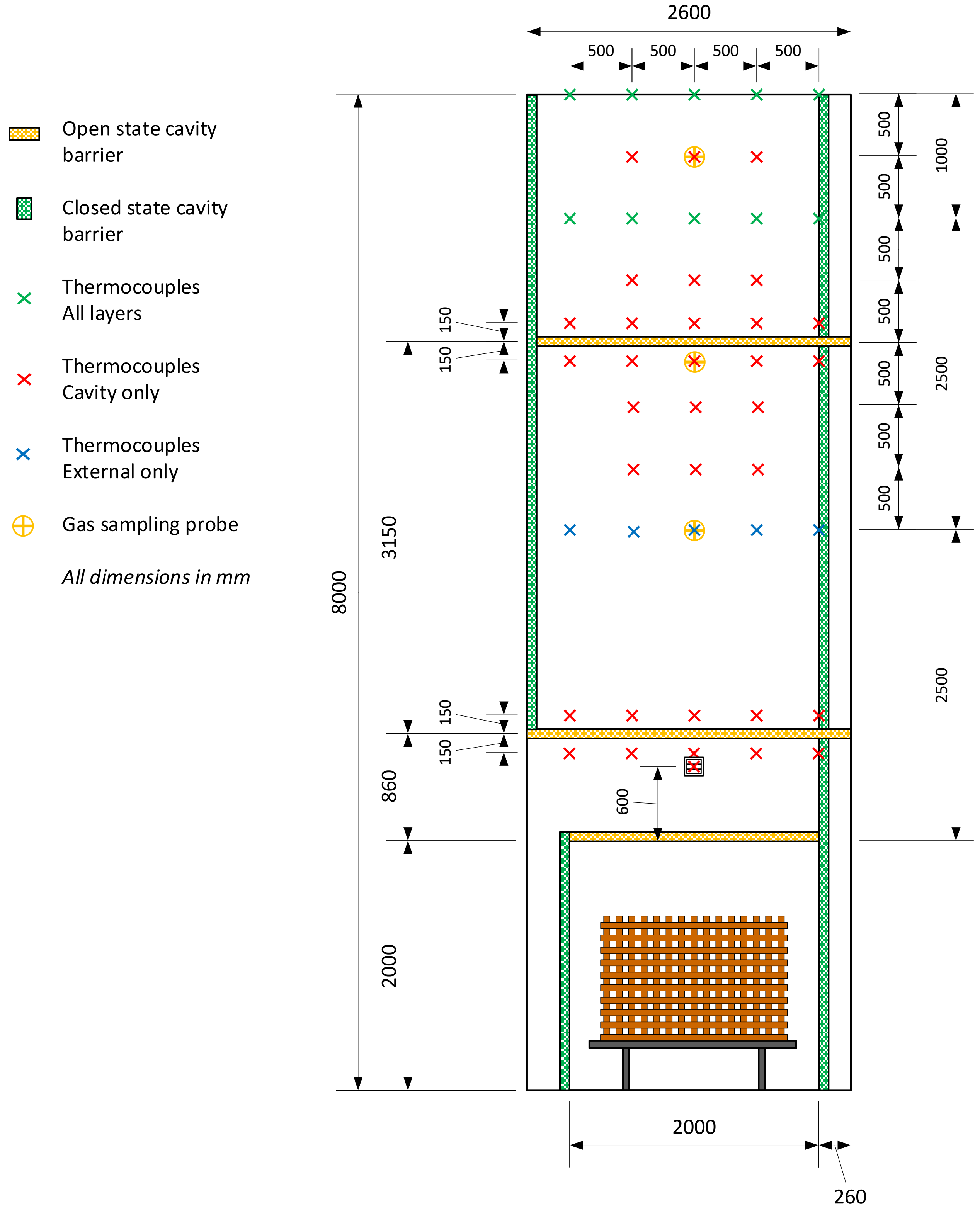
Figure 65 - Test 2 - Top of test rig detailing

7.3.5 Instrumentation

7.3.5.1 Instrumentation locations

The instrumentation and cavity barriers were located as shown in Figure 66.

Figure 66 - Instrumentation locations for validation tests



7.3.5.2 Thermocouples

Thermocouples were positioned as specified in BS 8414-1:2015. External thermocouples were 2500 mm and 5000 mm above the burn chamber opening, protruding 50 mm from the face of the façade. These locations are referred to as Level 1 and Level 2 respectively. Five thermocouples were installed at each level, at 500 mm intervals, with the central thermocouples in line with the centre of the burn chamber opening.

BS 8414-1:2015 also specifies that thermocouples must be installed through every layer more than 10 mm thick, at the Level 2 location. Five thermocouples were therefore installed in the middle of the insulation and five thermocouples in the middle of the cavity at Level 2. A side view of these thermocouple locations is shown in Figure 67.

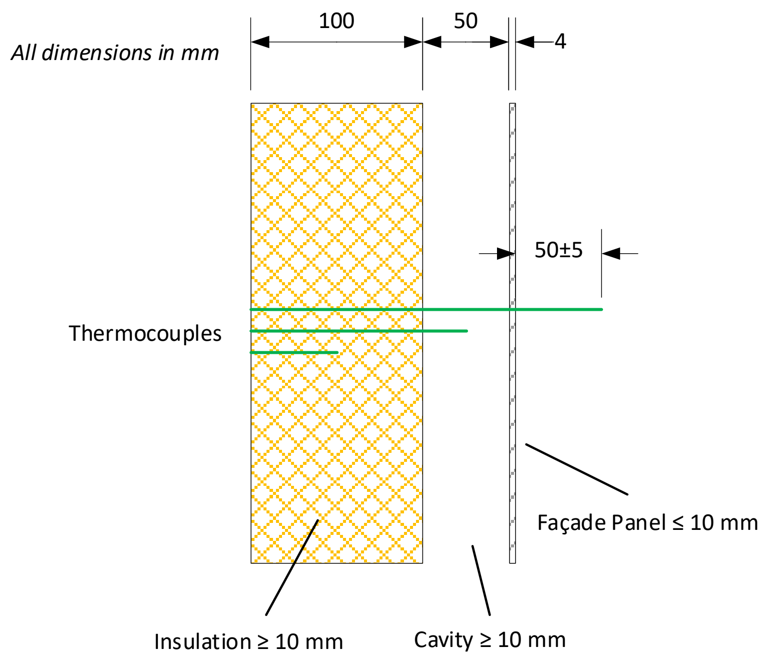
Thermocouples were also positioned as specified in RISC 501. 6000 mm above the burn chamber opening, with five thermocouples in the insulation, five thermocouples in the cavity and five thermocouples protruding 50 mm from the front of the façade. These were spaced 500 mm apart, with the central thermocouples in line with the centre of the burn chamber opening.

For these tests, additional thermocouples were installed to understand the influence of the cavity barriers. They were installed into the middle of the cavity, 150 mm above and below each horizontal cavity barrier, at 500 mm intervals across the width of the cavity. These locations correspond with the locations used by the FPA for their research into the performance of open-state cavity barriers.

To understand the fire spread through the cladding system, thermocouples were also installed every 500 mm vertically, above level 1. Three thermocouples were installed at each level, in the centre of the cavity, in-line with the centre of the burn chamber opening and 500 mm either side. They were not installed if there were thermocouples already there.

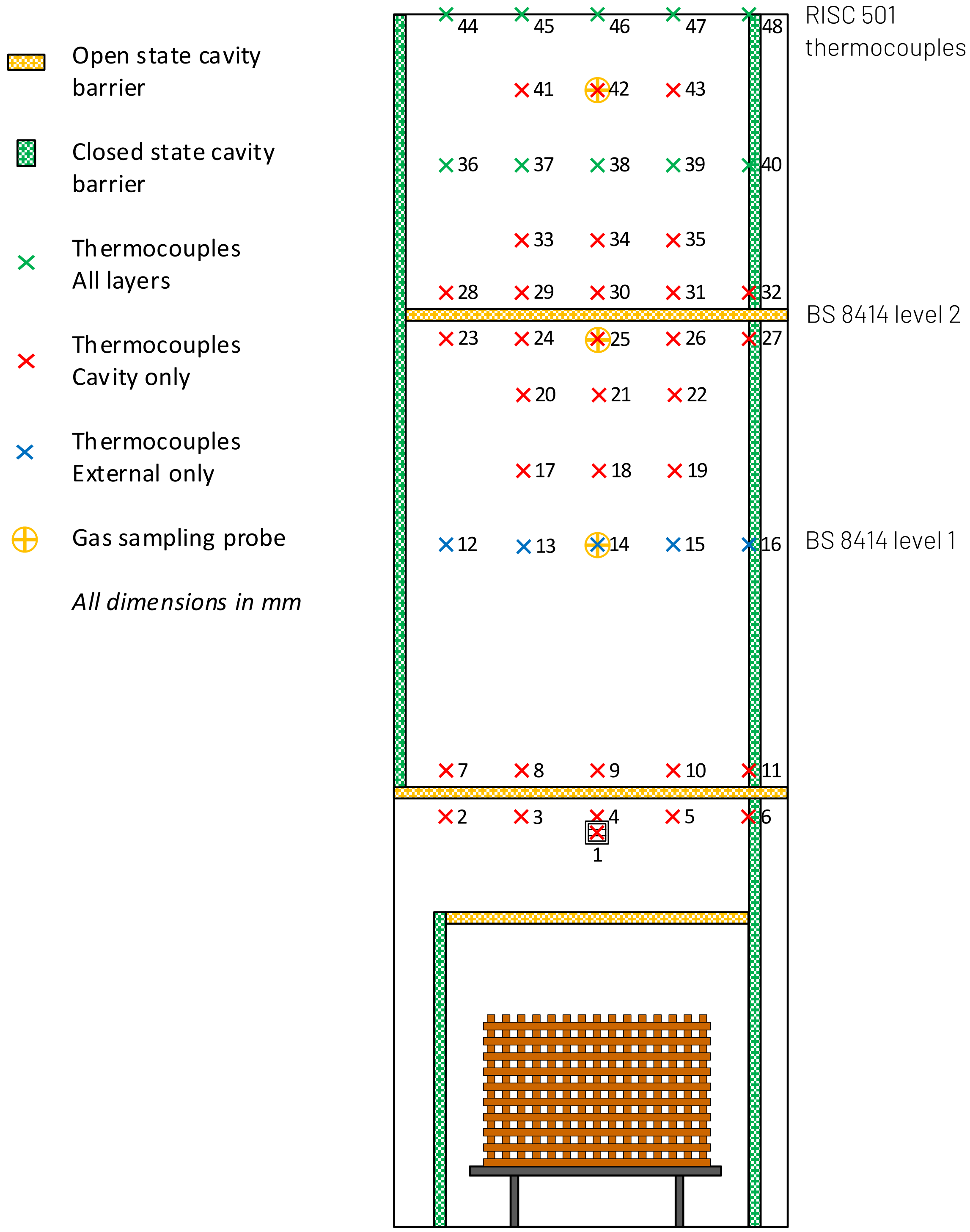
A final thermocouple was installed inside the PVC vent, in-line with the centre of the cavity.

Figure 67 – Side view of thermocouple installation at BS 8414 levels 1 & 2 and the RISC 501 thermocouples (36-40 and 44-48 in Figure 68)



The thermocouples were labelled as shown in Figure 68. At locations 36-40 and 44-48 there were three thermocouples, in the insulation, in the cavity and external located as shown in Figure 67. These were labelled C, B and A respectively such that the external thermocouple at location 36 would be labelled 36A.

Figure 68 - Thermocouple Labels



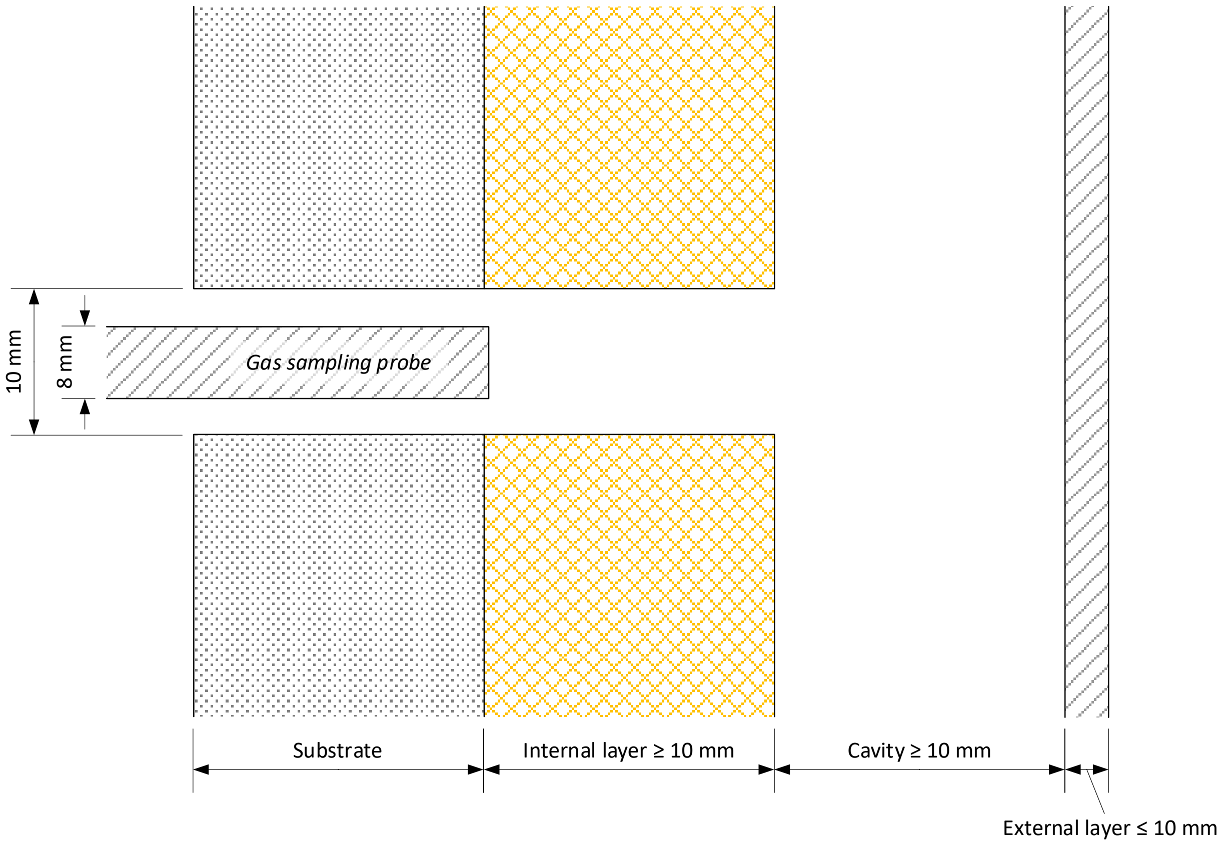
7.3.5.3 Gas sampling

Three gas sampling probes were installed on the test rig as shown in Figure 66.

One was installed (3750±100) mm above the centre of the burn chamber opening as specified in the proposed RISC 501 standard. The other two were installed ~1500 mm above and below to monitor how gas concentration varied, with height, during a fire test.

The gas sampling probe consisted of an 8 mm, inside diameter, coper tube. It was inserted through a 10 mm hole at the back of the test rig. The hole extended through every internal layer, but not the outer layer, as proposed in RISC 501 and shown in Figure 69.

Figure 69 – Gas sampling probe



The gas was analysed using three Andros 6500 NDIR, one for each sampling line. This contained a differential pressure sensor and a Lumisence electrochemical O2 cell as recommended by 'Bench and Large-scale Assessment of Smoke Toxicity' [105].

A 0.3 um in-line HEPA (high efficiency particulate air) filter was used to protect the gas sensors. A glass wool filter, with loosely fitted glass wool, was placed before the HEPA filter to prevent it from becoming blocked with soot during the test.

Gas was extracted using a pump set to a rate of 1 lpm.

7.4 Test Conditions

The ambient conditions and fuel load conditions are shown in Table 25 below.

Table 25 – Ambient test conditions for test 1 and test 2

	Test 1 - MW	Test 2 - PIR
Test Date	18/07/2023	04/08/2023
Ambient temperature	18.6°C	15.3°C
Wind speed	< 0.2 ms^{-1}	< 0.2 ms^{-1}
Fuel load	300 m softwood pinus silvestris 50 mm x 50 mm sticks arranged in a stacked crib	300 m softwood pinus silvestris 50 mm x 50 mm sticks arranged in a stacked crib
Ignition package	16 strips of low-density fibreboard, 25mm x 12mm x 1000mm. Uniformly soaked in 5 litres of white sprit	16 strips of low-density fibreboard, 25mm x 12mm x 1000mm. Uniformly soaked in 5 litres of white sprit
Fuel load wood density	472.8 kg/m^3	494.7 kg/m^3
Fuel load moisture content	14.3%	13.6%

7.5 Test Data

All time is taken from the ignition of the crib.

7.5.1 Video Recording

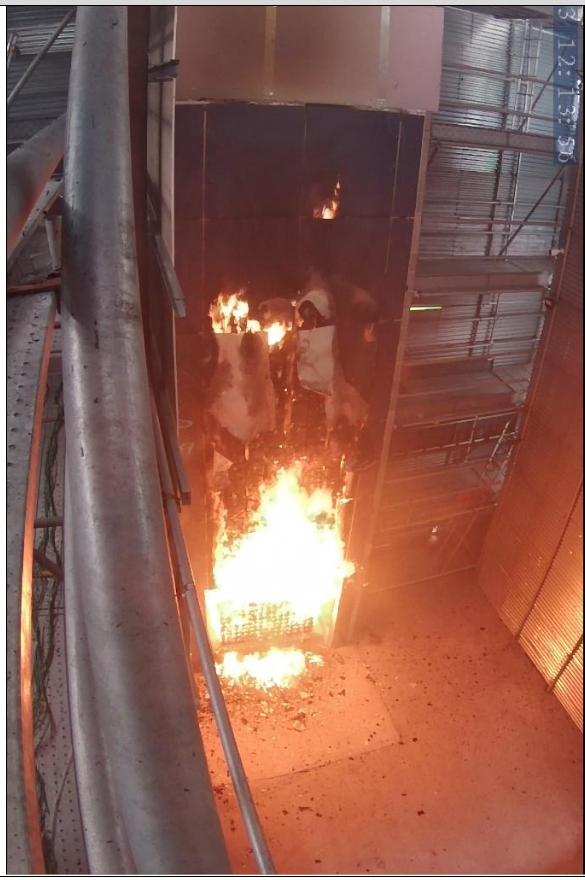
Table 26 shows still images of each test at 5-minute intervals between ignition and 35 minutes after ignition. There were no significant changes after 35 minutes in either test.

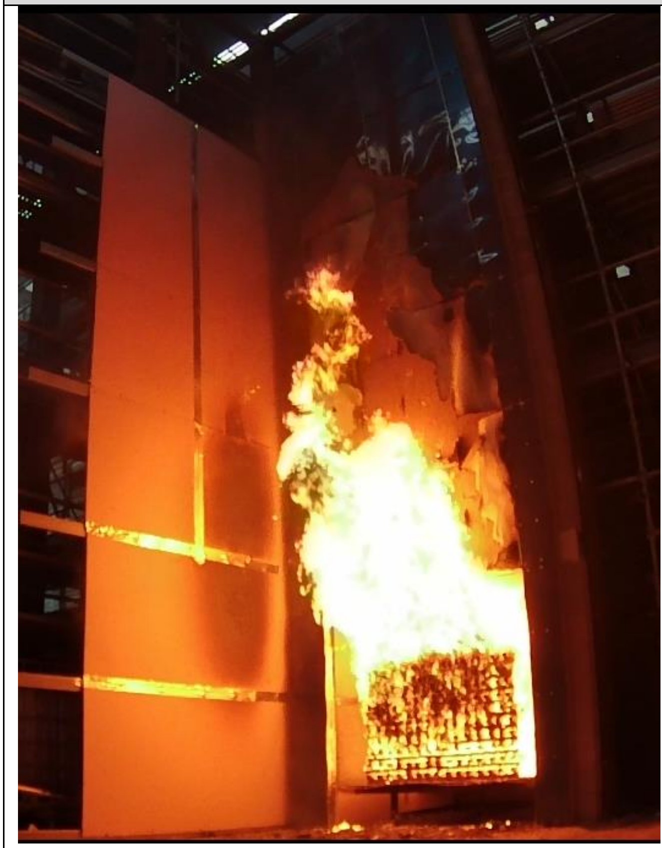
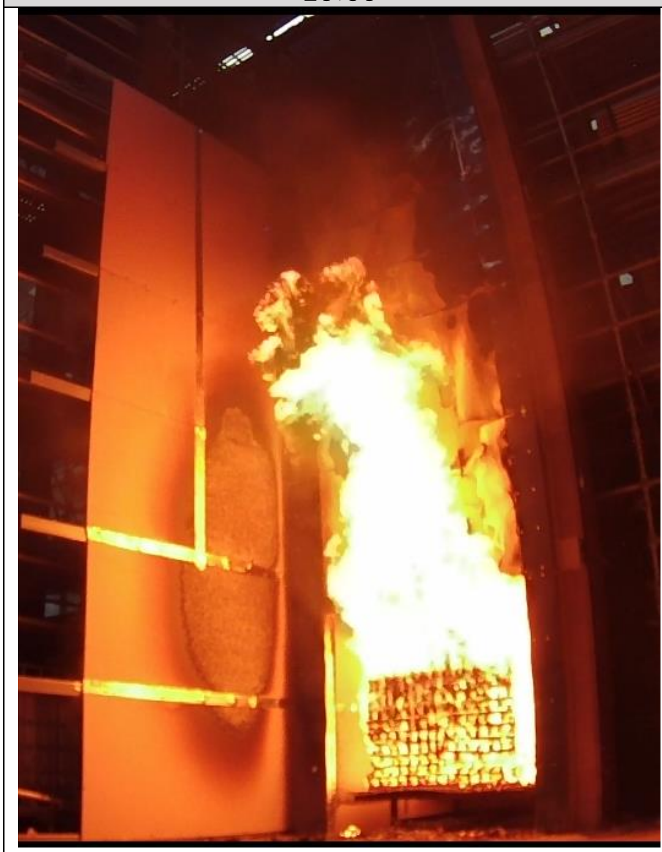
A still image is taken 29 minutes and 50 seconds after ignition, 10 seconds before the wooden crib is extinguished, in accordance with BS 8414-1:2020 [13].

The main camera for test 1 cut out after 20 minutes. The camera was repositioned for test 2 to protect it for the duration of the test.

Table 26 – Test 1 Video Screenshots (time mm:ss)

Test 1 – MW	Test 2 - PIR
00:00	00:00
	

Test 1 – MW	Test 2 - PIR
05:00	05:00
	
10:00	10:00
	

Test 1 – MW	Test 2 - PIR
15:00	15:00
	
20:00	20:00
	

Test 1 – MW	Test 2 - PIR
25:00	25:00
	
29:50	29:50
	

Test 1 – MW	Test 2 - PIR
35:00	35:00
	

7.5.2 Visual Observations

Figure 70 shows the façade panel labels which were used in the visuals observations shown in Table 27 and Table 28.

Figure 70 – Façade Panel Labels

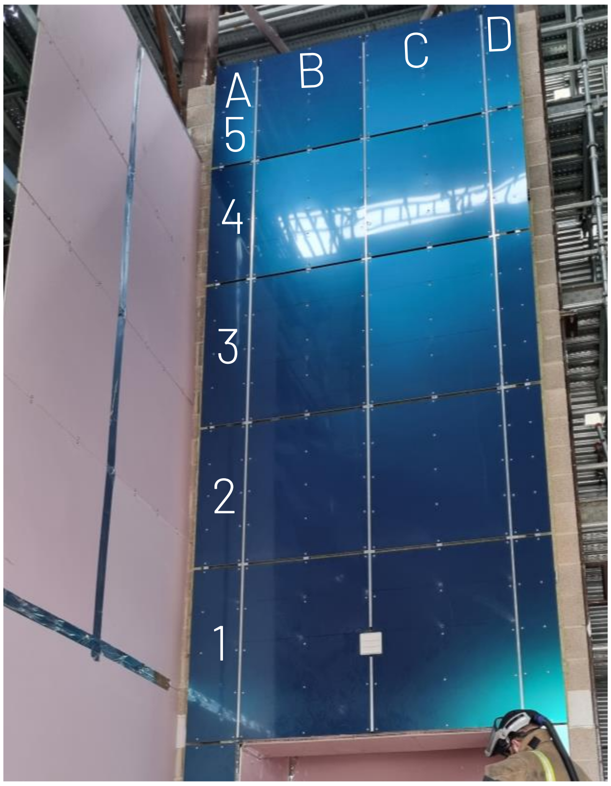


Table 27 – Test 1 Visual Observations

Time from Ignition (mm:ss)	Visual Observation
-06:00	Fibreboard sticks inserted into crib
00:00	Ignition of crib
01:28	Flames tips reach level 1 thermocouples
01:32	Flames behind façade panels B3 and C3
01:34	Flames briefly above top of test rig
01:42	Flames no longer above test rig or protruding out from the burn chamber. Flames still visible behind façade panels
02:00	Flames protruding out from burn chamber and plastic vent ignites
02:00	Façade panels B4 and C4 distorted
03:00	Fallen burning material from vent area
03:30	Façade panels B3 and C3 distorted
04:00	Façade panels B5 and C5 distorted
05:45	Façade panels B1, B2, C1 & C2 melted/burnt away exposing mineral wool
06:30	Pool fire from fallen burning material appears notably larger
12:00	Façade panels B3 & C3 partly melted/burnt away partially exposing mineral wool
12:00	Flaming behind panels D1 & D2
20:34	Main camera cuts out
30:00	Crib extinguished

Table 28 – Test 2 Visual Observations

Time from Ignition (mm:ss)	Visual Observation
-05:30	Fibreboard sticks inserted into crib
00:00	Ignition of crib
01:23	Flames tips reach level 1 thermocouples
01:23	Flames behind façade panels B3 and C3
01:25	Flames briefly above top of test rig
01:45	Plastic vent burnt/melted away
02:00	Flames behind vent
02:30	Fallen burning material from vent area
04:00	Façade Panels B1, C1, B2 & C2 begin distorting
04:30	Façade Panels B1 & C1 melting/burnt away with insulation behind burning
04:45	Flames behind façade panels B1 & C1
05:00	Increase in fallen burning material in front of crib
05:30	Flaming behind panels B1 & C1 protruding in front of panels B2 & C2
06:15	Panels behind flames from crib completely melted/burnt away
07:45	Panels B3 & C3 opening up, revealing insulation behind burning
08:00	Flames behind and above panels B4 & B5 (above second cavity barrier)
11:00	Panel B3 & C3 distort open
12:00	Flames above top of test rig, behind façade panels
12:00	Panels B4 & C4 melting/burning away
12:45	All insulation, above the burn chamber onwards, appears to be burning
16:30	Panel B3 detaches and falls to floor
24:30	Large section of insulation behind panel B3 detaches and falls to the floor and continues to burn
26:00	Plasterboard falls on crib from burn chamber ceiling
30:00	Crib extinguished
30:05	Flaming on fallen material ceased
30:05	Flaming on majority of rig ceased
30:05	Flaming continues behind panels A1-A5 and above A5
35:00	Flaming above A5 ceased, some smouldering combustion continues
39:00	No further combustion visible

It is unknown whether the aluminium melted or combusted. Solidified molten aluminium was not found in significant quantities post-test, implying that some combustion was involved.

7.5.3 Fire Spread and Start Time

Table 29 shows the start time and start temperature, as specified in BS 8414 and BR 135, for Test 1 and Test 2.

Table 30 shows the peak temperature measured by the level 2 thermocouples within 15 minutes of the start time (ts), as specified in BR 135. The level 2 thermocouples are located 5000 mm above the burn chamber opening as specified in BS 8414. Table 30 shows that Test 2 exceeded the BR 135 criteria. It was exceeded 9 minutes and 40 seconds after ignition.

Table 31 shows the peak temperatures measured by the thermocouples located 6000 mm above the burn chamber opening as specified in RISC 501. Test 2 also exceeded the RISC 501 criteria. It was exceeded 12 minutes and 30 seconds after ignition.

Test 1 met both the BR 135 and RISC 501 criteria.

Table 29 – Start temperature and start time

Parameter	Test 1 – MW	Test 2 – PIR
Ts, Start temperature – the mean temperature of the thermocouples at level 1 during the 5 minutes before ignition	18.6°C	15.3°C
ts, Start time – the time when the temperature of any external thermocouple at level 1 equals or exceeds a 200 ˚C temperature rise above Ts, and remains above this value for at least 30 seconds	95 s	85 s

Table 30 – Peak temperatures measured by level 2 thermocouples within 15 minutes of start time (ts)

Location	Test 1 – MW	Test 2 – PIR
Level 2, external thermocouples	420.4°C	635.7°C
Level 2, thermocouples in cavity	432.8°C	856.0°C
Level 2, thermocouples in insulation	60.8°C	706.0°C

Table 31 – Peak temperatures measured by RISC 501 thermocouples within the duration of the test

Location	Test 1 – MW	Test 2 – PIR
RISC 501 external thermocouples	341.4°C	753.3°C
RISC 501 thermocouples in cavity	270.9°C	860.6°C
RISC 501 thermocouples in insulation	87.8°C	907.2°C

The maximum temperatures at the RISC 501 thermocouples are higher than the maximum temperatures at the BS 8414 level 2 locations, despite being 1000 mm further away from the fire. This is because the temperatures are measured over a longer period.

7.5.4 Temperature Criteria

7.5.4.1 BR 135 Criteria

Figure 71 to Figure 76 show data from the thermocouples located at level 2 in BS 8414-1:2020, located 5000 mm above the burn chamber. A dashed line indicating 600+At is also shown, where At = Ambient Temperature. Test 1 is shown on the left and Test 2 on the right.

External Thermocouples

Figure 71 – Test 1 – BR 135 external thermocouples

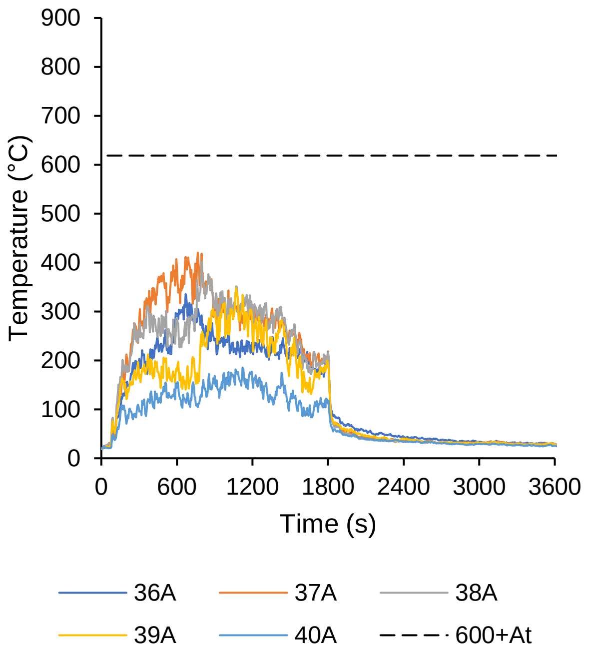
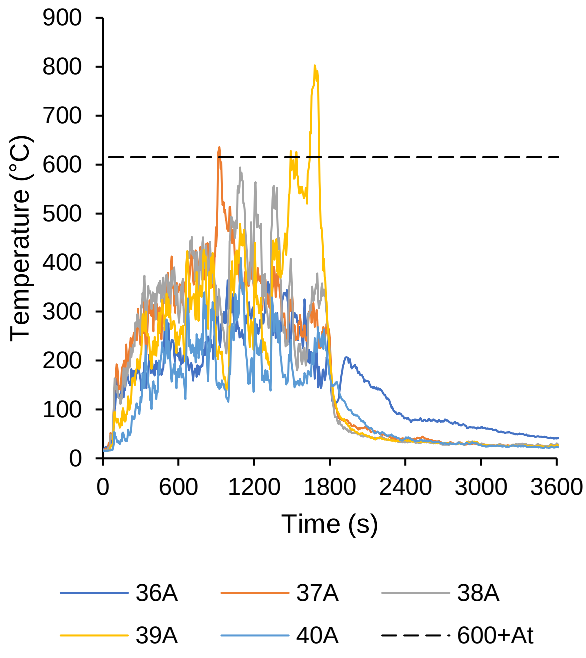


Figure 72 – Test 2 – BR 135 external thermocouples



Cavity Thermocouples

Figure 73 – Test 1 – BR 135 cavity thermocouples

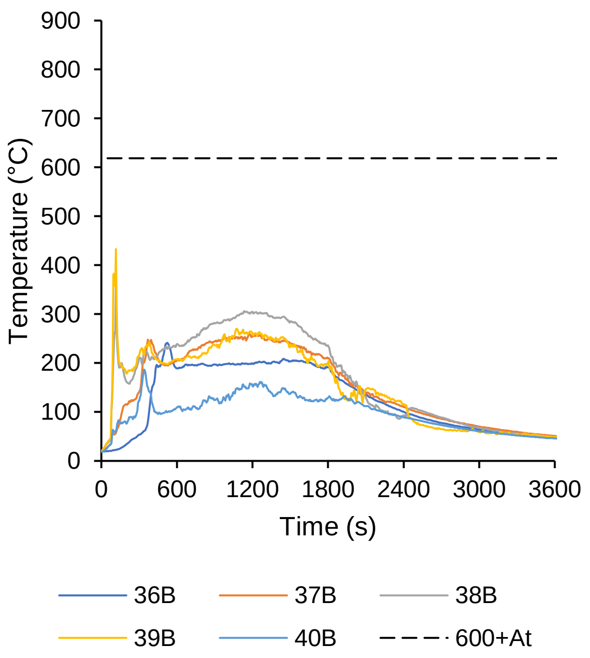
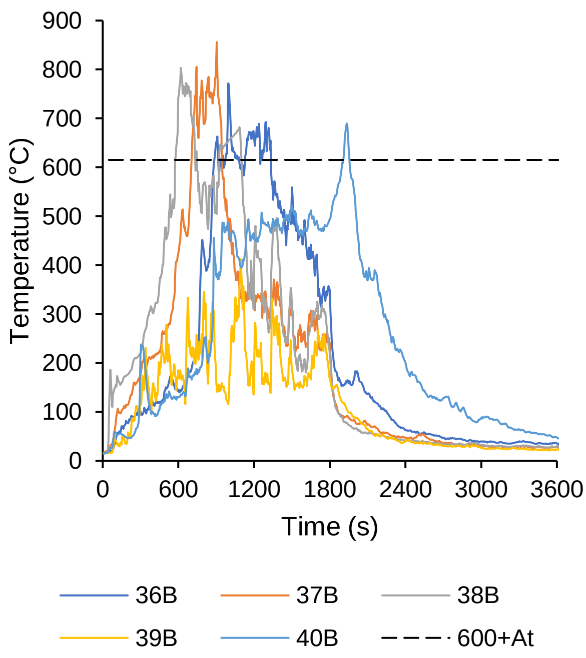


Figure 74 – Test 2 – BR 135 cavity thermocouples



Insulation Thermocouples

Figure 75 – Test 1 – BR 135 insulation thermocouples

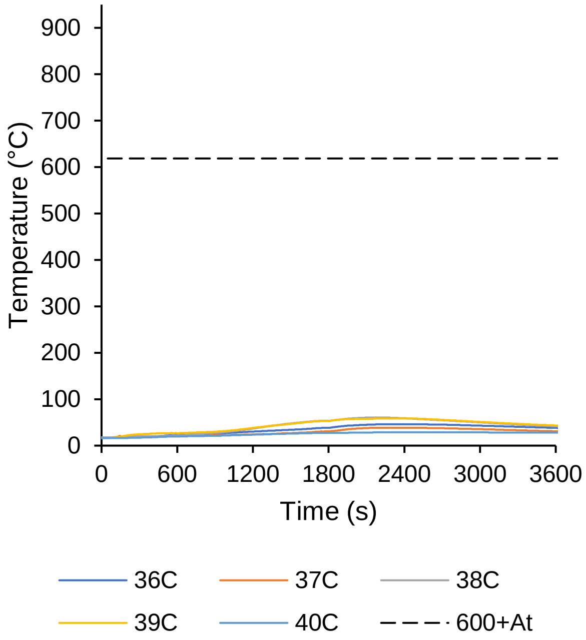
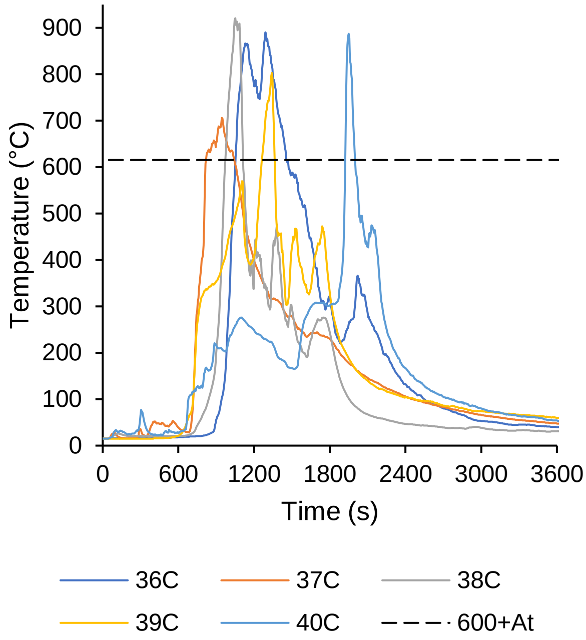


Figure 76 – Test 2 – BR 135 insulation thermocouples



7.5.4.2 RISC 501 Criteria

Figure 77 to Figure 82 show the data from all thermocouples specified in RISC 501, located 6000 mm above the burn chamber. The temperature criteria from RISC 501 are also shown. To meet the criteria, no thermocouples can rise above 500°C + 2At. Where At = Ambient Temperature. Test 1 is shown on the left and Test 2 on the right.

External Thermocouples

Figure 77 – Test 1 – RISC 501 external thermocouples

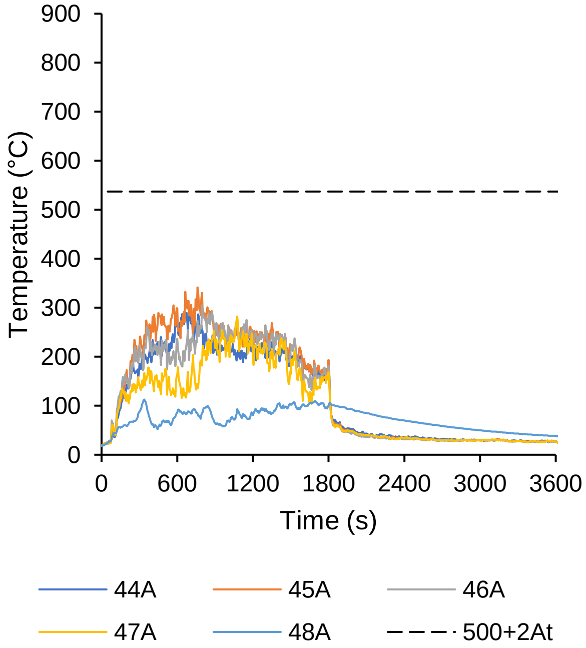
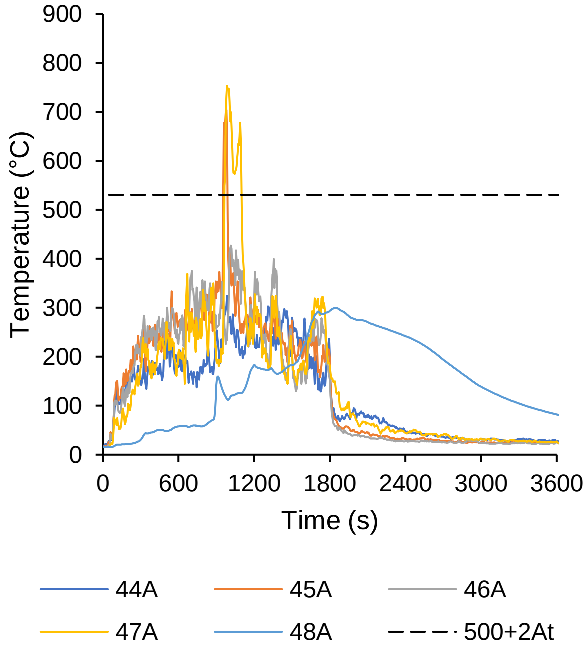


Figure 78 – Test 2 – RISC 501 external thermocouples



Cavity Thermocouples

Figure 79 – Test 1 – RISC 501 cavity thermocouples

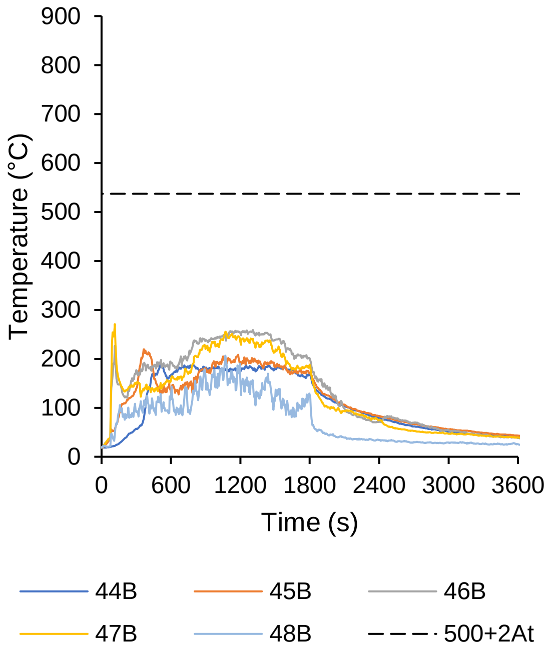
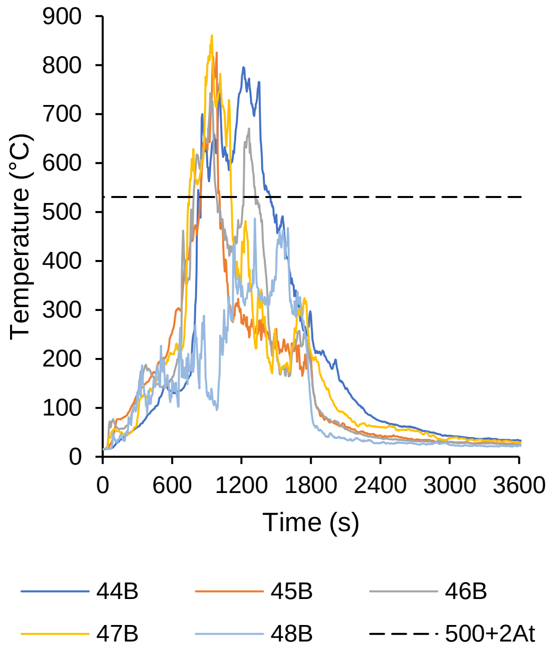


Figure 80 – Test 2 - RISC 501 cavity thermocouples



Insulation Thermocouples

Figure 81 – Test 1 – RISC 501 insulation thermocouples

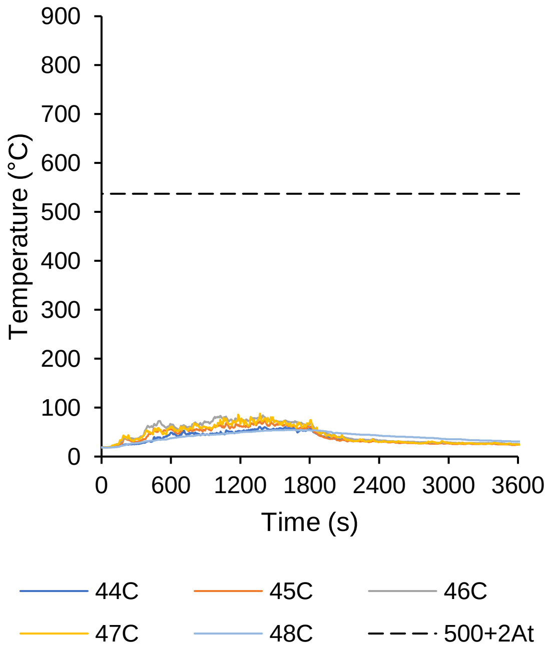
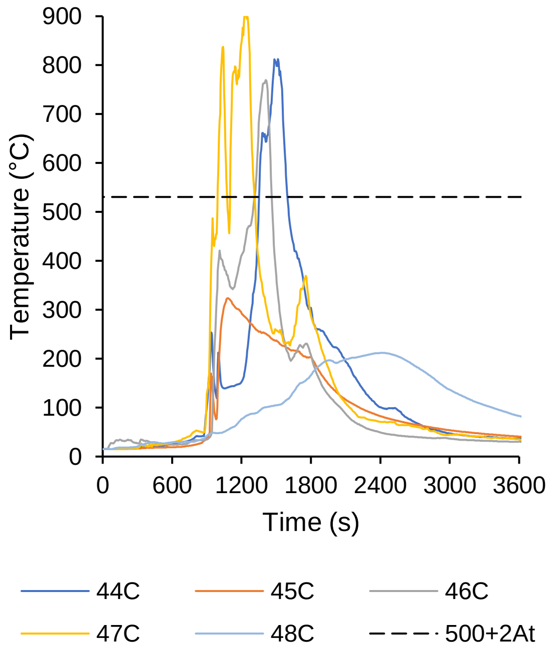


Figure 82 – Test 2 – RISC 501 insulation thermocouples



7.5.5 Fire Spread

Vertical fire spread was monitored through all central thermocouples in the cavity and is shown below. Figure 83 shows a consistent temperature profile between thermocouples, indicating heat transfer from a static source, i.e. no fire spread vertically up the system during Test 1. Figure 84 shows dynamic peaks at different times for different thermocouples, indicating that a heat source is moving through the system during Test 2. During test 1 the highest temperatures were measured at the bottom of the test rig, near the wooden crib. During test 2 the highest temperature was measured near the top of the test rig, indicating that fire has spread through the system.

Figure 83 – Test 1 – Central cavity thermocouples

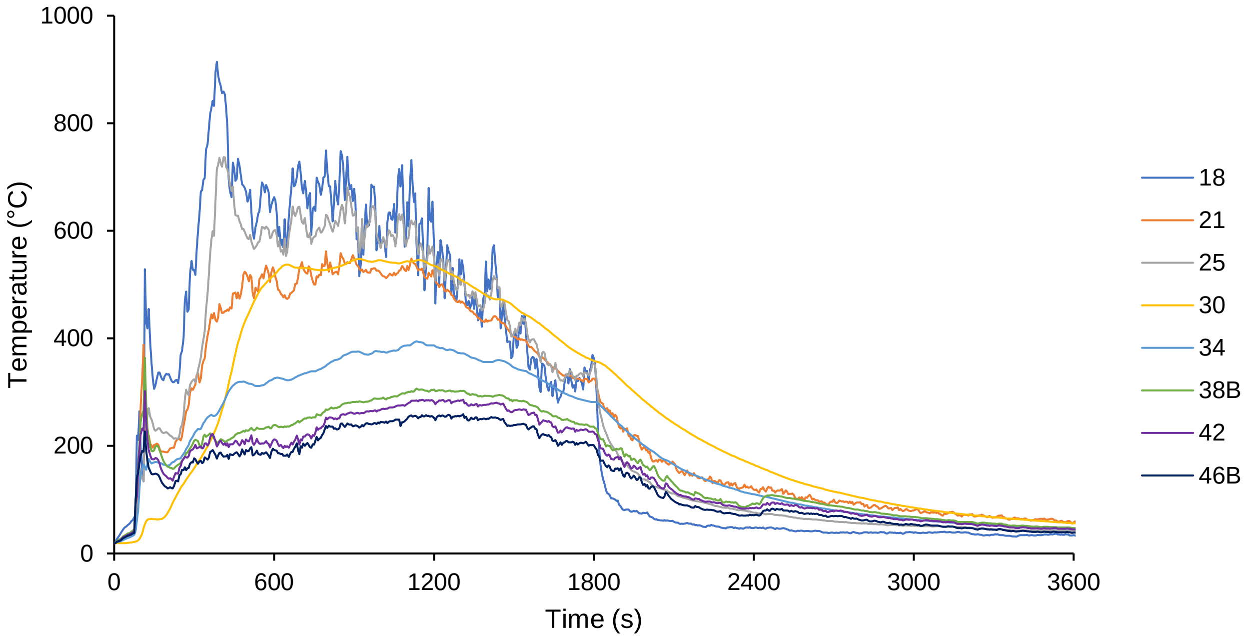
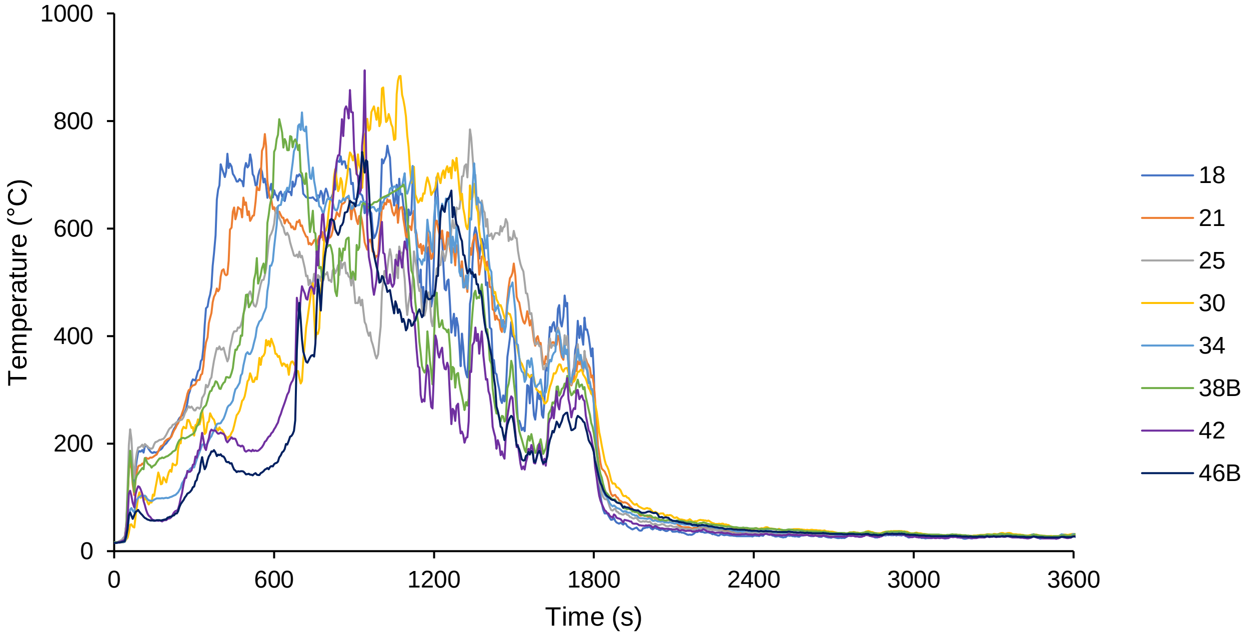


Figure 84 – Test 2 – Central cavity thermocouples

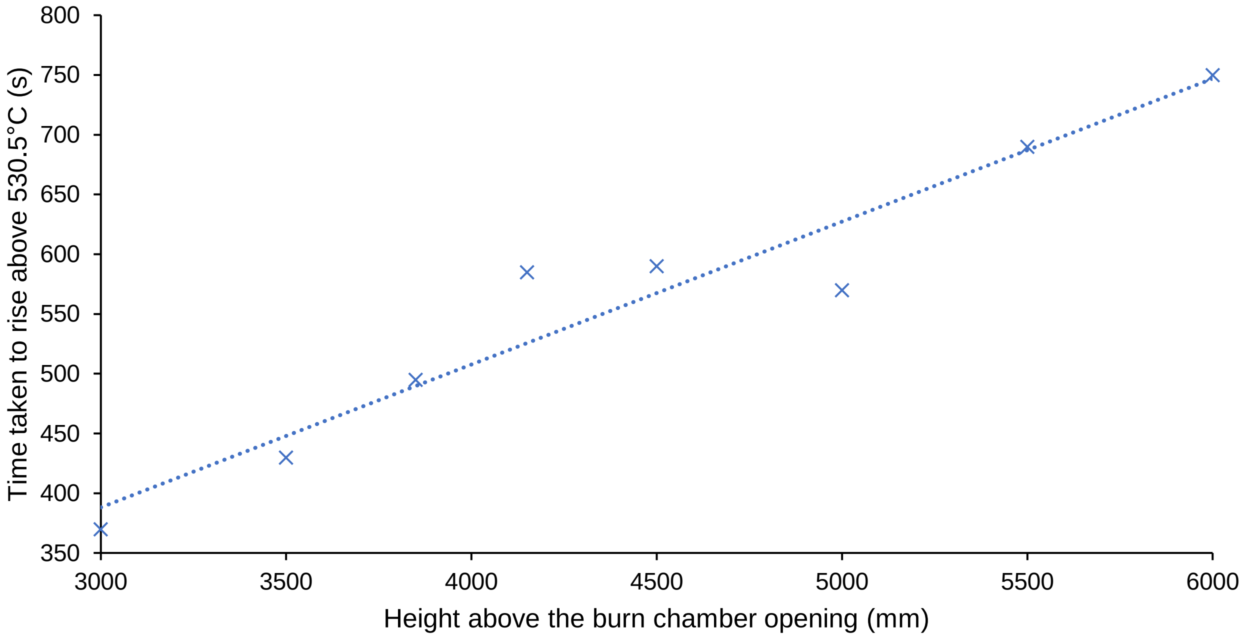


To investigate if the rate of fire spread during test 2 was accelerating or decelerating up the test rig the time taken for a thermocouple to rise above 530.5°C was plotted against the height above the burn chamber opening, shown in Figure 85. Decelerating fire spread would indicate that the fire may self-extinguish as it moves away from the timber crib heat source.

530.5°C being 500°C + 2 x the ambient temperature for test 2. This was done for any thermocouple in the cavity at each height level above the burn chamber opening.

The data suggests the fire was spreading at a steady rate and there isn't enough evidence to determine whether the fire was accelerating or decelerating.

Figure 85 – The time taken for any thermocouple at a height above the burn chamber opening to rise above 530.5°C during test 2.



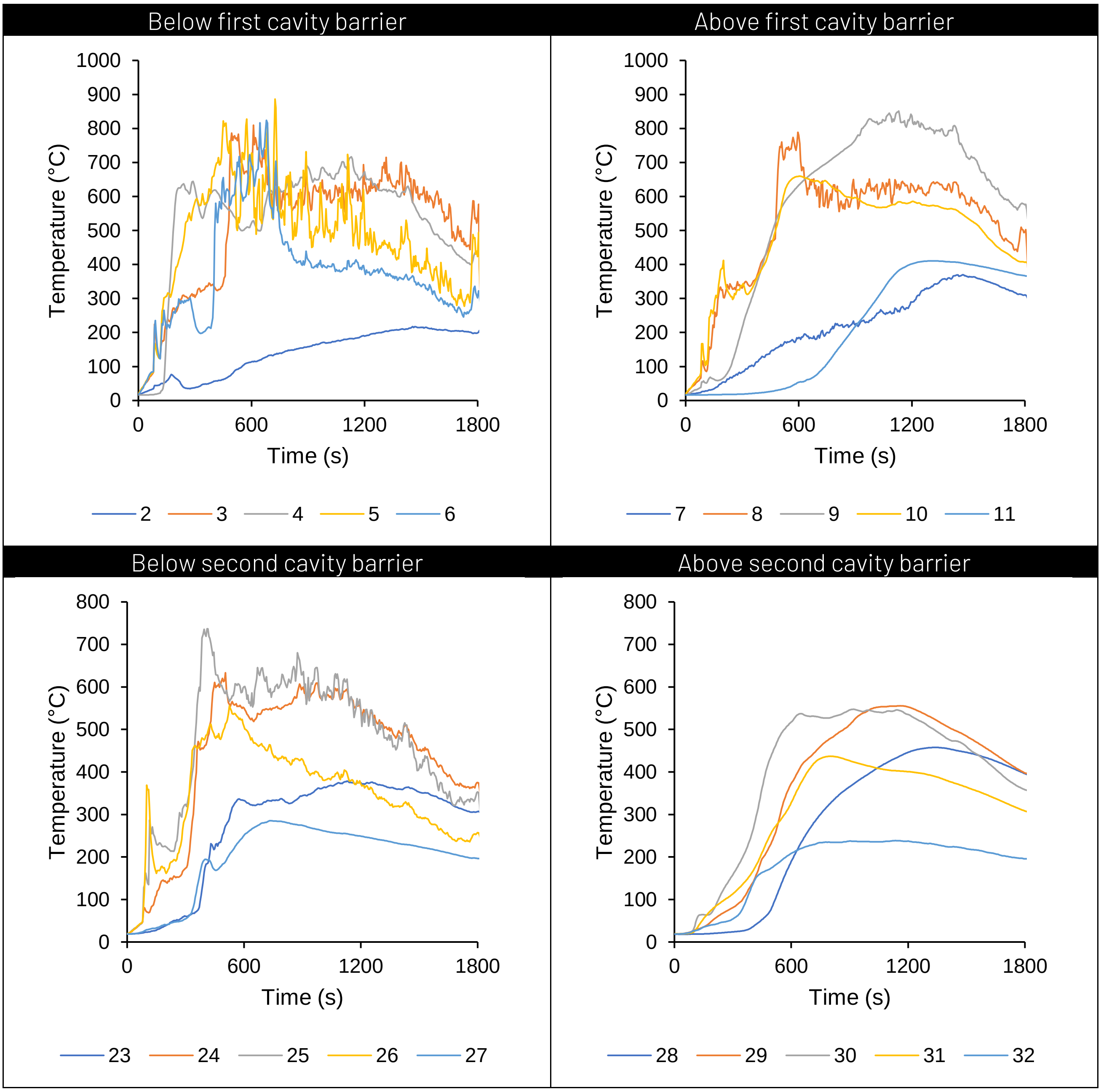
7.5.6 Cavity Barrier Performance

7.5.6.1 Test 1 – Mineral Wool

Figure 86 shows the thermocouple data 150 mm above and below the two horizontal cavity barriers for test 1. The cavity barriers are located 860 mm and 4010 mm above the burn chamber respectively.

Figure 86 suggests that flames broke through the first cavity barrier almost immediately. The temperatures reach 550°C at the second cavity barrier, but there are no regular spikes in temperature. It was therefore assumed that there were no flames breaking through and the cavity barrier provided a damping effect. It was not possible to determine when the façade panels in front of the first cavity barrier melted/burnt away, due to the flames from the wooden crib obscuring the cameras vision. The façade panels in front of the second cavity barrier remained in place throughout the duration of the test, although they were distorted which may have affected the cavity barrier's ability to seal against them.

Figure 86 – Thermocouples above and below cavity barriers for Test 1 during the first 30 minutes

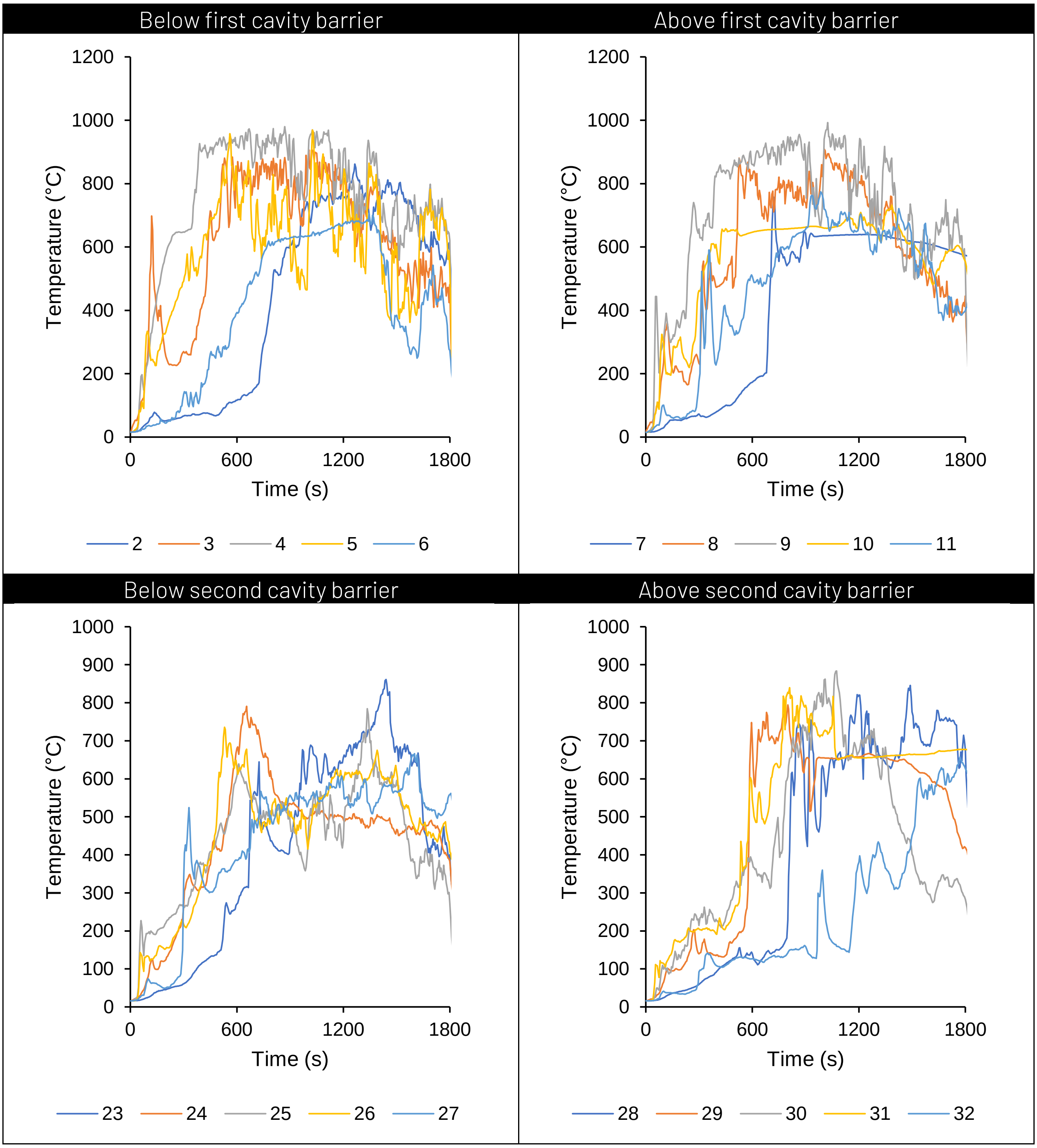


7.5.6.2 Test 2 – PIR

Figure 87 shows the thermocouple data 150 mm above and below the two horizontal cavity barriers for test 2. The cavity barriers are located 860 mm and 4010 mm above the burn chamber respectively.

Figure 87 suggests that flames broke through the first cavity barrier almost immediately. Flames broke through the second cavity barrier after 9 minutes and 10 seconds. The façade panels in front of the second cavity barrier were observed to melt away after 12 minutes, at which point there would have been no surface for a functioning cavity barrier to seal against. It was not possible to determine when the façade panels in front of the first cavity barrier melted/burnt away, due to the flames from the wooden crib obscuring the cameras vision.

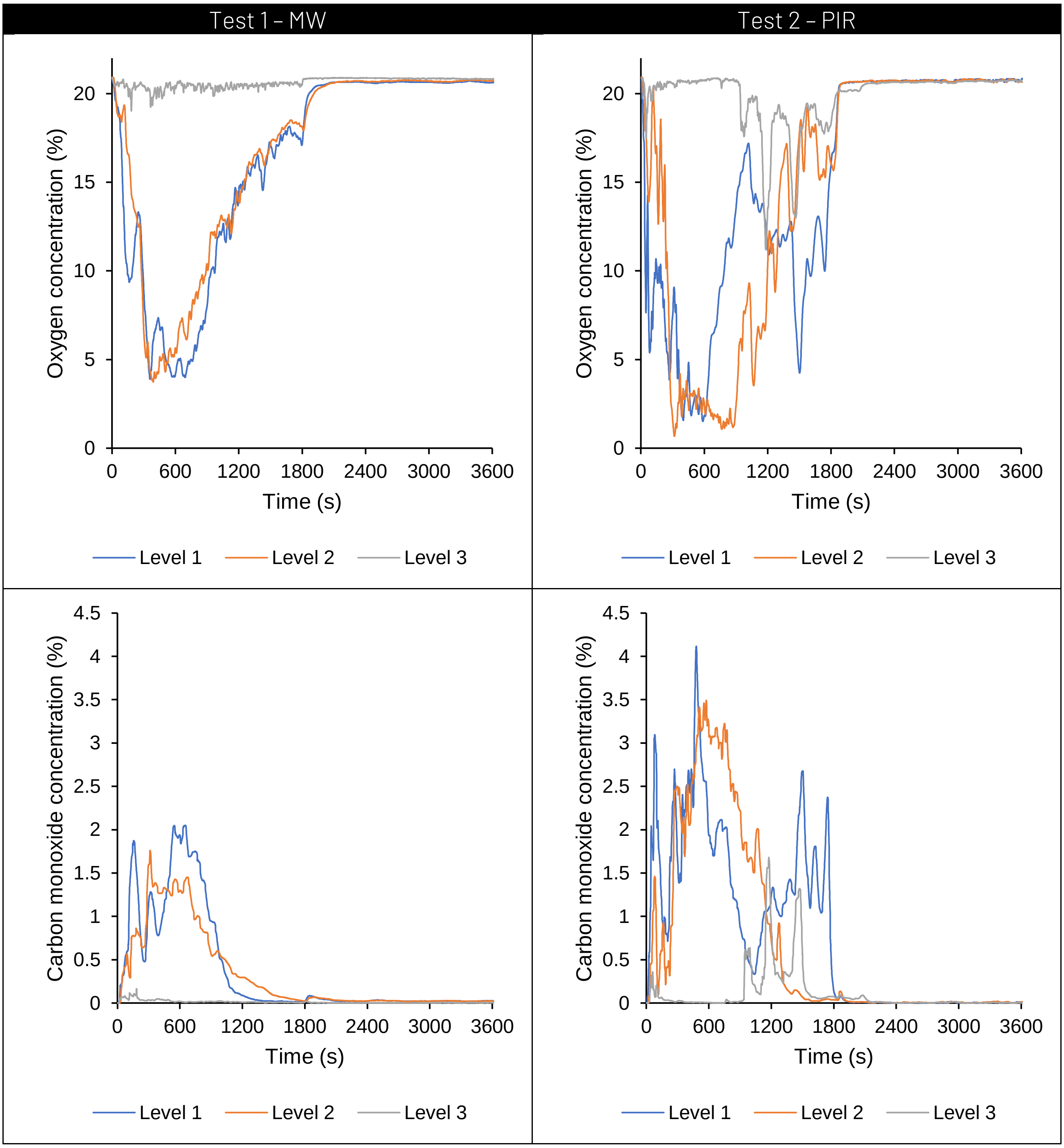
Figure 87 – Thermocouples above and below cavity barriers for Test 2 during the first 30 minutes



7.5.7 Gas Sampling

Figure 88 shows the oxygen, carbon dioxide and carbon monoxide concentration during test 1 and 2. These were measured at three different levels referred to as level 1, level 2 and level 3, shown in Figure 66. These were located 2500 mm, 3850 mm and 5500 mm above the burn chamber opening respectively. These do not correspond with the three levels from BS 8414-1:2020.

Figure 88 – Gas Sampling Results



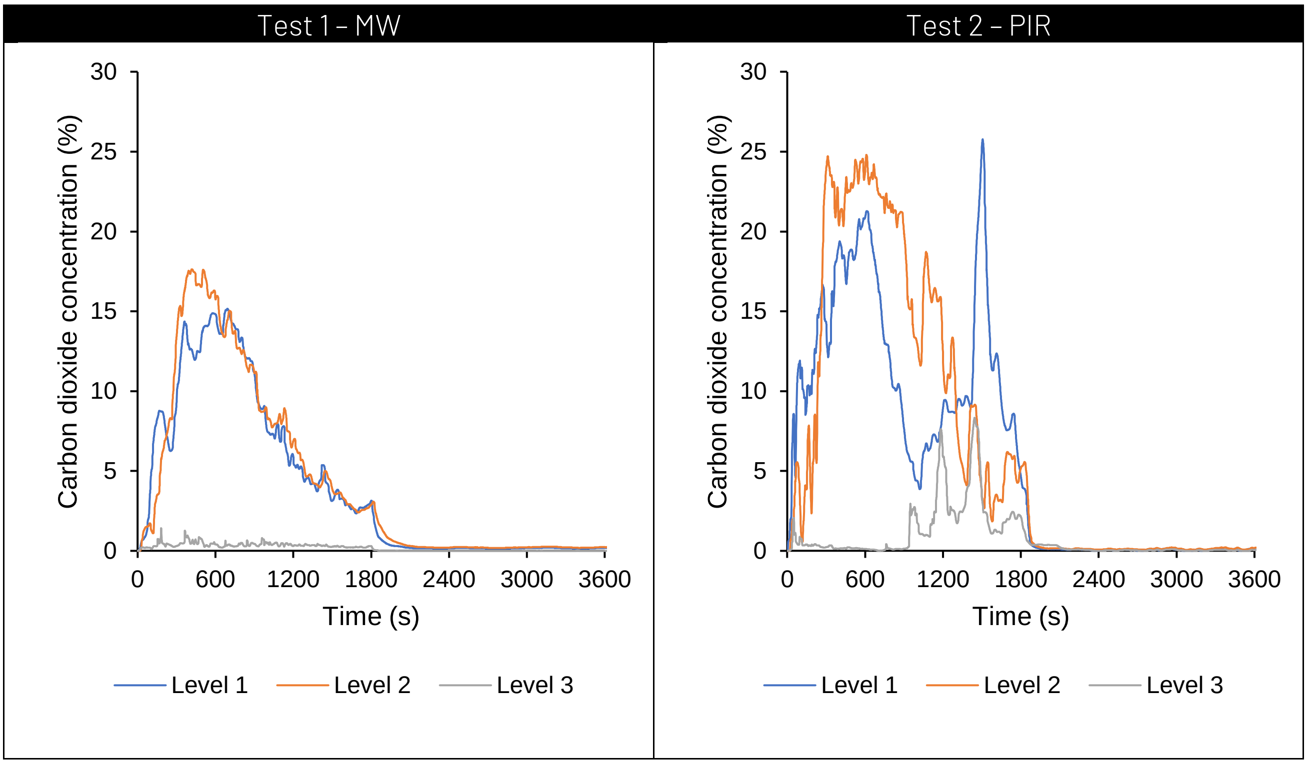


Table 32 shows the minimum oxygen concentration, the maximum carbon monoxide concentration and the maximum carbon dioxide concentration measured during Test 1 and Test 2. It should be noted that the carbon dioxide sensor was calibrated between 0% and 5% CO_2. It can measure outside this range, but the accuracy of those measurements is more uncertain. While the absolute accuracy is limited, it can still provide a relative comparison between test measurements.

The sensor was calibrated within this range because at the time of calibration, before the test had been conducted, it was anticipated that most results would be within this range.

Table 32 – Minimum/Maximum gas concentrations during Test 1 and Test 2

		Test 1 - MW	Test 2 - PIR
Min O_2 concentration (%)	Level 1	3.9	1.5
	Level 2	3.7	0.7
	Level 3	19.0	11.2
Max CO concentration (%)	Level 1	2.1	4.1
	Level 2	1.8	3.5
	Level 3	0.2	1.7
Max CO_2 concentration (%)	Level 1	15.2	25.8
	Level 2	17.6	24.8
	Level 3	1.4	8.3

The carbon dioxide concentrations measuring during Test 2, reported as 25.8% and 24.8% are likely inaccurate. With only 21% atmospheric oxygen available at the start of the test, achieving carbon dioxide levels of 25.8% is not feasible without additional oxygen, which was not provided. Furthermore, the 79% of unmeasured gases would need to be displaced, which does not seem plausible here.

The true carbon dioxide concentration is likely to be lower than 21%. Given that the measured values exceed this limit, it is reasonable to infer that that sensor readings are overestimated by a factor of at least 1.2. Therefore, measurements above 5% CO_2 are likely to be systematically overestimated.

Figure 89 to Figure 91 shows the CO/CO_2 ratio at level 3 for tests 1 and 2. This ratio can be used as an indicator of how well-ventilated a fire is. A CO/CO_2 ratio less than 0.05 can indicate a well-ventilated fire. A CO/CO_2 ratio greater than 0.1 can indicate an under-ventilated fire [106]. During test 1 the fire appears to be initially under-ventilated until the crib becomes fully involved after 900 seconds. Test 2 displayed signs of an under ventilated fire for the majority of the test as the burning wooden crib consumes most of the oxygen leaving the PIR to burn inefficiently under oxygen depleted conditions.

Level 2 during Test 2 recovers briefly once the façade panels have deformed or fallen away, exposing the PIR insulation to open air.

Figure 89 - CO/CO_2 ratio at level 1 for tests 1 and 2

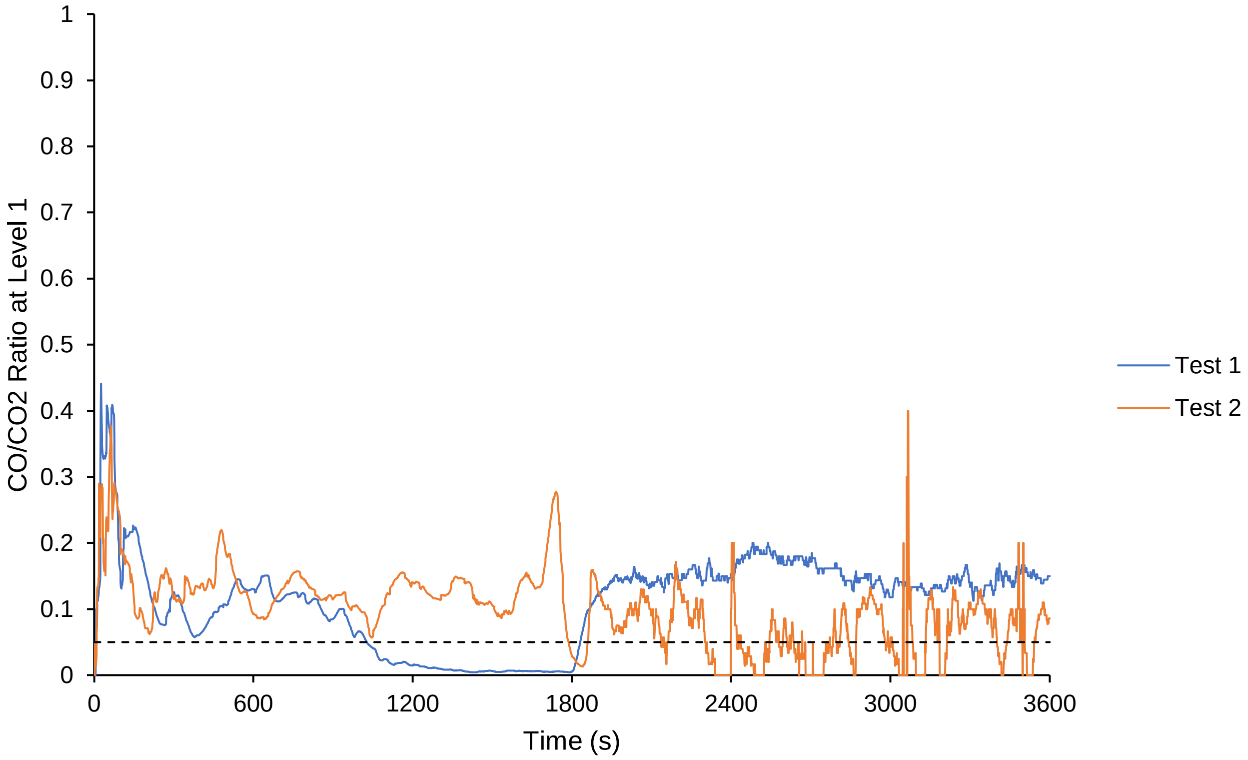


Figure 90 - CO/CO_2 ratio at level 2 for tests 1 and 2

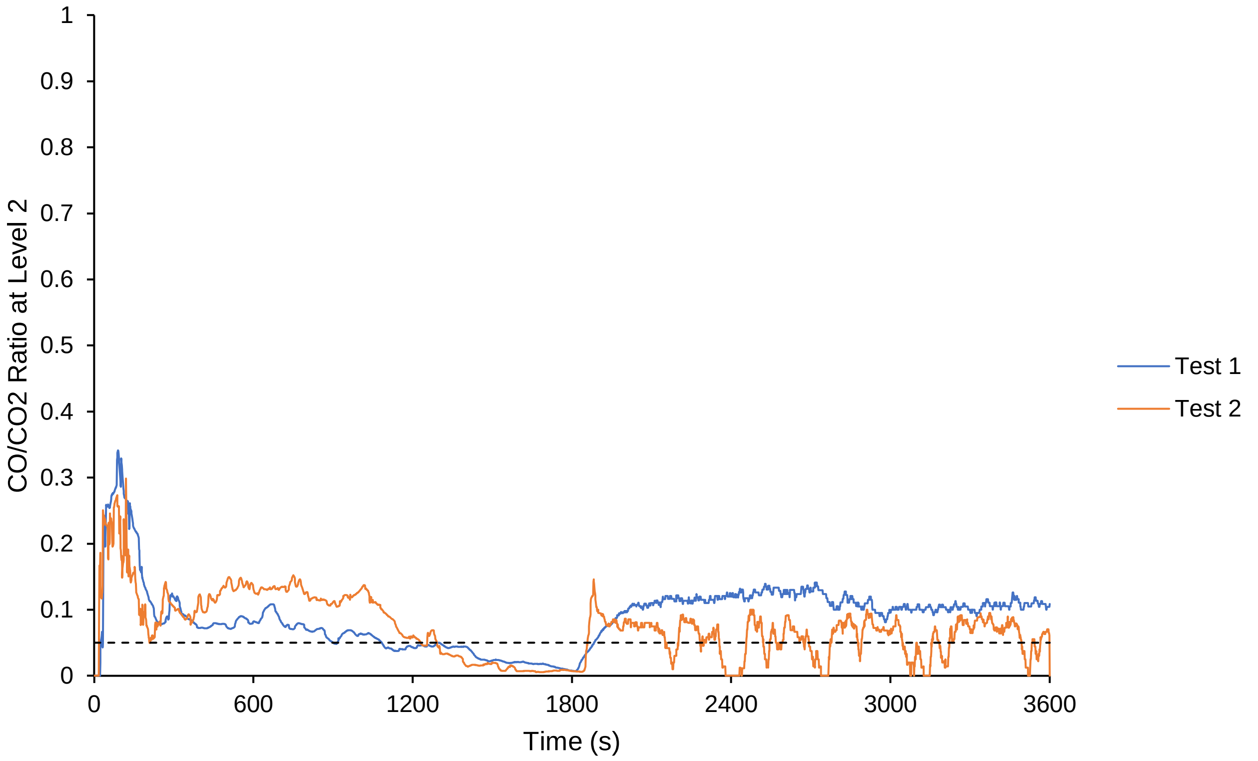
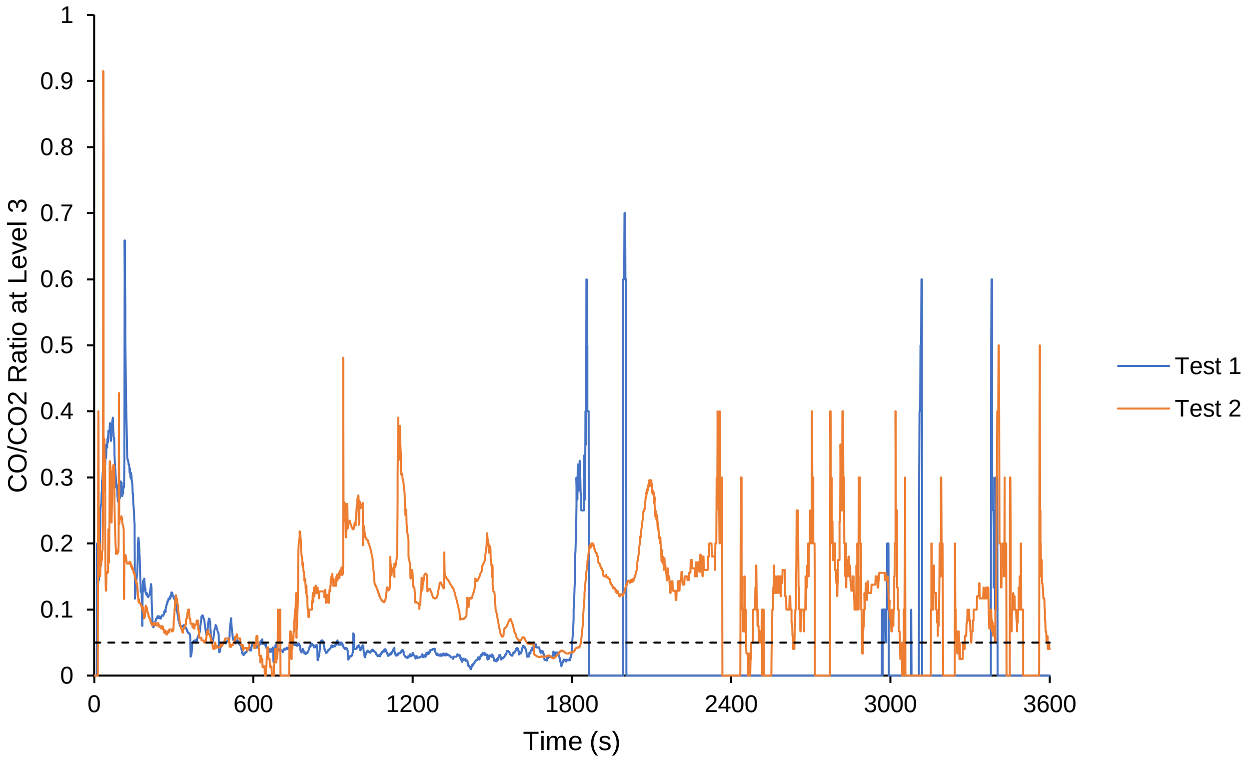


Figure 91 - CO/CO_2 ratio at level 3 for tests 1 and 2



Fire effluent can incapacitate evacuating occupants, preventing them from escaping a fire unaided. The Fractional Effective Dose (FED) to predict incapacitation was calculated and shown in Figure 92. An FED equal to 1 predicts that 50% of healthy adults would suffer incapacitation or death [42].

It was calculated using the method described in a study of the Smoke Toxicity of Rainscreen Façades, with a multiplication factor for CO_2 driven hyper-ventilation used to account for increased respiration caused by high CO_2 concentrations [42].

Smoke Toxicity of Rainscreen Façades simulated fire effluent travelling from the cladding system to a kitchen, via a kitchen vent. It measured an average flowrate of approximately 0.0125 m^3s^{-1} during the first 30 minutes of a BS 8414 fire test [42]. This estimates that it would fill 75% of a 30 m^3 room, within 30 minutes, assuming plug like flow. Plug like flow assumes the fire effluent flowing into the room displaces the ambient air already in the room.

Using the same flowrate of 0.0125 m^3s^{-1}, modelling the fire effluent flowing from the cladding system into a 30 m^3 room, the FED predicting incapacitation during Test 1 and Test 2 was estimated.

CO_2 increases respiration rate and so a multiplication factor for CO_2-driven hyperventilation, VCO_2 is included in the calculation, using Equation 5 [42].

$$V_{CO_2} = 1 + \frac{\exp(0.14[CO_2]) - 1}{2}$$ *Equation 5*

CO_2 is expressed in volume %.

Equation 6 was used for the estimation of incapacitation by the asphyxiant gases carbon monoxide and hydrogen cyanide [42].

$$FED = \left\{ \sum_{t_1}^{t_2} \frac{[CO]}{35000} \Delta t + \sum_{t_1}^{t_2} \frac{[HCN]^{2.36}}{1.2 \times 10^6} \Delta t \right\} \times V_{CO_2}$$ *Equation 6*

Gas concentrations are expressed in ppm
Time (t) is in minutes

The values used for CO and CO_2 were integrated over the first 30 minutes of the fire test.

PIR has the potential to produce significant quantities of hydrogen cyanide (HCN) during combustion. The FED from the HCN produced during Test 2 was estimated from the carbon monoxide production. 'Smoke Toxicity of Rainscreen Façades' calculated an FED for HCN of approximately 0.5 when the FED for CO was approximately 1 during PIR combustion [42]. The FED for CO was therefore multiplied by 0.5 to estimate the FED for HCN. Although this is a gross extrapolation of the data, it attempts to estimate the effect of the unquantified HCN.

The resultant value for FED represents the fire effluent at 100% concentration. It was multiplied by 0.75 to represent the concentration of fire effluent filling 75% of a room in 30 minutes. The results are shown in Figure 92.

Figure 92 – FED for predicting incapacitation from CO and estimated HCN during the first 30 minutes of Test 1 and Test 2 using measurements from level 2

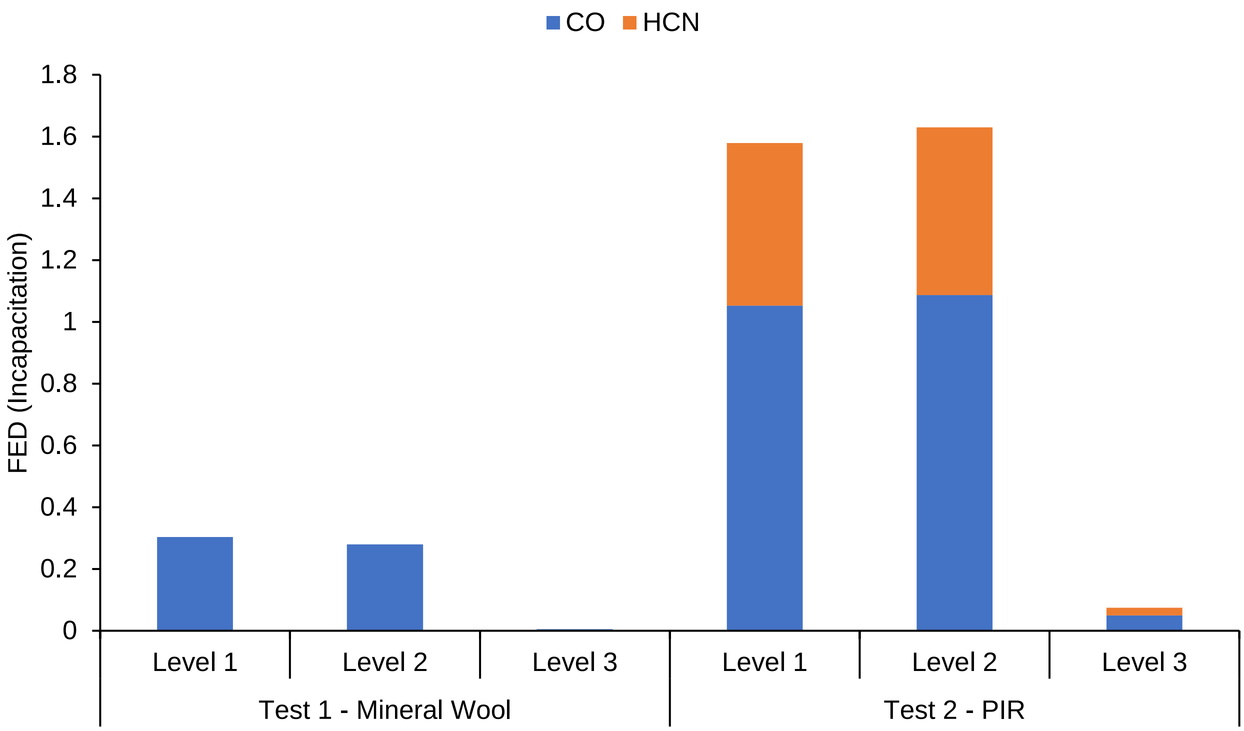


Figure 92 shows the FED for Test 2 was estimated to be over 1 from the CO alone. This suggests that after 30 minutes there is a 50% chance for a healthy human to be incapacitated from carbon monoxide poisoning. This is a human inside a compartment within the building, inhaling fire effluent coming from the external cladding system.

It is important to note that the calculation carries a substantial margin of error due to various assumptions that had to be made, most notably:

- 'Smoke Toxicity of Rainscreen Façades' only measured flowrate for 27 minutes [42] and it was assumed to have the same average flowrate for the duration of the test, despite the flowrate increasing throughout the test.
- The flowrate through the vent was propelled by natural buoyancy and was assumed to be the same rate at all heights on the test rig, despite this being influenced by many factors.
- The FED relationship between CO and HCN during PIR combustion was assumed to be linear, despite it also being influenced by many factors.

7.5.8 Mechanical Performance

No significant fallen parts were identified during Test 1. Around 30% of the façade panels had melted or combusted away, exposing the insulation behind. The intumescent from the first horizontal cavity barrier had disintegrated, the second had intumesced and remained intact.

95% of the façade panels and 60% of the insulation had melted, combusted or detached during Test 2. The intumescent on both cavity barriers had disintegrated.

After Test 2, several fallen façade panels or sections of façade panel were identified. The largest of these weighed 2.18 kg and consisted of two panels still riveted together. This would not meet the RISC 501 mechanical performance criteria as it had sharp edges less than 6 mm thick and weighed over 1 kg.

8 Review of Proposed Test and Assessment Method

Two validation tests were successfully conducted to the proposed RISC 501 fire test standard. Test 1 was conducted with a non-combustible rainscreen system with mineral wool insulation. Test 2 was conducted with a combustible rainscreen system with PIR insulation.

The non-combustible system served as a baseline, meeting the requirements of RISC 501. The combustible system failed to meet the temperature requirements of RISC 501, 12 minutes and 30 seconds after ignition. The test would have been terminated after 60 seconds, failing to meet the visual observation criteria, due to flames rising above the test rig, but was continued for the full 60 minutes for research purposes.

There were no physical challenges identified or conflicts identified with the required test setup. Although the level 3 gas sampling probe was identified to be at the same level as one of the structural steel test frame horizontal beams, making it harder to install. This probe was only included for research purposes and is not included in the RISC 501 test standard.

The test successfully distinguished flame spread in combustible systems compared to non-combustible systems. The disparity in peak temperatures measured was more pronounced with the RISC 501 thermocouples and temperature criteria compared to BS 8414 thermocouples and BR 135 temperature criteria as shown in Table 30 and Table 31 (page 102) . This was most likely due to both being further away from the wooden crib and being measured over a longer time period. This shows that the thermocouples were influenced less by the heat from the wooden crib and were better able to identify flame spread through the combustible system. The modified thermocouple locations and maximum temperature criteria also correlated well with the visual observations for identifying flame spread, as both were taken from the same location, at the top of the test rig.

The test successfully identified mechanical failure in the combustible system, due to the fallen façade panels. Interestingly, the same façade panels used in the non-combustible system did not lead to mechanical failure, likely because the temperatures in the non-combustible system remained lower. The mechanical performance criteria do not permit falling objects over 5 kg in mass. They also do not permit sharp falling objects over 1 kg in mass, with sharp being defined as less than 6 mm. This clause could have a significant impact on metal composite façade panels, which are typically 4 mm thick.

The gas sampling method clearly differentiated between the non-combustible system and the combustible system. The non-combustible system served as a baseline, demonstrating the change in gas concentration, caused by the wooden crib, at different heights on the test rig. The results also showed how they could be used to predict the Fractional Effective Dose for incapacitation, demonstrating how a PIR system could be lethal to occupants trapped in the room above a fire. The prediction comes with a substantial margin of error and further research should be conducted on how the smoke toxicity within a cladding system correlates with the smoke toxicity inside the building.

Overall, the proposed test standard, RISC 501, was found to meet the aim of improving property protection, by using criteria relevant to fire spread and not relying on intervention by the Fire Service to prevent fire spread.

The proposed standard was found to meet the aim of conferring compliance with BS 8414-1:2015+A1:2017, allowing it to confer compliance with BR 135 for the systems tested.

Additional clauses have been included in the test standard to meet the aim of making it more resilient to gaming. The additional test construction requirements appeared to have a significant impact on fire performance as similar cladding systems, with PIR insulation combined with non-combustible ACM façade panels, have been found to meet the BR 135 requirements. However, when a PIR insulation combined with non-combustible ACM façade panels was tested to RISC 501, it failed to meet the BR 135 temperature requirements within 10 minutes of ignition. This would have been influenced by factors such as the following:

- The horizontal cavity barriers being limited in number.
- The horizontal cavity barriers being spread further apart.
- The top of the test rig being open, allowing exhaust gases to escape the cavity and fresh air to enter at the bottom.
- The detailing around the burn chamber providing minimal fire protection.
- Larger gaps between façade panels.

It will also have been influenced by its simplified design for testing purposes.

It was acknowledged that trade names and identification marks did not guarantee that a product supplied for fire testing is the same product supplied to market. A method for material characterisation for identifying fire rated insulation products was therefore developed. The method involves using microscale combustion calorimetry and infrared spectroscopy to produce a chemical fingerprint of each significant cladding system component. The methods were found to be capable of identifying the inclusion of new chemical substances, loss of existing substances and changes to the combustion properties of a material and the extent of process reactions, such as the formation of isocyanurate rings.

The proposed standard was also found to meet the aim of not resulting in a non-combustible system failing to meet the temperature requirements, for the non-combustible system tested. It also showed a larger disparity in peak temperatures between the RISC 501 thermocouples and temperature criteria compared to BS 8414 thermocouples and BR 135 temperature criteria. This suggests that it was better able to differentiate between combustible and non-combustible systems. The non-combustible system was found to fail to meet the visual observation criteria for flame spread, due to the cavity being open the entire way up the test rig. Once the cavity barriers had activated flames were no longer visible at the top of the test rig. This emphasises the need for some fire protection around the burn chamber opening, which would be the case for a typical cladding system.

9 Summary

Façade fires have been increasing globally, with the United Kingdom (UK) reporting the third most casualties per population from façade fires of any country. Combustible cladding systems are approved on high rise buildings in England by the performance based route to compliance, using the BS 8414 test method and BR 135 assessment criteria. Questions have been raised regarding the appropriateness of the fuel source, test construction, construction detailing, assessment criteria and availability of test results.

This study aimed to develop a new test standard that could be conducted alongside BS 8414 so that the results would confer compliance with both BR 135 and the proposed new test standard, RISC 501.

A database was populated with data from various fire tests of external cladding systems conducted according to the BS 8414 test method and evaluated against the BR 135 performance criteria. The database was populated with standardised fields to examine a variety of test specimens, the corresponding testing conditions and their influence on performance criteria.

The results identified that some systems were protected from fire spread using methods that could not be reproduced on real buildings. For example, horizontal cavity barriers were often spaced 2.5 m apart, which is significantly closer than would typically be used on a real building, where the cavity barriers would be located at floor level. These are devices designed to reduce fire spread and using more cavity barriers will generally help prevent fire spread.

It was also identified that the typical flame heights from the fuel load specified in BS 8414 would reach 6 m from the ground. This is in close proximity to the thermocouples located 7 m above the ground, which are used for the BR 135 performance criteria. The BR 135 performance criteria are only assessed over a 15 minute period, despite the test being 1 hour long. The close proximity between the thermocouples and the fuel load prevents systems from being assessed over a longer period of time as it would result in non-combustible systems failing to meet the performance criteria. It also prevents the maximum temperature criteria from being lowered for the same reason.

It was identified that the close proximity between the thermocouples and the fuel load restricts the ability for fire spread to be assessed, as it is effectively only assessed through the cladding system over a 1 m distance between the fire and the relevant thermocouples. This makes the test more of an assessment of systems which significantly contribute to the total heat release and less an assessment of systems which promote rapid fire spread. It may be the case that a system could ignite and produce significant quantities of thermal energy, but not be able to spread due to design features such as fire breaks. Conversely it was identified that some systems could visually ignite and spread fire to the top of the test rig without releasing enough thermal energy to exceed the BR 135 temperature criteria, which are designed to identify fire spread.

The study recognised that trade names and identification marks may not guarantee that a product used for fire testing matched those available in the market. To address this concern, a novel method for characterising fire-rated insulation products was developed. This method employs microscale combustion calorimetry and infrared spectroscopy to establish a unique chemical fingerprint for each major component of a cladding system. Notably, this approach can identify new chemical substances, detect the absence of existing ones, assess changes in combustion properties, and quantify process reactions, such as the formation of thermally stable isocyanurate rings.

A fire test standard named RISC 501 was developed, specifying a test method and assessment criteria for the fire performance of external cladding systems. It was recognised that features like the fuel load were unable to be changed while still conferring compliance with BS 8414. The proposed standard includes different criteria for the test construction, material characterisation and temperature criteria.

It also included criteria for mechanical performance and sampling the potential toxicity of fire effluent. The critical thermocouples for assessing fire performance were located at the top of the test rig, 8 m above the ground, to address the aforementioned concerns. This allowed the maximum temperature criteria to be lowered and assessed over a longer time period, without incorrectly failing to approve non-combustible systems.

The test construction criteria mandate all systems to design against the same virtual building. The virtual building is not actually constructed on the test rig but specifies locations for floor heights and window openings. This ensures that all cladding systems tested are designed on the the same basis, allowing results to be comparable and preventing systems from being overprotected from fire spread by designing against an unrealistic building.

It was identified that falling parts regularly interfere with firefighting operations, so mechanical performance criteria were set based on performance requirements for firefighting helmets. With no falling parts over 5 kg being permitted and no sharp falling parts over 1 kg being permitted by the RISC 501 assessment criteria.

As smoke toxicity is an emerging issue, criteria were set for extracting and measuring gases from the rear of the cladding system. No performance criteria were set as further research is required on the relationship between the concentration of toxic products produced by a cladding system and the potential concentration of toxic products in an adjacent room inside the building. It was mandated that oxygen, carbon monoxide and carbon dioxide were measured so that the potential for producing toxic gases could be estimated and compared between cladding systems.

Validation tests were conducted against the proposed RISC 501 standard. A baseline non-combustible system was compared against a similar combustible system, comparing the results of predicted performance with experimental data to verify the accuracy and validity of the prediction.

The tests did not identify any physical challenges with the implementation of the prescribed test setup. The test was able to identify flame spread through a known combustible cladding system and it was able to identify a lack of flame spread through a known non-combustible cladding system. The difference in performance between the two systems was highlighted more profoundly with the RISC 501 criteria than it would have been with the BR 135 criteria.

The test identified mechanical failure in the combustible system, due to some falling façade panels. Interestingly, the same façade panels used in the non-combustible system did not lead to any mechanical failure, presumably because the temperatures in the non-combustible system were lower.

The proposed gas sampling method and extraction location clearly differentiated between the non-combustible system and the combustible system. The results also showed how they could be used to predict the Fractional Effective Dose for incapacitation.

In summary, this study investigated critical issues related to façade fires and the fire testing of external cladding systems, particularly in the UK, where combustible cladding systems are approved for high-rise buildings. The findings from that research were used to develop the fire test standard and assessment method RISC 501 – Fire Safety Assessment Test for External Cladding systems.

10 Further Research

This research provides a valuable foundation for understanding cladding fire behaviour, but limitations inherent to the MSc degree format restricted the scope of the investigation. Future research efforts could significantly benefit from a broader data pool encompassing both real-world cladding fires and controlled fire tests.

A significant challenge exists in the lack of standardised reporting for real-world cladding fires. The composition of cladding systems often remains unknown due to the absence of a structured data collection protocol. Developing a standardised data collection and reporting method for fire services could significantly improve the availability and quality of real-world fire data.

Similarly, expanding the data pool from fire tests would enable a more comprehensive understanding of cladding fire behaviour. Future research should prioritise the collection of data on fuel sources, particularly regarding the impact of moisture content and fuel load wood density on fire spread. With a substantial dataset, statistical analysis could potentially isolate the influence of these variables, even in tests with uncontrolled factors.

Currently accepted fuel loads may not accurately reflect real-world scenarios and its relevance should be investigated. Experiments should be conducted to evaluate the heat release rate of a burning compartment in flashover and how this correlate to the heatflux imparted on the external cladding system.

One of the factors notably omitted from this research is the influence of the fire performance of cladding membranes. These components can possess high combustibility and are allowed on buildings over 18 m without requiring any fire testing. Further investigation into the fire behaviour of membranes and their potential contribution to cladding fires is warranted. A critical question is whether combustible membranes can spread fire within the cavity faster than the cavity barriers can deploy, rendering them ineffective.

RISC 501 includes provisions for installing a plastic vent due to the lack of comprehensive data on the impact of service penetrations within the cavity. Future research should prioritise the impact of service penetrations with variations in location, size and combustibility.

The current test method is constructed in a L shape with a main wall and a return wall. The removal of the return wall in fire tests represents a significant cost saving. Further investigation is necessary evaluate the impact of the return wall on fire spread. This will enable a cost-benefit analysis to determine if the inclusion of a return wall is essential for replicating a realistic worst-case scenario.

RISC 501 introduces a method for gas sampling to allow of a comparison of the potential toxicity of fire effluent from different cladding systems. Further research is needed to identify the most critical gasses to measure during a cladding fire test, in terms of their impact on human health. A method for estimating the potential impact on occupants within in a building needs to be developed based on the quantity of gases produced. Alternative measurement techniques should be investigated, such as Fourier-Transform Infrared Spectroscopy (FTIR), which is currently used in 'PD ISO/TS 21397:2021 – FTIR analysis of fire effluents in cone calorimeter tests' to measure a wide range of fire effluent gases.

RISC 501 also introduces material characterisation using a combination of FTIR and Microscale Combustion Calorimetry (MCC). Further research should be conducted on the variation of results for each material over manufacturing batches and with ageing of samples, both in laboratories and on buildings. An investigation should also be conducted to identify how the heat release rate measured during both aerobic and anaerobic MCC compares to the heat release rate during a full-scale cladding system fire.

Lastly, further research should be conducted on the considerations required for novel cladding systems such as living walls. A living wall is a vertical garden with plants growing on a structure, often used on buildings for both aesthetics and environmental benefits. A method needs to be developed for consistently preparing living walls for fire testing. This includes standardised planting and watering regimes to ensure both realistic and reproduceable conditions.

Addressing these areas for further research, will enhance the accuracy of cladding fire tests, leading to the development of safer and more fire-resistant buildings.

11 References

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Appendix A – Database Entries

A version of the 'Historic 8414Test Results Database' has been provided separately with commercially sensitive information redacted.

Lists of the test reports and database fields are provided in Table 33 to Table 37 below.

Table 33 - Test reports submitted to database

Test Date	Test House	Report ID	Test Standard Version
17/06/2010	BRE	BRE262211	2002
15/09/2010	BRE	BRE264425	2002
08/12/2010	BRE	BRE266619	2002
09/06/2011	BRE	BRE269340	2002
10/11/2016	BRE	P105752-1000	2002
23/07/2017	BRE	DCLG Test 1	2015
30/07/2017	BRE	DCLG Test 2	2015
30/07/2017	BRE	DCLG Test 3	2015
06/08/2017	BRE	DCLG Test 5	2015
06/08/2017	BRE	DCLG Test 4	2015
13/08/2017	BRE	DCLG Test 7	2015
16/08/2017	BRE	DCLG Test 6	2015
28/11/2018	FPA	101512.002	2015
20/09/2019	FPA	101994.001	2017
23/10/2019	FPA	102035.001	2017
21/11/2019	FPA	102105.001	2017
22/11/2019	FPA	101870.002	2017
13/01/2020	FPA	102069.001	2017
26/02/2020	FPA	102217.002	2017
24/03/2020	FPA	101386.001	2017
23/04/2020	FPA	102417.001	2015
28/04/2020	FPA	102113.001	2017
11/05/2020	FPA	102169.001	2017
26/05/2020	FPA	102499.001	2017
11/06/2020	FPA	102169.002	2017
24/06/2020	FPA	102169.003	2017
09/07/2020	FPA	102169.004	2017
15/07/2020	FPA	102510.001	2017
16/07/2020	FPA	102169.005	2017
30/07/2020	FPA	102169.006	2017
11/08/2020	FPA	102169.007	2017
26/08/2020	FPA	102169.008	2017
01/09/2020	FPA	102254.001	2017
03/11/2020	FPA	102495.002	2017
17/11/2020	FPA	102394.001	2017
24/11/2020	FPA	103097.004	2020
25/11/2020	FPA	102517.001	2017
09/12/2020	FPA	102394.002	2017
14/12/2020	FPA	102455.001	2020

Test Date	Test House	Report ID	Test Standard Version
11/01/2021	FPA	102547.001	2017
14/01/2021	FPA	102547.002	2017
04/02/2021	FPA	102630.001	2020
09/02/2021	FPA	102455.003	2020
10/03/2021	FPA	102640.001	2020
17/03/2021	FPA	102640.002	2020
08/04/2021	FPA	102875.001	2020
20/05/2021	FPA	102955.002	2020
25/05/2021	FPA	102874.001	2020
27/05/2021	FPA	102887.001	2020
28/06/2021	FPA	102579.001	2020
29/06/2021	FPA	102579.002	2020
06/07/2021	FPA	102872.001	2020
12/08/2021	FPA	103093.001	2020
07/10/2021	FPA	103097.005	2020
14/10/2021	FPA	103097.006	2020
20/10/2021	FPA	103205.001	2020
26/10/2021	FPA	103097.001	2020
11/11/2021	FPA	103097.002	2020
16/11/2021	FPA	103097.003	2020
05/01/2022	FPA	103173.001	2020
08/02/2022	FPA	103173.002	2020

Table 34 - Test Construction Database Feilds

Field Entry	Description
Predominant brackertry material	ARIR (as recorded in report)
Predominant fixing materials	ARIR
Insulation - Manufacturer	ARIR
Insulation - Product	ARIR
Insulation - Type	ARIR or from the manufacturer. Categorised as polyurethane foam (PUR), polyisocyanurate foam (PIR), Phenolic foam (phenolic), Mineral Wool or expanded polystyrene (EPS)
Insulation - Thickness (mm)	ARIR or inferred from drawings
Insulation - Fire classification	Where multiple insulation products were used the most combustible was entered
Vapour Membrane	Name of membrane used
Cavity thickness (mm)	ARIR or inferred from drawings
Façade Manufacturer	ARIR
Façade material	ARIR or from the manufacturer
Façade thickness (mm)	ARIR or inferred from drawings
Façade fire rating	Where multiple façade products were used the most combustible was entered

Field Entry	Description
Horizontal cavity barrier manufacturer	ARIR
Horizontal cavity barrier material	ARIR or from the manufacturer
Horizontal cavity barrier state	ARIR or from the manufacturer. Categorised as 'open' or 'closed'
Horizontal cavity barrier integrity (I)	ARIR or from the manufacturer
Horizontal cavity barrier insulation (E)	ARIR or from the manufacturer
Number of horizontal cavity barriers	ARIR or inferred from drawings
Horizontal cavity barrier locations	The distance from the burn chamber opening to each cavity barrier, as recorded in the report, or inferred from drawings
Vertical cavity barrier manufacturer	ARIR
Vertical cavity barrier material	ARIR or from the manufacturer
Vertical cavity barrier state	ARIR or from the manufacturer. Categorised as 'open' or 'closed'
Vertical cavity barrier integrity (I)	ARIR or from the manufacturer
Vertical cavity barrier insulation (E)	ARIR or from the manufacturer
Number of vertical cavity barriers	ARIR or from the manufacturer
Vertical cavity barrier locations	The distance from the centre of the burn chamber to each vertical cavity barrier, as recorded in the report, or inferred from drawings
Top edge detailing	The detailing around the top of the test rig. Is it enclosed?
Vertical edge detailing	The detailing at the edges of the test rig. Are they enclosed?
Opening detailing	The detailing around the burn chamber opening, is it enclosed and with what material?

Table 35 - Test Conditions Database Fields

Field Entry	Description
Height of test specimen	ARIR
Wind speed	ARIR
Wooden density	ARIR
Wooden crib moisture content	ARIR
Ambient start temperature	The mean temperature of the thermocouples at level 1 during the 5 minutes before ignition, as recorded in the report
Start time	ARIR
Notes/Deviations	Any relevant notes or deviations ARIR

Table 36 - BR 135 Assessment Database Fields

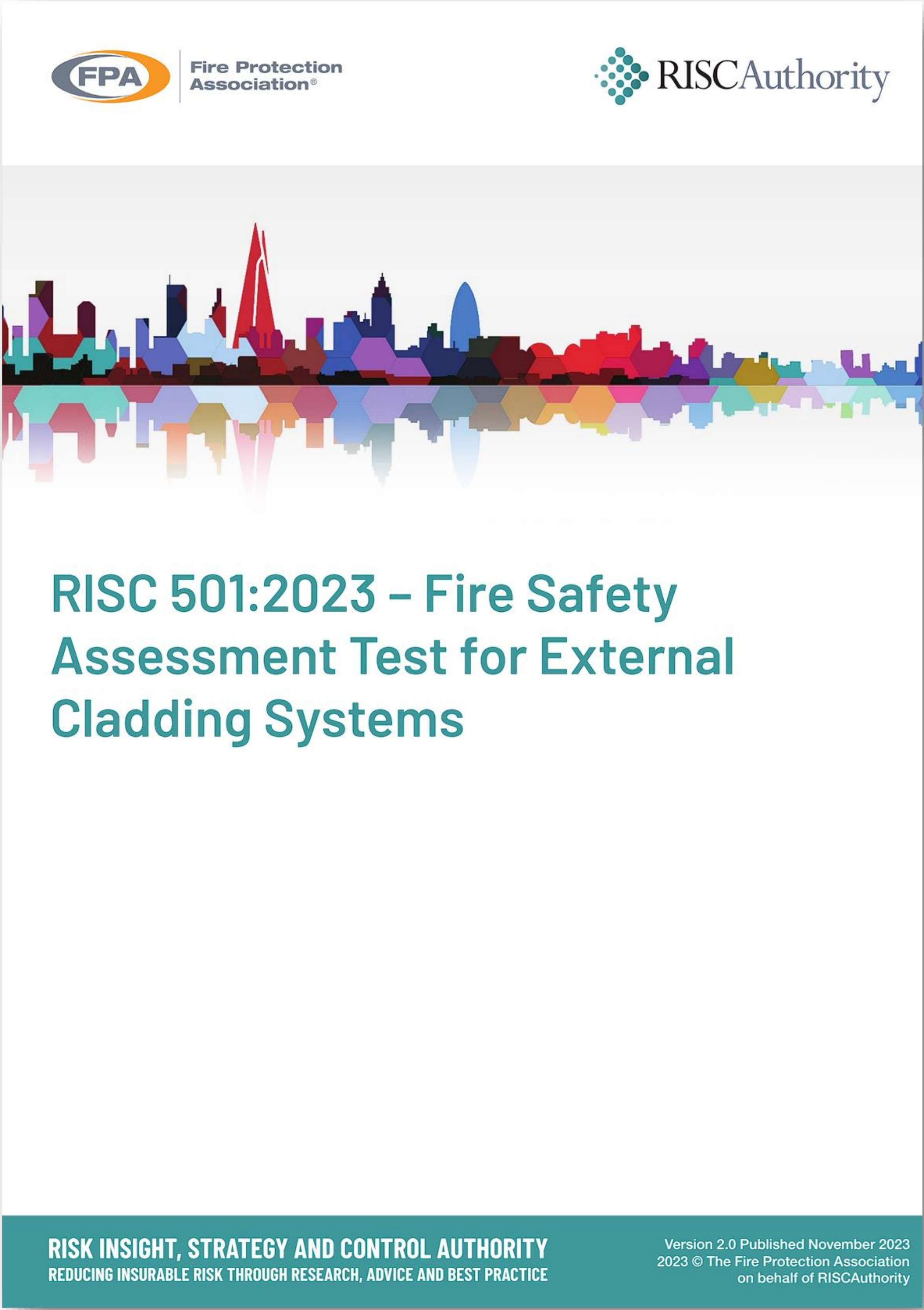
Field Entry	Description
Peak external temperature (°C)	ARIR
Peak internal temperature (°C)	ARIR
Peak level 3 temperature (°C)	ARIR
Tested full duration	ARIR
Time to temperature failure (s)	ARIR or inferred from data
BR 135 assessment	ARIR
Mechanical damage (%)	ARIR or an estimate based on a cross sectional area percentage from the post-test photos
BR 135 Failure on wing wall or main wall	Did the failure occur on the wing wall or on the main wall

Table 37 - LPS 1581/2 assessment inferred from data, observations and photographs presented in the report

Field Entry	Description
Early test termination	Failure of the system was deemed to have occurred if the test was terminated within the duration of the full test period for any safety reasons.
Visible flaming	Failure of the system was deemed to have occurred if visible flaming, which exceeded the confines of the test rig either vertically or laterally during the full 60 minute test period, was observed. For the purposes of this clause, visible flaming was defined as a continuous flame which was observed for more than 60 seconds duration (IE not intermittent or glowing).
External fire spread	Failure due to external fire spread was deemed to have occurred if the temperature rise above the 'ambient start temperature' of any of the external thermocouples at level 2 exceeded 600°C for a period of at least 30 seconds, within 30 minutes of the 'start time'.
Internal fire spread	Failure due to internal fire spread was deemed to have occurred if the temperature rise above 'ambient start temperature' of any of the internal thermocouples at level 2 exceeded 600°C, for a period of at least 30 seconds, within 30 minutes of the 'start time'.
Mechanical performance	Failure was deemed to have occurred if there was collapse of the system or part thereof, flaming or not onto the floor of the test facility outside the designated crib collapse zone, within the duration of the full 60-minute test period (see Note 1).
Burning debris	Failure was deemed to occur if burning debris or a pool fire developed on the floor of the test facility, outside the designated crib collapse zone (Note 1).
Glowing combustion	Failure in relation to this clause was deemed to have occurred if the area of system damage spread vertically beyond level 2 or reached the outer edge of the wing wall, in the area between Level 1 and Level 2, within 24 hours of the termination of the full 60-minute test period.
LPS 1581/2 assessment	If there was no evidence that a test has not met the above criteria, then it was deemed to have met the requirements of LPS 1581/2

Note 1 - The crib collapse zone is defined as a 2.4m x 1.2m positioned centrally on the centre line of the hearth opening (2.4m length parallel to the face of the hearth).

Appendix B – RISC 501:2023 – Fire Safety Assessment Test for External Cladding Systems



Fire Protection Association®

RISCAuthority

RISC 501:2023 – Fire Safety Assessment Test for External Cladding Systems

RISK INSIGHT, STRATEGY AND CONTROL AUTHORITY

REDUCING INSURABLE RISK THROUGH RESEARCH, ADVICE AND BEST PRACTICE

Version 2.0 Published November 2023

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Contents

Background

Enhancing cladding system fire safety

The occurrence of large cladding system fires has been increasing since 1990. This is of particular concern as a building's cladding system has the potential to spread fire around a building, bypassing the internal fire compartments.

Combustible cladding systems are approved on high-rise buildings in the UK by the performance-based route to compliance, using the BS8414 test method and BR 135 assessment criteria. However, a number of limitations have been identified with this route in relation to the appropriateness of the fuel source, test construction, construction detailing, assessment criteria, and availability of test results.

Following an extensive research project involving the University of Central Lancashire, external consultants, and insurers, the FPA has developed a new fire safety assessment test through RISCAuthority to address these limitations. An annually funded research scheme administered by the FPA, RISCAuthority comprises a group of UK insurers that actively support a number of working groups to develop best practice guidance for the protection of people, property, business, and the environment.

RISC 501 is designed to evaluate the fire safety performance of non-loadbearing external cladding systems and goes beyond the basic life safety standards, aiming to ensure resilient systems that can effectively prevent vertical spread. The test method is intended to be conducted either alongside BS 8414 so that the results can confer compliance with BR 135 and RISC 501, or as a standalone assessment.

1 Scope

This is a fire test and assessment method used to assess the fire safety performance of the design and materials of non-loadbearing external cladding systems, from a property and life safety perspective.

The test measures the potential of the cladding system to restrict vertical fire spread when the front face is exposed to a fire. The fire load simulates a fully developed fire in a compartment, venting out of a window and attacking the cladding system.

This method is designed to be conducted concurrently alongside BS8414-1 or BS8414-2[1, 2]. Notable differences include:

- different thermocouple locations
- different thermocouple criteria
- additional design requirements affecting floor heights and cavity barrier locations
- additional design requirements affecting detailing around the burn chamber opening and edges of the test rig
- additional service penetration requirements
- additional gas sampling requirements
- additional material characterisation requirements
- additional mechanical performance requirements.

The limits of the cladding system include any components attached to and external to the loadbearing construction.

2 Tolerances

2.1 Measurement of Uncertainty

All measurements must be inside the specified tolerances with a 95% confidence level.

If the tolerance specified is ±100 mm and the accuracy of measurement is ±10 mm then the object must be measured within ±80 mm.

If the tolerance specified is ≥100 mm and the accuracy of measurement ±10 mm then the objected must be measured to be ≥110 mm.

2.2 Value Tolerances

Unless otherwise stated, the following tolerances shall apply:

Table 1 - Value tolerances

Value	Tolerance
Length	±2%
Temperature	±5%
Volume	±5%
Gas concentration	±5%
Time	±5 s/h
Angle	±1°

3 Test Apparatus

3.1 Test Rig

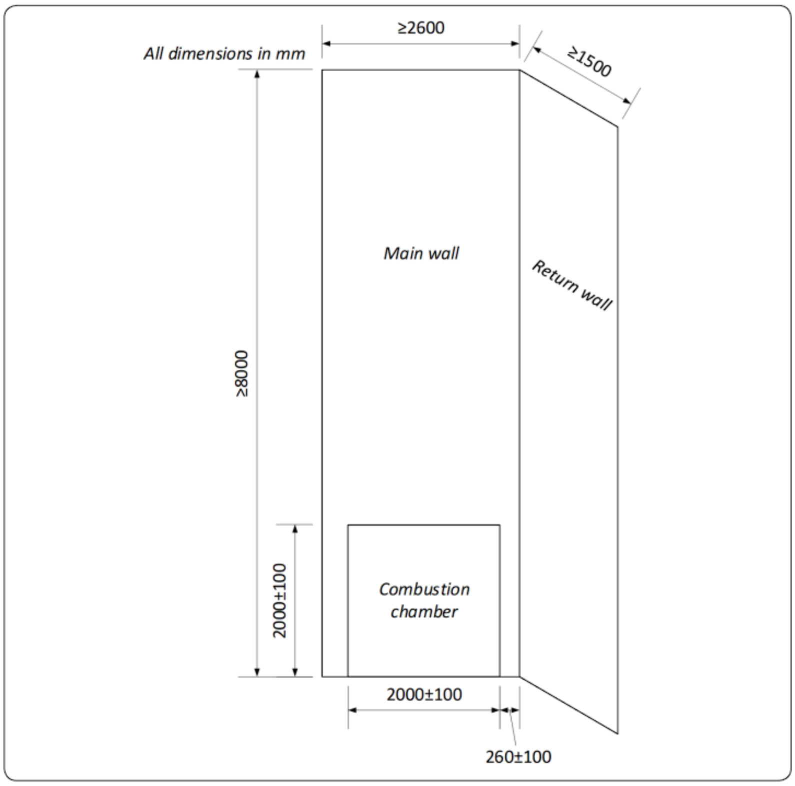
The test rig consists of a structural frame, covered by the test specimen. It is composed of a main wall and a perpendicular return wall. The return wall may be located on either side of the main wall.

It shall be:

- composed of materials representative of the end use application
- capable of supporting the test specimen
- capable of enduring the effects of the test without suffering undue damage or distortion
- constructed with the dimensions in Figure 1 below.

The test rig's protection shall not influence the test outcome.

Figure 1 – Test rig dimensions



3.2 Combustion Chamber

The fuel load is placed at the bottom of the test rig, inside an opening referred to as the combustion chamber. This is representative of a window opening. It shall be constructed as specified in either BS8414-1:2020[1] or BS8414-2:2020[2]. This shall include the lintel across the head of the chamber opening, capable of supporting the structure above it and enduring the effects of the test procedure.

3.3 Heat Source

The heat source shall be as specified in BS8414-1:2020 Annex A[1].

3.4 Data Recording

3.4.1 Thermocouples

Thermocouple data shall be recorded at least every 10 seconds and averaged over a 30 second period.

All thermocouples shall conform to BS EN 60581-1:2013[3], Type K (Chromel/Alumel). The thermocouples shall be mineral insulated and have a 1.5 mm nominal diameter.

Thermocouples shall be positioned 6 m above the combustion chamber opening in accordance with Figure 3 below.

Thermocouples shall be positioned within the test specimen, at the mid-point of each layer and cavity with a depth ≥ 10 mm.

Thermocouples shall be positioned (50±5) mm in front of the external face of the test specimen.

Figure 2 – Side elevation of a compliant thermocouple installation

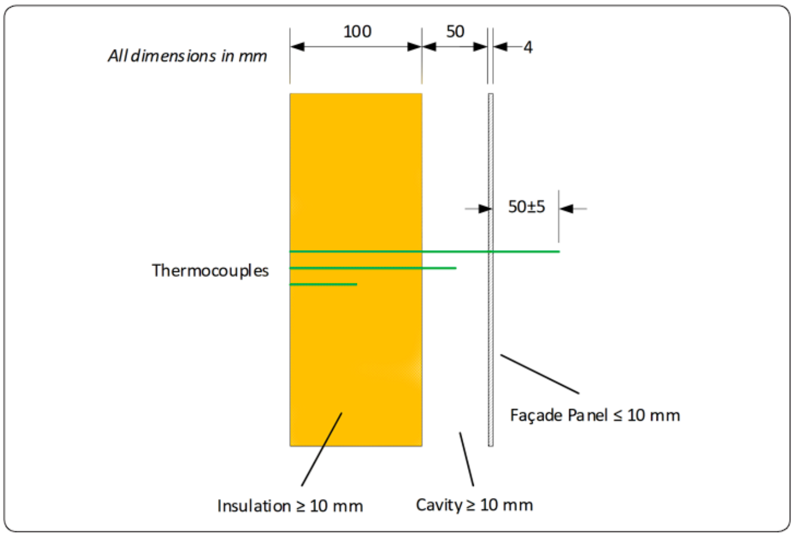
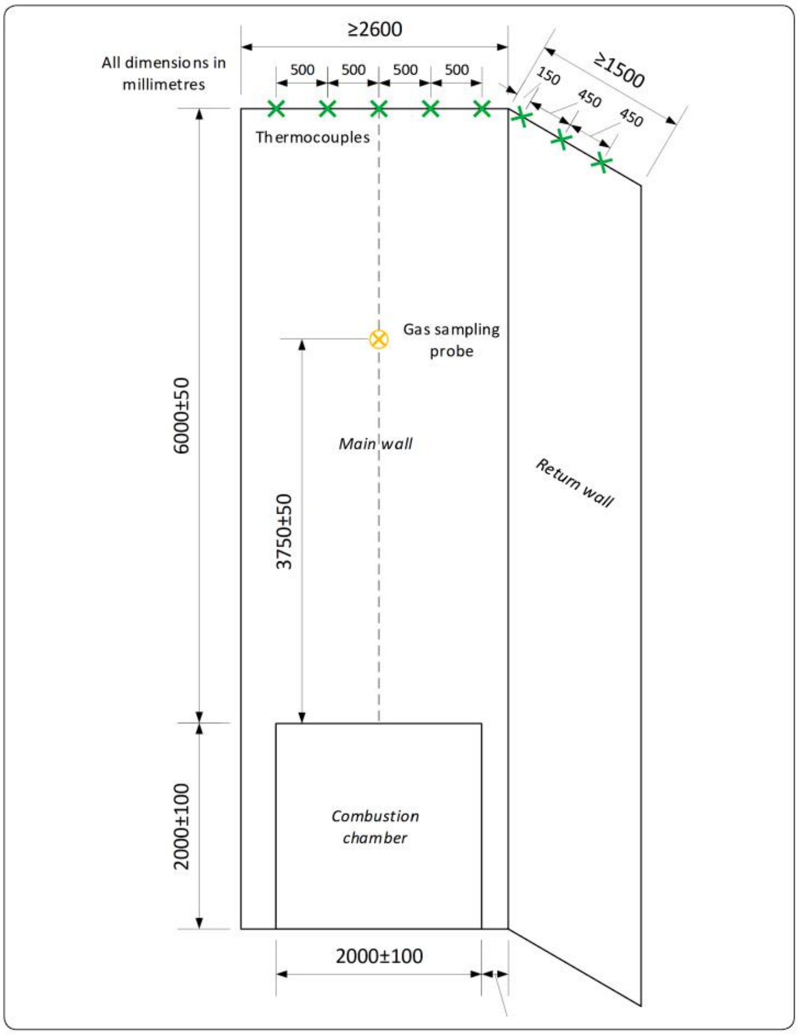


Figure 3 – Front elevation of instrumentation locations relative to the combustion chamber



3.4.2 Gas Sampling

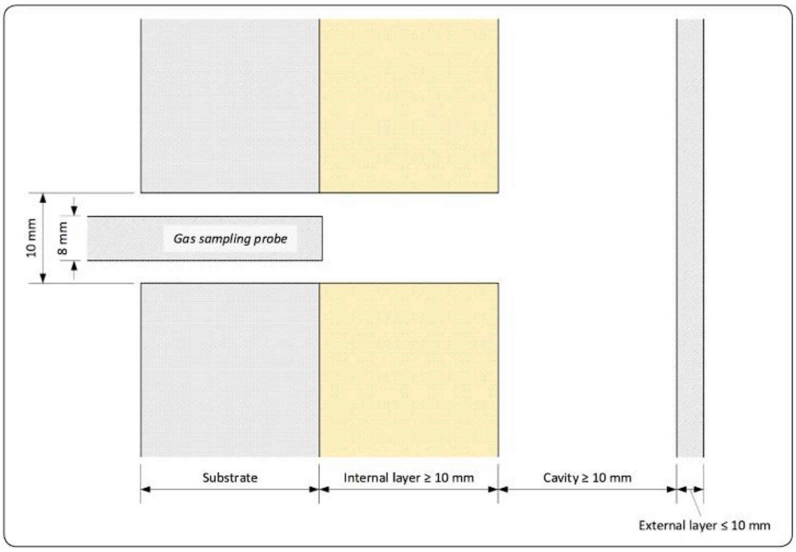
3.4.2.1 Gas Sampling Probe

A gas sampling probe shall be located (3750±100) mm above the combustion chamber as shown in Figure 3 above.

- The tip of the probe shall be positioned in line with the rear of the test sample as shown in Figure 4 below.
- The probe shall be inserted through a hole, in the rear of the test specimen, made through each internal layer. The hole shall not extend through the outer layer.
- The probe shall have an internal diameter ≥ 8 mm.
- The probe shall be sufficiently non-reactive and capable of surviving the duration of the test.

It has been found that 5 mm copper tube with 0.6 mm wall to BS 1057[4] soft is sufficient.

Figure 4 – Side elevation of a compliant gas sampling probe



3.4.2.2 Gas Sampling Measurement

Air shall be extracted from the gas sampling probe at a rate of 1 lpm. It shall be measured for O_2, CO_2 and CO concentration and they shall be recorded at least every 10 seconds.

3.4.3 Video Recording

The full duration of the fire test shall be recorded including ignition. The cameras shall:

- have a nominal frame rate ≥5 frames per second
- be of sufficient quality to enable the extraction of clear still images
- be positioned to cover the full height and width of the front face of the cladding system
- be positioned to identify flame spread at the top of the rig.

3.4.4 Classification Line

A line shall be marked (6000±50) mm above the combustion chamber opening so that it is clearly visible on camera.

It is appropriate for the top of the rig to be used as the test classification line if it is located (6000±50) mm above the combustion chamber opening.

The test may be terminated if flames are identified at this point.

4 Test Specimen

4.1 General Requirements

The external cladding system shall be installed onto the main wall and return wall of the test rig. The components to be tested shall be supplied together with design and installation criteria, operational instructions, drawings and technical data sufficient for the identification of the components.

The level of quality control used for the test installation shall match the standard used for a real installation.

4.2 System Design

The design of the system shall adhere to the same principles used for an actual installation. The virtual building depicted in Appendix A shall be used as the basis for design.

Information concerning system design and installation, critical to meeting the performance requirements, shall be provided to ensure that the system can be replicated as tested.

4.3 System Dimensions

The cladding system shall extend horizontally from the finished internal corner between the main wall and the return wall, covering a minimum distance of 2400 mm on the main wall and 1200 mm on the return wall. The specimen must extend from the base of the test apparatus up to a height of (6000±100) mm above the combustion chamber opening, on both the main and return wall, without blocking the combustion chamber opening.

4.4 Vertical Joints

Where vertical joints are incorporated into the cladding system, including expansion and movement joints, at least one joint shall extend upwards from the centre line of the combustion chamber opening ±100 mm.

4.5 Combustion Chamber Opening

The perimeter around the combustion chamber shall comprise of products, details and components that are intended for use in closing the aperture and related cavities in the final design.

It is appropriate to model the combustion chamber as a window opening for this purpose.

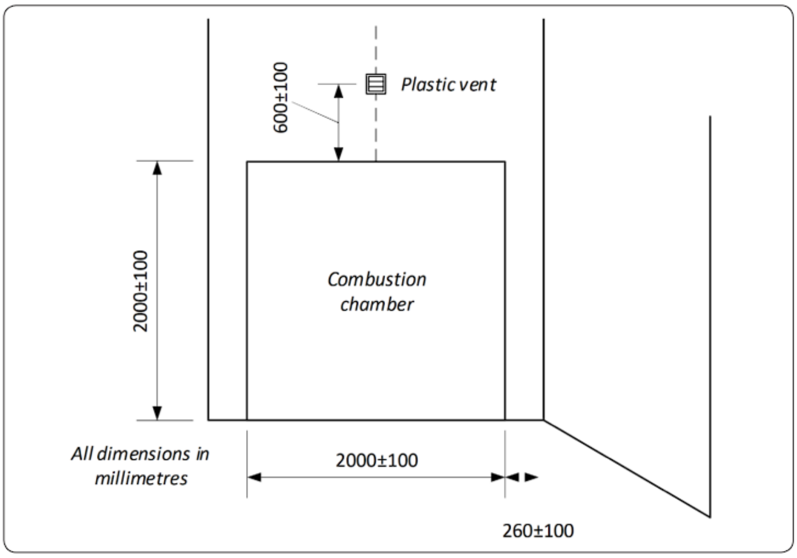
4.6 Edges of Test Rig

No detailing is permitted at the edges of the test rig. The test rig shall be modelled as a continuous flat surface and shall not be sealed around the external edges.

4.7 Service Penetrations

If the system design principles do not include provision for fire stopping around service penetrations, then a 100 mm Ø polyvinyl chloride (PVC) vent shall be included in the test rig. It shall be located (600±100) mm above the combustion chamber opening and shall be centred with respect to the combustion chamber as shown in Figure 5 below. The vent shall consist of PVC ducting which penetrates the entire way through the cladding system and a PVC grille on the front face of the cladding system.

Figure 5 – Front elevation of potential plastic vent location



4.8 Cavity Barriers

If cavity barriers and fire breaks are required for system performance, they shall be installed with the system's design principles applied against the virtual building in Appendix A.

If the design principles require one horizontal cavity barrier per floor, then they shall be installed at locations appropriate for the virtual building, 3150 mm apart.

4.9 Material Characterisation

Samples of each significantly combustible component shall be taken and subjected to material characterisation testing excluding:

- components which meet classification A1 or A2 S1 D0 when tested to BS EN 13501-1[5]
- components which are exempt from regulation 7[2] as noted in Approved Document B[1, 2].

The samples shall be selected at random by the test house.

Samples shall be tested to the procedure in Appendix B.

4.10 Conditioning

After the test specimen has been installed, it shall be conditioned as specified in BS 8414-1:2020[1].

5 Fire Test Procedure

5.1 Environmental Test Conditions

5.1.1 General Conditions

The test specimen shall not be affected by adverse weather conditions.

5.1.2 Wind Speed

The ambient air velocity shall not be greater than 2 m/s.

It shall be measured:

- in line with the test classification line, (8000±100) mm from the ground and (1000±100) mm away from either face of the cladding system
- in three perpendicular axis:
  - facing the main wall
  - horizontal to the main wall
  - vertical to the main wall
- between ignition and 30 minutes prior to ignition
- with the same ventilation conditions used during the test.

5.1.3 Ambient Temperature

The ambient temperature shall be between (5-35)°C.

It shall be measured:

- as an average of all external thermocouples
- as an average between ignition and 5 minutes prior to ignition
- with the same heating and ventilation conditions used during the test.

The facility may be artificially pre heated/cooled prior to the test if it has been proven that the test facility can remain within tolerance,for at least 65 minutes, once the artificial heating/ cooling is removed. This shall be proven during similar or worse ambient weather conditions.

5.2 Data Recording

The recording of thermocouple and toxicity data shall commence 5 minutes prior to ignition and continue until the test is completed or terminated.

5.3 Heat Source

The commencement of the test shall be considered the moment when the heat source is ignited. It shall be ignited using the procedure in BS8414-1:2020 Annex A[1].

The heat source shall be extinguished 30 minutes after ignition as specified in BS8414-1:2020[1].

5.4 Test Observations

Observations during the test, including changes in flaming conditions, mechanical behaviour of the cladding system, and detachment or fire penetrations in any part of the system, shall be recorded.

5.5 Test Duration

The test shall end 60 minutes after ignition.

5.6 Post-test Examination

5.6.1 General Examination

Following the fire test, an examination shall be conducted to record any relevant changes, including combustion, melting,deformation and detachment.

Smoke discolouration does not need to be recorded.

Still images shall be recorded of each layer of construction after the fire test.

5.6.2 Falling Parts

The largest part of each component which has fallen to the floor shall be weighed.

The largest part of each component with an edge ≤ 6mm which has fallen to the floor shall be weighed.

Parts shall be weighed dry.

If a part has been observed to break upon impact, it is acceptable to weigh an equivalent piece.

6 Classification Criteria

6.1 Visual Observation

Flames should not be observed extending beyond the classification line (section 3.4.4) or out the back of the test specimen.

6.2 Temperature Criteria

Thermocouple data shall be continuously sampled and averaged over a rolling 30 second period. The 30 second average shall not exceed the temperature criteria.

Temperature criteria shall be calculated using the following equation based on the ambient temperature (calculated in 5.1.3):

$$TC = 500 + 2AT$$

TC = Temperature Criteria

AT = Ambient Temperature

If it has been exceeded, the time taken to exceed the temperature criteria from ignition shall be recorded.

6.3 Mechanical Performance Criteria

No falling parts should exceed 5 kg.

No sharp falling parts should exceed 1 kg. Sharp is defined as any edges which are ≤ 6 mm.

7 Limits of Application

The results apply to the specific system specification tested. The application of multiple tests may be extended by applying the principles in BS 9414[6], when approved by a suitably qualified and experienced person.

If a service penetration was not installed in accordance with section 4.7, then the results shall not apply to systems which do not require additional protection around service penetrations.

If the system has undergone testing multiple times, it shall meet the classification criteria successfully more times than it fails to meet them.

8 Test Report

A report of the test shall be produced including:

- unique reference and date of report
- name and address of the fire test laboratory
- name and address of the test sponsor
- details of the test rig structural frame
- description of the system tested
- system design principles in accordance with section 4
- all products and components used in the test specimen
- results of the material characterisation tests specified in Appendix B
- drawings of the system in A4 portrait format including:
  - 1:50 scale elevations (or smaller) of each construction layer:
    - including the backing wall, brackets and support systems, insulation and fire barriers, cladding panels, and combustion chamber opening reveal
  - 1:5 scale details (or smaller) of vertical sections:
    - base of main wall
    - lintel
    - floor detailing (at each floor if different)
  - 1:5 scale details (or smaller) of horizontal sections:
    - edge of main wall (and return wall if different)
    - centre of combustion chamber
- the installation process, including still images of each significant layer of construction and still images of the edges of the test specimen
- installation start and end date
- reference to the test method used
- date of the fire test
- identification of the measurement instrumentation locations
- environmental test conditions
- test observations and test duration
- still images of the front face of the cladding system at 5 minute intervals from ignition until the end of the test
- graph of all temperatures and gas concentration measurements
- peak temperature, peak carbon monoxide concentration, peak carbon dioxide concentration, and minimum oxygen concentration
- time taken to exceed the temperature criteria (if exceeded)
- identification and mass of the heaviest falling part
- post-test examination including still images of each layer of the cladding system after the fire test
- a statement of compliance/non-compliance with section 6
- a statement of the limits of application in accordance with section 7
- a statement of all deviations noted.

9 Open Access Results

The test house shall publish publicly the details of the system tested with the results of the test including:

- company name and contact details
- unique report reference and date
- details of the test rig structural frame
- description of the cladding system including insulation and front panel
- whether cavity barriers and/or fire breaks were used
- classification result.

10 References

[1] "BS 8414-1:2020, Fire performance of external cladding systems - Test method for non-loadbearing external cladding systems fixed to, and supported by, a masonry substrate," British Standards Institution, London, 2020.

[2] "BS 8414-2: 2020, Fire performance of external cladding systems - Part 2: Test method for non-loadbearing external cladding systems fixed to, and supported by, a structural steel frame," British Standards Institution, London, 2020.

[3] "BS EN 60584-1:2013, Thermocouples - Part 1: EMF specifications and tolerances," British Standards Institution, London, 2020.

[4] "BS EN 1057:2006+A1:2010, Copper and copper alloys. Seamless, round copper tubes for water and gas in sanitary and heating applications," British Standards Institution, London, 2006.

[5] "BS EN 13501-1:2018, Fire classification of construction products and building elements. Classification using data from reaction to fire tests," British Standards Institution, London, 2018.

[6] "BS 9414:2019, Fire performance of external cladding systems - The application of results from BS 8414-1 and BS 8414-2 tests," British Standards Institution, London, 2019.

Appendix A – Virtual Building

The dimensions of the virtual building shall be considered when designing the system for test.

The virtual building exists for the purpose of defining dependent variables such as the location of cavity barriers. It does not need to be built.

Figure 6 – Front elevation of virtual building floor to floor detail

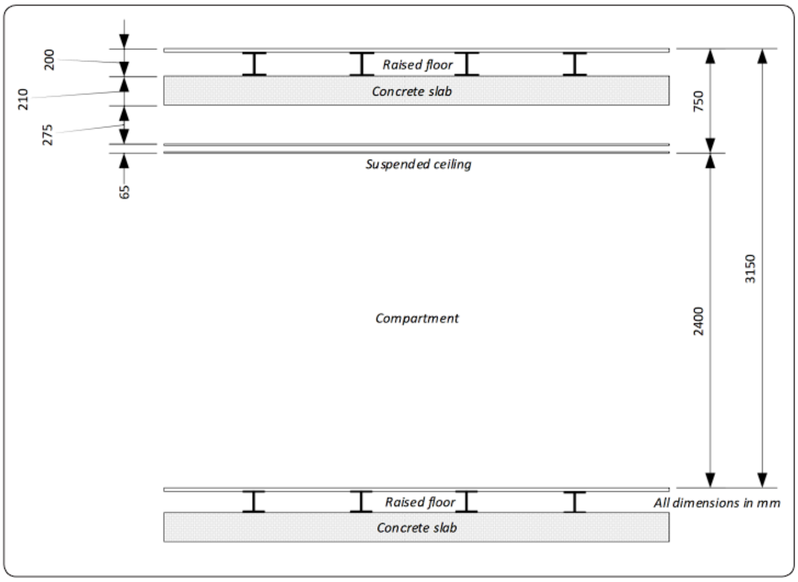
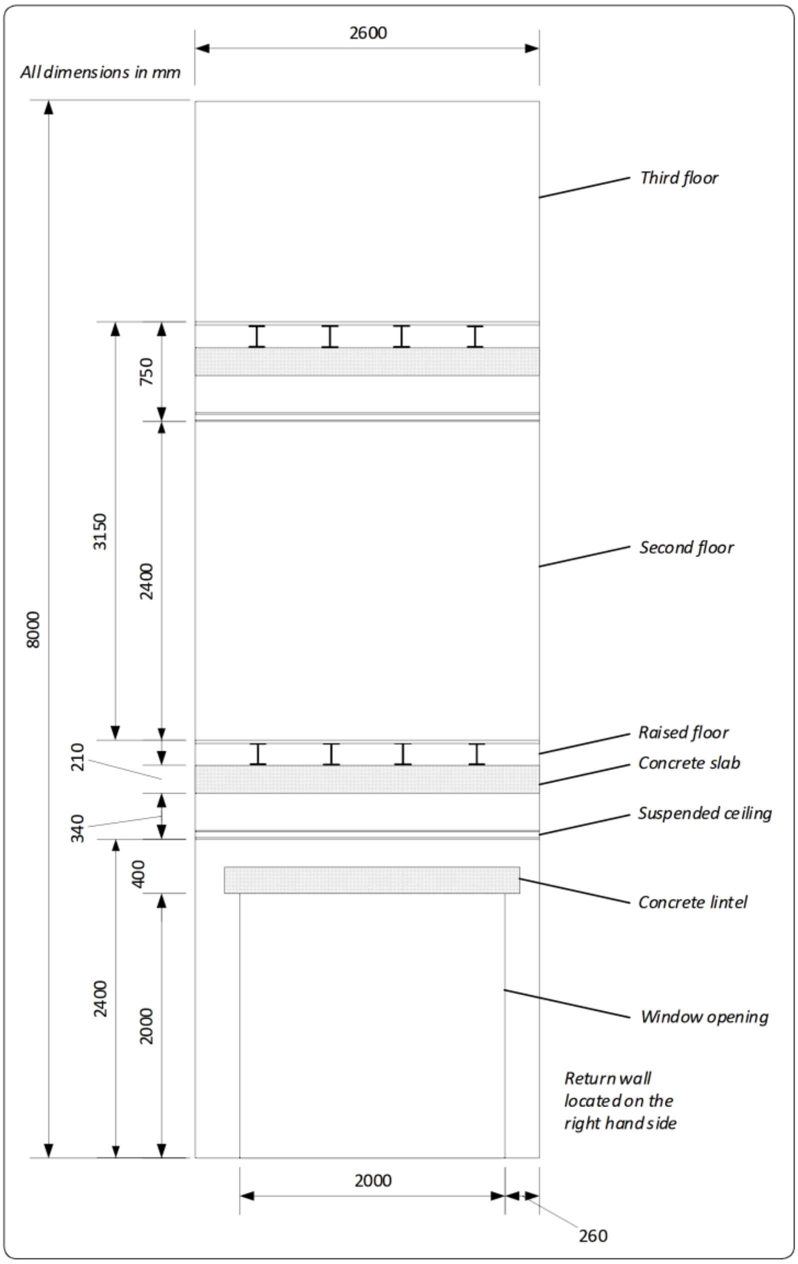


Figure 7 – Front elevation of virtual building



Appendix B – Material Characterisation Test Method

B.1 Sample Preparation

Product samples shall be cut with a method that removes the unclean edges. Samples shall be taken from a clean-cut edge and centrally throughout the thickness ±5 mm.

Samples shall remain dry.

This can be achieved by conditioning at (23 ± 2)°C and a relative humidity of (50 ± 5) % for 2 weeks prior to analysis in accordance with BS EN 13238:2010[7].

B.2 FTIR Procedure

Samples shall be ≥ 0.05 g, compressed into a flat disk with a KBr pellet press at a pressure ≥ 7 tons/cm^2 for at least 2 minutes.

Samples shall be evaluated using Diamond-Attenuated Total Reflectance-Fourier Transform Infra-Red spectrometry (D-ATR-FTIR). At least 32 scans shall be done per sample at a resolution of 4 cm^{-1}. A background scan shall be conducted first and subtracted from the sample.

B.3 MCC Procedure

Samples shall be between 2.000 and 3.000 mg.

Tests shall be conducted in triplicate in accordance with both method A and method B from ASTM D7309-21b – Standard test method for determining flammability characteristics of plastics and other solid materials using microscale combustion calorimetry[8].

The combustor shall be set to 900°C and the samples should be pyrolysed from 150°C to 750°C at a rate of 1.5°C per second.

B.4 References

[7] "BS EN 13238:2010 Reaction to fire tests for building products - Conditioning procedures and general rules for selection of substrates," British Standards Institution, London, 2010.

[8] "ASTM D7309-21b, Standard Test Method for Determining Flammability Characteristics of Plastics and Other Solid Materials Using Microscale Combustion Calorimetry" ASTM International, West Conshohocken, PA, 2021.

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