EVALUATION OF EXTERIOR WALL CAVITY FIRES USING AN INTERMEDIATE SCALE TEST METHOD

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ABSTRACT

External wall (EW) cavities are an integral part of an external wall system (EWS), providing space for structures, building services, insulation, waterproofing membranes and drainage. Over the past three past decades, the number of external wall fire incidents have gradually risen worldwide, with the most notable of these being the Grenfell Tower fire in London. The 2017 Grenfell Tower fire started when a non-flashover kitchen fire spread into the external wall cavity which included combustible insulations and combustible external cladding. Within wall cavities, combustible insulation can provide fuel load and vertical air gaps provide an arrangement that helps shield and insulate fires during the incipient stage, while at the same time supplying enough ventilation to support fire spread.

This study aims to investigate fire spread within an EW cavity containing combustible materials within an otherwise, ‘deemed’ non-combustible EWS. The cavity test rig design was based on FM Global’s Cavity Fire Test method referenced within the FM4411-2020 standard. The experimental component of this research has selected different test parameters (such as ignition type, ignition size, cavity widths and chosen test specimens) to that examined under the FM Global Cavity Fire Test study, to gain further understanding of fire behaviours within an EW cavity. These test parameters included the following:

- Liquid fuel based ignition sources of either methylated spirits or heptane.
- Three fire ignition sizes created by using either:
  - One tray, ~6-8 kW methylated spirits fire (fuel surface area of 0.0125m^2),
  - One tray, ~80kW heptane fire (fuel surface area of 0.0125m^2),
  - Two trays, ~200kW heptane fire (fuel surface area of 0.025m^2).

  The Heat Release Rate (HRR) of these ignition sources were influenced by the surrounding boundary conditions created within the cavity.
- Main cavity width of 65mm air gap plus the thickness of the installed insulation (a cavity air gap width of ~130mm was used to conduct Cavity Rig characterisation tests only).
- A range of cavity materials of varying fire performance that included two thermoplastic insulations (polystyrene board and polyester batts), two thermosetting insulations (polyisocyanurate foam and phenolic foam) and one type of foil faced polypropylene sarking. The thermosetting materials were supplied with a protective facing adhered to both sides. These materials were tested with and without the protective facing.

Three ignition sizes were chosen to represent a range of possible cavity fire scenarios. The size of the one tray methylated spirits fire (reduced scale ignition) represented a small, localised fire, developing on materials, created from an electrical fault. The exposure conditions and ignition size of the methylated spirits fire also, most closely represents the ignition source devised for the FM Global Cavity Fire Test under FM4411-2020.

The size of the heptane tray fire (base scale ignition) represented a pre-flashover (or post flashover) compartmental fire breach into the cavity (such as was evident for the Grenfell Tower fire). An additional two tray heptane fire (sensitivity scale ignition) was adopted to examine if an increased fire size would reveal further discriminatory data and/or fire behaviour between the chosen materials.

The one tray heptane fire was concluded to be sufficient in establishing ignition and providing discriminatory results (in terms of HRR, temperature, radiant heat and fire progression and post-test damage data). It also revealed a range of reaction-to-fire behaviours between the tested materials. Such behaviours included the swelling of char layer formation on the polyisocyanurate material, extended smouldering combustion of both polyisocyanurate and phenolic foams after the ignition source burnout, and differing formation of molten flow and pool fire spread between polyester batts and polystyrene board.

Except for the single type of foil faced polypropylene sarking, all materials experienced fire spread to the top of the cavity under one and two tray heptane fires. The methylated spirits fire ignition source did not promote fire spread for most materials (it did involve the aluminium paper facing on phenolic board and resulted in some limited spread on exposed PIR).

Fire hazards associated with thermoplastic materials such as the production of pool fires that have the potential to flow and spread laterally within a cavity floor, are not fully captured by small-scale test methods like AS1530.2 and AS1530.3. The fire size and exposure conditions of these tests are too small and do not represent cavity fire scenarios. Currently, large-scale tests provide the most reliable information in predicting real-scale fire risk posed by a particular EWS design, however large-scale test methods do not address potential fire hazards resulting from fires originating within a cavity. The intermediate scale sized test rig addresses the shortcomings of both small- and large-scale test methods in representing cavity fire scenarios.

Overall, the design of this cavity fire test successfully enabled investigation of ignition and reaction to fire behaviour of a range of different types of cavity insulation and sarking within an end-use arrangement.

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DECLARATION

I, Neythra Geetanjelee Weerakkody, declare that the Master of Research Practice thesis entitled "Evaluation of exterior wall cavity fires using an intermediate scale test method" is no more than 50,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures.

Signature: [redacted] Date: 28.02.22

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LIST OF ABBREVIATIONS

ACP	Aluminium Composite Panels
EPS	Expanded Polystyrene
EWS	External Wall Systems
FIGRA	Fire Growth Rate Index
HBCD	Hexabromocyclododecane
HRR	Heat Release Rate
IST	Intermediate Scale Test
MW	Mineral Wool
NCC	National Construction Code (Series)
BCA	Building Code of Australia
NFPA	National Fire Protection Association
PB	Polyester batts
PF	Phenolic foam
PIR	Polyisocyanurate
PPT	16 ft. Parallel Panel Test
SMOGRA	Smoke Growth Rate
XPS	Extruded Polystyrene

TERMINOLOGY

Building Classification – Under the National Construction Code (NCC), buildings and structures are classified into Class 1a, 1b,2, 3, 4, 5,6, 7a, 7b, 8, 9a, 9b, 9c, 10a and10b according to their function, design and construction. For example, a health-care building such as a hospital is Class 9a and a shop/retail establishment is Class 6.

Building Ministers Forum – A forum that consists of federal, state and territory government minsters. They oversee policy and regulatory framework that affect Australia's building and construction industry.

External Insulation and Finish System (EIFS)– A type of External Wall System that comprises of a rigid foam board insulation (most commonly expanded polystyrene). The insulating board is encapsulated by a mesh that is imbedded in 2-3 layers of cement or acrylic based render; providing a weather-proof finish.

Fire Compartment – a part of a building separated by the remainder of the building through the use of fire-resisting construction for the walls, floors and ceilings.

Fire Load - the total calorific value (MJ) of all combustible items within a fire compartment (see above) that is expected to contribute to fire growth and spread. It includes both removable (i.e., furniture, furnishings) and fixed items (i.e., wall and floor linings).

Flashover – The transition from a localized fire to the combustion of all exposed surfaces within a room or compartment.

Factory Mutual (FM Global) – A company based in the United States that provides third party testing and certification (FM Approvals) to manufacturers and/or building owners seeking insurance. FM Approvals allows FM Global to insure buildings that are constructed to certain, known standard.

Intermediate Scale Test (for External Wall Systems) – see Section 3.1.2

Heat Release Rate – the rate at which heat is released in a fire (in kW or MW).

High-rise Construction – in accordance with the BCA, a high-rise building is one that is either >25m in height or greater than 4 storeys (above effective ground level).

Performance Requirements – The minimum level of performance a building must achieve. An example of a performance requirement stated in the National Construction Code that is applicable to external wall systems is CP2 " A building must have elements which will, to the degree necessary, avoid the spread of fire to – exits; and sole-occupancy units; and between buildings; and in a building.[3]"

Polyols – An alcohol that contains three or more hydroxyl groups (-OH)[2].

Sheathing board - A board that includes either engineered timber, plywood, plasterboard (gypsum) or oriented strand board (OSB).

Thermoplastic – Polymer materials that melt and soften when heated and may harden again once cooled. This process can be repeated so long as the heating of the material does not result in decomposition.[3]

Thermosetting – Polymer materials that hardens and 'sets' irreversibly when heated. [3] Materials that exhibit this behaviour often form a blackened charred layer.

Type of Construction – The minimum type of fire-resisting construction prescribed by Clause C1.1 of the National Construction Code that is required for a building of a particular classification (see *'Building Classification'* above) and is dependent on the rise in stories of the building. Type A construction is the most stringent and Type C is the least stringent.

1 INTRODUCTION

1.1 Background

Over time external walls of buildings have evolved to become increasingly complex systems, required to fulfill multi-faceted objectives that go beyond just supporting the roof structure. The need for more sustainable, energy efficient buildings that are both cost-effective and aesthetically appealing have driven the innovation for new products and systems for external wall construction. Unfortunately, materials and systems that provide versatility in these areas are often combustible by nature. The use of combustible components have resulted in an alarming number of external wall fires. The number of fires have increased seven fold in the last three decades to a rate of 4.8 fires per year[4]. This includes the Lacrosse and Neo200 high-rise apartment building fires in Melbourne.

The impact of external wall fires on life safety have been low, until the Grenfell Tower fire that occurred London in 2017. This fire incident tragically claimed 72 lives[5] and as a result; prompted worldwide debate and review of current fire testing standards, product certification, building approval processes and building regulatory control for External Wall Systems (EWS).

The role of fire testing standards in providing regulatory control for EWS plays an important part of the debate. After Grenfell tower fire, the *Building Ministers Forum* (BMF) recognised the need to clarify fire *performance requirements* and definitions for exterior wall systems (EWS) in order to prevent non-compliant use of combustible cladding. This resulted in an out-of-cycle NCC amendment (BCA 2016 Vol. 1 Amendment 1). The Amendment 1 introduced a Verification Method (CV3) for EWS that meets the *performance requirements* of the NCC. This Verification method refers to AS 5113 - a full scale classification standard (see Appendix B2) for exterior wall systems. Data from the test can be used by industry to verify the performance of EWS, offering an avenue to seek compliance to the NCC.

However, AS 5113:2016 full scale classification standard can be time consuming and expensive. The test applies a large 3 MW fire to the specimen and has stringent acceptance criteria, making it difficult for systems to pass all test criteria. At present, only full-scale test standards (such AS 5113:2016 full scale classification standard) are considered to provide the most reliable assessment in exterior wall fire performance but they do not represent all external wall fire scenarios.

An intermediate scale test method can provide further scope and can be used to investigate EWS response to smaller fire exposures conditions/scenarios such as those occurring in exterior wall cavities or localised flame impingement on cladding. Intermediate scale test methods may also be used as tool to efficiently screen out poor performing EWS before full scale application.

After conducting a thorough literature review, we decided to focus on EW cavity fires and its possible representation as an intermediate scale test method.

1.2 Definition of an External Wall Systems (EWS)

Exterior Wall Systems (EWS) or facades systems forms the outer, exposed shell of a building and plays an integral part in shielding its occupants from the wind, rain, heat, cold and sound while also offering aesthetic significance. Modern EWS in high-rise construction can account for up to 25% of the total project costs[6].

The basic assembly of an EWS includes a structural substrate (load-bearing component), insulating layer and external finish or cladding. The insulating layer enhances the thermal performance of the building, while the external finish provides protection from the outside climate as well as aesthetic appeal. The construction of EWS may also include a ventilated cavity and sarking (a type of weather resistive membrane - WRM). The cavity and sarking layer work together to drain away condensation and moisture build up while protecting the insulation from any moisture damage.

In general, EWS are constructed as either[1, 7]

- **a non-ventilated system - Structural wall with an external cover**

  An insulating layer is directly attached to a structural wall. The insulation is either adhesively bonded or mechanically fixed to the structural wall and the external finish is directly attached to the insulation to form a protective, weatherproof barrier.

- **a ventilated system (present in curtain wall/rainscreen cladding systems)**

  A drained, ventilated cavity sits behind the exterior cladding. The exterior cladding is connected to steel or aluminium rails/ tracks that are in turn installed directly onto layer of insulation or sarking. The air gap created by the rail or track usually extends to the top and bottom of the wall to allow for adequate drainage. If it is structural timber or steel framed wall, a WRM such as sarking will be installed between the insulation and frame, creating a cavity with limited ventilation. Alternatively, the insulation may be installed in between each stud of the wall frame (see Figure 1).

Figure 1 demonstrates the differences between a ventilated and non-ventilated EWS.

Combustible materials such timbers, polymer plastics and GRP significantly increase the fire hazard of an EWS. Apart from combustible components, the presence of air cavities, installation method, configuration and types of active/passive fire safety systems installed in the building, all have an impact on EWS fire performance.

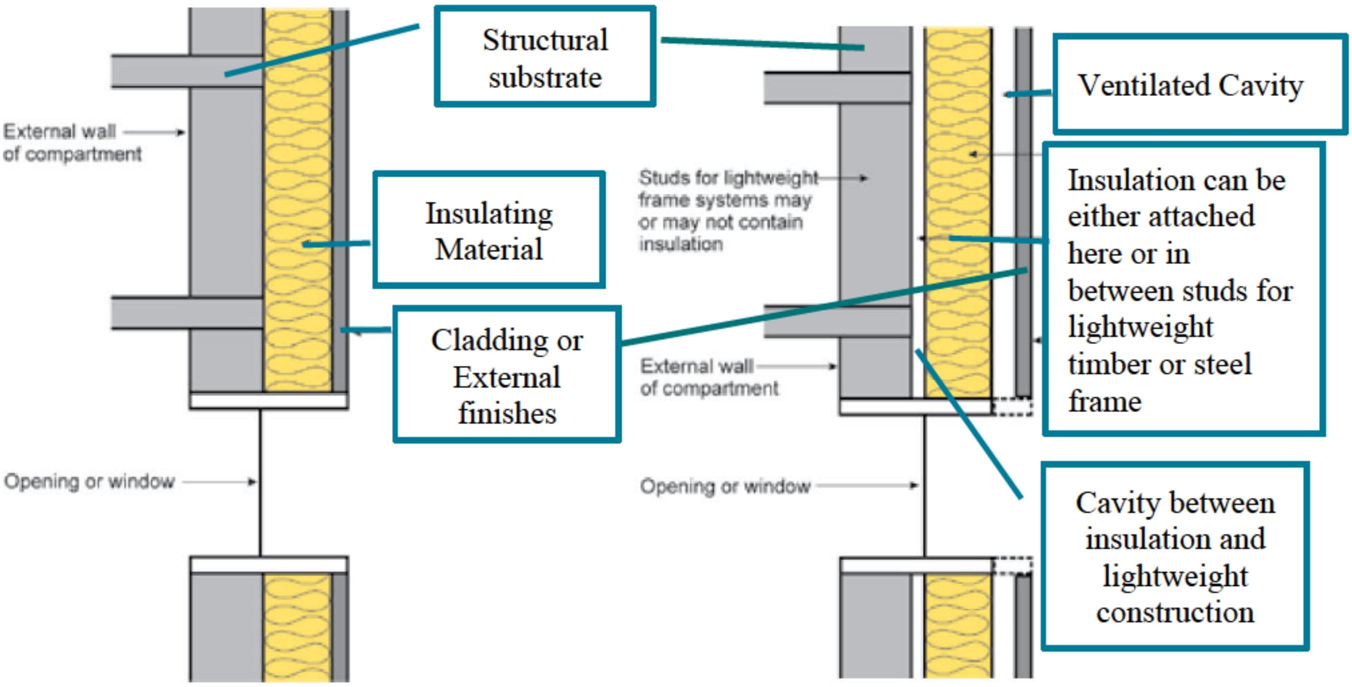


Figure 1: Elements of a non-ventilated wall (left) and ventilated cavity wall (right)[1]

Modern building construction practices of external walls systems include air cavities of various depths and locations. Cavities may extend up to the full height of the building or be capped by non-combustible cavity barriers (see Section 2.1.1).

1.3 Research Aims

The aims of this study are to examine an intermediate-scale test method that can represent a range of cavity fire scenarios to study the fire spread potential for different cavity materials and arrangements found within an EWS. The objectives are grouped into two categories: Literature Review Objectives and Experimental Component Objectives.

1.3.1 Literature Review Objectives

The basis of the literature review was to find answers to the following questions:

1) What are main components/materials of an EWS and definition of an external wall cavity?
2) What are the common materials found in external wall cavities?
3) What characterises overall EW fire spread and what specifically characterises spread within cavities of an external wall system?
4) What evidence of fire incidents exists that include cavity fire scenarios?
5) What are the current test standards and experimental tests that regulate/study EWS fire material performance and what role does intermediate scale test methods have in regulating such systems or materials?

1.3.2 Experimental Component Objectives

The experimental component of this study focuses on designing a cavity fire test method to investigate the following:

1) What impact does ignition size, ignition type and cavity arrangement have on the test outcomes?
2) Do the chosen characteristics of the test method (ignition size, type and cavity configuration) successfully expose different reaction to fire behaviour between groups of materials and provide discriminatory results?
3) How does the design of the cavity test compare to exposure conditions of relatable intermediate scale cavity test, namely the FM Global Cavity Fire Test method?

1.4 Research Scope

It is important to note that external wall fire performance is dependent on the overall system performance rather than the performance of its individual components[8]. This paper will however focus on external wall fire spread via external wall cavities. This includes the ventilated cavity (behind the external cladding) and cavities that innately exist within lightweight construction (steel or timber frame construction). NFPA Fire Risk Assessment Tool[9] documents most component variables of an EWS and how they may individually contribute to external wall fire spread. Table 1 below has listed these components and how they may specifically relate to cavity fire spread (under column heading 'Relation to Cavity Fire Spread'). Only component variables specifically relating to cavity fire spread (highlighted in blue) are further explored in this literature review.

Table 1: Elements of EWS and influence on fire performance

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
EWS components	Structural substrate wall	Aluminium, Steel or timber frame, masonry, Cross laminated timber (CLT)/Massive timber or concrete (pre-cast or in-situ).	Steel or aluminium stud frames), masonry and concrete are non-combustible materials. Timber stud frames are combustible so their use in buildings is restricted. CLT is also combustible but recent testing and research examining CLT fire performance has permitted its acceptance into high-rise construction.	Cavities exist within the stud frame or between the stud frame and external cladding layer (see Figure 1). Cavities provide avenues for fire spread (**see Section 2.2.1**). The presence of timber and air gaps within the cavity (such as for timber stud frame construction) are factors that can increase the overall fire load of an EWS. The fire properties of light-weight timber construction and CLT will be discussed in the Literature review (see **Section 2.1.4),** however will not be examined further as part of the Experimental Component of this study. The Experimental Component will focus on combustible cavity materials

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
				(insulation and sarking) within an otherwise non-combustible EWS.
	External Finishes (cladding)	Aluminium Composite Panels (ACP) or Metal Composite Material (MCM), timber, High Pressure Laminates (HPL), timber composites, Glass Fibre Reinforced Polymers (GFRP), cement board products, External Insulation Finishing Systems (EIFS) or External Thermal Insulation Composite System (ETICS) and Insulating Sandwich Panels (ISP).	The fire performance of these materials depends on fixing details, material composition and manufacture process. A comprehensive summary of external wall claddings is covered by the book 'Fire Hazards of Exterior Wall Assemblies Containing Combustible Components' by Nathan White and Michael Delichatsios[7]	Although the outer wall face of a ventilated cavity is the exterior cladding – this literature review has focused on cavity fires in an otherwise non-combustible external wall system. Therefore, a detailed account of the fire performance of each cladding type is out of scope for this paper.
	Insulation	Common combustible insulation on the market includes polyester fibre, Expanded Polystyrene (EPS), Fire retardant EPS (EPS-FR), Extruded Polystyrene (XPS), Polyurethane (PUR), Polyisocyanurate (PIR), Phenolic foam.	Details of reaction to fire performance for these insulation types are discussed in **Section 2.1.2** of this report.	Insulation is the main source of potential fuel within cavities. The reaction-to-fire attributes of common combustible insulations (as well as cavity ventilation conditions) significantly impact on cavity fire spread.

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
		Non-combustible insulations are also available and mainly include mineral or glass wool.		
	Location of insulation within EWS	For most external wall systems, the insulation layer is commonly located within the cavity or between the spacings of a stud frame. For EIFS or ISP cladding systems, the foamed insulation layer faces the outside environment. The insulating layer in these systems are weather proofed with either acrylic cement render (for EIFS) or thin steel or aluminium facing (ISP).	Burning characteristics (ignitability, heat release rate and flame spread rate) of combustible insulation will depend on the properties of the material, where it is situated within the EWS, type of protective layer (if any) and how it is installed (mechanically fixed or glued).	Fires within a cavity are typically ventilation controlled and therefore the burning characteristics of the insulation is impacted. This study will focus fire spread on insulations contained within the air cavity, and not on insulations that form part of the exterior 'cladding' layer (such as EIFS and ISP).
	Cavities in EWS	Ventilated cavities or air gaps help drain away wind driven rain and/or condensation build up behind the exterior cladding. Cavities can vary in width, typically >0 to 100mm.	Cavity widths influence the rate of fire spread within an EWS.	The relationship between cavity widths and rate of fire spread is discussed further under **Section 3.3** of this paper.

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
	Sarking (or other weather resistive membranes -WRM)	Building wraps that are flexible membranes such as cellular insulation wraps, polyurethane sheet, sarking, fluid or paint applied membranes such as polymeric and asphaltic sprays.	The relative fuel load of sarking (or other weather resistive barriers) is significantly lower than that of combustible insulation and cladding. The heat potential of sarking in an otherwise non-combustible EWS will most likely not cause major fire spread.	Influence of sarking in fire spread in the presence of combustible insulation has not been explored in literature and forms part of the experimental study of this research. See **Section 2.1.3.**
EWS installation	Un-filled joints	Joints exist in all EWS and can remain unfilled.	Un filled joints provide an avenue for flame spread.	N/A
	Joints filled with sealants	A variety of combustible sealants exist, such as silicone.	Sealant in joints is easily ignitable and as above, provide an avenue for flame spread. However, in isolation (without the presence of combustible insulation or cladding), represent a small portion of the overall façade system and therefore do not contribute significantly to the fire load.	N/A
	Cladding or insulation fixing method	Adhesively bonded (using double sided tape) or mechanically fixed (using bolts, screws or proprietary fixing methods).	The heat generated in a fire can more readily disengage adhesively bonded cladding and/or insulation panels than mechanically fixed cladding or insulation.	N/A

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
EWS configuration on a building	Continuous or broken sections of vertical or horizontal sections of combustible cladding found on the façade of a building.	High-rise office buildings tend to have mainly glazed facades with horizontal spandrels at floor slab levels, whereas residential buildings tend to have smaller openings and cover more area in cladding. Although full glazed height does exist at elevated levels for residential buildings too.	Vertical strips of combustible cladding that are continuous (i.e., remain unbroken between floors of the building) will experience an increased rate of fire spread than continuously horizontal sections of combustible cladding.	N/A
	Balconies or other horizontal projections (such as canopies)	Balconies are cantilevered platforms that can be fully or partially enclosed. Fire performance of a façade can depend the length and width of these horizontal projection.	The cantilevered platform tends to hinder floor to floor fire spread. However, the combustible items commonly found on balconies (such as outdoor furniture, plants, clothing etc) and/or balcony balustrades or parapet walls, cladded with combustible cladding can promote fire spread. Balconies also present multiple sources of ignition (such as BBQ, unextinguished cigarette butt or faulty air conditioning external unit).	N/A

Aspect	Sub-aspect	Variables	Fire performance	Relation to Cavity fire spread
	External wall outline	Inside corners, U-shaped walls (channels) or straight external wall face	Inside corners or U-shaped walls (channels) have parallel faces that help insulate a fire and provide re-radiating surfaces that help increase the rate of fire spread.	N/A
Passive fire safety measures	Fire Blocking, window lintels and cavity barriers	The measures are adopted in varying degrees depending on code requirements and design.	Cavity barriers of fire blocking are designed to inhibit or slow down the spread of fire within external wall cavities.	See **Section 2.1.1** and **Section 3.2**.
	Perimeter stopping	Presence of fire blocking or fire barriers between edge of fire rated floor and ventilated (curtain wall) EWS.	Fire blocking delays or deters spread of smoke and fire between floors.	See Section 2.1.1 and Section 3.2.
Other	Age of EWS	The EWS becomes weathered and damaged over time, exposing combustible layers such as the polyethylene cores of ACP panels or the polymer foam core of rendered EIFS.	Exposed combustible layers are more susceptible to ignition sources.	

1.5 Thesis Outline

Chapter 1 contains thebackground topics to intermediate scale cavity wall fire testing and includes typical external wall construction and external wall fires. It also contains the research aims, objectives as well as an outline of the thesis.

Chapter 2 presents the detailed literature review on fire spread within an EW cavity. This includes types of combustible components and their contribution to fire spread (Section 2.1) and Mechanisms of fire spread within an EW cavity (Section 2.2). The final part of this chapter details case studies of external wall fire incidents that include cavity fire scenarios (Section 2.2).

Chapter 3 aims to discuss fire testing (both experimental and test standards) and building regulations concerning external wall material or system construction. This chapter includes existing small, intermediate and large-scale fire testing (Section 3.1) and corresponding building code requirements currently applied to regulate external wall fire performance (Section 3.2). Non-standardised, experimental research into behaviour of fires within a cavity arrangement and test methods used to study fire spread within cavities containing combustible specimens concludes this chapter (Section 3.3).

Chapter 4 details the methodology of the planned experimental study (Sections 4.1 to 4.5), results (Sections 4.6) and discussion on experiment outcomes (Section 4.7 and 4.8). Test results include cavity characterisation tests (cavity fire tests conducted in the absence of combustible materials). Analysis of recorded data includes HRR, temperature distribution (within cavity), radiant heat (incident heat flux), post-test damage and live and video recordings for each test. Snapshot taken from test videos, depicting the fire progression of each tested material are included.

Chapter 5 includes main conclusions that summarises subject of this paper, contribution to knowledge and recommendations. The chapter answers the experimental component objectives set out in the introduction (Chapter 1), drawing on literature review findings where applicable.

2 COMPONENTS OF EXTERNAL WALL CAVITIES AND MECHANISMS OF FIRE SPREAD

2.1 Components of EWS

2.1.1 Cavity barriers and fire stops

Cavity barriers prevent or significantly slow down the rate of fire spread within an EWS.

Cavity barriers can be installed within any joint or junction of an EWS:

- as vertical cavity barriers to create a fire resistive junction between fire compartments on the same floor,
- as horizontal cavity barriers to create fire resistive junction between floors,
- to tops of cavities,
- around openings such as windows, doors, or vents and
- at any other intermediate section of an external wall cavities (including cavities in floors or ceilings)

In Australia, Cavity Barriers are only required within 'fire protected timber' (Timber frame or Cross Laminated building elements with a non-combustible fire resistive covering such as gypsum plasterboard). Building Code of Australia (BCA) Volume, 1 Specification C1.13 states that cavity barriers must either consist of timber or polyethylene-sleeved mineral wool slabs/ strips. Mineral wool thickness required (as per Table 2) is of the thickness achieved under compression.

Table 2: Cavity barrier Requirements (as presented in BCA Vol. 1, Spec C1.13)[10]

System Required FRL	-/60/60 or -/90/90	-/120/120, -/180/180 or -/240/240
Timber barrier, minimum required FRL	-/45/45	-/60/60
Timber or mineral wool required minimum thickness	45 mm	60 mm

The FRL of cavity barriers are assessed under AS1530.4 – Fire Resistance Test on Construction elements, against the performance criteria used for assessing control joint systems.

There is no cavity barrier that is applicable for all types of fire scenarios. Table 3 details the type of cavity barrier and applicable fire scenario.

Table 3: Types of Cavity Barriers to suit particular fire exposure conditions[11]

Cavity Barrier Type	Section view	Suitable fire exposure condition(s)
Intumescent Strip		Compartmental fires – This type of barrier is suitable for slow increase in temperatures within cavity. If flash or direct flames occurs – it is possible for fire to breach barrier prior to expansion.
Perforated metal barrier or metal sheet labyrinth		Wildfire ember and flame attack.
Flame quenching mesh with intumescent element		Ember attack, sudden fire flame exposure, compartmental fires (slow increase in temperature within cavity) and façade fires.
Solid Barrier (non-ventilating) – includes wood, mineral wool, calcium silicate, gypsum/ sheet metal.		Compartmental fires (slow increase in temperature within cavity) and façade fires.

Fire stops refer to the seal that spans between the floor slab (spandrel) and the curtain wall system. They are designed to maintain the designed fire resistance level (FRL) of the wall or floor assembly. Fire stops also provide a fire-resistant seal around penetrations between walls and floors. Fire stop materials include caulks, putties, pillows (fire large penetrations), mastics, boards, silicone foam and cementitious slurries[12]. These materials either expand and form a tight seal around the penetration, char and form a protective, insulating layer or absorb heat and release moisture to protect the material underneath.

2.1.2 Building Insulation

Installing or retrofitting an external wall of a building with insulation is the most effective way in improving its overall thermal performance. The market emphasis on reducing building energy costs, along with building regulations introducing minimum insulating values have dramatically increased the use of insulation[13]. The thermal resistance of insulating materials can only be evaluated by analysing the entire design and construction of the wall system. Other attributes such as acoustic performance, mechanical stability, moisture, and fire resistance also dictate the choice of insulation.

In Australia, the market is dominated by two types of insulations: inorganic fibrous materials (mainly stone or glass wool) and organic foams (mainly of expanded polystyrene but also polyurethane, polyisocyanurate and phenolic foam).

Stone wool or glass wool are generally either non-combustible or have a low combustibility and therefore will not be discussed further. In terms of fire performance, ignition and fire spread characteristics of combustible insulation highly depends on their end-use conditions.

Detailed information that dictates fire performance of commercially available insulating products, such as the chemical composition or manufacturing process, are sometimes difficult to identify or not readily available. This lack of information may lead to inability to predict or interpret test outcomes of an otherwise ‘known’ product. For example, EPS insulation found in Australia may not state the presence of fire retardant, HBCD.

Polyester Fibre

Polyester batts (PB) made from spun Polyethylene Terephthalate (PET) are used in building insulation. Polyester batts available on the market contain recycled PET predominantly acquired from used bags or bottles[14].

Polyester fibre is a thermoplastic material with very poor fire properties.

Expanded Polystyrene (EPS)[15-17]

EPS is a thermoplastic material with a closed cell rigid foam structure. Polystyrene is ring shaped hydrocarbon polymer made from the monomer styrene, with chemical formula $C_6H_5CH=CH_2$.[18] Petrochemical’s benzene and ethylene are the derivatives of styrene. The styrene monomer is suspended in water and other additives to polymerise into polystyrene beads.

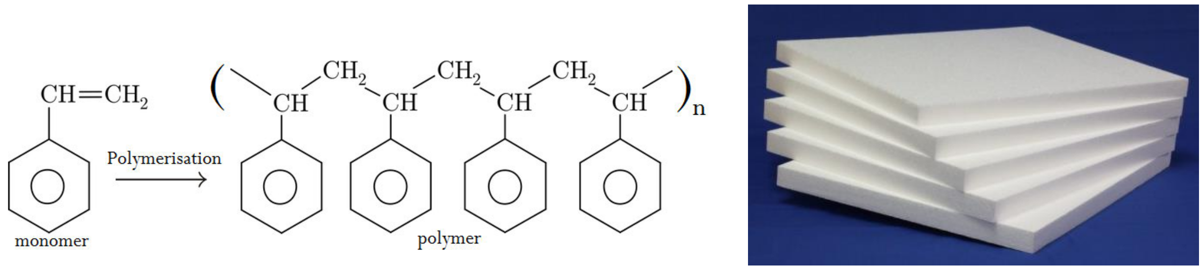


Figure 2: Molecular diagram of styrene monomer polymerising into polystyrene (left)[10], polystyrene insulation boards (right)[11]

Moulded EPS is 98% air and 2% EPS material by volume.

Fire performance of raw EPS is poor. EPS surfaces can readily ignite when exposed to small flame or radiant heat sources of 10-13kW/m^2[17]. At approximately 100℃, EPS begins to soften and contract away from the heat source[15, 16]. At higher temperatures, molten EPS further decomposes into gaseous oxides of carbon, water and soot[17]. Ignition of the pyrolyzed EPS depends on the surface temperature, duration of exposure and air flow at the combustion zone. Once sustained ignition is established, fire spreads easily across the surface and will continue to burn until all EPS is consumed.

Fire performance of EPS based insulation can be significantly improved if protected or fully encapsulated within a non-combustible material, such as metal sheeting or cementitious render. However, during full-scale façade fire tests, room fire tests or fire resistance testing, the integrity of protecting material can delaminate and cause the EPS behind to shrink or melt awat. These events can lead to rapid fire spread. This is directly due to EPS's relatively low melting temperature.

Extruded Polystyrene (XPS)[19-21]

XPS (also known as 'Styrofoam') undergoes a different manufacturing process to create EPS. Polystyrene resin is forced through an extruder, where the compressive heat melts it into a viscous fluid. A blowing agent with a low boiling temperature (such as CO, CO_2 /ethanol or hydrofluorocarbon) is added and fed through a die, causing the liquid to expand[21]. The expanded foam is then trimmed to the desired dimensions. As a result of this process, the blowing agent remains in the foam for the lifetime of the material.

XPS has a closed cell structure. It is denser and has superior compressive strength and moisture resistance and to EPS. The closed cell, dense structure makes it difficult for moisture to infiltrate the material (see Figure 3). This characteristic enables XPS to maintain its insulating characteristics over the life of the material.

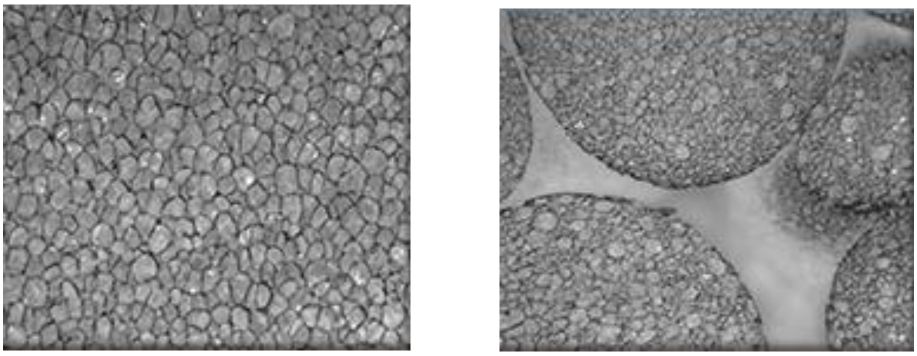


Figure 3: Difference between XPS (left) and EPS (right) on magnified 25 times. The presence of interconnected voids in EPS enables water ingression and reduce the thermal resistance over time[21]

Unlike EPS, XPS is a common insulating material that does not require a metal film or cement-like render to protect its surface from moisture damage. Its fire performance is very similar to EPS.

Fire retardant Expanded/Extruded Polystyrene (EPS-FR/XPS-FR)[22, 23]

Hexabromocyclododecane (HBCD), a brominated aliphatic hydrocarbon with bromine content of 74.7%, is the most commercially used fire retardant for EPS. Very low levels of HBCD are required to achieve desired resistance to ignition; with only 0.5% by weight for EPS and 0.5-1.0% by weight for XPS. HBCD interferes with the partially oxidised gases of EPS, effectively quenching the reaction. The delay in ignition allows EPS to shrink and contract away from the flame, however significant flame infringement and high heat fluxes can be easily overcome the fire-retardancy of HBCD. Once overcome, EPS/XPS-FR will continue to burn in a similar manner to non-fire rated polystyrene.

The risk associated with the manufacture and handling of HBCD has been identified as being toxic to reproduction health and classed as Persistent Organic Pollutant (due to its persistence, bioaccumulation, and toxicity).

Polyurethane (PUR)[24, 25]

Polyurethane is polymer consisting of carbamate group ($-NHCO_2$) as the molecular base structure. Rigid polyurethane (RPUR) is used for building insulation. RPUR is a thermosetting foam that consists of a highly cross-linked polymeric structure. Treated RPUR produces dense smoke and weak char layer when exposed to localised fire sources. However, larger flame infringement can ignite the surface and spread rapidly, releasing toxic by-products such as hydrogen cyanide, oxides of nitrogen and carbon monoxide[25]. The charring layer of PUR is unstable and can easily break off or crack to expose the raw foam underneath.

Common fire-retardant additives for PUR include aliphatic phosphates that are mechanically mixed into the PUR during manufacture (i.e. not chemically bonded to PUR)[24]. Some fire-retardant additives tend to leach out during manufacture or during the life of the insulation, which leads to loss of retardancy over time.

RPUR for insulation can be sprayed or installed as a rigid foam panel within the wall cavity.

Polyisocyanurate (PIR)[25-27]

Like PUR, PIR is also a closed cell thermoset material. Synthesis of PIR is similar to PUR where a greater proportion of methylene diphenyl di-isocyanurate (MDI) is used to react with a polyol, in the presence of a catalyst and blowing agent[26]. An exothermic reaction takes place, evaporating the blowing agent, and trapping the gas within the closed cells. The excess MDI may react with itself upon creating a complex, heavily cross-linked structure, that offers PIR superior dimensional stability, thermal and fire resistance to PUR.

PIR behaves similarly to PUR-FR during early stages of a fire. PIR forms a char layer that protects the raw PIR underneath from further decomposition, and thus significantly inhibiting further fire spread. At temperatures between 500℃ - 650℃, the charred surface starts to oxidise (smoulder) and intumesce[27]. At higher temperatures and heat fluxes, the charred layer becomes brittle, breaking off to reveal the raw material underneath, giving way to rapid fire spread.

PIR does not undergo flaming combustion when tested under AS1530.2 Flammability test[25]. Burning of PIR generates toxic smoke containing hydrogen cyanide (HCN) and carbon monoxide (CO), and concentrations of HCN can increase dramatically when fire conditions change from well-ventilated to under-ventilated.

Phenolic Foam (PF)[25, 28, 29]

PF is the best thermally efficient and fire-resistant insulation commercially available. The high performance of PF is owed to is thermoset and closed cell structure.

PF foam is manufactured by reacting phenol and formaldehyde, in the presence of a catalyst. A blowing agent (commonly pentane) is added and boils within the mixture creating gas bubbles. The foam mixture is poured into a closed mould, increasing in temperature while expanding under pressure. Finally, the foaming process requires external heating of 50-80℃ to further dry and cure the foam.[28]

When exposed to a flame the surface of PF initially discolours. Gradually a protective char layer is formed with little to no fire spread beyond area of flame infringement. Burning PF generates ~ 155 times fewer smoke emissions than EPS, with little to no smoke or toxic gases produced[25].

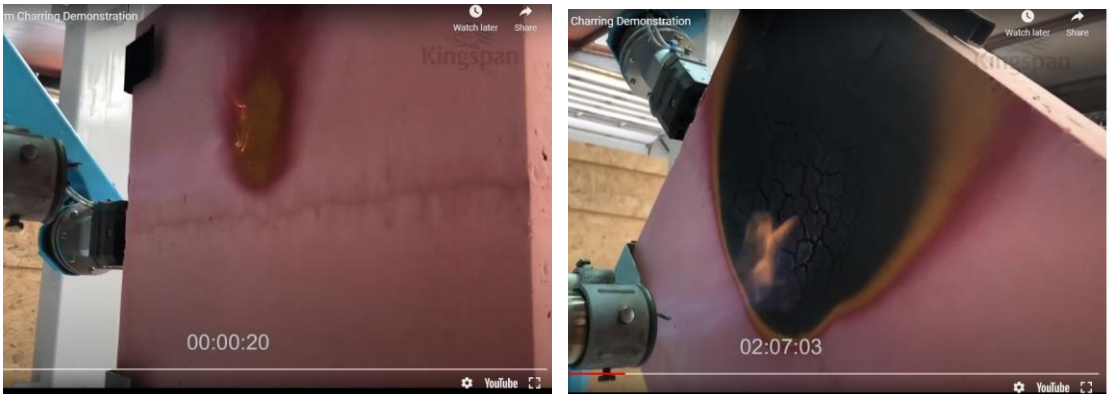


Figure 4 - Left - @20s - onset of flame on surface causes PF to discolour, Right - @~2 mins – Stable char layer is formed, preventing further fire spread with little to no smoke being emitted. [29]

2.1.3 Sarking (Type of Weather Resistive Barrier)[7]

The function of water/moisture resistive membrane (sometimes referred to as 'vapour barriers') are used to protect the inner wall from condensation and wind driven rainwater infiltration. They are commonly installed against the surface of the insulating layer. Some WRB contain an insulating layer to help reflect radiant or convective heat transfer. In Australia, a common WRB used in residential construction is sarking. Sarking is a self-adhesive or mechanical fixed membrane known as sarking or building wrap. These are typically made of woven and bonded polyethylene fibre.

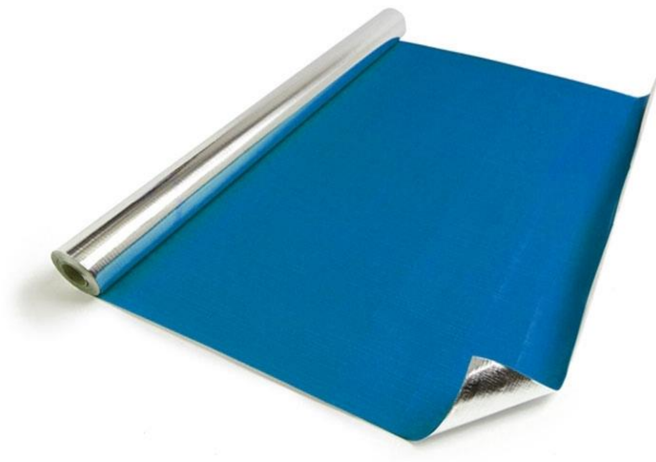


Figure 5: Typical roll of sarking[30]

The use of sarking is regulated in accordance with AS1530.2 Flammability test. AS1530.2, a small-scale test method (refer to Section 3.1).

The relatively thin membrane of sarking means that the contributing fire load is low in comparison to common insulations found within EWS. However, its presence and potential to contribute to fire spread within a cavity containing combustible insulation is unknown. No published research has been available to study the effects of sarking in conjunction with other combustible components to fire spread within cavities or overall fire performance of EWS[4].

2.1.4 Combustible Structural Walls – Use of Timber[31-33]

Steel, concrete and/or timber are the most common material of choice in structural wall construction. However, unlike concrete and steel, timber is combustible and therefore poses a fire safety risk when used in buildings.

When sufficient heat is applied the surface of timber undergoes pyrolysis (thermal degradation), producing combustible volatiles. A charring (burned carbon) layer starts to form and grows with continued exposure to heat. Most timbers tend to char at ~300℃[31]. The char layer shields the raw, unburnt timber below from fire exposure, retarding further fire spread. The fire may momentarily retreat as the charred layer becomes formed. However, with continued exposure at elevated temperatures, the charred layer can form cracks and break off; causing further flame spread to occur.

Due to its combustible nature, building regulations in most countries restrict the application of timber to only certain building heights (e.g. 6 or less storeys) and/or occupancy types [33]. The construction industry's need to lower its energy costs and environmental impact has seen the resurgence of timber as a viable building material, mainly due to its low embodied energy. Furthermore, better forest management practises have ensured a sustainable and reliable supply.

Extensive testing and research in timber structural design and research combined with advances in building fire safety design and planned fire and rescue services allow to effectively mitigate against potential fire risk.

Lightweight timber construction[31, 34]

Timber wall studs are either made of sawn timber or engineered wood products. A timber frame needs to be protected with fibre reinforced plasterboard (Fire-rated plasterboard) to achieve the required fire resistance. The temperature of the fire exposed side of paper faced plasterboard plateaus at 100℃[31]. The free water and water of crystallisation can keep the temperature of the plasterboard relatively stable as heat is conducted through the board. Fire stopping (commonly timber blocks) are used to conceal cavities formed between the floor and the wall frame. Insulation batts are typically placed in between the studs of the frame and are used to improve the wall's overall thermal and insulating properties. During a fire, the insulation can cause the gypsum board to heat up more readily causing the plasterboard to fall off. If the exposed insulation is non-combustible (such as mineral and stone wool), it may remain in place, providing protection to timber studs and unexposed lining.

Massive Timber Cross Laminated Timber[32, 34]

CLT is an engineered wood product that can be used as standalone, loadbearing wall or timber panel that can support larger spans. In general, CLT is made up of 10-40mm thick and 90-240mm wide softwood timber that are cross layered in odd number of layers, varying from 3 up to 9. The layers are glued together under pressure using a polyurethane adhesive.

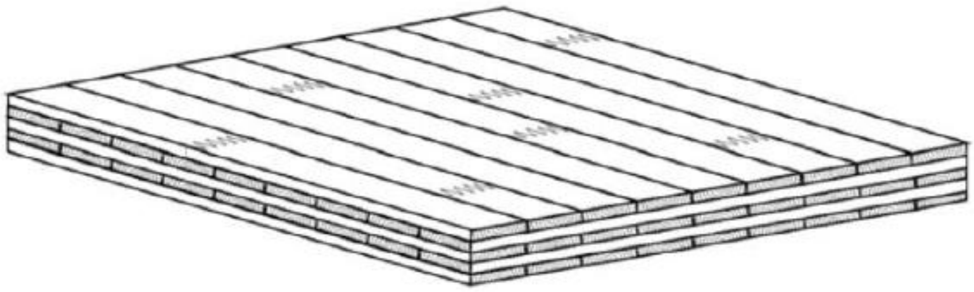


Figure 6: Example of a CLT panel

CLT constructed wall systems contain less air gaps or cavities in comparison to lightweight timber construction. The lower number of cavities inherent in its construction minimises the potential fire spread risk posed, but at the same time increases the overall fire load of the EWS.

As with light weight timber construction, the fire resistance of CLT can be greatly improved by lining enclosures with FR plasterboard or normal plasterboard. The exterior surface of massive timbers are protected from the weather by an external (rainscreen) cladding such as ACP.

Construction using massive timbers are not common in Australia, but interest of its use and benefits are increasing.

2.1.5 Summary Discussion

- Organic foam insulations provide a cheaper alternative to non-combustible inorganic insulations such as mineral wool and therefore more readily used in buildings. However, the calorific value of organic foam insulations significantly increases the overall fire load of an EWS and can greatly increase the risk of fire spread.
- Good fire performance of organic insulations is greatly dependant on the ability of the material to form a stable char layer. The char layer is able protect the raw material from flames and can readily slow down or prevent further fire spread. Density also plays a role in dictating fire spread.
- The insulating layer of most EWS are contained within the exterior wall cavity. Therefore, the risk of fire spread is also dependant on the ventilation conditions within the cavity. Other

combustible elements within an external wall cavity is sarking (and other weather resistive membranes) and timber members. Sarking and other weather resistive barriers are used to effectively drain away any moisture build-up within the EW cavity. Although sarking is combustible and readily ignitable (using a small, localised flame), it is a thin membrane and contributes minimally to the overall fire load of an EW and thus the potential fire risk posed is minimal. However, the presence of sarking in combination with combustible insulation has not been studied.

- Timber is another common combustible material found in cavities. The ability of timber to form a stable char layer is the main characteristic that allows timber to exhibit superior fire performance to plastic (organic) foam insulation. Although deemed combustible, the NCC permits the use of timber, light-weight construction under certain conditions (namely to buildings <25m or <4 storeys in height). External walls comprised of massive timber is less likely to support cavity fire spread than lightweight timber construction due to the inherent reduced number of cavities and greater resistance to heat transfer of solid timber surfaces. Both timber frame and massive timber are lined with FR plasterboard to areas requiring additional fire resistance (such as walls near property boundaries).
- Cavity barriers may be installed to deter fire spread within EWS. Both non-combustible inorganic fibre (stone wool) /or solid timber elements are used as cavity barriers. In Australia, their use is only required for timber lightweight construction.

The next section will examine mechanisms of cavity fire spread by studying international fire incident reports and news articles.

2.2 Mechanisms of external wall fire spread

Fires on external walls offers the quickest pathway for a fire spread up a building. Within a relatively short period of time, it can challenge existing fire safety systems of a building (such as sprinklers) and overwhelm the fire brigade, rendering firefighting efforts futile.

Avenues of cavity fire spread can be characterised as:

- Fire spread on cladding (either by window flames or external fire impingement on exterior wall) breaches surface and enters cavity,
- Pre-flashover compartment fire spread entering a cavity - A fire near a window opening can breach the reveal (such as uPVC window reveal in Grenfell Tower incident) or enter via vent or exhaust and
- Fire originating within cavity (such an electrical spark from faulty wiring)

Avenues of overall EW fire spread are provided as a background under Appendix A .

2.2.1 Wall Cavity Fire Spread

As mentioned under Section 1 & 1.5, cavities allow moisture and condensation to leave the interior parts of a wall system and play a critical role in the overall façade design. Fires occurring or spreading within cavities can be particularly hazardous as they may bypass many stories of a building (compromising the protective barrier between fire compartments), while remaining virtually undetected from the building's fire protection system and/or occupants.

A review of cavity fire incidents in Section 2.3 reveals that there are four (4) avenues of fire spread into exterior wall cavities:

1) **<u>Ignition caused by an electrical wiring fault.</u>**

   If the width of the cavity is limited, flaming combustion and fire spread may not occur. Depending on the presence and properties of a given combustible material, a spark may result in smouldering combustion. Smouldering combustion (fires) requires significantly less oxygen, than flaming combustion. The heat produced by the combustion process is contained within the surface or inside a porous material (such as insulation), supporting pyrolysis to occur. A smouldering fire can burn slowly and can remain undetected within a cavity for extended periods of time. The pyrolysis gases may cause smoke to spread into the interior of the building. Fires initiating in cavity wall are very rare and the ignition sources are so small that they cannot cause significant spread.

2) **<u>Pre-flashover compartment fire spread into cavity.</u>**

A pre-flashover fire that occurs in close proximity to an external wall, can either breach existing wall openings (other than window glazing) or create an opening before spreading into the external wall cavity. Post-fire analysis of the Grenfell tower concluded that the fire spread to the external wall system occurred prior to flashover. A kitchen fire at apartment 16 on Level 4, caused by a faulty fridge located next to the window, entered the cavity. It was evident by the post-fire analysis of the kitchen there were several avenues in which the pre-flashover fire could have breached the interior wall, into the cavity (refer to Section 2.3.1 for more details).

3) **<u>Post-flashover fire emitting from exterior wall opening (such as broken window)</u>**

A post-flashover fire emitted from a window can cause simultaneous spread into the cavity of the external wall. Upon breakage of a window, a smoke plume of 500-900℃ is released[11]. The circumference of an emitting plume will start flaming as it becomes into contact with oxygen in the air while hot, dense smoke enters cavities of the wall system. Initially, the under ventilated conditions within cavities would not cause ignition of gases immediately. The increasing buoyancy force of hot gases, creates pressure differentials between the exterior of the cladding and inside the cavity, causing an increase flow of air and combustible gases to enter the cavity. As flow of hot gases leaves the top of the cavity opening it burns, causing even greater flow and entrainment of hot gases below. This phenomenon is referred to as the chimney effect. The chimney effect can allow flames to enter the cavity – causing cavity fire spread.

4) **<u>Exterior fire impinges on external wall cladding and enters cavity.</u>**

Large flame impingement (such as a car fire or waste bin fire) can damage or deform the external cladding system and enter the cavity. The ease of fire breach of the cladding surface depends on material properties of the cladding components and type of joints/sealants used. For example, temperatures of a typical bin or car fire can cause the polyethylene (PE) core within some ACP cladding (namely ACP-PE or ICA Type A) to melt and cause local delamination, exposing the wall cavity.

The exterior wall cavity can shield the fire during its incipient stage, allowing it to grow to a substantial size, while the presence of combustible insulation within cavities can promote fire spread. Flames tend to be elongated within cavities, in search of fuel and oxygen to sustain combustion. The chimney effect, reradiation of interior wall surfaces of the cavity and absence of convective cooling afforded by external environment makes fire spread within cavities far more rapid than on the outside (cladding) surface of an EWS.

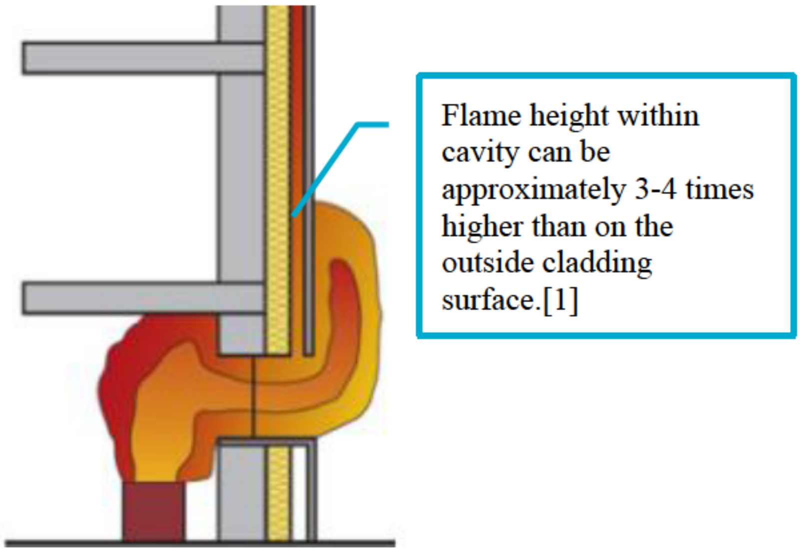


Figure 7: Post flashover compartmental fire entering cavity[1]

If the exterior cladding is combustible, this can further accelerate the rate of spread.

If sufficient flow of hot, unoxidized smoke entering an exterior wall cavity (such as from a post-flashover fire emitting from a broken window), fire can propagate rapidly without the presence of combustible insulation. However, the presence of combustible insulation will increase the intensity and ferocity of spread.

2.2.2 Mechanisms to Deter Cavity Fire Spread

The use of non-combustible material is the most effective means in preventing fire spread within external wall cavities. If combustible insulation is used, complete encapsulation of the material within a non-combustible material can significantly delay, minimise or prevent the involvement of the combustible core. However, if the encapsulation is damaged or material melts out to form a pool fire then significant involvement of the core can still occur. Such construction may include placing the combustible insulation between studs of a metal frame structure and completely sealing both sides of the frame with non-combustible lining such as thin sheet metal.

The use of cavity barriers (see Section 2.1.1) can prevent or significantly slow down the spread of fire within external wall cavities. They are installed at regular intervals, both vertically (such as at each floor level), horizontally (between fire compartments on same floor) and at points vulnerable to fire penetration (such as around window openings).

The effectiveness of cavity barrier is heavily reliant on the quality of construction. Post-fire analysis of the Grenfell Tower found that in many locations' cavity barriers were not installed[35], revealing significant gaps in protection. However due to the extremely high fire load of the EWS, building code compliant installation of cavity barriers would not have proven effective.

2.2.3 Summary Discussion

Once a fire has breached either the interior (inside of the building) or exterior (external wall cladding) to enter an EW cavity, fires can spread exclusively within the cavity (behind non-combustible cladding) or re-spread to the exterior cladding (if combustible) via the cavity. The next chapter will discuss fire incidents involving EW cavities that detail various cavity fire scenarios summarised under this chapter on mechanism of cavity fire spread.

2.3 Fire incidents involving cavities

This section will focus on literature containing detailed investigations that have reported fire spread within or via exterior wall cavities. A comprehensive review of external wall incidents between 1990 - 2013 has been documented within NFPA report *Fire Hazards of Exterior Wall Assemblies Containing Combustible components* by Nathan White and Michael Delichatsios.

In summary, past external wall fire incidents can be characterised as follows:

- Except for the Grenfell Tower incident in 2017, exterior wall fires result in low to nil death or injury. Death occurs due to toxic smoke inhalation rather than direct contact with flame or heat of fire.
- Post-flashover interior fire spread to exterior walls represent the most common and severe form of spread to external walls.
- External wall fires scenarios represent small percentage of total fires, but post-fire damage repair costs are significantly high.

2.3.1 The Grenfell Tower Incident, London (2017)[35, 36]

The Barbara Lane Report Inquiry into the Grenfell Tower Fire documents the likely sequence of events that lead to the catastrophic fire on the early hours of June 14th, 2017[35]. The Grenfell Tower incident was declared a catastrophe as a total of 72 fatalities occurred as a direct consequence of the fire.

Forensic investigator Professor Niamh Nic Daeid compiled an expert report that was submitted as documentary evidence for the Grenfell Inquiry[37]. This report shows Thermal Imaging Camera footage of the London Fire Brigade crew as they entered the kitchen, for the second time. It indicates that the fire development at the time of entry was a localised fire plume, located near the window area (see Figure 8). No compartmental (kitchen) flashover had occurred at this time. The fire crew managed to extinguish the fire within the kitchen but it likely that the fire spread to the rainscreen cladding system had already occurred via the wall cavities (see Table 4).

From 2012-2016, The Chelsea & Kensington Tenant Management Organisation requested to implement several refurbishments works to the Grenfell Tower. The scope of works included an upgrade to the external wall system in order to improve the building's overall thermal efficiency (see Figure 9).

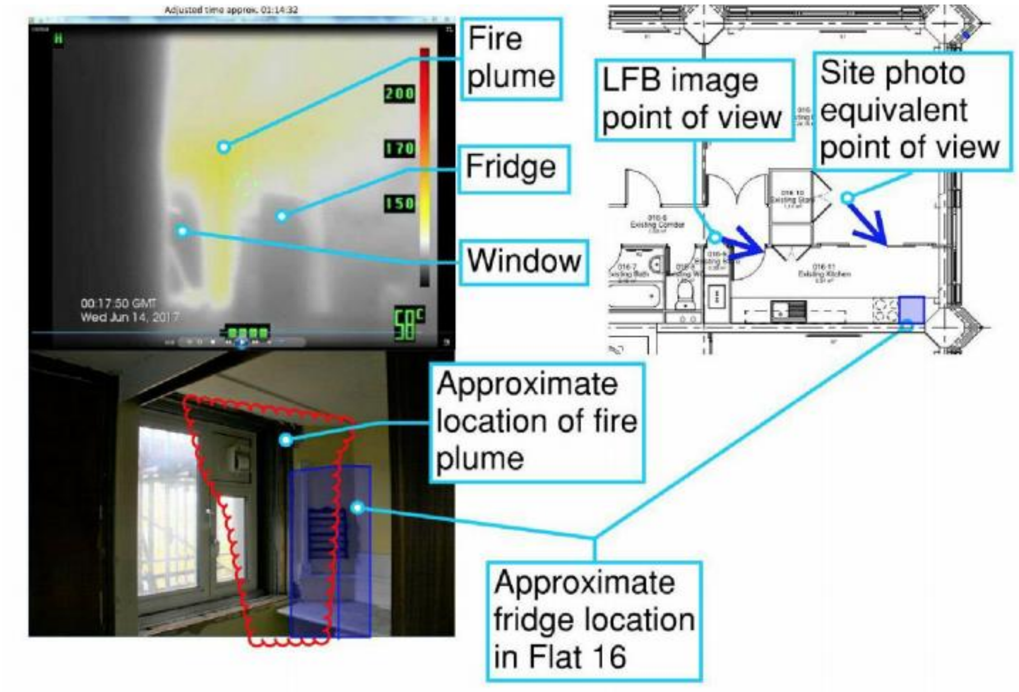


Figure 8: Top Left - Thermal Camera image showing fire plume (in yellow), Bottom Left: Site photo showing approximate location of fire plume in an equivalent kitchen, Top Right: Facing direction of thermal camera and site photo towards window area.

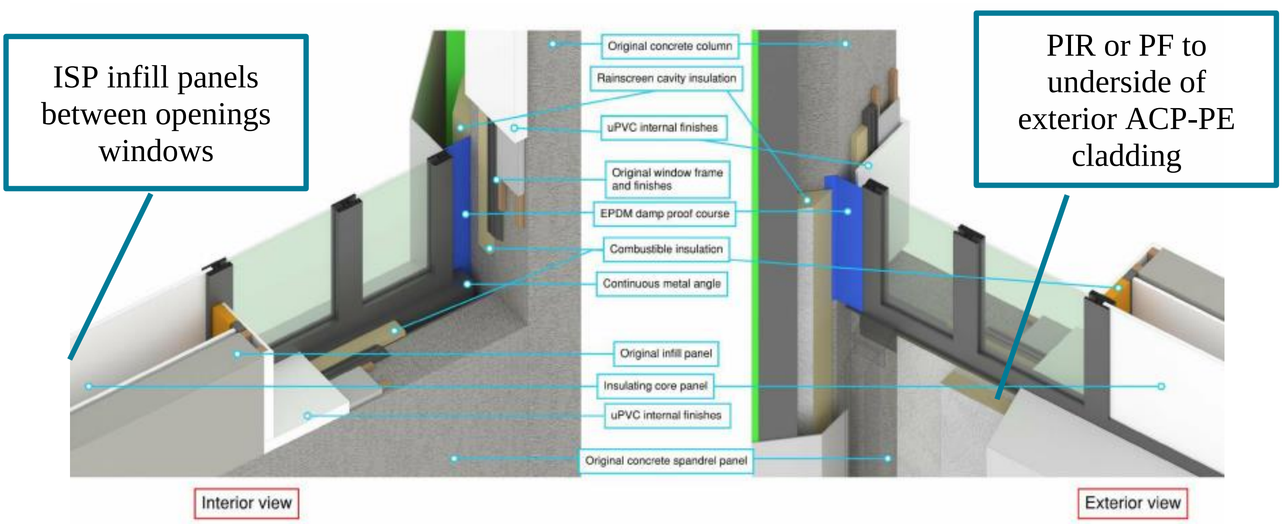


Figure 9: Interior and Exterior view of retrofitting works to the Grenfell Tower external wall

This was achieved by installing polymeric insulation foam (either Celotex RS 5000 Polyisocyanurate, 'PIR' or Kingspan K15 Phenolic foam, 'PF') directly onto the pre-existing concrete structure with a protective rainscreen cladding outer layer (Reynobond 55 PE Aluminium Composite Panels). Furthermore, new uPVC thermally broken windows with 25mm Insulated Sandwich Panels (ISP) infill panels replaced all original aluminium framed windows (non-combustible). These refurbishment works added highly combustible material of a significant fire load onto the exterior wall of the building.

Pathways of spread from interior of building to the exterior wall

The retrofitted works introduced a network of interconnected cavities that ran both laterally (within each floor) and horizontally (above and below each floor) encompassing the entire exterior surface area of the building. The arrangement of combustible materials within these cavities are documented in Section 9 of Dr Barbara Lane's expert report[36] and were presented as evidence into the Grenfell Tower Inquiry. Table 4 details five possible pre-flashover fire spread routes from the kitchen window area to the EWS via the exterior wall cavities.

Table 4: Possible pathways of fire travel, from the interior to the exterior face of the building.[36]

	Origin of Fire	Route of fire spread
1	<u>Under windowsill</u> Flames and hot gases may attack nosing of sill and if gap is present, enter the wall cavity. Hot plume gases passing the level of the sill may deposit burning particles and radiate heat on to the sill, igniting uPVC reveal.	Once entering the sill cavity, the fire can spread laterally in both directions until it comes in contact with EPDM rubberdamp proof course (located at the column interface) or the XPS infill core panel (on the opposite end).
2	<u>On the windowsill</u> Curtains or other combustibles located above or on the windowsill may ignite uPVC	As above.
3	<u>Beside column side of the window</u> Burning curtain or other combustibles positioned against window jamb next to building column.	Once penetrating underneath uPVC side reveal, the fire can penetrate EPDM rubber dampproof course into the column rainscreen cavity containing either phenolic foam or PIR insulation or spread onto combustible insulation located around the window frame and/or under the window reveals.

4	At side of window, next to combustible in-fill panel	Fire may deform uPVC reveal, exposing in-fill panel XPS to fire spread.
5	Head of the window frame	Fire can soften and deform head of uPVC reveal, exposing window frame insulation or pre-existing timber head reveal. Or it may also ignite uPVC head directly. The panel housing the kitchen ventilation fan consisted of XPS board (as observed on site visit) is a combustible material. The combination of the uPVC reveal, pre-existing timber reveals and/or the XPS board housing the ventilation fan – can cause fire to spread from the cavity situated above the top reveal and then to the rainscreen cladding system situated above the window.

The series of cavities created between the existing concrete structure and retrofitted exterior wall system helped to shield the non-flashover fire from direct wind. The arrangement and type of combustibles with the cavities allowed the fire to develop and spread rapidly.

The absence of adequate fire barriers and series of cavities encompassing and connecting the entire building, helped cause multiple fires to occur on each level, breaching fire compartments and floors.

In addition to the shattered windows, it is these routes of fire spread (listed in Table 4) that provided the same pathway of travel for the fire to re-enter the building. It was noted that even if cavity barriers were adequately installed, the significantly high fire load would have allowed the fire to bypass these barriers rendering them useless.

2.3.2 Apartments Block, Luleå, Sweden (2013)[38]

Fire spread via the cavities of a 5 storey, timber framed residential apartment up to the attic and then proceeded to spread to several other compartments, destroying most of the building. The building was constructed using prefabricated modular units assembled on-site. The modular units are placed in between steel framed construction elements that provide the loadbearing support for the building.

Figure 10: Infrared camera showing downward spread via cavities formed between modular units (left), Post-fire damage to building (right)

The placement of these modular units in between the steel frame gave rise to cavities. The cavities were filled with combustible insulation and mineral wool cavity fire barriers. The fire started in the kitchen due to a saucepan of oil left on the stove and spread into the exhaust hood, spreading up to the attic via the ventilation shaft (bypassing installed cavity barriers). The remnants of cardboard and protective plastic layer within the ventilation shaft (left during the construction phase) contributed to the fire spread. The fire burnt through the attic within 1.5 hours and then continued to spread downwards via the cavity to floors below. The fire brigade found it hard to locate the fire and consequently had to destroy walls and floors to extinguish the fire.

2.3.3 Apartments Block, Umeå, Sweden (2008)[38]

The apartment building structure was concrete with a masonry façade. The external wall cavity contained combustible insulation. A stove fire in the kitchen ignited the cupboard located above the rangehood and was successfully extinguished by the fire brigade. Several hours later it was discovered that the fire had spread undetected into the attic. The fire investigation revealed that the fire in the attic was able to spread down other walls of the building into locations that were absent of any cavity barrier.

2.3.4 Knowsley Heights, UK (1991)[7, 39, 40]

A rubbish bin compound fire impinged on the external wall of a 11-storey apartment building and spread rapidly to the top floor via the cavity. The concrete wall behind the cavity was coated with rubberised paint (a type of weather resistive barrier used to protect the concrete surface). Other than the rubberised paint, no other combustible materials were found within the cavity. Fire brigade tried applying water from the outside but weren't able to penetrate the cladding layer to effectively attack the fire. The cladding material (that formed the outer wall of the cavity) was classified as 'Class 0' in accordance with BS476 part 6 and 7 – a small-scale test method (see Appendix B1). The fire damage to the windows and external wall was extensive, however no flame or smoke entered the building.

The Knowsley Heights fire incident highlighted the concerns surrounding external walls fire spread and prompted further investigation into existing test methods, which lead to the introduction of the full-scale test method, a similar test method to the current BS 8414 part 1 and 2 full-scale external wall fire spread standard.

Figure 11: Post fire damage to Knowsley Heights external wall

2.3.5 Water Club Tower, USA (2007)[41]

A hotel and casino tower in Atlantic City caught fire while under construction. The fire started on the 3rd floor of the building and spread via the cavity to the 41st floor. The fire had spread to side of the building installed with ACP-PE. No smoke or fire was able to penetrate the 6-feet concrete wall behind the cladding. Within 10-15 minutes of the fire brigade arriving, fire had already started to diminish due to rapid consumption of fuel load. Only the side with ACP-PE was affected by the fire, with significant amounts of cladding debris found within ¼ mile radius of the building.

2.3.6 Wanxin Complex, Shenyang, China (2011)[42]

The Wanxin consists of three towers (Towers A, B and C) that sit on top of a 10 storey 'skirt' building (Building D). Tower A is a 45-storey hotel building with Towers A and B having 37 stories containing residential and office spaces respectively. EPS insulation with a combustibility rating of 'B1' and XPS insulation with a combustibility rating of 'B2' (in accordance with EN13501-1 Fire classification of materials – see Appendix B.1.1) were used on Towers A and B respectively. The outside cladding material for all towers was both ACP and Aluminium cladding (a non-combustible material). Distances between Towers A and C and A and B was 6.5m with Tower B and C spaced 63m apart.

Figure 12: Perspective view of Wanxin Complex showing location of fire, Building Towers and Building Skirt (left), Post fire damage to part of Wanxin Complex (Tower B and Tower A)

At midnight, Chinese New Year fireworks sparks landed on plastic grass covering the roof of Building D, starting a fire that spread to the external wall of Tower B within minutes. The fire penetrated the ACP cladding and ignited the XPS insulation, located in the cavity behind. High temperatures of the burning XPS caused the ACP cladding to fall off, exposing the insulation to air and flames. Within 15 to 20 minutes, the fire reached the top of the 37 storey Tower before spreading to the east and west elevations.

The sprinkler system activation prevented fire spread to interior of the building at the lower levels. However, the fire was able to build momentum as it consumed more combustible insulation and cladding travelling up the building, overwhelming sprinkler protection at higher levels, and causing significant interior damage. One hour later, the south side of Tower A was ignited by what was believed to be flaming debris and radiant heat flux from Tower B. Fire brigade were able to control the blaze soon after, with only partial spread to east and west sides of Tower A. No spread to Tower C occurred.

2.3.7 Cavity fires in timber framed construction[43]

These set of fire incidents involving cavity fire spread were collected from a report prepared by Building Research Establishment (BRE) for the Department for Communities and Local Government, UK. The purpose of the report was to review issues of fire and smoke spread within concealed spaces such roof voids, wall and floor cavities. The buildings are of lightweight timber construction. Details about the specific location and name of buildings were not provided in the BRE report for confidentiality reasons. Table 5 (below) provides a detailed summary of the cavity fire spread cases presented in the BRE report.

Table 5: Timber framed buildings from BRE Report[43]

Case Study	Ignition Source	Fire spread mechanism into cavity	Details of fire
Three-storey timber framed residential building	Nail penetrating lighting cable	Ignition within cavity	Fire travelled up the cavity, but horizontal cavity barriers were effective in stopping lateral spread. The building was clad with EIFS.
Five storey modular timber-framed block residential building	Electrical consumer unit fault	Compartment fire spread into cavity	Fire on the first floor entered gap between timber modules where Oriented Strand Board (OSB) lined the cavity. The fire spread laterally covering two flats before spreading to floor voids below and up to second, third and fourth floor wall cavities. Fire spread occurred within cavities between compartments only (not exterior wall of building).
Three storey timber-framed, brick veneered block of flats	Hot works	Fire from hot works performed outside the building, entered into cavity via external wall pipe penetration	Fire spread from ground floor up cavity and was seen breaking out at roof of building. Compressed fitted cavity barriers were present. Post-fire analysis of building showed signs of slippage and no fire stopping (in gap between external wall and floors). Vertical cavity barriers with sheathing board were completely burnt away. Fire reached the roof void and led to subsequent collapse of ceiling. Adhoc tests and observations by BRE indicate 'breather

			membrane' (sarking) and plastic wrapping around cavity barrier allowed the fire to spread during the early stages.
Four storey timber-framed block of flats	Not stated	Compartmental fire spread into cavity	Compartmental fire was extinguished by fire brigade. Thermal imaging camera was used prior to fire brigade leaving, to ensure no spread had occurred into cavity. One and half hours later, a call was received by the fire brigade that the fire within the external cavity and had spread into the roof space. From the roof space, fire spread down unaffected wall cavities which lead to the ultimate collapse of the building. It was found that timber battens were used to bridge cavities between fire floors. The battens were wrapped with bituminous damp proof course to prevent moisture damage. Low density bitumen impregnated with fibre board was used as a sheathing layer. This material was known to perform very poorly when tested under BS EN 11925-2 Small scale flame test.
Three-four storey timber block of flats	Discarded cigarette into wood/bark chips of flower bed	Flower bed fire spread into cavity via plastic ventilation bricks located at base of external wall.	40 minutes after initial external wall fire was reported, smoke was seen emitting out at roof level of building and from openings in the cavity at various levels. The building was evacuated immediately as fire brigade adopted a defensive approach to combat spread. The fire ultimately led to roof and partial external wall collapse.
Three storey timber block of flats	As above	As above	Fire spread up cavity to roof space causing significant structural damage. The fire brigade adopted defensive strategy when it was apparent that structural stability of building had been compromised. Cavity barriers for the building were either installed poorly or missing.

Three storey timber framed terrace house	Not stated.	Compartmental fire spread via uPVC window frame	Fire in upper floor bedroom spread into cavity. Absence of a vertical cavity barrier allowed fire to enter cavities within internal bounding walls (between occupancies) and spread downwards. Fire damaged beams supporting wall sections at both first and second stories. Little fire damage to roof space was attributed to the presence of adequate compartmentation between occupancies.

Table 6: Cavity fires in timber construction from other sources

Case Study	Ignition Source	Fire spread mechanism into cavity	Details of fire
5 storey, 1970's timber framed apartments (Christmas Day 2007 - Croydon, UK)[38]	Child playing with matches	Compartment fire spread into cavity	Fire spread to wall cavity and spread rapidly into the roof space. Fire was reported to be initially extinguished, however fire brigade was called back an hour later as fire had re-established. The fire brigade worked overnight to supress the blaze, but the building had to be demolished due to substantial damage. Council inspected eleven (11) other timber framed buildings on estate to assess fire risk. Following inspection, contractors were assigned to cap the top-of-wall cavities within the roof space, build fire separation walls, fire-proof all flues, pipes, vents and electrical sockets and provide extra protection for window reveals.
Lakanal House[39] – 14 storey concrete and timber framed building	Electrical fault in portable TV set[40]	Compartment fire spread into cavity	Fire on 9th floor spread through structure resulting in 6 casualties.

(July 2009, Camberwell London, UK)			

2.3.8 Summary Discussion

It is evident from review of fire incidents that cavities remarkably enhance the rate of fire spread. The close proximity of parallel surfaces insulates the heat during the incipient stages of the fire. The lack of ventilation allows for greater velocity of air entrainment to either side of the fire, driving up the height of the flame. This in turn allows for greater radiant heat dispersion to surfaces above the fire zone, promoting fire spread. The presence of combustible surfaces in cavities therefore significantly increases the fire load of the EWS and provides for ample fuel to support fire spread.

- Fire spread can occur in cavities with combustible materials, in an otherwise non-combustible EWS. This is evidenced by many BRE reports compiled for the Department for Communities and Local Government UK, on timber framed masonry buildings, the Knowsley Heights Highrise building and Umeå building in Sweden.
- The presence of thin membrane materials (such as sarking) was concluded to help establish cavity fires during the incipient stage (by ad hoc tests conducted by BRE).
- Ignition sources can range from pre - flashover flame entering cavity via wall vent or exhaust to electrical wiring spark occurring inside cavity. In all these circumstances – the presence and type of combustible cladding, and ventilation conditions of the cavity will dictate ease of ignition and fire spread.
- Cavity barriers and fire stops can delay fire spread to allow for fire brigade intervention. However, the performance of cavity barriers and fire stops are reliant on the workmanship at construction. The installation of cavity barriers and/or fire stopping in accordance with building code requirements can prove inadequate if fire load of an EWS is significant. In the timber framed buildings cases reviewed by BRE, adequate cavity barriers were reported to significantly halt fire spread.
- For several cases involving timber framed buildings, the fire progressed up the cavity unhindered and without the knowledge of occupants, until it reached the roof space. In some instances, the continued smouldering of timber would re-ignite after being declared extinguished by the fire crew.

Various test standards regulate a variety of combustible components found in EW cavities. The outcomes of these test methods are included as prescriptive requirements within building codes. The next chapter will discuss the reaction-to-fire standards that help regulate combustible cavity materials within building code requirements. Other experimental test methods that explore cavity fire spread are also presented.

3 REACTION-TO-FIRE TEST STANDARDS, BUILDING CODE REQUIREMENTS & OTHER EXPERIMENTAL TEST METHODS

3.1 Reaction-to-fire Test Standards

In general, reaction to fire test methods is categorised into three scaled groups, namely small-scale, intermediate-scale and large-scale, and are based on size and conditions of fire exposure, size of specimen and degree in which specimen represents end use conditions. There is no formal characterisation of fire test methods by professional testing community or body and some methods can be viewed as either small-intermediate or intermediate-large.

This chapter will focus on test standards referenced in building codes. Other relevant test standards applicable for external wall systems will be noted.

3.1.1 Small-scale tests

Small-scale (or sometimes referred to as bench-scale) test methods exposes a single or composite and/or layered material to relatively narrow set of exposure conditions; either using flame impingement, radiant or conductive heat to test for material fire performance. The outcomes of this method predominantly produce discrete fire characteristics such as the ignitability, flame spread (extent and rate), heat release (total and rate) and smoke development.

The specimen is a component of a building system that is not tested within its end use configuration. The severity of the fire or heat source is relatively low and does not represent real-scale fire scenarios. The outcomes of small-scale test methods do not correlate to real-scale fire performance. Instead, they are used to classify, or rank specimens based on a set of performance criteria for regulatory purposes. Small-scale tests offer quicker turnaround times at a significantly lower cost.

A list of prominent small-scale tests are included in Appendix B .

The NCC vol. 1 reference three small scale test standards that are used for regulating external wall materials.

- **AS 1530.1 Combustibility Test -** AS 1530.1 defines the combustibility of a material within the NCC for regulatory purposes. If a material meets the standard, it is deemed not combustible. Five sample sizes with a diameter of 45mm and height of 50mm are placed into a conical furnace. The furnace is set an average temperature of 835℃ ±10℃. This test procedure determines the combustibility of a material as defined the following criteria:
    - Mean duration of sustained flaming is other than 0s
    - Mean furnace thermocouple temperature rise exceeds 50℃
    - Mean specimen surface thermocouple temperature rise exceeds 50℃
    - Limited mass loss

  AS 1530.1 Combustibility test is not suitable for laminated, faced or coated materials

- **AS1530.2 Test for Flammability[44] –** This test method is designed to determine the susceptibility of thin sheet or woven fabrics (2mm or less in thickness) to flame spread when exposed to a pilot flame. A rectangular strip of material, 535mm (H) by 75mm (W), is mounted on to a vertical frame with a backward incline of 3-4 degrees. A trough of 0.1mL of alcohol is placed, 12.5mm below the specimen and is ignited. The height of the specimen is divided into 21 equal marks. A Flammability Index, 'I' is then allocated to the material based on:
    - the speed (Speed Factor) to reach the top (21 marks line) within 54s or
    - height reached after 54s has ended (Spread Factor) and
    - The net gain in temperature within the flue added for the 180s test period.

  AS1530.2 are used by industry to evaluate fire performance of sarking and some insulations found in cavities, for regulatory purposes (see Table 8). The standard specifically states that this test is 'unsuitable for materials which melt readily or shrink away from an igniting flame'[44].

- **AS1530.3 Simultaneous determination of ignitability, flame propagation, heat release and smoke release –** This test method assesses the potential fire hazards, in terms of ignitability, flame propagation, heat release and smoke release, of wall linings. A rectangular test specimen (~600mm x ~400mm) of nominal thickness is mounted onto a timber frame that is thermally insulated at the edges of the frame and behind the test specimen. The timber frame with specimen is progressively moved towards a ~300mm square, gas fired radiant heat panel. The following fire hazards are calculated and a numerical index is applied for regulatory purposes:

- Ignitability (mins)– mean ignition time of specimen (if ignited). The ignitability index ranges from 0-20 and is equal to mean ignition time minus 20 minutes. Therefore, a ‘0’ index indicates that no ignition took place.
- Flame propagation (sec) - time taken for radiation intensity to reach 1.4kW/m^2 after ignition. If the ignitability index is zero, then the Spread-of-Flame Index (based on flame propagation) is equal to zero. If mean flame propagation time x 1.33 is >270s, then an index of ‘zero’ is allocated. Each incremental decrease of 30s in mean flame propagation time, results in an incremental increase of 1 in index, i.e. a mean flame propagation time x 1.33 of >240s and <270, results in an index of ‘one.’
- Heat Release integral (kJ/m^2)– difference between instantaneous radiation intensity (taken after 120s from ignition) and the radiation intensity before ignition. This is only applied to specimens that ignite, hence if the ignitability index is ‘zero’, then the Heat Evolved Index (based on the heat release integral) is also equal to zero. A mean HR integral (KJ/m^2) of <25 results in an index of ‘zero’. Each incremental increase of 25 KJ/m^2, results in an incremental index increase of 1, i.e., a mean HR integral of between >25 and <50 is allocated an index of 1.
- Smoke Release – the mean optical density (m^{-1}). The smoke developed Index (based on Smoke Release) is determined separately for materials that do not ignite. A mean optical density (m^{-1}) of < K (K is a constant equal to 0.0082), results in an index of 0. Each exponential increase of a factor of 1 in K, results in an incremental index increase of 1, i.e., a integral of between >25 and <50 is allocated an index of 1.

The test method uses radiant heat panel, calibrated to a 2.4kW/m^2, inflicts a maximum heat flux of ~25-30kW while also applying a small pilot ignition flame to volatiles to prompt ignition. For materials that tend to shrink or melt away from the applied radiant heat source (such as batts, sheets, blankets or foam insulations), a welded mesh, with no less than 12mm x 12mm apertures, is mechanically fastened over the specimen.

AS1530.3 is referenced in the NCC and is used to regulate insulations found in cavities (see Table 8) and therefore insulation products are often tested to AS1530.3.

The foam type insulation EPS-FR (a thermoplastic material) typically receives indices of:

- Ignitability Index =0
- Spread of Flame Index = 0
- Heat Evolved Index = 0
- Smoke Index = 1-3

These indices indicate that EPS-FR did not ignite and was separately tested to determine the smoke release. These indices demonstrate good fire performance in terms of potential fire hazards.

3.1.2 Intermediate-scale testing

An intermediate-scale test is considered as an end-use assembly type test that is of a reduced height and width, offering a limited area to evaluate extent of fire spread. Due to their reduced size, intermediate-scale tests generally apply an ignition source that is larger than small scale test methods but smaller than their full-scale counterparts.

An intermediate scale test can be defined as a fire test having at least one of the following characteristics:

- Ignition source of between 5kW-300kW and/or
- Specimen exposure surface to be ≥4m in height and ≥2m in width.

The test arrangement of intermediate-scale tests is often designed as parallel panel, as channels, or as re-entrant corner to promote re-radiation of surfaces to increase thermal exposure (to mimic full-scale exposure levels) or exclusively test an element of EWS (i.e., cavity fire spread). Other tests, such as ISO13785-1 intermediate scale test, are designed to simulate small, localised fire scenarios to effectively test low end tolerance levels of EWS, before full-scale application. See Table 7, Figure 13 and Figure 14 detailing summary and images of available intermediate-scale test methods.

DIN 4102-20 is an intermediate scale test method adopted in Germany to regulate EWS with combustible cladding, commonly EIFS. This test method can be considered large-scale due to the geometric proportions of the test rig and arrangement of the test specimen. However due to the relatively small size of the ignition source, it can be deemed as an intermediate scale test method.

Apart from DIN 4102-20, intermediate scale test methods are generally not adopted to assess fire performance of external wall materials or assemblies for regulatory purposes.

Intermediate scale tests (IST) can represent external fire or post-flashover compartmental flame impingement using a smaller test rig compared to full-scale tests. Their presence in regulating fire performance of an EWS is limited (in comparison to full-scale methods).

Based on this preliminary literature review, it has been hypothesised that IST method has five possible applications:

1. An assessment method to evaluate fire performance of an individual exterior wall element i.e., cavity widths, types of insulation, types of cladding, fixtures/fittings, façade geometry etc
   The Cavity wall Test Method only evaluates type of combustible insulation and cavity width influence on fire spread, not cladding fire performance.
2. An assessment method to evaluate exterior wall system reaction to small, balcony sized localised flame impingement (to primarily assess ignition threshold, localised fire growth and then rate of spread).
3. Provide data for correlation studies in order to predict full-scale test outcomes. Parallel Panel Test and Vertical Channel Test of Canada were developed to correlate with existing large-scale test methods.
4. A tool to screen out poor performing façade prototypes before full scale application such as ISO 13785-1 test method.
5. Extend scope of a validated full-scale tested systems. Small changes in geometry and/or thickness of a components can be assessed on an intermediate scale to validate these changes using a scientifically based assessment[8]. This scientifically based assessment may utilise data from small-scale (material-based) tests also. At present, the literature exploring the extension of scope was not found.

Across Europe the varying fire safety requirements and the large-scale façade test standards has made it difficult for manufacturers of external wall systems to achieve compliance between countries. Due to the lack of a uniform testing regime for external wall systems, many European countries have adopted the EN13501-1 classification system in combination with their national large scale EWS testing standards to classify EWS reaction to fire. The EN13501-1 test standard consists of three small scale tests and one intermediate scale test to classify internal linings in terms of their contribution to fire load and growth (see Section B.1.1 under Appendix B for details of the EN13501-1 test standard). The EN13501-1 is designed to test internal wall linings and therefore, do not represent fire conditions that can accurately test for weakness of an EWS in its end-use condition. A need to harmonise EW fire performance requirements between countries, in order to streamline compliance for the introduction of products to market was realised. In 2016, the Standing Committee of Construction (SCC) requested a harmonised approach to external wall fire assessment. This approach to formalise a uniform test standard is detailed in Section B3 under Appendix B . In general, harmonised assessment method proposes DIN 4102-20 test to be used as the medium exposure test and BS 8414 to be used as a large exposure test method.

Table 7: Intermediate-scale Test Methods

Test Standard	ASTM Vertical Channel Test[1][45]	ISO 13785-1[46]	JIS A 1310[2][47]	16 ft Parallel Panel Test[48]	DIN 4102-20[46]	Önorm B 3800-5[46]	PN-B 02867[3][46]	FM Global Cavity Fire Test [49]
Country	Canada	International standard (formally adopted in Czech Republic)	Japan	USA	Germany	Austria & Switzerland	Poland	USA
Test scenario	Post-flashover compartmental fire.	Localised flame impingement (along bottom edge).	Post-flashover compartmental fire.	Flame contact on surface.	Compartmental fire impingement onto surface	Compartmental fire impingement onto surface	External fire, flame impingement	Wall cavity fire
Test purpose	Designed as an intermediate scale test for full scale CAN/ULC S134 test.	Outcomes to support performance-based solution under ČSN 73 0810 Fire safety of buildings: General Requirements.[46] Screening test method (other countries)	Screening test method applied in Japan	Designed as an intermediate scale test method to FM Global 25ft and 50ft corner fire tests.	Used as building regulatory test method.	Similar test method to DIN 4102-2.	Outcomes of test used to classify facades for regulatory purposes.	Used to test combustible materials within an external wall cavity in an otherwise non-combustible EWS. Cavity widths from 51mm to 102mm are tested and represent the width range of most EW cavities.
Overall rig dimensions (WxH)	0.8m x 9.4m	2.4m x 2.8m (inc. enclosure)	1.82m x 4.095m	5.2m x 1.1m	Same as test area.	As per DIN 4102-20	Same as test area.	1.2 x 2.7m (305mm sand burner below parallel walls of rig)
Test area (WxH)	0.8m x 7.32m	L-shaped rig. 2.4m x 1.2m (main wall), 0.6m x 2.4m (wing wall).	1.82m x 2.73m (above chamber)	1.07m x 4.9m (Each parallel panel)	L-shaped rig. ~1.8m* x ~5.5m (main wall) ~1.2m x ~5.5m (wing wall).	L shaped rig. ~1.8m* x ~5.5m (main wall) ~1.2m x ~5.5m (wing wall).	1.8m x 2.3m	1.2m x 2.4m
Other rig features	Two 500mm wing walls on either side, creating channel.	Test rig is shielded with an enclosure (see Fig XX).	The test frame is made from light gauge steel with the test rig substrate consisting of calcium silicate boards.	Parallel panels are separated by 0.53m.	Light-weight concrete wall structure.	As per DIN 4102-20	Test is performed outside.	The parallel panels are separated by either 51mm or 102mm. These distances represent typical range in width of EWS cavities. The base and top of the parallel panels are sealed off to simulate similar air flows existing in cavities.
Fire size	1.16MW	100kW	600kW	360kW	360kW (maximum)	25kW	None specified.	5.8kW (51mm cavity) 9.4kW (102mm cavity)
Combustion chamber and opening dimensions	Opening is split into two sections: air intake opening of 0.63m height is located on the bottom with flame outlet area above.	N/A	1.35 x 1.35	N/A	1m x 1m opening located on the main wall; located in the corner junction between main and wing wall. Test chamber is 1m W x 1m H x 0.8m D.	Opening size as per DIN 4102-2. Test chamber is 1m W x 1m H x 1m D.	N/A	N/A
Fire source	Two propane gas burners	Linear propane burner – 1.2m L x 0.1m W. Located 0.25m below bottom edge of main wall.	600mm square burner located rear centre of chamber.	Gas fired sand burner of 0.53mm W x 1.07m L x 0.3m H.	Either timber crib or gas burner. Timber crib is more commonly used. Crib is 30kg (±1.5kg) of softwood	Timber crib as per DIN 4102-20.	20kg timber crib. Either 200ml of petrol or pure alcohol used to ignite crib. Crib is placed in close	Propane gas burner of 305mm L x 305mm H (width of burner to suit cavity width being tested)

Test Standard	ASTM Vertical Channel Test[1][45]	ISO 13785-1[46]	JIS A 1310[2][47]	16 ft Parallel Panel Test[48]	DIN 4102-20[46]	Önorm B 3800-5[46]	PN-B 02867[3][46]	FM Global Cavity Fire Test [49]
					rods, stacked to have an air to wood ratio of 1.1.		proximity to surface of EWS.	
Test Duration (mins)	20	30	20	15	20 (gas burner) 30 (timber crib) Observations are made until all flaming or smoke production has ceased or after 1hr.	30	None specified. During test, a fan supplies air flow of 2m/s to increase incident heat flux to specimen surface.	15
Test Measurements								
Radiometer	None specified.	Centreline radiometer on top of main wall.	Centreline radiometer placed just above test area.	None specified.	None specified.	As per DIN 4102-20	None specified.	None specified.
Thermocouples	Wall exterior and intermediate layers/cavities at vertical, intervals of 1 m starting from 1.5 m above opening.	0.5m intervals up main and side test walls.	Five thermocouples are placed at the following heights from chamber opening: T1 – 500mm T2 – 900mm T3 – 1500mm T4 – 2000mm T5 – 2500mm	None specified.	Wall surface, intermediate layers and cavities, 3.5m above opening.	As per DIN 4102-20	Situated on non-specimen side of wall (location not stated).	None specified.
HRR		None specified.	Oxygen consumption calorimetry.	Oxygen consumption calorimetry.	None specified.	As per DIN 4102-20	None specified.	Oxygen consumption calorimetry.
Exposure Conditions (with non-combustible wall)								
Heat Flux	50 kW/m^2 at 0.5m above opening, 27±3 kW/m^2 at 1.5m above the opening. Above exposure averaged over 20 mins steady burner output.	None specified.	Heat flux at following heights above chamber 500mm - 17.9 kW/m^2 900mm – 11.3 kW/m^2 1500mm – 7.9 kW/m^2 2000mm – 5.9 kW/m^2 2500mm – 4.7 kW/m^2 (sample Heat flux measurements taken before test for 600kW output)	Minimum 100kW/m^2 heat flux to parallel panel surfaces.	60kW/m^2 at 0.5m above opening, 35kW/m^2 at 1.0m above opening and 25kW/m^2 at 1.5m above opening.	As per DIN 4102-20	None specified.	40kW/m^2 incident heat flux at 152mm above burner for both cavity widths (51mm and 102mm).
Temperature	None specified.	None specified.	Temperatures at following heights above chamber 500mm (T1) - ~479℃ 900mm(T2) - ~395℃	None specified.	780 – 800 ℃, ~1m above opening soffit.	As per DIN 4102-20	None specified.	None specified.

Test Standard	ASTM Vertical Channel Test[1][45]	ISO 13785-1[46]	JIS A 1310[2][47]	16 ft Parallel Panel Test[48]	DIN 4102-20[46]	Önorm B 3800-5[46]	PN-B 02867[3][46]	FM Global Cavity Fire Test [49]
			1500mm (T3) - ~254℃ 2000mm (T4) - ~234℃ 2500mm (T5) - ~198℃ (sample temperatures taken without combustible material for 600kW output)					
Flame Height	None specified.	None specified.	None specified.	1.1m height for 360kW propane burner	Extends up to 2.5m above opening.	As per DIN 4102-20	None specified.	None specified.
Performance Criteria	Flame spread ≤5m above opening. Heat flux to be <35kW/m^2, 3.5m above opening.	None specified (in test standard) No spread of flame above 500mm at 100kW during 30-minute test duration (applied in Czech Republic)	Not stated in resource.	830kW ≤ Peak HRR ≤ 1100kW – Maximum approval height of cladding is 50ft (15.2m). ≤830kW - Unlimited height	• No burn damage above 3.5m opening. • Temperatures of wall not to exceed 500℃ • No continuous flaming >30s, ≥3.5m above opening. • No flames at top of rig at any time. No falling debris or burning droplets to occur. Lateral flame spread to cease after 90s of fire source being extinguished/turned off.	As per DIN 4102-20	Maximum temperature on non-specimen surface to be <800℃. Test is conducted three times before classifying EWS. Facades are classified as 'NRO' (non-fire spreading), 'SRO' ('weakly' fire spreading) and 'SIRO' (highly fire spreading)	• A peak HRR of <100kW and A visible flame height to be ≤1.8m
Comments/Notes	BRANZ developed test rig using ASTM test method with reduced test wall from 7.32m to 5m. This test is not in use.	-	JIS1310 – is a published test standard in Japan. However, the information presented in this table is from experimental studies in aid of establishing the test standard. Therefore, the parameters presented in these studies may not be adopted.	Parallel surfaces are used to intensify exposure conditions of cladding to simulate post flashover conditions.	*Width of main wall is 2m if propane burner is used.	-	-	-

1. The geometry and fire size of the ASTM Vertical channel test falls outside the definition of intermediate scale test method. However, ASTM Vertical test method was designed as low-cost alternate, intermediate-scale test to the CAN/ULC S134 test standard and it therefore included in this paper as an intermediate scale test method.
2. This overall height of the test rig is >4m and the fire size is >300kW and therefore it may be recognised as a large-scale test method. However, the height is only marginally taller (by ~95mm) and thus may geometrically fall within the intermediate-scale test category.
3. PN-B-02867 test standard have been collected from the European Commission's report proposal for the harmonised façade test standard 'Development of European Approach to assess the Fire Performance of Facades' and not from test standard.

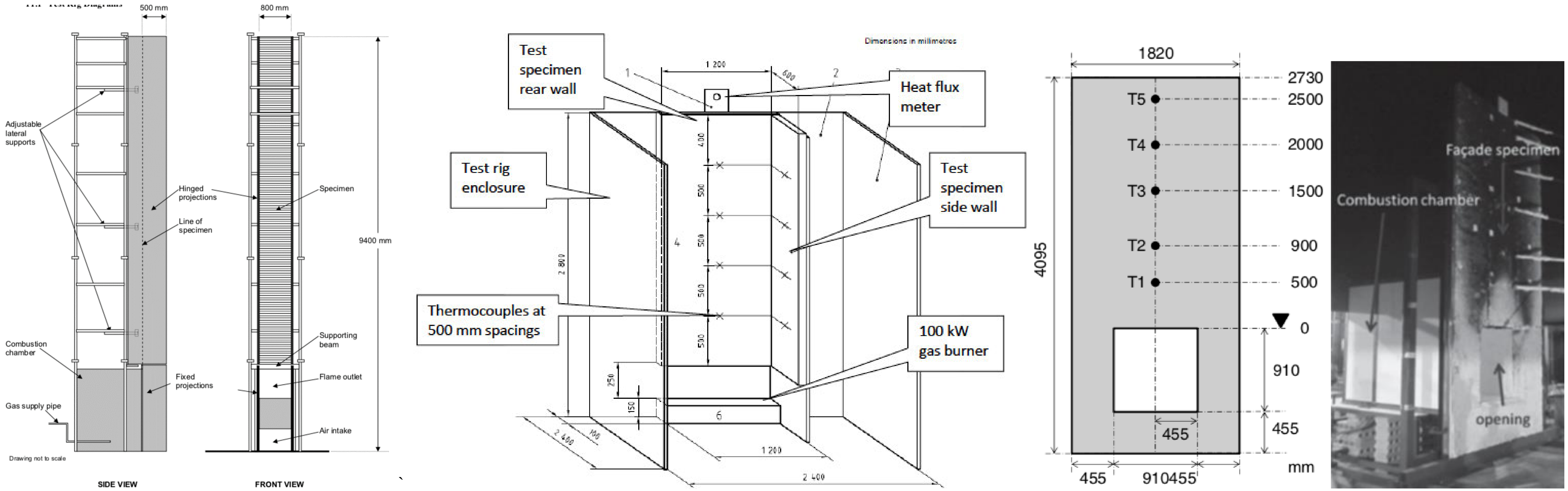


Figure 13: From left to right - 1) ASTM Vertical Channel Test rig, 2) ISO 13785-1 test rig, 3) JIS 1310-1 test panel diagram showing overall dimensions and thermocouple locations and 4) Image of JIS 1310-1 showing combustion chamber and facade.

Figure 14: From left to right - 1) FM Global 16ft Parallel Panel Test Rig diagram 2) FM Global 16ft Parallel Panel performing test, 3) DIN 4102-20 Test rig 3) PN-B 02867 test rig during performing test.

3.1.3 ANSI/FM Approvals 4411-2020 – American National Standard for Cavity Wall Systems

The intermediate-scale Cavity Fire Test was designed to test the flammability of combustible cavity materials installed within an otherwise non-combustible external wall.

FM Global provides third party testing and certification to manufacturers and/or building owners seeking FM Approvals for insurance purposes[50]. FM4411-2020 – American National Standard for Cavity Wall Systems provides test requirements for cavity wall systems including non-fire requirements such as wind loadings, hail resistance, corrosion resistance and manufacturing quality control. The test methods relating to fire performance of cavity wall systems include the following[3]:

- The Cavity Fire Test method described in Appendix B of FM Approvals tests standard 4411-2020 (see Table 7 and Section 3.3.3) – This test is used to assess the interior (cavity) resistance to fire spread.
- The 16ft Parallel Panel test (see Table 7) - is test method used to evaluate fire spread on the exterior surface (cladding) of a cavity wall system.
- The Fire Propagation Apparatus described under ASTM E2058 to determine flammability of synthetic polymer materials – The adoption of this test is optional. It is used to determine the non-combustible rating of insulation (removed of adhesive or facers). The insulation must show no visible flaming when 50kW/m^2 heat flux is applied in an 40% oxygen enriched environment.

The Cavity Fire Test method (referenced under ANSI FM 4411-2020 test standard) is discussed further under Section 3.3.3.

3.1.4 Full-scale testing

In 1994, an extensive fire spread up a newly refurbished high-rise apartment fire in Knowsley Heights England, prompted the need for a full-scale (or large-scale) fire test method to understand the complexities of EWS fire spread[1].

A full-scale test method displays the whole building product or assembly in its end-use configuration. The high-length scale (area of impact) and severe exposure conditions of large-scale tests allows for vulnerabilities of the external wall system to be revealed. The radiant heat and flames resemble real-fire conditions and range from large, localised flame impingement to post-flashover compartmental fire scenarios. Although, the majority of full-scale test methods utilise post-flashover compartmental fire scenarios as they represent the worst credible EWS fire spread.

Full-scale test methods can test a greater range in fire performance characteristics that may be inherent in the EWS design itself (such as fixing details, location of cavity materials, jointing details etc). In summary, the list of testing characteristics addressed by full-scale test methods include[46];

- Extent of Flame Spread - Vertical and horizontal flame spread within cavity and surface of cladding.
- Flame spread to above compartment
- Fire breach of junction between façade and floor
- Fire breach through Window
- Smouldering
- Falling debris
- External fire flame impingement or post-flashover

Many large-scale test methods are available today however no uniformity exists between these test methods in terms of scale, geometric size, exposure conditions, subsequent fire classification of EWS or how the outcomes of the test are used to regulate EWS.

Furthermore, full-scale test methods do not represent cavity fire scenarios (fires that originate within the exterior wall cavity). These ignition sources are electrical faults or welding sparks that are significantly smaller (~10kW) than post-flashover compartment fire. Although a full-scale test method represents an EWS its entirety (including cavity and presence of any cavity barriers), the opening sides of fire compartment is well sealed, disallowing exiting flames to spread within cavity, but directly impinge on external wall surface. Only when the exterior face is breached will cavity fire spread be observed.

3.1.5 AS 5113.1:2016 Large scale façade test classification standard

In Australia, AS5113.1:2016 is referenced under a verification method in the NCC vol.1. Fire performance of EWS under AS5113.1:2016 can be classified by two parameters:

a) External Wall (EW) – fire spread resulting from direct flame impingement from a post compartment size fire

b) Building to Building (BB) – ignition and fire spread resulting from radiant heat exposure from adjacent building fire. A 3mx3m specimen representation of the EWS is exposed to radiant heat level prescribed under AS1530.4. Radiant Heat exposure of external walls is not directly involved in cavity fire spread and therefore not discussed further in this paper.

AS 5113.1 can be performed using either the ISO 13785-2 or BS 8414 test rig. The relevant performance criteria referenced in AS5113.1 is dependent on the test rig adopted. Currently, laboratories around Australia are using BS 8414 test rig as it is a more accepted method internationally. Therefore, BS8414 test rig and performance criteria as referenced in AS 5113.1 is detailed in Section B2 under Appendix B

3.1.6 Summary Discussion

Although large scale façade test simulates post-flashover compartmental fire, representing worst case exposure conditions, they do not represent all EW fire scenarios. Current large scale test methods are expensive and onerous with industry preferring to find alternate fire engineered performance solutions in meeting the requirement of the code (such as limiting the amount of combustible cladding installed in combination with introducing more or upgrading the fire safety systems of the building).

Intermediate scale tests can offer scope to evaluate EW fire performance. Its representation of smaller fire source can be represented as localised flame impingement on EW cladding (balcony type fire scenarios) or fire initiating in or spreading into an external wall cavity (cavity wall fire scenarios). Industry may evaluate fire performance of these fire scenarios to screen out poor performing EWS before full scale application, representing more severe exposure conditions.

In Australia, the NCC references both AS1530.2 and AS1530.3 to regulate fire performance of cavity type materials (such as insulations and sarking). However, both these test methods utilise a small ignition source and simulate exposure conditions that do not represent the fire scenarios within an EW cavity. Furthermore, AS1530.2 is not suitable for materials that melt or shrink away from a heat source. AS1530.3 test standard utilises a mesh to be placed over the top of materials that melt or shrink away from the applied radiant heat source. Typically, materials that exhibit this type of behaviour demonstrate good fire performance under AS1530.3.

Typical reaction-to-fire behaviour of thermoplastic materials and indeed thermoplastic insulations (EPS and Polyester batts) demonstrate this type of behaviour.

The test series within EN 13051-1 was designed in recognition that an intermediate scale test method (in conjunction with small scale testing) was needed to represent materials in their end-use condition to adequately evaluate internal wall lining fire performance.

In 2016, Standards Committee of Europe took the initiative to harmonise EW large-scale test across Europe have also recognised the need of including an intermediate scale test method, DIN 4102-20 alongside large-scale test, BS 8414-1 to broaden scope of fire scenarios for external wall fire assessment.

At present, intermediate scale test methods are not used in most countries for regulatory purposes.

In 2020, FM Global, an insurer of buildings, introduced the Cavity Fire Test method into the series of tests (under FM4411-2020) to evaluate fire and other performance requirements of EWS containing cavities. FM4411-2020 references both the Cavity Fire Test and the 16ft Parallel panel test. It is important to note that although the test rig arrangement of the Cavity Fire Test and the Parallel Panel Test is similar (i.e. both utilise two vertically parallel panels), the Cavity Fire Test examines the fire spread behaviour within the interior (cavity) of an EWS (see Section 3.3.3) and the 16-ft Parallel Panel Test (see Table 7) evaluates resistance of the exterior face (cladding surface) to fire spread. FM 4411-2020 is not a pathway to meeting code requirements under International Building Code or NFPA 5000 but designed for building owners seeking insurance under FM Global.

The Cavity Test rig referenced within FM 4411-2020 test standard will form the basis of the experimental component (see 3.3.3 for more details).

3.2 Building code reaction-to-fire requirements

Most regulation around the world now allow for buildings to have an alternate/performance-based design to prescriptive requirements specified in the code. In terms of building fire safety matters, the fire engineer is appointed to conduct a fire safety performance-based analysis, in line with the code performance requirements.

Key prescriptive aspects of regulation that influence fire performance of external walls has been identified[7] and are listed below:

1) Reaction to fire requirements for building materials including those used for external walls
2) Fire stopping (between floors and curtain wall) and/or cavity barriers provisions

3) Distance between buildings (in terms of separation of unprotected openings between two buildings) requirements.
4) Separation (spandrel heights) or protection (use of horizontal projections) of openings between floors requirements and
5) Provision of sprinkler protection for certain types of buildings

Aspects 1 and 2 are relevant to preventing cavity fire spread. Mitigating material reaction to fire (aspect 1) is the most effective way in preventing fire spread across EWS and will be the focus of this chapter.

Aspects 3 to 5 are out of scope of this paper and therefore not discussed further. The book, Fire Hazards of External Wall Assemblies Containing Combustible Components (2012), discusses all aspects of the code relating to fire safety from other countries. Building code requirement stated in this book may not be current, however it offers a detailed understanding of how the above aspects are addressed within building code requirements.

3.2.1 Regulatory Reaction-to-Fire Requirements in Australia

In Australia, the national building code is a performance-based code. The current code in application is the National Construction Code (NCC) 2019. The NCC 2019 contains: *performance requirements* - qualitative statements that describes the level of performance and *deemed-to-satisfy (DtS) provisions* – prescriptive provisions that are deemed to satisfy the performance requirements.

The NCC comprises of three Volumes. Volume One, Amendment 1 covers the building requirements for Class 2 to 9 buildings (buildings other than single, sole occupancy dwellings or attachments (sheds/garages)).

Clause C1.9 of NCC Vol. 1[10] states all components and elements within an external wall (and common walls) of *Type A and B construction*, must be non-combustible. This includes façade coverings, framing, insulation and ancillary elements (stated under Clause C1.14). Ancillary elements (non-integral parts of the wall system such as attachments) must not be fixed, installed or attached to internal or external parts of an external wall that is required to be non-combustible. AS 1530.1 Non-Combustibility Test method (refer to Section 3.1), is used to define the combustibility of materials. Clause C1.9 provides exception for materials that do not meet AS 1530.1 non-combustibility Test criteria but contribute minimally to fire spread. These materials include plasterboard, gypsum board, sarking and the like.

Fire tests methods referenced in NCC vol.1 applicable for External Wall systems are listed in Table 8 below.

Table 8: Fire test methods referenced in NCC Vol. 1 that are applicable for External Wall Systems

Test Method	Scale	Building Element	NCC Vol. 1 reference
AS 1530.1: 1994 – Combustibility Test for materials	Small	All materials	Test method is referred in NCC as to define combustibility of construction materials.
AS 1530.2:1993 – Test for Flammability of Materials	Small	Sarking	Clause C1.9, e) vii) -. Sarking-type materials that do not exceed 1mm in thickness must achieve a *Flammability Index* not greater than 5 can be used wherever a non-combustible material is required.
AS 1530.3:1999 – Test for Simultaneous determination of ignitability, flame propagation, heat release and smoke release	Small	Bonded Laminate material, sarking & insulation	Clause C1.9, e) vii) C) – Bonded Laminates to have a Spread-of-Flame Index and Smoke-Developed Index to not exceed 0 and 3 respectively. Clause C1.10 vii) - Sarking type materials (other than in Fire control room) to have Flammability Index does not exceed 5. Clause C1.10 ix) – insulation to have Spread-of-Flame Index does not exceed 9 and Smoke-Developed Index does not exceed 8 (if Spread-of-Flame Index is >5).
AS1530.4:2014 – Fire Resistance Tests for Elements of Construction	Med/ Large	Cavity barriers	Spec C1.13 2) f) - assess cavity barriers within fire resisting timber construction in accordance with Schedule 5, applying criteria for control joints specified in Section 10
AS5113:2016 – Classification of external walls of buildings- based on reaction-to-fire performance	Large	EWS	CV3(Clause C1.9) to classify overall performance of EWS to compartmental post-flashover fire scenario.

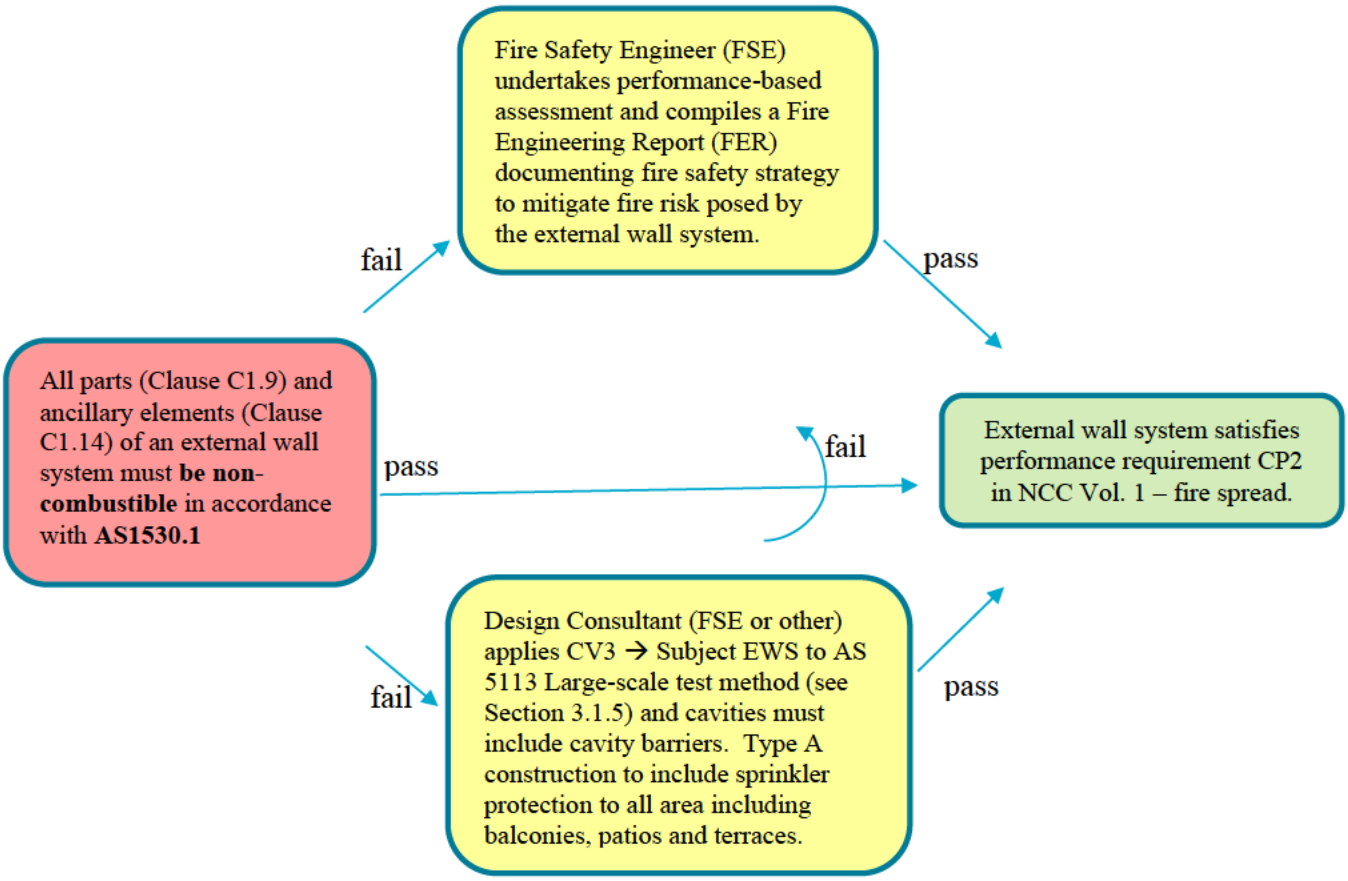


Figure 15: Pathway to compliance under Verification Method CV3

The NCC Vol. 1 offers a pathway for compliance for external wall systems, through Verification Method CV3. Figure 15 explains the pathway to compliance under CV3.

Verification Methods, such as CV3, are not mandatory. They are either a test, inspection, calculation or other method that demonstrates whether a performance solution meets the applicable performance requirements[10]. Therefore, demonstrating EWS compliance via the full-scale AS5113 external wall test is not mandatory.

3.2.2 Regulatory Reaction-to-Fire requirements in other countries

New Zealand[51]

New Zealand's Building Code is also a performance-based code. Combustibility of materials are defined in accordance with either AS1530.1 or EN13501.1; a standard that uses a combination of three (3) small scale tests and one intermediate scale test (Appendix B.1.1).

Amendment 2 of the C/AS2 -buildings other than Risk Group SH (single homes) was released in November 2020. Compliance to the NZ Code can be achieved by either meeting set reaction-to-fire prescriptive requirements (referred to as acceptable solutions) for the entire EWS or just the cladding portion of an EW (see Table 9). Performance requirements of the on small-scale and large-scale test methods referenced in the NZBC are in Appendix C .

Table 9: Acceptable solutions for EWS compliance to NZ building code

Building Height (m)	Distance to boundary (m)	External Wall requirements		Cladding Type
-	≤1m	Clause 5.8.1 – EW to be non-combustible/limited combustibility in accordance with either AS1530.1 or EN13501.1		A
-	≥1m	Clause 5.8.2 – Buildings containing Risk Group SI* must have all elements of an external walls to be non-combustible/limited combustibility in accordance with either AS1530.1 or EN13501.1	Or achieve	A or B
≥ 10m to ≤ 25m		Clause 5.8.3 – EW to be non-combustible/limited combustibility or EWS to be tested to a large-scale external wall test (Clause 5.8.4). Either AS5113:2006, BS 8414-1, BS8414-2 or NFPA 285 large-scale test method can be adopted.		A

*SI risk group – buildings that house people who are incapacitated, require assistance in escaping or can may be delayed while escaping. These include hospitals, residential care facilities, prisons and detention spaces etc.

Foam plastics must comply with flame propagation criteria specified in AS1366, which is a small-scale test method.

United Kingdom

Approved Documents provide guidance on how to meet building regulations in the UK and Approved Document B deals with fire safety. Approved Document B contains two volumes; Volume One - Dwellings and Volume 2: Buildings Other Than Dwellings. 'Relevant building' (any building with an effective height >18m containing one or more dwellings for institutional or residential purposes (including student accommodation, aged care, hospitals and the like)).

Buildings (other than 'relevant buildings') must the following requirements for:

1) External surfaces
2) Materials and Products – any insulation product, filler material (core materials of Metal composite panel, sandwich panels and window spandrels) should achieve an A2-s3, d2 or better and
3) Cavity Barriers (as described in Section 9 of Approved Document B: Vol 2).

For ‘Relevant Buildings, ‘materials that do not achieve a classification of A2-s1,d0 in accordance with EN 13501-1 but do meet BRE 135 performance criteria (for large scale test method BS8414-1 or BS8414-2) are not permitted.

Table 10: Reaction-to-fire Requirements for external surfaces - Approved Documents B 2019, Volume 2 - Table 10.1

Type of Building	Building Height	Less than 1000mm from relevant boundary	100mm or more from the relevant boundary
‘Relevant Buildings’		Class A2-s1, d0 or better	Class A2-s1, d0 or better
Assembly and recreation buildings	>18m	Class B-s3, d2 or better	Ground level to 18m: C-s3, d2 or better From 18m and above: B-s3, d2 or better
	≤18m	Class B-s3, d2 or better	Ground level to 10m: C-s3, d2 or better Up to 10m above a roof where public may have access to): C-s3, d2 or better Above 10m: no provisions
All other buildings	>18m	Class B-s3, d2 or better	Ground level to 18m: C-s3, d2 or better From 18m and above: B-s3, d2 or better
	≤18m	Class B-s3, d2 or better	No provisions

Buildings (other than ‘relevant buildings’) must meet the following requirements for:

1) External surfaces
2) Materials and Products – any insulation product, filler material (core materials of Metal composite panel, sandwich panels and window spandrels) should achieve an A2-s3, d2 or better and
3) Cavity Barriers (as described in Section 9 of Approved Document B: Vol 2).

Or meet the performance criteria described under BRE 135 from test data taken from BS8414-1 or BS8414-2 full-scale façade test.

For ‘relevant buildings’, materials must meet a Euro classification of A2-s1, d0 or Class A1 for all materials within the EWS. Materials included in external wall systems that meet BRE 135 performance criteria are not permitted.

Classifications are determined by using one or two of three small scale tests – 1) ISO 1182 - Non-combustibility Test, 2) EN ISO 1716 – Gross Calorific value 3) EN ISO 11925-2 Small Flame Test, and an intermediate scale test EN 13823 Single Burning Item. Order of classification from combustible to non-combustible is F, E, D, C, B, A2 and A1. ‘S’ classification denotes level of Smoke Growth Rate Index with

United States

There are two model codes that are in use in the USA:

- ***The International Building Code[52] (IBC)*** is widely adopted by jurisdictions across the United States. The IBC is revised every 3 years; however, every individual jurisdiction (at state and/or municipality level) have the liberty to adopt it or not.
- ***National Fire Protection Agency (NFPA) 5000[7] –*** is the alternate building code but is not adopted by most states.

Both the IBC and NFPA 500 specify prescriptive requirements depending on type of combustible materials, including ‘general combustible external wall’ coverings, Metal Composite Materials (MCM) such as ACP, foam plastic insulation, light transmitting plastic wall panels, fibre reinforced polymers and High-Pressure Laminates (HPL). Reaction-to-fire requirements may vary depending on type of combustible cladding, height of building and/or distance to boundary or building (‘separation distance’).

In general, buildings greater than 12.192m in height must be tested to NFPA 285 full scale façade test. If all listed prescriptive requirements are met, then testing to NFPA 285 to demonstrate compliance is not required. All reaction to fire properties, such as flame spread index, smoke developed index, self-ignition temperature used small-scale based test methods.

A summary list of reaction-to-fire requirements and other set requirements (such as limitation on area of coverage) for IBC model code (the main model code in the US) is summarised in Section C2, under Appendix C

Germany

Two model Building Codes are in use in Germany: The Model Building Code, MBO – Musterbauordnung and Building Regulations for high rise buildings, HBO – Musterhochhausrichtlinie). DIN EN13501-1 test standard (similar to EN13501-1 test described in Section B.1.1) is used to classify combustibility and flammability requirements of external walls.

Stringency to reaction-to-fire requirements is determined in accordance with building height (see Table below)

Table 11: Reaction to fire requirements in German Building Code

Building Height	Test Method	Requirement for EWS
Up to 7m	DIN EN 13501-1 and 2	Low flammability
7m-22m	DIN EN 13501-1 and 2 and additional requirements using DIN 4102-20, an intermediate scale test method (see Table 7)	As above. Additionally, EWS must meet requirements of DIN 4102-20. EIFS with EPS must be tested to Technical Regulation A2.2.1.5 - A 200kg crib fire from outside building).
>22m	DIN EN 13501-1 and 2	Non-combustible

3.2.3 Building code requirements for fire stops and/or cavity barrier

In Australia, fire stops/cavity barriers (Aspect 2) are only required for building with lightweight timber construction. NCC Vol. 1 references schedule 10 of AS1530.4 test method (fire resistance furnace heated in accordance to the standard time-temperature curve) and references the test criteria for control joints to determine fire resistance of cavity barriers. Cavity Barrier FRLs are expressed in terms of integrity (i.e. prevention of flame penetration through the barrier) or insulation (maximum temperature above the barrier) and are required to match the FRL of the external wall in which they are installed in. The NCC Vol. 1, Spec 1.13[10] specifies cavity barriers to be installed in fire-protected timber construction only (not to other types of construction) and required to be installed at 5m centres to the horizontal and 10m centre to the vertical.

In general, other countries stipulate cavity barriers/fire stops to be tested using fire resistance standards and must match or exceed the FRL of the building element they are installed within. The requirement to install them are dependent on height of building and presence of combustible materials within the EWS.

Other than fire resistance testing, adequacy of cavity barriers/fire stops can be effectively determined within large-scale external wall test methods. The fire size and exposure conditions of intermediate-scale test methods do not effectively challenge the cavity barrier/fire stop.

3.2.4 Summary Discussion

Reaction to fire limits of external wall materials are dependent on the distance to adjoining boundary or building, building classification (type of occupancy), height of the building and whether the building is provided with sprinkler protection. Many countries regulate materials in terms of reaction to fire attributes using small scale testing methods or allow for combustible materials if tested in end-use conditions, using a full-scale testing method.

Test outcomes of small-scale methods are conservatively applied, taking into account that tested materials are not represented in end-use configuration or exposed to real-fire conditions. In the countries discussed, full-scale test methods are not a mandatory requirement to seek compliance to the code.

Majority of countries do not adopt IST methods for regulating external wall materials. However, it is recognised that there is some scope for IST methods for regulation:

- The European Harmonisation project (see Appendix B3) introduces DIN 4102-20 as medium-scale test method (alongside BS8414-1 full-scale test standard) to provide more breadth in classification of EWS for regulatory purposes.
- At current, for lack of a harmonised test method EN13501-1 test series is accepted in many European countries to regulate EW material performance. EN13501-1 test series recognises that fire performance of material is not solely dependent on the intrinsic properties (calorific value and combustibility) and flame attack (Small Flame Test) but also dependant on its end use application (EN 13823 Single Burning Item). See Appendix B.1.1 for more details.

3.3 Literature Review on Experimental Studies of Cavity Fires

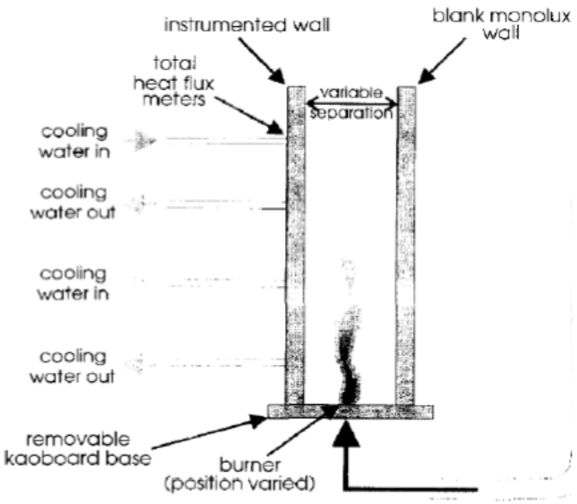
This chapter examines research studies that focus on cavity fire phenomena and associated test apparatuses. Initial research on the effects of fire between two parallel surfaces was studied in the context of warehouse storage rack fires. The findings of these experimental studies can be extended to external wall cavities.

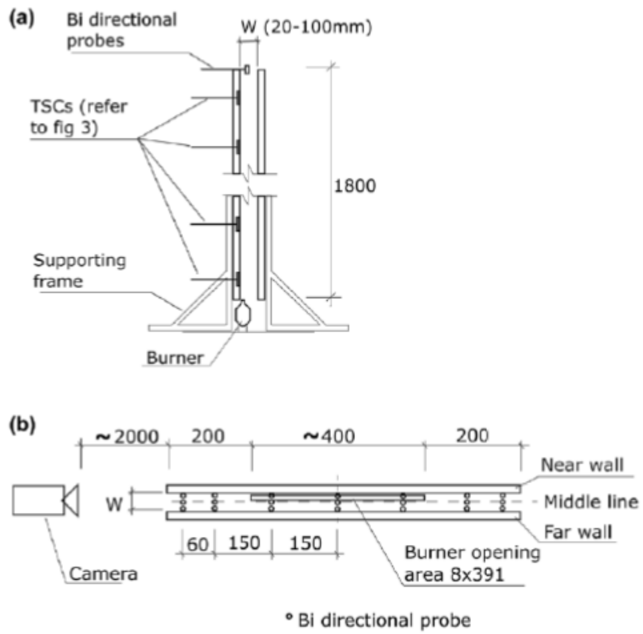
3.3.1 Studies of the behaviour of fire within a cavity, void of combustible materials.

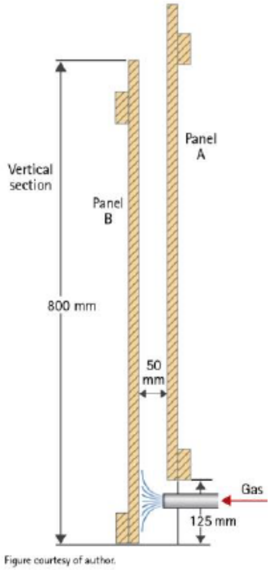
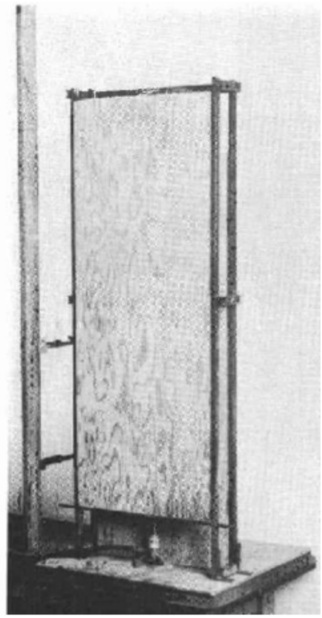
Table 12 details experimental programs designed to study the effects of fire within two, inert parallel walls/panels. Elements studied include heat flux to interior wall surfaces, air flow velocity, flame heights and temperature gradients within cavity arrangements.

Table 12: Experimental Programs using intermediate scale test apparatus to study fire and heat development between two vertical surfaces

Experimental Program(s)	Test Apparatus and Instrumentation	Test Duration	Varied Parameters	Main Conclusions/Comments
Foley, M and Drysdale D.D (1995) Heat transfer from flames between vertical parallel walls[53]	The test rig height of 813mm is similar to the Schlyter Test (see 'Skyler Test' in this table, Table 12). Non-combustible 610mm W x 25mm D Monolux board are used for the parallel walls. Sixteen (16) heat flux measurements were recorded from four equal vertical and horizontal positions from the centreline. It was assumed that heat flux distribution would be symmetrical across vertical centreline. Kao wool was placed at the base of the rig to prevent air flow. A line gas burner with area dimensions of 600mm x 10mm sat in the centre. Four separate experiments had to be done to	9 min.	• Cavity widths of 60, 100 mm and infinity gap (single wall configuration). • Burner positions at instrumented wall, centre of gap and opposing wall • Open and closed base	The series of tests concluded that small changes in the separation distance can result in significant change in heat flux. When the base of the rig is sealed, the flame height is elongated up at the centreline, as air is entrainment from the sides to support combustion (rather from open base). With the base open, the flame behaves like a sheet with uniform height.

Experimental Program(s)	Test Apparatus and Instrumentation	Test Duration	Varied Parameters	Main Conclusions/Comments
	obtain the heat flux reading at 16 points as only four Gardon Gauge radiometers were available. The vacant holes were plugged with Kao wool. 		• 5 and 9 litre/min gas flowrates that resulted in heat output of 7kW and 12.5 kW respectively	The prevention of air flow at base significantly influences heat flux to surfaces than other parameters studied (burner output, separation distances, burner position and air flow patterns). However, the effect is further enhanced by reducing the separation distances. Burner output and position of burner not only influence magnitude of heat flux to walls but can alter distribution.

Experimental Program(s)	Test Apparatus and Instrumentation	Test Duration	Varied Parameters	Main Conclusions/Comments
Livkiss, K and Svensson, S (2018)[54] Investigate the influence of cavity width on flame heights, fire driven flow and incident heat flux A total of 77 tests were done.		3 mins	• Cavity widths (m) of 0.1, 0.06, 0.05, 0.04, 0.03, 0.02 and one wall configuration. • Average burner heat outputs of 16.5kW/m, 24.8 kW/m, 32.3 kW/m and 40.4 kW/m.	As cavity widths decreased, fire plume tended to fill up cavity (both extend lengthwise and fill up cavity width). This phenomenon occurred at widths of 0.03m at heat outputs of 16.5kW/m, 24.8 kW/m and 32.3 kW/m; and at 0.04m for heat outputs of 40.4kW/m^2 Reducing cavity widths resulted in increased incident heat flux to parallel wall surfaces. Reduction of cavity created sooty flames (due to lack of oxygen to sufficiently combust pyrolyzed gases), which in turn lead to increased radiative feedback between parallel walls. Outflow velocity within cavity increased linearly when burner output was increased (with cavity at same width). Reducing the width from 0.04m to 0.02m did not alter flow significantly. Flow velocity was greatest at the centreline position.

Experimental Program(s)	Test Apparatus and Instrumentation	Test Duration	Varied Parameters	Main Conclusions/Comments
Babrauskas, V (2018) Skyler test Apparatus[55]	In 1939, Ragnar Schlyter, the head of the Swedish National Testing and Research Institute (SP), demonstrated the increased burning rate observed when a vertically oriented combustible panel is placed closely in front of another panel. The Schlyter apparatus consisted of two slabs (800mm high) oriented vertically with small air gap (50mm) in between. SP used this apparatus to test the propensity for flame spread (flammability) of materials.  Cross-sectional view of Schlyter Apparatus	**N/A**	**N/A**	The published FM Global Cavity Fire Test is a similar, scaled-up proportions to the Schlyter test (see Section 3.3.3 below). A modified Schlyter test apparatus was used at the Forests Products Laboratory (Wisconsin USA) to test flame retardancy coatings for wood claddings such as shingles (see figure below)[56, 57] 

Literature on studies evaluating cavity fire scenarios involving typical combustible materials used in exterior wall cavities is limited. The 2-storey duct apparatus and FM Global's Cavity Fire test method are the two main test methods found examining combustible material fire spread using cavity fire sizes.

3.3.2 Ventilation cavities with insulation - using 2-storey duct apparatus[58, 59]

The apparatus is 5m high by 1.25m wide rectangular duct. An 25mm high opening was situated at the base of the rig and used to insert a natural gas burner set at a constant heat output of 25kW. Three sides (left, right and rear faces) of the rig were formed by 13mm calcium silicate board. The front face was made of gypsum board with 25mm high viewing ports vertically spaced to enable observation of flame spread height within the duct. The position of front face was adjustable to suit the width of the cavity being applied. The internal back face of the duct was lined with the insulation being tested. The burner was applied for a period of 10 minutes, then switched off to observe flame propagation within the cavity.

A typical post-flashover compartment fire (containing fire loads of between 20-40 kg/m^2) can last up to 30 minutes. It is presumed gypsum thermal barrier (attached to the frame) is expected to protect the insulation for the first 20 minutes of exposure. From this information, it was presumed that a post flashover fire breaching into an external wall cavity can last up to ~10 minutes. Therefore, a 10-minute test duration was used.

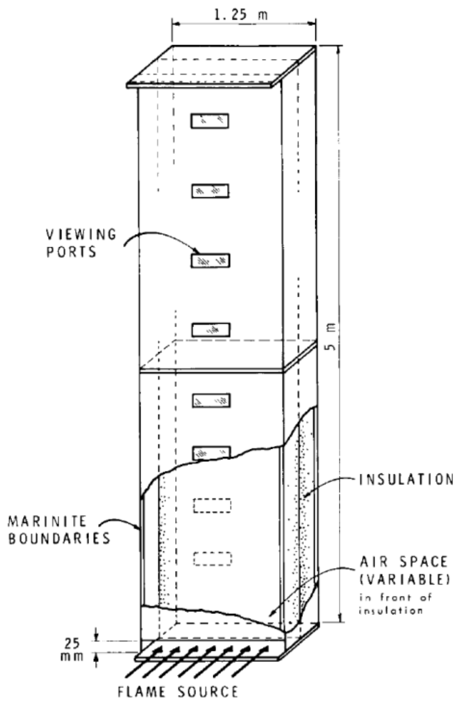


Figure 16: Two-storey Duct apparatus simulating external wall cavity conditions

Two studies were conducted using this two-storey duct apparatus. In Taylor (1983) study, foamed insulation with different ASTM E-84 Steiner Tunnel test flammability spread classifications (FSC) were tested. Two series of tests were performed.

Series 1 with polyurethane foamed insulations (PIR/PU board (50mm), PU board (50mm) and sprayed PU (85mm))

The experimental tests concluded that ASTM E-84 Steiner Tunnel test flame spread classifications were not a factor in determining fire spread and instead dependent on the material properties of insulation, width of cavity and ventilation conditions within cavity. Irrespective of the Fire Spread Classification, fire spread was generally limited to 1-2m height for cavity widths ≤25mm and propagated to full height of the test rig for 40mm cavity width.

Series 2 with polystyrene type insulations (Moulded (EPS) and Extruded (XPS) polystyrene board, both at 75mm)

For this series of tests – flame entry into cavity was introduced at the base and mid height of the rig. In general, the fire spread for both types of insulations were very similar for all tests performed. With flame entry at base and no air gap - only melting was observed with no fire spread. The molten EPS/XPS formed a pool at the base opening and burnt. The heat from the pool fire continued to melt the material within the cavity after the burner was switched off. The weight of the XPS molten pool was double that of EPS because of the greater density of XPS.

No flame spread and melting was observed for both insulation types with mid height flame entry, with and without air gap. Molten material was observed to reach up to 0.5m below without air gap. With the introduction a cavity (either 25mm or 40mm), molten dripping below flame entry point was reduced to between 75-100mm.

Study performed by Choi and Taylor (1984)[59]

For the second study the two-storey duct apparatus was used to determine the validity behind the glass wool permitted by the National Building Code of Canada to have no height restriction for its application. Although glass wool is deemed non-combustible the binder used to bind the fibres is combustible.

Other than flame spread observations, further oxygen concentration and temperature measurements were taken for this study:

- O_2 concentration in cavity was measured by placing probe 1m from bottom.

- Thermocouples were put at 46cm equal distances up along centreline to indicate accurate measurement of flame front. A mean cavity temperature of 220℃ at 2.3m height measured prior to performing tests. A temperature rise of greater than 220℃ during experiments would indicate that the foam insulation was involved.

Cavity widths of 13, 19, 25 and 38mm using glass wool insulation were tested.

Experiments found that the rate of replenishment of O_2 into cavity is what determined flame spread. Oxygen is consumed two ways: from fuel from the gas burner and from pyrolyzed gases from the burning of foam insulation. At narrow widths, restricted air flow hindered combustion. With increasing cavity widths, the rate of oxygen replenishment also increased to a point where continuous burning could be supported. This width was found to be 25mm. Also, higher peak temperatures were recorded with increasing widths (from ~60-70℃ at 13mm to ~500-550℃ at 38mm).

3.3.3 FM Global Cavity Fire Test Study (applied within FM 4411-2020 in the USA)[49]

In 2016, USA based FM Global Cavity Fire Test was developed in recognition of the need to address the potential for ignition to occur within EWS cavities, such as electrical sparks, fire via penetration with inadequate fire stopping or grinding or welding sources during construction phase. The test consists of two parallel panels, one panel of made of non-combustible construction and the other panel installed with insulation with or a without weather-resistive barrier, that houses the typical contents of a wall cavity. The parallel panels are set either 51mm or 102mm apart simulating an air gap between the face of the test specimen and the non-combustible construction, with 51mm – 102mm representing the range of most cavity widths typical in external wall construction. The two vertical panel frames are made of steel that is 1.2m wide by 2.4m high. The top of the parallel panels is sealed off using steel sheet flashing to simulate a vertical cavity stop. The bottom of the two panels is fitted with a sheet metal with an opening to accommodate the sand burner of 305mm long by either 51mm or 102mm wide.

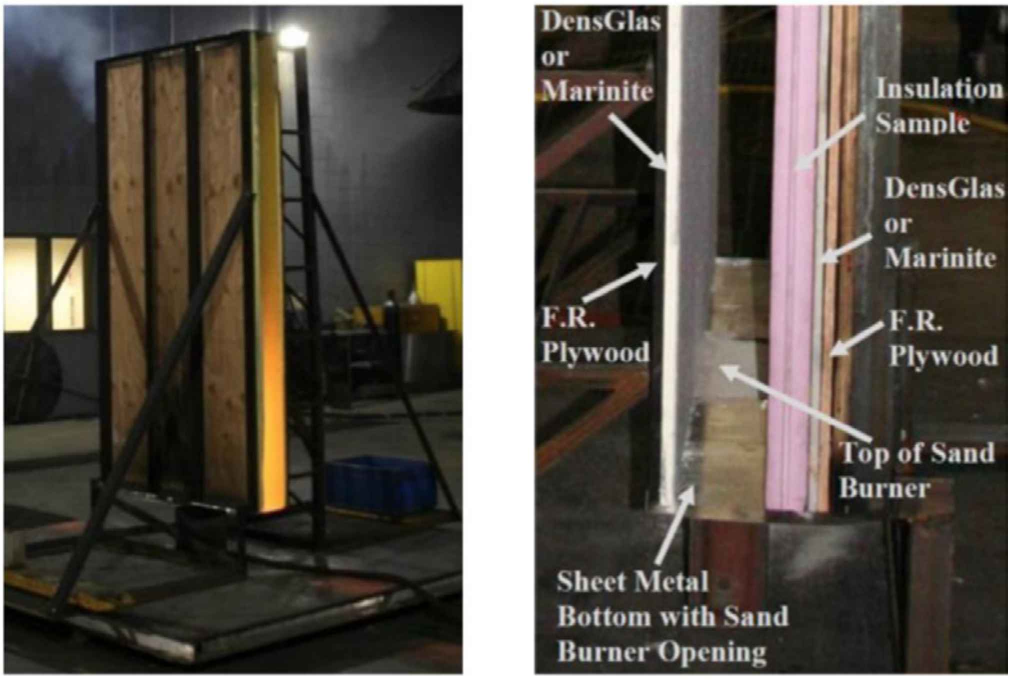


Figure 17: Cavity Fire Test Rig (left), Close-up view of Cavity Construction within Rig (right)

Sand burners of the Cavity Fire test were designed to have the same HRR output of 60kW to match FM Approval 4910 8ft Parallel Panel test. This equated to be 323 kW/m^2, giving the 51mm x 305mm HRR output of 5kW and 102mm x 305mm HRR output of 10kW. This correlated well with the HRR of a typical oxyacetylene torch (used in welding) that ranges from 4.0kW to 12.1kW.

For comparability, it was important to maintain a similar incident heat flux to the specimen surface for both burner/cavity width sizes. It was found that at 305mm above the burner, the incident heat flux was equal (20kW/m^2) for both 51mm and 102mm cavity widths tests, however differed by 20kW/m^2 at a height of 152mm. Therefore, the HRR for both burner sizes of 51mm and 102mm were adjusted to 5.8kW (slight increase) and 9.5kW (slight decrease) respectively. This achieved a uniform incident heat flux of 40kW/m^2 for both widths at 305mm above the burner.

A total of 11 demonstration tests were conducted using rigid extruded polystyrene foam and sprayed polyurethane foam to evaluate chosen test parameters such as duration and exposure levels. A 5MW oxygen calorimetry hood was used to measure HRR. The results and measured test parameters are shown in Table 13 below.

Table 13: Cavity Test Parameters and Results

Test	Insulation	Test Duration (min)	Cavity/burner width (mm)	Sand burner output (kW)	Peak HRR (kW)	Maximum Flame height (m)	Height of Char (m)
1	Rigid Extruded Polystyrene	15	51	5.8	835	>2.4	2.4
2		15	51	5.8	1020	>2.4	2.4
3		15	51	5.8	1100	>2.4	2.4
4		15	102	9.5	1270	>2.4	2.4
5		15	102	9.5	1630	>2.4	2.4
6		15	102	9.5	1460	>2.4	2.4
7	Sprayed Polyurethane foam	20	51	5.8	<100	1.8	1.8
8		20	102	9.5	<100	1.2	1.2
9		20	102	9.5	<100	1.1	0.9
10		15	102	15	<100	2.3	2.1
11		30	102	15	<100	2.1	1.8

Test duration of test number 7-9 and Test 11 were increased to 20 minutes and 30 minutes respectively to evaluate whether chosen 15 minutes test period was adequate in discerning between good and poor performance. No additional flame spread was observed beyond the initial 15minute test exposure confirming adequacy of test period.

The severity of the 9.5kW burner output was confirmed by increasing the burner output to 15kW for Tests 10 and 11.

For Tests 1-6, the flames were observed to go above 2.4m height of the test rig. For Tests 1-3, the central portion of the insulation was consumed for the entire height of the panel whereas for Tests 4-6, nearly all the insulation was consumed.

The peak HRR for the 51mm cavity width tests (Tests 1-3) were less severe than for the 102mm cavity (Tests 4-6) . This was due to the increased cavity width allowed for more air entrainment to support surface burning and resulted in an increase in radiant feedback between panels.

Sprayed polyurethane foam is better fire performing polymer insulation with peak HRR below 100kW for all tests (Tests 7-11). Maximum flame heights were lower and most of the insulation was consumed at the area of burner flame impingement (bottom centre of the panel) with significant charring extending beyond this region up to a maximum height of 2.1m.

Although the exposure period of 30 minutes for Test 11 was double the exposure period for Test 10, the observed maximum flame height was lower. This can be attributed to the difference in application of the sprayed polyurethane between the test samples. Therefore, quality of on-site application and install of insulation has an impact on overall fire safety.

The acceptance criteria for cavity wall construction based on this study was concluded to be:

- A peak HRR of <100kW and
- A visible flame height to be ≤1.8m.

3.3.4 Summary Discussion

Many experimental programs found that the decrease in cavity widths was the dominant parameter in increasing heat flux to vertical surfaces, increasing air temperatures and elongating flames within cavities. Limiting air flow or sealing off the base of cavity also significantly impacts on surface heat flux. A threshold is reached where further narrowing of a cavity will no longer support continuous combustion. This width was determined to be 25mm [59] for experiments using the double storey duct apparatus.

A hypothetical optimum cavity width to promote fire spread can be derived from converging effects of increasing heat flux to parallel panel surface (by decreasing cavity width) and increasing heat release within cavity (dependant on availability of air and material (fuel) properties within cavity). The effects of both heat flux and heat release rate can describe the ‘flammability index’ within a cavity [24]. However, the ‘flammability index’ will vary depending on the varying fire conditions, critically ventilation.

The test parameters used within the FM Global Cavity Test Study were incorporated within FM 4411-2020 series of test standards to evaluate and control cavity fire spread risk (also see Section 3.1.3). Therefore, this test method has been chosen to form the basis of the experimental component of this research into evaluating cavity fire spread using combustible insulation and sarking.

4 EXPERIMENTAL STUDY OF CAVITY FIRE SCENARIOS

This test study proposes to examine cavity fire spread scenarios. The test standard developed by FM Global – FM 4411 Cavity Fire Test will be used as a basis to extend the experimentation. The test aims (as outlined under the Chapter 1 – Introduction) is as follows:

1) What impact does ignition size, ignition type and cavity arrangement have on the test outcomes?
2) Does the chosen characteristics of the test method (ignition size, type and cavity configuration) successfully expose different reaction to fire behaviour between groups of materials and provide discriminatory results?
3) How does the design of the cavity test compare to exposure conditions of relatable intermediate scale cavity test, namely the FM Global Cavity Fire Test method?

Many previous experimental studies outlined in Section 3.3 above, studied the effects of varying cavity widths and ventilation conditions on flame and burning behaviour. However, these variables **were not explored further** in this study. Examining these variables, in addition to material behaviour would have rendered the number of experiments impractical to be foreseeably completed within the time constraints of this Masters. It was decided that studying material behaviour under varying ignition sizes within a cavity was of greater interest and thus the focus of this study. See Section 4 below for more details.

4.1 Test Lab

The series of tests were performed at CSIRO Fire Laboratory in North Clayton, Melbourne.

The Fire laboratory at CSIRO is used to perform the AS1530.8.1 Bushfire radiant heat test of building materials. The lab is also used to perform other types of fire experiments with a fire size no larger than ~1MW. The series of experimental tests will be conducted under 2m x 2m hood.

The exhaust hood is installed with instrumentation for collecting and measuring HRR (see below for more details). The combustion gases that enter the hood, pass through a wet scrubber in order to remove any flue gas contaminants before being released into the atmosphere.

Figure 18: 2m x 2m exhaust hood

4.2 Construction of the Test Rig

The test rig design is based on FM Global's Approval Standard for Cavity Walls and Rainscreens (Class 4411) with modifications to suit this experimental project. Each 1.2m wide x 2.4m high vertical panel is constructed using lightweight steel stud frames. Each panel sits on a support base that is constructed using 40mm square steel tube sections. Two, 40mm 'L' steel angle lengths are used to erect each 1.2m W x 2.4m H panel up and join it to the square steel tube support base. Two vertical panels face parallel to each other, simulating a cavity in an EWS. The top of the panels is sealed off using Fire Resistant (FR) plasterboard to simulate a horizontal cavity stop. Each support base is set on four (4) wheel castors to allow for manoeuvrability, equipped with brake pedals. The width of one support base is 1.4m long and the other is 1.6m long. These lengths enable one support frame to fit within the other, providing base stability for when the panels are loaded with instrumentation and test specimens. A layer of 2.4m high x 1.2m long, 12mm plywood is attached directly onto each vertical steel frame. Two layers of 13mm thick FR plasterboard form the inner linings of the simulated cavity. The test specimen (insulation and/or sarking) are fixed onto one of the vertical panels ('Test Panel'). Instrumentation such as water-cooled Schmidt-Boelter type heat flux meters (radiometers) and K-type thermocouples were inserted through the back of the other vertical panel ('Instrumented Panel'), into the cavity space. Two sheets of FR plasterboard were laid on the floor beneath the test rig to protect the lab floor from burning debris. Levellers were used to lift cavity rig to accommodate height of Load Cell for Cavity Characterisation Tests (see Figure 19 below).

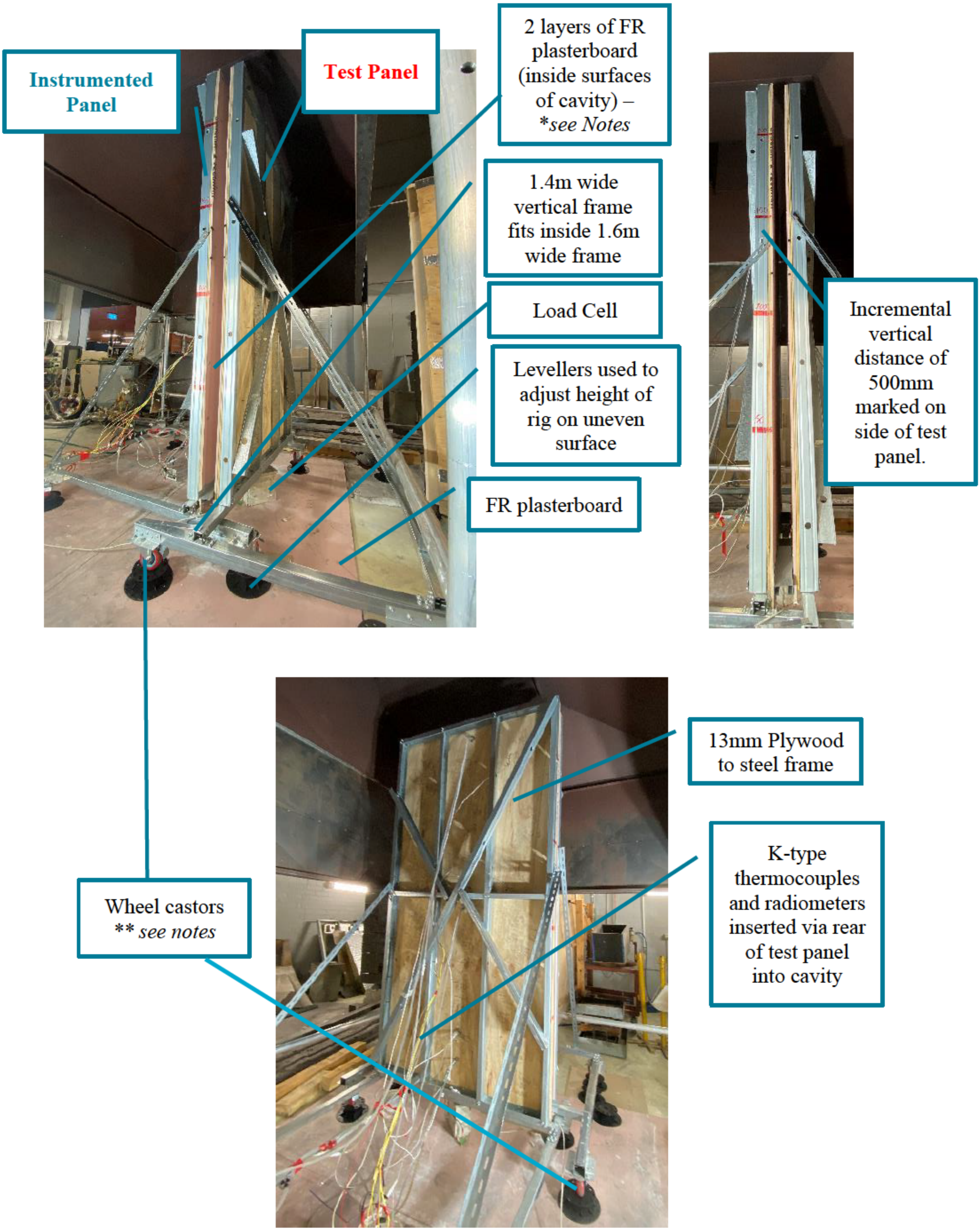


Figure 19: Images of Cavity Test rig taken before conducting Cavity Characterisation Tests - Top, left – Side view of Cavity Test Rig, Top, right – Close-up view of side of Cavity Test Rig and Bottom – Rear view of Instrumented Panel.

The base of the cavity was sealed using FR Plasterboard (a piece of steel battens was screwed to each panel to create a ledge to support the FR plasterboard). The 50mm wide x 250mm long x 50mm high rectangular fuel tray was be placed on top of the FR Plasterboard, at the base of the cavity. The thickness of the steel used to fabricate the fuel trays was 0.5mm. The fuel tray was constructed using sheet metal that was cut, folded and welded together to form the fuel tray shown below. A larger piece of FR plasterboard sealed the top of the cavity. The sealing of the base and top of the cavity propose to create ventilation conditions commensurate to an external wall cavity.

Figure 20: Left – Image of fuel tray, Right - Close up view of two fuel trays within cavity for Test 1

Notes:

**Initial image showing Cavity Test Rig set up (Figure 19) does not show the two layers of FR plasterboard. However, while conducting the series of tests – it was found that two layers of 13mm plasterboard was necessary to withstand heat and potential fire spread to the plywood. Thus in between tests, the top layer of FR plasterboard was replaced between experiments as required.*

*** The original wheel castors had to be replaced with steel wheel castors after front wheels of the Instrumented Panel melted during polyester batt insulation test.*

4.3 Test Measurements

4.3.1 Heat Release Rate (HRR)

The HRR is the main parameter that defines the size of a fire and was used to quantify the size of fire for each cavity fire test performed. The HRR was measured using two methods, via oxygen consumption calorimetry and the Load Cell. The Load Cell was adopted to measure HRR of liquid fuel fires (i.e methylated spirits and heptane fires) during cavity rig characterisation tests as resolution of oxygen consumption calorimeter could not measure HRR outputs of <10kW.

Oxygen Consumption Calorimeter[60]

The heat generated by the burning of most fuels is experimentally determined to be equal to the unit mass of oxygen consumed in the reaction. This approximated to be 13.1 MJ/kg (±5%) at 25 deg C and 101.3 kPa. Open air fires do not undergo complete combustion and therefore CO_2 and CO concentrations must also be determined for an accurate measurement of HRR.

In general, the oxygen consumption calorimetry instrumentation (oxygen analyser) and measurements are as follows:

- The fire is undertaken under an exhaust hood and all combustion gases are extracted via the exhaust duct.
- HRR is measured by analysing the composition of combustion gases and volumetric flow rate within the exhaust duct.
- Exhaust duct gas sample is extracted via probes and pumped to fire lab containing the oxygen analyser and non-dispersive InfraRed (NDIR) sensors (used to measure CO_2 and CO concentrations).
- The gas volumetric flow rate is determined by the differential pressure (measured by Mc Caffery bidirectional probes) and temperature measurements taken at the centre of the exhaust duct.
- A filter may remove any water vapour from the exhaust gases before entering the analysers.

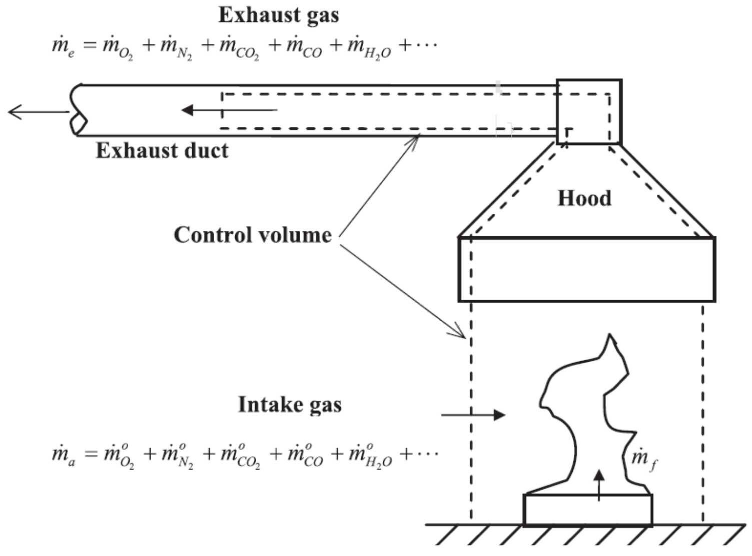


Figure 21: Open Oxygen Consumption Calorimetry Schematic[60]

Load Cell

The fuel trays are placed on the Load Cell that measures the instantaneous mass loss of fuel. If the heat of combustion of the fuel is known, then a theoretical HRR of the fuel can be determined by multiplying the mass loss rate with the heat of combustion:

$$\dot{q} = \Delta H_c \dot{m}_{fuel}$$

Figure 22 shows an image of the Load Cell used to measure free burn (outside cavity rig) fuel tray fires.

Figure 22: Image of Load Cell used outside cavity rig for a heptane fire burn. Fuel tray placed on top of steel stud piece attached to Load Cell.

4.3.2 Incident Heat Flux

Water cooled Schmidt-Boelter type heat flux meters (radiometers) with a measurement range between 0-100kW/m^2 were used. During the cavity characterisation tests four radiometers were centrally located at the following heights from the base of the cavity: 152mm, 305mm, 1200mm (mid-height) and 2250mm (top). For the material specimen tests, the bottom two radiometers (152mm and 305mm from cavity base) were removed to avoid damage during tests. The bottom two incident heat flux measurements are used to compare exposure conditions proposed for FM Global Cavity Fire Tests (see Section 3.3.3).

4.3.3 Temperature

Air temperature measurements are taken during fire tests to help determine flame front position. It is important to note that rising hot gases from burning material may not give accurate, real-time position of flame front however the combination of visual observations and post-test damage will provide overall understanding of flame progression.

MIMS Type K 1.5 mm thermocouples are used to measure air temperature distribution and flame progression up the cavity. Nine thermocouples are evenly spaced above the expected flame impingement line of the heat source.

If temperatures recorded during the test series are greater than mean temperatures recorded during the calibration test (without test specimen), then this increase in temperature may indicate the involvement of cavity material.

4.3.4 Visual observation

A Go-Pro camera was positioned at the RHS of the rig to capture flame progression within cavity.

Visual observations of significant events (such as such as flame emerging out of sides or top, melting or charring, smoke colour and density and approximate flame progression heights) will be recorded.

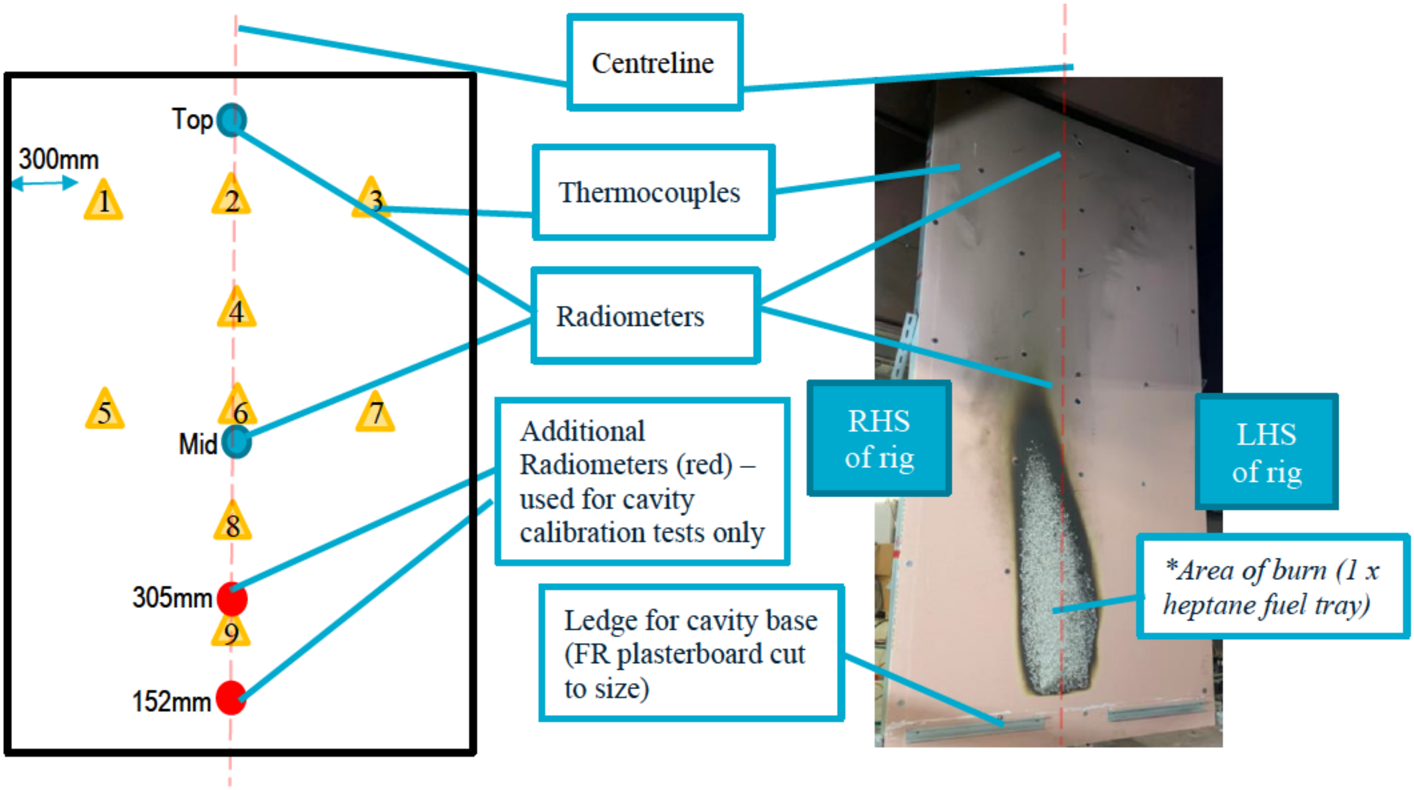


Figure 23: Location of thermocouples and radiometers on Instrumented Panel.

**Note: Flame impingement area imprinted on the Instrumented Panel indicates that the flame of the ignition source (in this case 1 tray heptane) was not symmetrical. As indicated in*

Figure 23, the flame has a tilt towards the right-hand side. This phenomenon is further discussed under Section 4.7.1)

4.4 Test Parameters

4.4.1 Ignition sources

The FM Global Cavity Fire Test standard used a gas sand burner that can be adjusted and controlled to the desired HRR. Adopting a gas burner for this research study would require extra fire safety equipment to operate and could not be sourced within a feasible timeframe (to suit the intended schedule for this paper) and therefore liquid fuels were chosen as the ignition source for this experimental study. The use of the fuel tray proved to offer practical benefits. The removal and cleaning of post-test molten debris and replacement of the fuel tray offered quicker turnaround times between experiments.

Selection of ignition size and fuel type

For this experimental series two sizes were selected to represent two key cavity scenarios identified in the Literature Review:

a) An electrical fault originating in cavity that rapidly develops into a small, localised fire involving small portion of combustible material and

b) A pre or post compartmental fire breach into cavity (such as described within experts reports on the Grenfell Tower Fire incident).

Methylated spirits is a predictable and clean fuel source that is readily available. Methylated spirits undergoes close to complete combustion for relatively small fires, therefore an accurate estimation of HRR can be obtained by measuring the fuel's mass loss rate.

A free burn 5kW HRR fire using methylated spirits in a fuel tray of dimensions 50mm L x 250mm W x 50mm H was estimated using the following empirically derived formula [17]:

$$HRR = C_{eff} \Delta h_C \dot{m}'' A$$

$$HRR_{Methyl} = (0.9)(26.8)(0.015)(0.0125) \approx 0.0045MW \ or \ 4.5kW \text{ per fuel tray.}$$

The key terms for the above formula is listed within Table 14 below.

Table 14: Key Terms for calculating HRR of Methylated Spirit pool fire.

Term	Definition	Value	Comment/source
C_{eff}	Combustion efficiency	0.9	Assume it is 0.9 due to its placement within cavity.
Δh_C	Heat of Combustion (MJ/kg)	26.8	Store bought methylated spirits contains ~95% Ethanol and ~5%Demineraised Water[61]. Heat of combustion for Ethanol as 26.8 MJ/kg[62].
A	Surface Area of the fuel (m^2)	0.0125	A fuel tray with the dimensions 50mm W x 250mm L x 50mm D. This equates to a fuel surface area = 0.0125m^2

Term	Definition	Value	Comment/source
$\dot{m}''$	Mass loss rate (kg/m^2. s)	0.015	Radiative feedback enhancing fire growth is minimal for alcohols (such as ethanol) therefore the effect on area (or change in diameter) of the pool fire size will have minimal effect on mass loss rate. Thus, depending on the diameter range in size. a constant mass loss rate can be applied, i.e. For a diameter <0.6m, the mass loss rate is: $\dot{m}'' = 0.015$ [62]

Based on the above calculation, it was determined that methylated spirits was a suitable fuel source to represent a small cavity fire scenario involving an electrical fault.

An Open fire burn tests with measured HRR via Load Cell were conducted for methylated spirits fires. The HRR data for this test is listed as Test C1 under Table 18 in Section 4.6 Results.

Liquid fuels of both heptane and kerosene were chosen to possibly represent the larger pre/post compartmental fire breach into an EW cavity due to their greater calorific value (and relatively larger HRRPUA than methylated spirits). Kerosene proved to be a particularly oily and messy fuel source that was difficult to ignite. Open fire burns of kerosene produced sooty flames suggesting that this behaviour would most likely increased under a restricted ventilated environment (such as within a cavity).

Heptane is an organic compound and is a commonly used fuel in aviation. The open heptane fire burnt more cleanly than kerosene and the peak and average HRR (recorded using a Load Cell), were within the anticipated range for a pre/post compartmental fire. The results of the open heptane fire burn is listed as Test C2 in Table 18 under Section 4.6 Results.

Burn duration of fuel source

The fuel type and surface exposure area of the fuel were selected to control ignition source HRR whereas the mass of fuel (depth of fuel in tray) was selected to control ignition source burn duration.

For the open fire fuel burns, it was determined that ~60g of methylated spirits and ~100g of heptane burnt for 5-6 minutes. It was found that the burning rate approximately doubled when the same amount of fuel was burnt inside the cavity rig. In order to maintain the same burning time (exposure period), the amount of fuel was doubled for both methylated spirits and heptane (i.e., adopted fuel amount of 120g for methylated spirits and 200g for heptane). Characterisation tests conducted within Cavity test rig used these increased fuel amounts (see Table 18).

4.4.2 Test Duration

The following events will signify the end of test:

a. Fuel tray has burnt out and no further fire spread has ensued.

b. Flame supported by fuel fire at base of cavity (from molten material) is minimal (<20mm in height) and fire spread has ceased on material surface.

c. Intensity of fire threatens integrity of either test rig, equipment, or instrumentation. Either CO_2 fire extinguisher or hose reel will be adopted to extinguish fire.

4.4.3 Test specimen

Based on the literature review, four types of combustible foam insulation ranging from poor to good performance: Polyester batts, Polystyrene foam (EPS), Polyisocyanurate board (PIR) and Phenolic foam (PF)) were selected for experimentation. A uniform thickness of 50mm was commercially sourced.

Foil faced polypropylene sarking paper that meets the NCC flammability index requirement, determined in accordance with AS 1530.2 was also selected (see Table 15).

Table 15: Manufacture supplied information of materials purchased for test series.

Material	Panel Dimension	Density (kg/m^3)[1]	Usual Installation Method	Fire Testing Information
Recycled Polyester batts R-value = 2.5	430mm W x 1100 H x 90mm D	38	Polyester batts are placed in between the studs of either a timber or steel framed wall.	None specified.
Expanded Polystyrene (EPS) M grade EPS	1200mm W x 2400mm H x 50mm D	18	Installed on concrete wall or outer surface steel or timber frame as part of EIFS. The outer surface of the EPS board is applied with a polymer modified fibre reinforced render. The inner surface is bare and faces the cavity.	AS 2122.1 – Flame Propagation Characteristics
Polyisocyanurate (PIR) Embossed thin aluminium sheet on	1200mm W x 2400mm H x 50mm D Thickness of embossed	36	Concrete wall – install over furring channel clips with wings of clip penetrating the insulation. Joints between panels to be	AS1530.3 – Ignitability Index =0, Spread of Flame Index = 0, Heat Evolved Index = 0

Material	**Panel Dimension**	**Density (kg/m^3)[1]**	**Usual Installation Method**	**Fire Testing Information**
both sides of insulation. R-value = 2.5	aluminium sheet[2] = 0.2mm-0.25mm		sealed using aluminium foil tape.	and Smoke Developed Index = 1. AS/ISO 9705 Room Corner Test (wall and ceiling lining) – Group 2 (using plastic fasteners and reinforced foil tape at joints).
Phenolic foam (PF) Composite foil paper stuck onto both sides of panel. R-value of 2.35	1200mm W x 2400mm H x 50mm D Thickness of foil paper[2] = 0.2mm	37	Concrete wall – install over furring channel clips with wings of clip penetrating the insulation. Steel/Timber frame – install on to external face of frame using galvanised clout nails or screws. Ensure fixing overlaps studs, top and bottom plate.	AS1530.3 test outcomes: Spread of Flame Index = 0, Smoke Development ≤ 3. Ignitability index and Heat Evolved Index not stated.
Sarking Sarking has 4 layers, consisting of reflective aluminium foil, polymer adhesive, woven polypropylene and polymer film on top. Sarking is classified as 'heavy' in accordance with AS/NZS 4200.1:2017.	Roll size: 1500 H x 60m L. Nominal thickness = 0.12mm	N/A	Sarking is installed to either steel or timber frame. Sarking is installed by rolling out sarking horizontally, against the stud frame and nailing/screwing into place. Sarking tape is used to seal overlapping sections of horizontally rolled sarking. Sarking is typically used to protect poor moisture resistive insulations such as polyester batts.	AS1530.2 Flammability Index ≤5

[1]Density measured at CSIRO lab by weighing panels and dividing by volume of material. Outer aluminium foil or metal sheet facing for phenolic foam and PIR are removed in calculation.

[2]Thickness of facing measured at CSIRO Lab

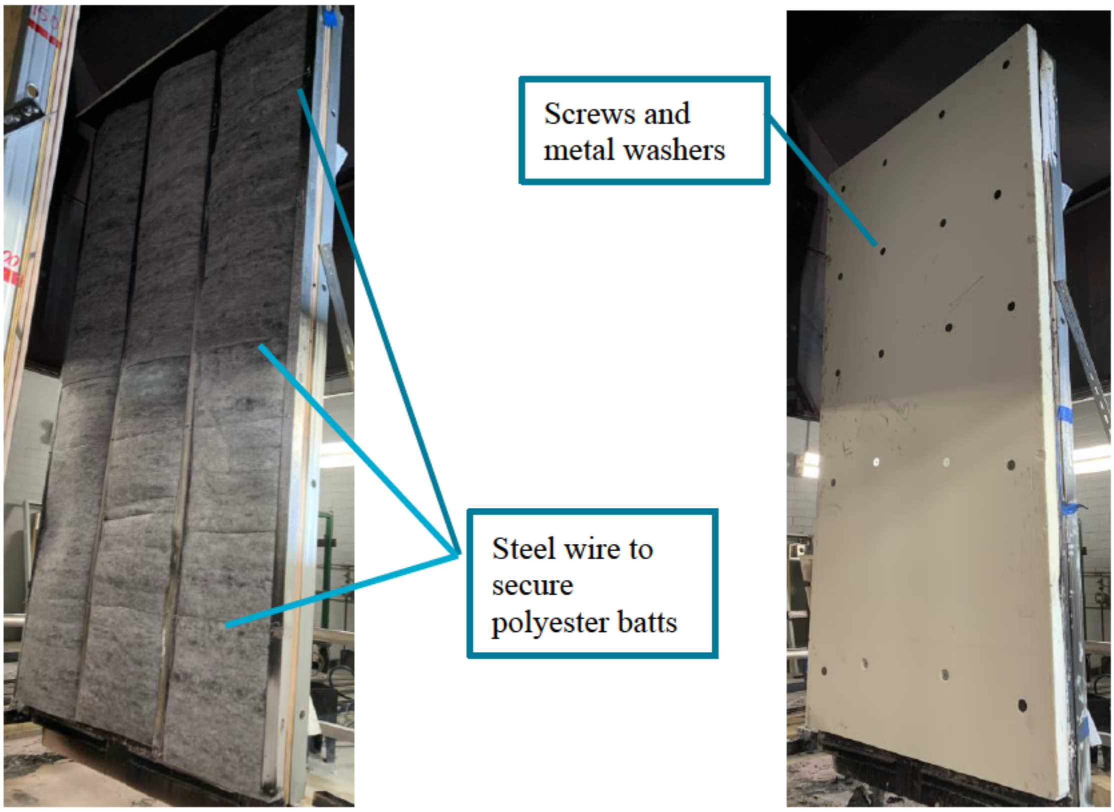
Figure 24: Test specimen from left to right, top to bottom: Row 1 – PE batts, PF (aluminium paper foil removed), PIR panel (with Metal sheet removed) and EPS board, Row 2 – Label for Sarking, tape used to seal between sarking overlapping sections and nails with plastic washers used to secure sarking to timber frame Row 3 – Close up view of installed sarking showing sarking, tape and screw fixings Row 4 Close up view of composite foil paper on phenolic foam board and close-up view of embossed metal sheet on PIR foam

Installation of sarking and insulations for Experimental Study

Sarking was also installed vertically (not horizontally as detailed in Table 15) against cavity steel studs. Sarking tape was taped across mid height The nails with plastic washers (used to install sarking onto frame) were replaced with metal washers and screws for ease of installation onto the steel stud frame, see

Figure 24.

The insulation boards (EPS, PIR and PF) were installed using galvanised screws with metal washers directly onto the Test Panel. A total of 20 screws (4 horizontally spaced screws x 5 vertically spaced screws) were evenly installed to secure insulation in place. Polyester batt insulation was pressed in between the steel studs. Steel wire was placed on the bottom, middle and top of the rig to prevent any potential dislodgement of the batt insulation during the experiment.



4.4.4 Cavity Width Explored

Typical construction of EWS contain cavities ranging between 50 and 100mm in width. A cavity width of 65mm is chosen as the lower limit as it represents the approximate width of a steel stud.

The Rig Characterisation Tests were performed using two main types of cavity arrangements:

- ~65mm cavity width– Typical steel stud existing within an EWS is of this width, and therefore will represent a typical cavity within a steel stud wall. Therefore, a typical cavity width of

~65mm was formed between two parallel panels to conduct a set of characterisation tests (see Figure 25, part a).

- ~130mm – Sarking is typically installed outside of a steel stud frame in order to protect fibrous insulation such as polyester batt (PB) insulation (installed between steel studs) from moisture and condensation. Therefore, for the sarking test series – a steel stud frame was installed within the cavity to install the sarking (see Figure 25, part b and c). While conducting the series of sarking tests, it was observed that the material tore away quite early on into the test, giving way to a greater cavity of 130-135mm (see **Error! Reference source not found.**, part c). It was decided to then perform cavity characterisation tests with the steel stud frame installed, to determine the effect of larger cavity on burning behaviour of the ignition source.

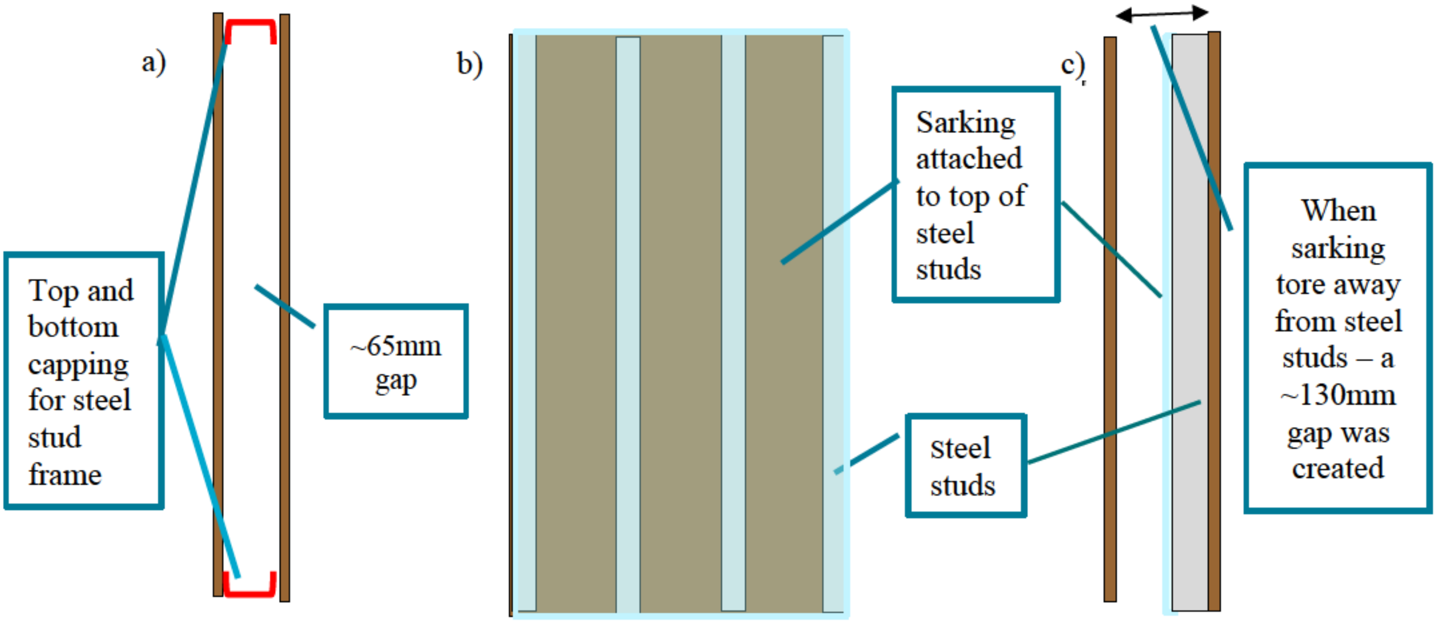


Figure 25: a) Cross sectional view of typical steel stud cavity (with no insulation) b) Elevation view of test panel showing installation of steel studs with sarking installed on top c) Cross-sectional view of steel studs and sarking within cavity. Images are not to scale.

4.5 Test Procedure

The following lists the procedure followed for each test:

1. HRR Calibration - An initial test to evaluate the accuracy of the measured HRR via oxygen consumption calorimetry equipment was conducted. A fuel tray filled with heptane was burnt directly under the hood. The results were compared to manual HRR calculations using the known calorific value of the fuel.

2. Span and zero HRR gas analysers

3. Conduct check of all instrumentation

4. Conduct safety overview of tests outlining:

a. Safe pouring of fuel, placement and ignition of fuel tray

b. Correct PPE equipment and attire (steel gap shoes, safety glasses, respirator masks, gloves and hair tied back)

c. Ignition and suppression procedure of fuel tray

d. Emergency extinguishing of fire. Fire extinguisher to be at hand before commencing series of tests.

5. Turn on Exhaust system, oxygen gas analyser, data takers and thermal oxidiser (after burner for pollution control).
6. Measure ambient temperature and humidity
7. Switch on camera on either side of cavity test rig
8. Pour fuel into tray and slide into position using wooden stick
9. Ignite fuel tray (lit match attached to wooden stick ignites fuel) and note stopwatch time, marking start of test (t=0). Stopwatch is used to synchronise data taker on roof (measuring gas flow for HRR) with data taker within lab (other instrumentation such as cavity air temperatures, incident heat flux and gas concentrations).
10. Observe test and note down any significant events.
11. Continue test observations for at least 15 minutes with fuel tray continually burning for this duration. If fire overwhelms rig and may have potential to damage rig, suppress fire using fire extinguisher. Note time of fire extinguisher application.
12. Download all data from data log (refer to Section 4.5.1).
13. Record extent of post-test damage within Cavity (refer to Section 4.5.24.5.1).

4.5.1 Data Acquisition

Each test measurement is to be logged using two DT85 model data takers.

One data taker will be located next to the exhaust duct (situated on the roof of the fire lab with access) and the other is located within the cone lab, the adjacent room behind the fire lab. The following measurements will be recorded via the data takers:

- Oxygen, carbon dioxide and carbon monoxide levels from O2 analyser

- A pressure transducer and thick rod thermocouple, inserted through the side of the exhaust duct, are to measure pressure differentials and temperature of the combustion gases respectively.
- Nine (9) thermocouples measuring air temperature distribution within cavity
- Radiometer heat flux readings taken 100mm below top of panel
- Mass loss rate to calculate HRR via Load Cell

The real-time data will be captured every 1 second of test.

4.5.2 Measurements of Post-test Damage

Figure 26 below depicts all point of measurement of panel post-test damage.

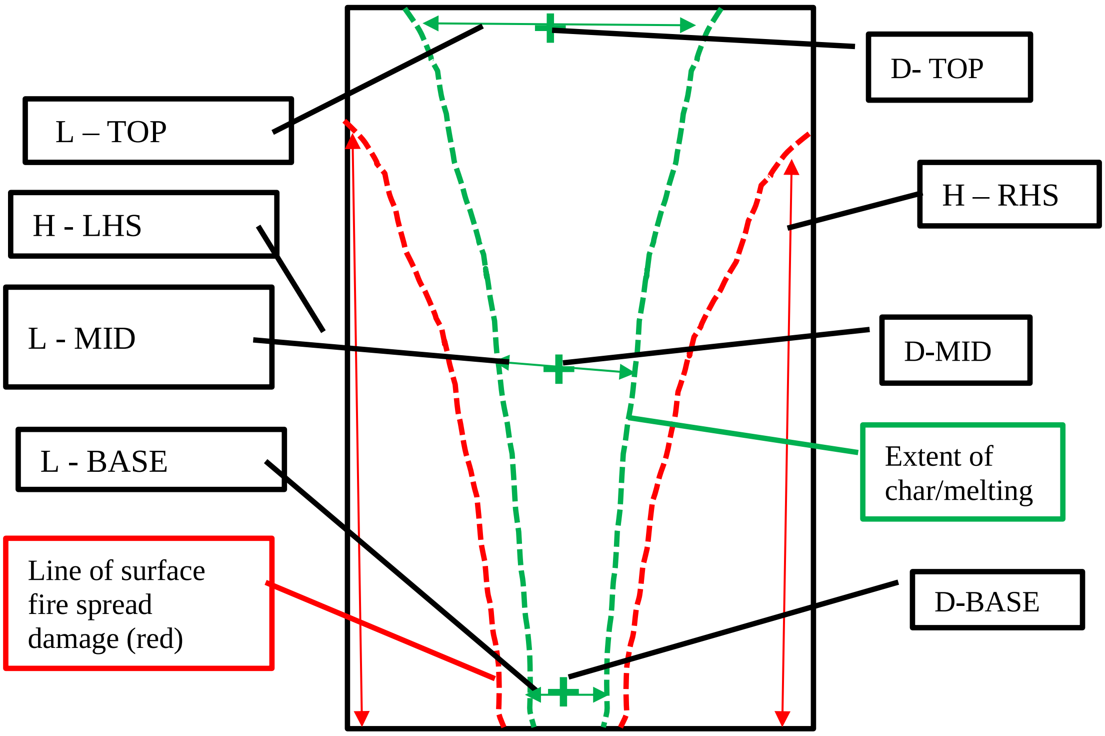


Figure 26: Post-test measurement locations

Areas of surface discolouration (due to radiant heat damage) will not be measured.

Table 16 (below) provides a description to post-test measurements detailed in Figure 26 above.

Table 16: Key to Post-test Measurements

H - RHS	Height of flame front damage at RHS of panel	**H- LHS**	Height of flame front damage at LHS of panel
L – TOP	Top Length of charred area	**D - TOP**	Centreline top charred depth
L - MID	Mid height length of charred area	**D - MID**	Mid height centreline charred depth
L - BASE	Base length of charred area	D - BASE	Base height centreline charred depth

These measurements are to give a good indication of severity of flame within cavity and potential for spread beyond test panel height. Post-test photos are collected.

Char depth method of measurement

Post-test observations (evident for PIR and PF) showed that the material has swelled when exposed to heat and flames and therefore the following method was used to determine the charred depth:

a) A sharp-edged instrument such as a flat head screwdriver was used to remove the charred layer of material to reveal the raw, unburnt material.

b) The instrument was used to pierce the remaining width of the raw material. The length of inserted portion was noted (usually using the tip of the fingers)

c) The inserted portion (within the uncharred layer) was removed from the material (with the tip of the fingers marking the depth). The length of the inserted portion was then measured against a ruler.

d) The uncharred layer depth was subtracted from the known thickness of the insulation board to ascertain the charred depth.

4.5.3 Cavity Characterisation tests

Repeated methylated spirits and heptane test burns were completed to characterise the Cavity Test rig in terms of centreline surface incident heat fluxes (at four heights), temperature distribution, average heat release rate and peak heat release rate (see Test series ‘C’ under Table 17: Experimental Program). The resolution of the Oxygen Analyser was too large to analyse concentrations of gases from a fire of <10kW. Therefore, the Load Cell was adopted in order to calculate the HRR via the burn rate (mass loss). However, the Load Cell was used in conjunction with the Oxygen Analyser to compare HRR measurements collected from the Analyser and Load Cell (see Table 18). The Load Cell was only utilised during the Cavity Characterisation Tests as it was expected that HRR of the fuel alone would be relatively low (especially for the methylated spirits burns).

Incorporation of Load Cell within the Cavity Test Rig

The fuel tray was balanced on piece of steel stud, that was suitably cut and attached to the Load Cell. The base of the cavity could not be fully sealed in order to accommodate the Load Cell with fuel tray. Instead, the Load Cell was placed in the centre, base of the cavity and the remaining parts of the cavity (on either side) were sealed using pieces of steel stud cut to suit the length. The top of the cavity was sealed.

4.5.4 Program for Testing Materials Specimens

Each test specimen was subjected to a base scale test – ignition source of 1 tray heptane with an peak HRR of ~30kW (see Table 18) and depending on the outcome of each test –either a severe scale or reduced scale ignition source (in comparison to the base scale) will be adopted for subsequent test(s).

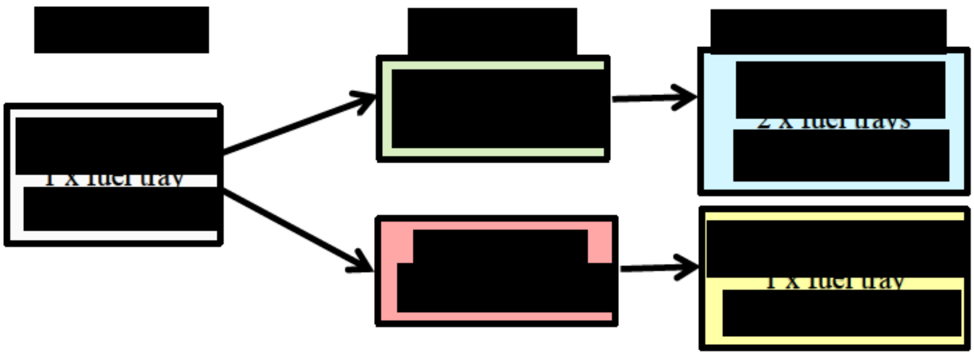


Figure 27: Subsequent test depending on outcome of Base Case test

The experimental test program developed based on Figure 27 (see Table 17). The aim of the experimental program was to study the effects of fire spread using two different ignition sizes on four types of insulations, ranging from poor to good performance. Both PIR and PF foam insulations were manufactured with an outer facing (refer to

Figure **24** above). Additional tests were performed on these insulations with and without the protective outer facing. Tests to examine potential influence of sarking in promoting fire spread on recycled polyester batts were also conducted.

Table 17 below contains the list of cavity characterisation and material specimen (insulation and sarking) experiments performed to fulfil the aim of this study A short-hand test name (last column of Table 17) describes the test parameters applied. The shorthand test name for each test will be referred to in the Discussion (see Section 4.8)

Table 17: Experimental Program

Test No.	Combustible Material(s)	Fuel source	Fuel amount/test arrangement	Shorthand test name
C1	Nil	Methylated Spirits	~60g (1 tray), Outside of Rig	M/S, outside rig
C2	Nil	Heptane	~100g (1 tray), Outside of Rig	1 hep, outside rig
C3	Nil	Methylated Spirits	~120g (1 tray)	M/S Test A,
C4			~120g (1 tray)	M/S Test B,
C5	Nil	Heptane	~200g (1 tray)	1 hep Test A
C6	Nil		~200g (1 tray)	1 hep Test B
C7	Nil		~400g (2 trays)	2 hep
C8	Nil	Methylated Spirits	~120g (1 tray) within larger cavity (steel studs)	M/S in steel stud
C9		Heptane	~200g (1 tray) within larger cavity (steel studs)	1 hep, in steel stud
C10	Nil	Heptane	400g (2 trays) within larger cavity (steel studs)	2 hep, in steel stud
1	Sarking	Heptane	Base Case, ~200g (1 tray)	sark + 1 hep
2			Sensitivity Case, ~400g (2 trays)	sark + 2 hep
3	Polyester Batts	Heptane	Base Case, ~200g (1 tray)	PB + 1 hep
4		Methyl.	Reduced size, ~120g (1 tray)	PB + M/S
5	Polyester Batts with Sarking	Heptane	Base Case, ~200g (1 tray)	PB + sark + 1 hep
6	Phenolic foam with aluminium paper facing	Heptane	Base Case, ~200g (1 tray)	PF facing + 1 hep
7		Methyl. Sprits	Reduced size, ~120g (1 tray)	PF facing + M/S
8		Heptane	Sensitivity Case, ~400g (2 tray)	PF facing + 2 hep
9	Exposed Phenolic foam (facing removed)	Heptane	Base Case, ~200g (1 tray)	PF exp + 1 hep
10		Heptane	Base Case, ~200g (1 tray)	PIR exp + 1 hep

Test No.	Combustible Material(s)	Fuel source	Fuel amount/test arrangement	Shorthand test name
11	Exposed PIR foam	Methyl. Sprits	Reduced size, ~120g (1 tray)	PIR exp + M/S
12	PIR foam with aluminium embossed facing	Heptane	Base Case, ~200g (1 tray)	PIR facing + 1 hep
13	EPS	Heptane	Base Case, 200g (1 tray)	EPS + 1 hep
14		Methylated spirits	Reduced size, 120 (1 tray)	EPS + M/S

4.6 Results

This section presents data sumarising key results and data for all cavity characterisation (test rig characterisation) tests and cavity specimen tests (tests including insulation and sarking). All data and results are presented in tables below and include HRR data, temperature data, incident heat flux data, fuel source peak flame heights and post test damage measurements. Section 4.7 and Section 4.8 provides a detailed discussion on the interpretation of all results and data pertaining to cavity characterisation tests and cavity materials tests respectively. All graphs plots of HRR, temperature distribution and incident heat flux (radiant heat) for each test are provided under Appendix D

It is important to note that the mass loss rate (recorded by the Load Cell) and HRR recorded by O_2 was smoothed over a 10 second period to remove any 'noise' from recorded data. As the resolution of the oxygen calorimeter cannot adequately capture HRR of <10kW, noise was more apparent for smaller fires (such as the methylated spirits fuel tray fires). The presentation of results (shown under Section 4.6) and graphs plots (shown under Section 4.7 and Section 4.8) display the smoothed data. Both the raw (1 second interval) data and smoothed data are presented in graphs shown in Appendix D

4.6.1 HRR data, temperature distribution, incident heat flux data and flame heights recorded for Cavity Characterisation Tests

Table 18 below summarises all the measured HRR data. The occurrence of intermittent and/or sustained flaming emitted at top sides of rig was also recorded. Additional notes are provided below Table 18, further explaining select data values. The Load Cell was utilised for characterisation tests from Tests C1 to C7 (~65mm cavity width). For these tests, the peak HRR, time to peak HRR and average HRR was calculated using mass loss rate data obtained from the Load Cell. For comparison, the total HR measurements obtained from the Load Cell and Oxygen Analyser were compared to total HR calculated by using the empirical formula; *Total HR = heat of combustion (MJ/kg) of fuel source X mass of fuel burnt* (see Table 18 below). As predicted, total HRR obtained from Load Cell instantaneous fuel mass loss data was more accurate in predicting actual total HRR than the HRR data obtained from the Oxygen Analyser. The Load Cell was not used for tests C8 to C10 as these tests were performed after Cavity Material test series were being conducted. At this stage, the Load Cell had already been removed from the Test rig. The events of intermittent and/or sustained flaming emitted at top sides of the rig indicates severity of the fire source.

Table 18: Summary of HRR data - Cavity Characterisation Tests (C1 to C10)

Test No.	Fuel (type, amount)	Cavity arrangement	Method of HRR measurement	Amount of Fuel burnt (g)	Fuel burnout time (s)	Peak HRR (kW)	Time at Peak HRR (s)	Avg. HRR (kW)	Total HR - Load cell (MJ)	Total HR - O2 Analyser (MJ)	Total HR - calculated (MJ)	FIGRA (kW/s)	Intermittent flaming out top edges of rig?	Sustained Flaming out top edges of rig?
C1	Methyl. Spirits, 1 tray	Outside test rig - Open fire	Load cell	~60[b]	599	4.3	190	2.4	1.4	Not used	1.6	0.007	N/A	N/A
C2	Heptane, 1 tray	Outside test rig - Open fire	Load cell	~100[b]	505	15.8	532	9.4	4.7	1.3	4.7	0.031	N/A	N/A
C3	Methyl. Spirits, 1 tray	Within cavity ~65-70mm	Load cell	~120	522	6.8	181	3.7	3.0	2.1	3.2	0.038	No	No
C4[a]	Methyl. Spirits, 1 tray	Within cavity ~65-70mm	Load cell	~120	510	8	150	6.4	3.3	1.7	3.2	0.053	No	No
C5	Heptane, 1 tray	Within cavity ~65-70mm	Load cell	~200	481	25.6	362	18.3	8.8	6.8	8.9	0.071	No	No
C6	Heptane, 1 tray	Within cavity ~65-70mm	Load cell	~200	435	28.0	329	20.2	8.7	6.6	9.0	0.085	No	No
C7	Heptane, 2 tray	Within cavity ~65-70mm	Load cell	~200	426	61.9	197	40.9	17.4	14.2	17.7	0.314	Yes	No
C8	Methyl. Spirits, 1 tray	Within steel stud cavity (~130-135mm)	O_2 consumption analyser	~120	747[c]	5.9	294	3.3	Not used.	2.26	3.2	0.020	No	No
C9	Heptane, 1 tray	Within steel stud cavity (~130-135mm)	O_2 consumption analyser	~200	289	80.4	205	28.7	Not used.	8.3	9.0	0.392	No	No
C10	Heptane, 2 tray	Within steel stud cavity (~130-135mm)	O_2 consumption analyser	~200	243	199.5	195	97.1	Not used.	23.6	18.1	1.023	Yes	Yes[d]

Notes:

a - Test C4 was performed after the test C5. The pre-heated rig may have resulted in the slight increase in peak and average HRR for Test C4, in comparison to Test C3.

b –Test C1 and C2 (outside rig fuel burns) used half the amount of fuel (60g of methylated spirits and 100g of Heptane) in comparison to other characterisation tests. The burning rate approximately doubled when the same amount of fuel was burnt inside the cavity, therefore the amount of fuel burned was doubled to maintain a similar test duration (exposure period) of 8-10 minutes.

c – For Test C8, a persistent small single flame caused an extended burnout time to be recorded.

d – Test C10 experienced a relatively short period of sustained flaming (~5s).

e - In general, FIGRA is defined as the rate of fire growth to reach peak: $FIGRA\ (kW/s) = \frac{Peak\ HRR\ (kW)}{Time\ to\ reach\ Peak\ HRR\ (s)}$

Table 19 below presents the temperature distribution and incident heat flux (radiant heat) data for the cavity characterisation tests. The cavity rig centreline temperatures (T/C 2, 4, 6,8 and 9, 5 thermocouples in total) are presented in this table. Temperature graphs showing all 9 thermocouple readings is presented under Appendix D View Table 19 in conjunction with Figure 28 to determine location of thermocouples referenced in Table 19.

Table 19: Summary of Temperature and Radiant Heat data - Cavity Characterisation Tests (C1 to C10)

			Maximum Temperatures:					Time at Maximum Temperatures:					Average Incident Heat Fluxes:				Peak Incident Heat fluxes:				Time at Peak Incident Heat Fluxes:			
Test No.	Fuel (type, amount)	Cavity material/arrangement	At 2100mm - centre top T/C 2 (°C)	At 1650mm T/C 4 (°C)	At 1200mm, centre mid T/C 6 (°C)	At 750mm T/C 8 (°C)	At 450mm, centre bottom T/C 9 (°C)	For 2100mm (s)	For 1650mm (s)	For 1200mm (s)	For 750mm (s)	For 450mm (s)	At TOP (kW/m2)	At MID-HEIGHT (kW/m2)	At 305mm above burner (kW/m2)	At 152mm above burner (kW/m2)	At TOP (kW/m2)	At MID HEIGHT (kW/m2)	At 305mm above burner (kW/m2)	At 152mm above burner (kW/m2)	At Top(s)	At Mid-height (s)	At 305mm above burner(s)	At 152mm above burner(s)
C1	Methyl. Spirits, 1 tray	Outside Cavity	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C2	Heptane, 1 tray	Outside Cavity	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C3	Methyl. Spirits, 120g	Within cavity ~65mm	91.4	113.1	170.6	344.8	816.1	319	320	322	243	350	0 9	3.6	25.1	44.1	1.2	5.0	35.9	52.0	463	316	78	83
C4	Methyl. Spirits, 120g	Within cavity ~65mm	96.8	121.0	188.7	366.2	832.0	194	196	325	265	264	1.1	3.5	25.6	47.7	1.5	4.6	37.5	64.2	304	264	88	91
C5	Heptane, 200g	Within cavity ~65mm	268.1	424.5	622.1	851.7	882.1	382	363	363	359	462	3 2	16.4	54 5	57.6	5.9	30.8	68.0	67.4	363	356	446	458
C6	Heptane, 200g	Within cavity ~65mm	318.4	486.6	718.6	894.3	879.8	352	344	352	345	421	3.7	22.6	60.8	56.1	7.2	44.6	74.3	69.1	348	347	417	112
C7	Heptane, 400g	Within cavity ~65mm	625.7	810.7	878.3	935.3	846.8	201	279	327	339	245	10.8	46.0	51 5	46.7	23.3	77.6	64.0	66.3	201	334	313	171
C8	Methyl. Spirits, 120g	Within steel stud cavity (~130mm)	72.5	78.7	99.3	167.6	491.4	488	498	498	401	459	0.6	1.4	-	-	0.97	2.19	-	-	477	468	-	-
C9	Heptane, 200g	Within steel stud cavity (~130mm)	464.5	512.0	706.3	806.1	858.3	219	225	225	245	256	4 9	16.3	-	-	12.9	38.3	-	-	221	220	-	-
C10	Heptane, 400g	Within steel stud cavity (~130mm)	667.9	734.0	861.6	972.3	987.6	202	202	193	198	195	13.6	34.8	-	-	30.8	104.6	-	-	193	207	-	-

Notes: No incident heat flux measurements were recorded for cavity containing steel studs.

Figure 28: Instrumented Panel showing location of thermocouples and radiometers

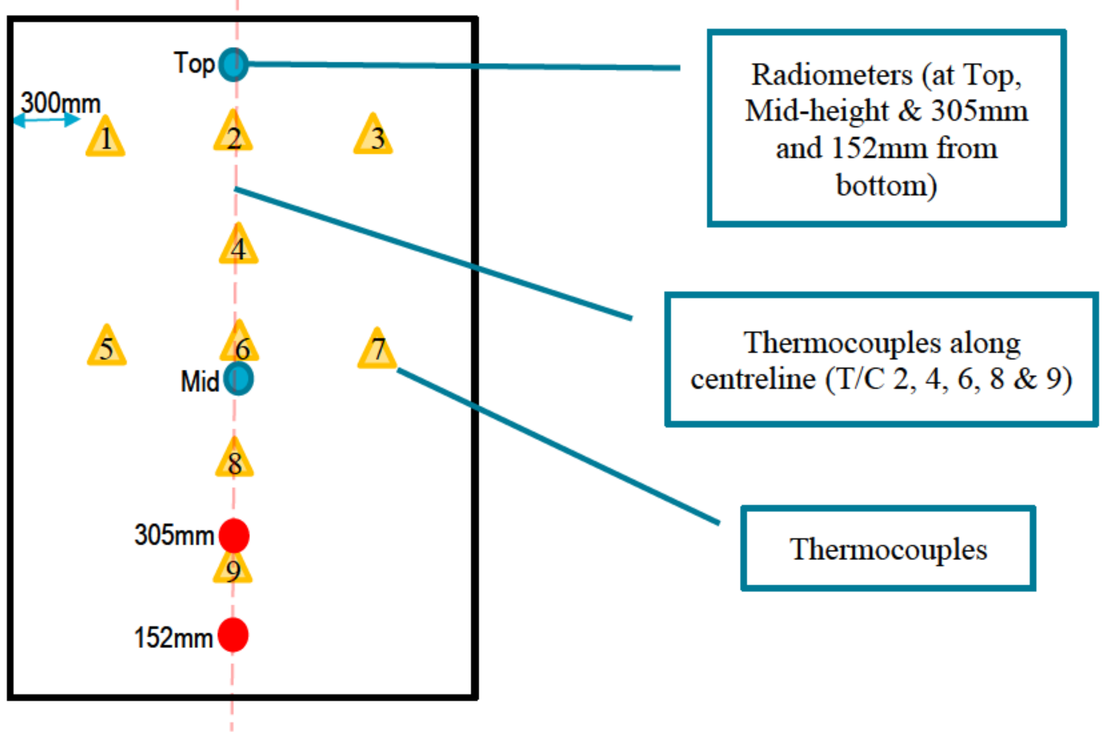
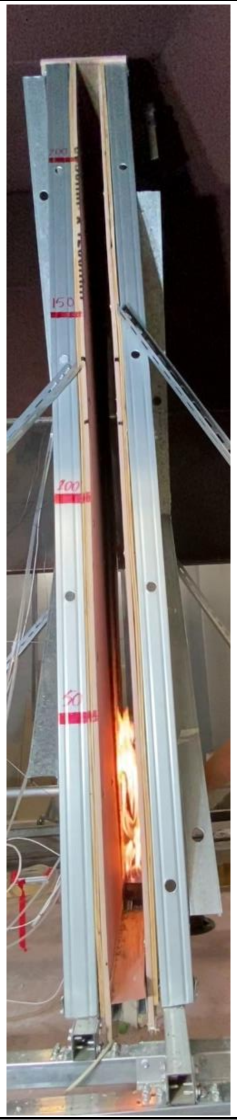
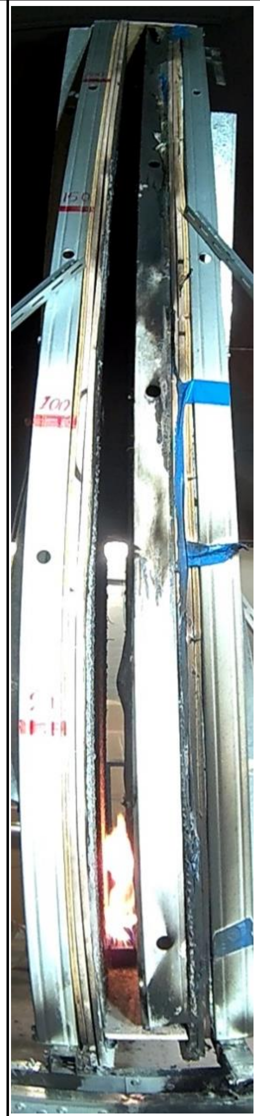
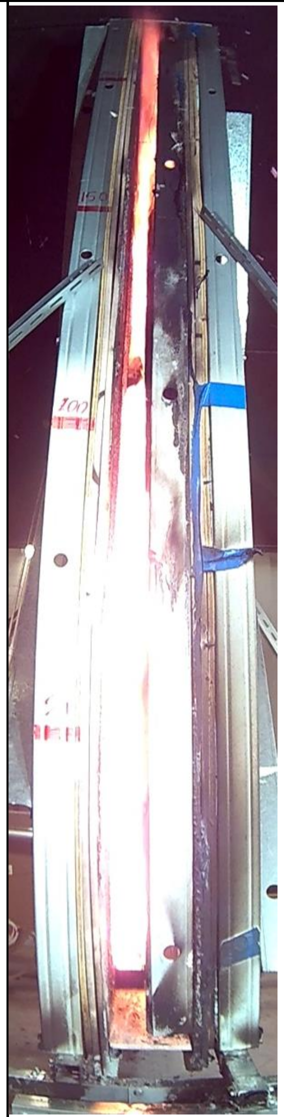


Table 20 (below) depicts the maximum flame height reached for Cavity Characterisation test, which corresponds to peak burning periods (during peak HRR). Test C1 and Test C2 were performed outside the rig. Visual inspection of the burning fuels reveals that the flame height approximately doubles within the cavity than when outside the cavity. The two tray heptane fires (tests C7 and C10) showed that the size of the fire alone was enough to produce flames that reached the top of the cavity during the peak burning period.

Table 20: Test video snapshot of flame heights during peak burning period - Cavity Characterisation Tests (C1 to C10)

Cal. test #	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Fuel, Tray, cavity arrangement	Methyl. Spirits, 1 tray, outside rig	Heptane, 1 tray, outside rig	Methyl. Spirits , 1 tray, inside rig	Methyl. Spirits , 1 tray, inside rig	Heptane , 1 tray, inside rig	Heptane , 1 tray, inside rig	Heptane , 2 tray, inside rig	Methyl. Spirits , 1 tray, inside cavity with steel studs	Heptane , 1 tray, inside cavity with steel studs	Heptane , 2 tray, inside cavity with steel studs
HRR method of measurement	Load cell	Load cell	Load cell	Load cell	Load cell	Load cell	Load cell	Oxygen Consumption Analyser	Oxygen Consumption Analyser	Oxygen Consumption Analyser
Flame at peak burn period										
Mean Flame Height during peak period (mm)	~200	~500	~500	~500	~1000	~1000	2400 (full height)	~250	~1500	2400 (full height)

4.6.2 HRR data, temperature distribution, radiant heat data recorded for Cavity Characterisation Tests

Table 21 shows HRR data for all cavity material tests performed. Both PIR and Phenolic foam insulations (the thermosetting materials) experienced a second peak in HRR. This occurred as the initial protective charred layer was penetrated by flames, to reveal the raw material underneath. The occurrence of intermittent and/or sustained flaming emitted at top sides of the rig indicates the potential for fire spread to occur beyond 2.4m height set by the rig.

Table 21: Summary of HRR data – Cavity materials Tests (Test 1 to 14)

Test No.	Cavity material/arrangement	Fuel type, amount	Test Duration (s)	End of test called at:	Fuel Burnout time (s)[a]	Peak HRR (kW)	Time at Peak HRR (s)	Avg. HRR (kW)	Total HR (MJ)	FIGRA (kW/s)	Intermittent flaming out top edges of rig?	Sustained Flaming out top edges of rig?
1	Sarking on steel stud frame	Heptane, 200g	243	Flame out	-	56.2	185	31.6	7.7	0.304	Nil	Nil
2	Sarking on steel stud frame	Heptane, 400g	255	Fuel out - but molten polypropylene still burning in tray.	-	153.8	194	81.3	20.7	0.793	Yes	Yes
3	Polyester batts within steel studs	Heptane, 200g	1050	Application of fire extinguisher on RHS of rig. Pool fire still burning under cavity test rig. Minimal burning within cavity.	-	252.0	184	56.4	61.3	1.370	Yes	Yes
4	Polyester batts within steel studs	Methy. Spirits, 120g	716	Flame out	386	10.1	245	2.0	0.92	0.041	No	No
5	Polyester batts within steel studs & sarking	Heptane, 200g	813	Application of fire extinguisher on RHS of rig. Pool fire still burning under cavity test rig. Minimal burning within cavity.	-	267.8	234	84.2	68.5	1.144	Yes	Yes
6	Phenolic - with facing	Heptane, 200g	419	Flame out, but smouldering combustion continuing on top half of cavity.	-	1st Peak 113.2 2nd Peak 130.5	1st Peak 71 2nd Peak 260	59.3	24.9	1st Peak 1.594 2nd Peak 0.502	Yes	Yes
7	Phenolic - with facing	Heptane, 400g	926	Flame out, but smouldering combustion continuing on top half of cavity.	-	1st Peak 125 2nd Peak 134	1st Peak 62 2nd Peak 430	59.6	55.2	1st Peak 2.016 2nd Peak 0.312	Yes	Yes
8	Phenolic - with facing	Methy. Spirits, 120g	554	Flame out	515	97.1	75	20.0	11.1	1.295	Yes	Yes
9	Phenolic - Exposed	Heptane, 200g	420	Flame out	342	109.8	337	50.8	21.2	0.326	Yes	Yes
10	PIR - Exposed	Heptane, 200g	724	Application of fire extinguisher on RHS of rig.	257	403.4	141	157.9	114.3	2.861	Yes	Yes
11	PIR - Exposed	Methy. Spirits, 120g	529	Flame out	433	1st Peak 26.5 2nd Peak 66.2	1st Peak 201 2nd Peak 394	17.5	9.2	1st Peak 0.132 2nd Peak 0.168	Yes	No
12	PIR - with facing	Heptane, 200g	802	Flame out	368	249.3	256	80.1	64.2	0.974	Yes	Yes
13	EPS	Heptane, 200g	752	Flame out on cavity wall - small flame of molten EPS persisting in tray.	478	700.1	131	57.3	43.0	5.344	Yes	Yes
14	EPS	Methy. Spirits, 120g	715	Flame out	-	17.4	348	9.3	6.6	0.050	No	No

Notes: a – Fuel Burnout Time was difficult to ascertain for some tests if molten material or debris collect in tray or view into cavity was made unclear due to smoke/fire.

Table 22 (below) details temperature and incident heat flux data for cavity material tests. Again, only cavity rig centreline temperatures (T/C 2, 4, 6,8 and 9 - 5 thermocouples in total) are presented in this table. View Table 22 in conjunction with Figure 28 to determine location of thermocouples referenced in Table 22. Temperature graphs showing all 9 thermocouple readings is presented under Appendix D For some materials, a second peak in cavity temperatures occurred. These peaks either occurred during periods of rapid flame spread (i.e. initial rapid surface spread produces excess smoke causing flame to retreat, thus creating a peak in temperature) or during peak burning periods.

Table 22: Summary of Temperature and incident heat flux data – Cavity material tests (Test 1 to 14)

Test No.	Fuel (type, amount)	Cavity material/arrangement	Max. Temp at 2100mm - centre top T/C 2 (°C)	Max. Temp at 1650mm T/C 4 (°C)	Max. temp at 1200mm, centre mid T/C 6 (°C)	Max. temp at 750mm T/C 8 (°C)	Max. temp at 450mm, centre bottom T/C 9 (°C)	Time at Max Temp for 2100mm (s)	Time at Max Temp for 1650mm (s)	Time at Max Temp for 1200mm (s)	Time at Max Temp for 750mm (s)	Time at Max Temp for 450mm (s)	Peak incident heat flux at TOP (kW/m²)	Peak incident heat flux at MID (kW/m²)	Time at Peak Incident Heat Flux - TOP(s)	Time at Peak Incident Heat Flux - MID(s)
1	Heptane, 200g	Sarking/ within steel stud cavity	1st Peak				535.8	1st Peak				108.0	1st Peak			
			294.5	308.4	342.9	384.9		122	112	100	111		8.1	8.0	52	89
			2nd Peak					2nd Peak					2nd Peak			
			340.6	318.2	260.7	436.4		207	213	214	219		10.8	9.2	208	210
2	Heptane, 400g	Sarking/ within steel stud cavity	549.5	568.1	674.7	822.9	920.0	181	181	180	173	179	28.4	61.4	183	183
3	Heptane, 200g	Polyester batts/within steel studs	671.2	859.8	867.1	978.7	1074.4	150	150	121	185	188	41.4	96.7	153	181
4	Methyl. Spirits, 120g	Polyester batts/within steel studs	128.3	188.8	266.1	1st Peak		223	193	189	1st Peak		0.6	9.5	303	208
						218.3	469.0				63	33				
						2nd Peak					2nd Peak					
						379.7	607.8				183	192				
5	Heptane, 200g	Polyester batts + sarking/ within steel studs	576.2	726.1	878.4	979.5	1077.8	235	228	111	204	208	24.7	67.3	229	183
6	Heptane, 200g	Phenolic with facing	1st Peak			963.2	897.3	1st Peak			290.0	298.0	1st Peak			
			610.3	489.9	587.5			64	60	54			25.3	28.9	66	53
			2nd Peak					2nd Peak					2nd Peak			
			893.3	868.3	906.9			258	265	262			112.7	120.3	252	294
7	Heptane, 400g	Phenolic with facing	1st Peak													
			990.4	22.1*	997.8	1011.3	932.0	402	1151	401	433	440	138.8	157.1	437	409
			2nd Peak													
			559.5	-	380.5	312.9	-	878	-	837	783	-	55.5	31.1	871	752
8	Methyl. Spirits, 120g	Phenolic with facing	524.7	418.7	396.2	434.3	694.1	70	62	56	309	351	13.8	12.8	68	56
9	Heptane, 200g	Phenolic - Exposed	960.2	937.8	919.4	985.0	900.4	326	323	327	333	339	152.4	134.9	323	327
10	Heptane, 200g	PIR - Exposed	1081.2	22.9*	1027.3	994.7	887.2	222	184	190	250	250	157.6	148.7	214	240
11	Methyl. Spirits, 120g	PIR - Exposed	1st Peak													
			176.3	258.3	358.6	540.8	842.4	170	169	174	164	201	3.1	17.1	164	164
			2nd Peak													
			550.5	692.4	764.7	747.9	886.2	434	433	432	419	433	17.1	65.1	434	417
12	Heptane, 200g	PIR with facing	1007.8	22.2	1005.3	950.9	974.9	517	198	293	297	335	131.0	132.9	261	292
13	Heptane, 200g	EPS	774.9	842.8	876.3	890.0	886.7	139	130	130	130	178	84.7	102.1	137	126
14	Methyl. Spirits, 120g	EPS	75.6	91.7	120.2	178.0	499.5	390	459	310	308	523	0.9	2.7	482	257

4.6.3 Post-test Damage

Table 23 and Table 24 below compares pre-test to post-test photos to show extent of flame, heat and/or smoke damage to cavity materials. A post damage report within the table gives post-test damage measurements a brief written account on the extent of damage. Refer to Section 4.5.2 provides a key to post-test measurements.

Table 23: Post-test damage to cavity material (Test 1 to 7)

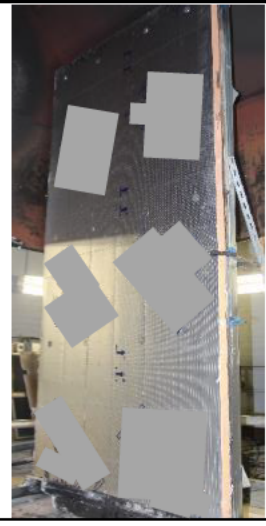
Test No.		1		2		3		4	5		6	7
Fuel (type, amount)		Heptane, 200g		Heptane, 400g		Heptane, 200g		Methyl. Spirits, 120g	Heptane, 200g		Heptane, 200g	Methyl. Spirits, 120g
Cavity material/arrangement		Sarking/ within steel stud cavity		Sarking/ within steel stud cavity		Polyester batts		Polyester batts	Polyester batts with Sarking		Phenolic foam with facing	Phenolic foam with facing
Pre -test Image				As per test 1				As per test 3				As per Test 6
Post-test image												
Post Damage Report	H-RHS	N/A	Flames and hot gases from fuel source mainly tore through sarking, causing some shrinkage to polypropylene along torn edges - however sarking did not support fire spread	N/A	Flames and hot gases from fuel source mainly tore through sarking. Small drops of burnt molten polypropylene were found within cavity base. Sarking was minimally involved in fire.	N/A	Most of Polyester was consumed in test (except for portion remaining on side at mid height, as per image). Remaining mass = 1.38kg (Total mass was 6.48kg)	2400mm (No damage)	N/A	All of Polyester and sarking either consumed in fire or melted away from cavity base, onto lab floor. No Polyester or sarking remained within cavity.	1800mm	2170mm
	H-LHS	N/A		N/A				2400mm (No damage)			1380mm	1950mm
	L-TOP	N/A		N/A				0mm (No damage)			1200mm (full length)	0mm (surface damage = 1200mm)
	L-MID	N/A		N/A				Minimal damage (surface melting only)			490mm	20mm (surface damage length = 500mm)
	L-BASE	N/A		N/A				410mm			360mm	270mm
	D-TOP	N/A		N/A		50mm (100%)		No damage			50mm (100%)	0mm (surface damage only)
	D-MID	N/A		N/A		50mm (100%)		No damage			50mm (100%)	1-2mm
	D-BASE	N/A		N/A		50mm (100%)		50mm (100%) – height of area = 530mmm.			35mm	25mm

Table 24: Post-test damage of cavity material (Tests 8 -14).

Test No.		8	9	10	11	12	13	14
Fuel (type, amount)		Heptane, 400g	Heptane, 200g	Heptane, 200g	Methyl. Spirits, 120g	Heptane, 200g	Heptane, 200g	Methyl. Spirits, 120g
Cavity material/arrangement		Phenolic foam with facing	Exposed Phenolic foam	Exposed PIR	Exposed PIR	PIR with facing	EPS	EPS
Pre -test Image		As per Test 6						As per test 13
Post-test image								
Post Damage Report	H-RHS	1200mm (1/2 height)	2080mm	1200mm	2400mm (no damage)	1970mm	2000mm (avg. width remaining = 15mm)	2400mm (No damage)
	H-LHS	900mm	1960mm	1200mm	2400mm (no damage)	2000mm	As above.	2400mm (No damage)
	L-TOP	1200mm (700mm, 50mm charred (100%))	1000mm	1200mm (full length)	0mm (surface discolouration only)	1200mm	1200mm	0mm (No damage)
	L-MID	580mm	650mm	1200mm (full length)	400mm	350mm	~950mm	0mm (No damage)
	L-BASE	450mm	450mm	500mm	470mm	200mm	~950mm	300mm (height =400mm)
	D-TOP	50mm (100%)	50mm (100%)	50mm (100%)	0mm (surface discolouration only)	50mm (100%)	50mm (100%)	0mm (No damage)
	D-MID	50mm (100%)	35mm	50mm (100%)	10mm	50mm (100%)	50mm (100%)	0mm (No damage)
	D-BASE	~30-45mm (from bottom to height of 400mm)	~25mm	50mm (100%)	30mm	~45mm (from bottom to height of 120mm)	50mm (100%)	50mm (100%)

4.7 Discussion of Test Rig Characterisation

This section discusses the performance of the cavity fire test method and rig designed for this experimental study, any unique observations that may have the potential to weigh upon test outcomes.

Figure 29 depicts location of all thermocouples (measuring cavity width air temperatures) and radiometers installed onto the instrumented panel. The instrumented panel faces test panel that houses the insulation and/or sarking. This figure is provided as an aid for discussions covered under this section (Section 4.7) and Section 4.8.

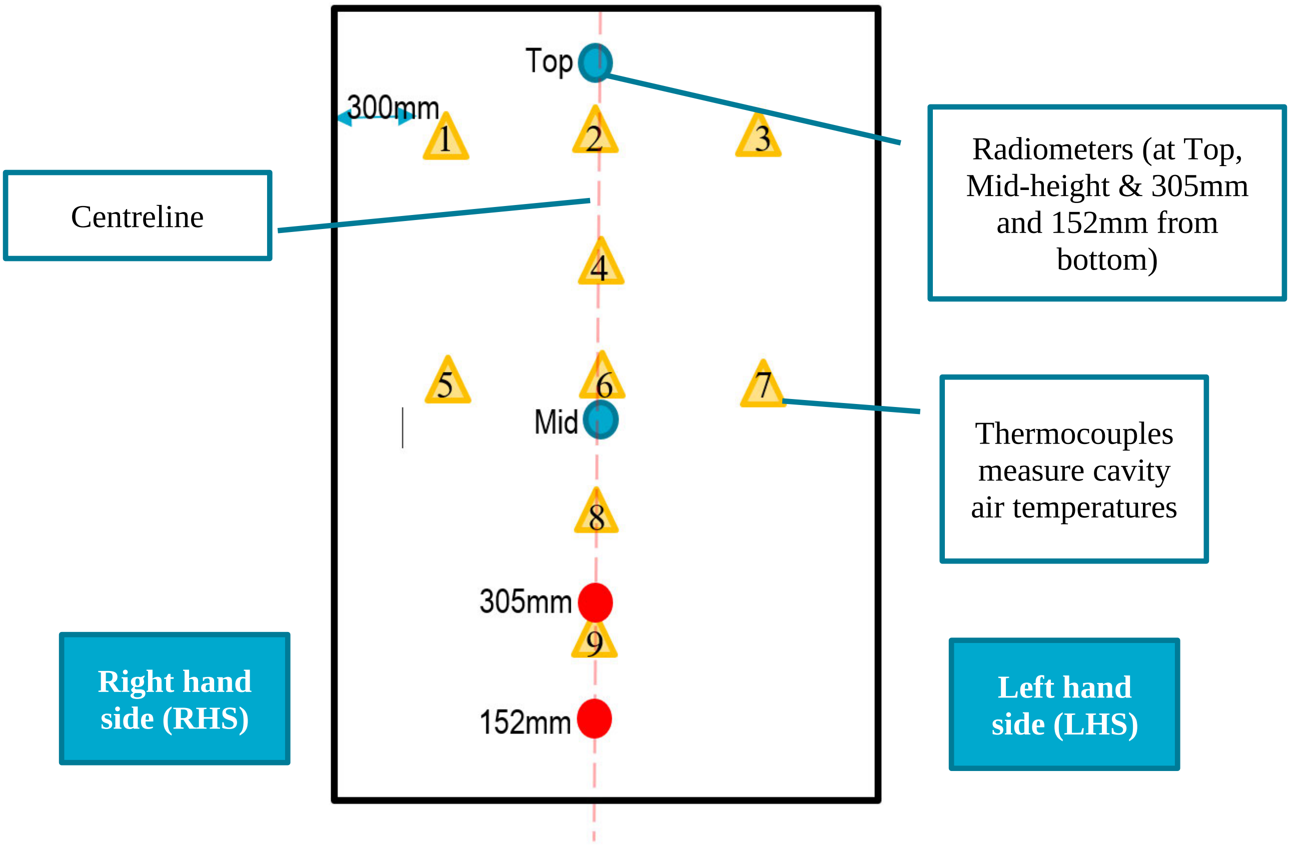


Figure 29: Instrumented Panel showing location of thermocouples and radiometers

4.7.1 Tilt of fuel tray flame

It was evident during the Characterisation Test the ignition source did not burn symmetrically, with an obvious tilt to the RHS of the rig. Temperature plots of each test show that thermocouple T/C 5, located on the RHS of the rig, was greater than the LHS thermocouple (T/C 7), indicating greater air entrainment occurring from the LHS. Refer to Temperature Graphs for Characterisation and Insulation Cavity Tests under Appendix D .

The test rig had to share the floor with other permanently fixed test equipment (such as the bushfire radiant heat panel) and therefore could not be placed in a centralised under the exhaust and the room of the lab. This unsymmetrical air entrainment is mainly due to the non-centralised position, causing greater air entrainment to occur on the LHS of rig.

This tilt in the initial flame height did not however affect the overall burning behaviour of the tests involving insulation within the cavity. The larger fire size and subsequent increase velocity of the fire plume created in the cavity from these tests, were able to override any disbalance in air entrainment. Post-test images of non-characterisation tests – do not show an unsymmetrical burn pattern (see Table 23 and Table 24). Figure 30 below compares the flame tilt of Test C5 characterisation test with a post-test damage shown on combustible insulation using a smaller fire, M/S (Test 14) and larger fire, 1 tray heptane (Test 9).

Calibration Test – Test C5 - Heptane fire (no combustibles in cavity)	**Test 9 – Exposed PF with 1 tray heptane**	**Test 14 – EPS with methylated spirits**
		
Unsymmetrical burn pattern of test clearly shows tilt in in flame.	Flame spread to top of rig. Post-damage indicates that possible tilt in flame did not effect burning pattern.	Flames did not progress past impingment zone. No tilt visible for post-damage observations.

Figure 30: Comparison of post-test damage of Calibration Test - C5 to select tests, Test 9 and Test 14, showing that air entrainment imbalance did not affect burn patterns.

4.7.2 Influence of cavity boundary conditions on ignition source HRR

The Cavity Characterisation tests performed (without combustible materials in cavity) for different ignition sizes revealed burning behaviour inherent to the boundary conditions created within the Cavity Test rig used for this experimental study.

Figure 35 and Figure 36 (shown below) collectively shows the HRR for Cavity Characterisation tests C1 to C10. Figure 35 plots Cavity Characterisation tests performed with methylated spirits and 1 heptane tray fires. Figure 36 plots Cavity Characterisation tests performed with 2 heptane trays. Both Figure 35 and Figure 36 are to be viewed in conjunction.

Please note that the measured mass of fuel for tests performed outside the rig, Test C1 (methylated spirits) and Test C2 (heptane), was 60g and 100g respectively. The mass of fuel utilised for tests performed inside the rig (Test C3 to C10) was doubled (to extent the burning period of the fuel) i.e. 120g of methylated spirits and 200g of heptane.

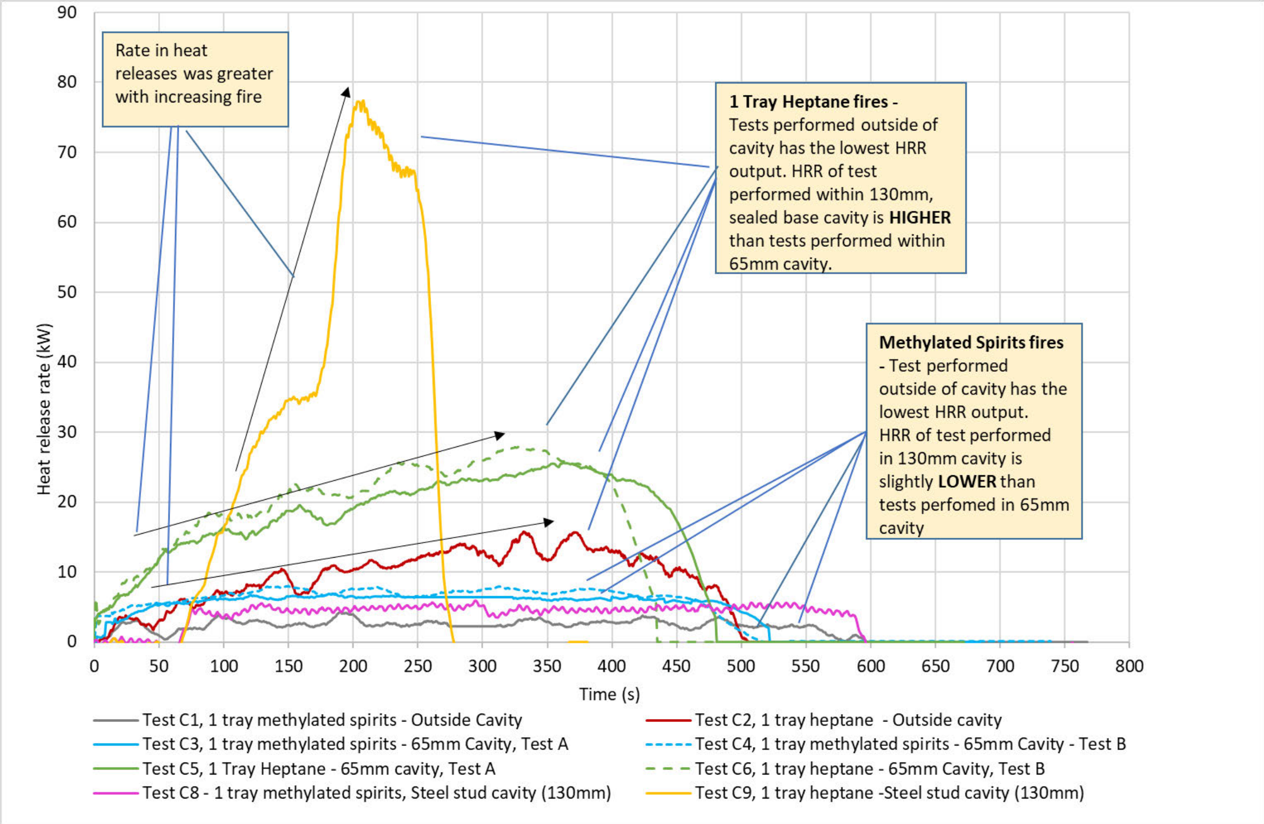


Figure 31: Comparison of HRR between 1 tray Heptane and Methylated spirits cavity characterisation tests performed outside cavity, inside 65mm cavity (with air gap within cavity base) and 130mm cavity (with sealed cavity base)

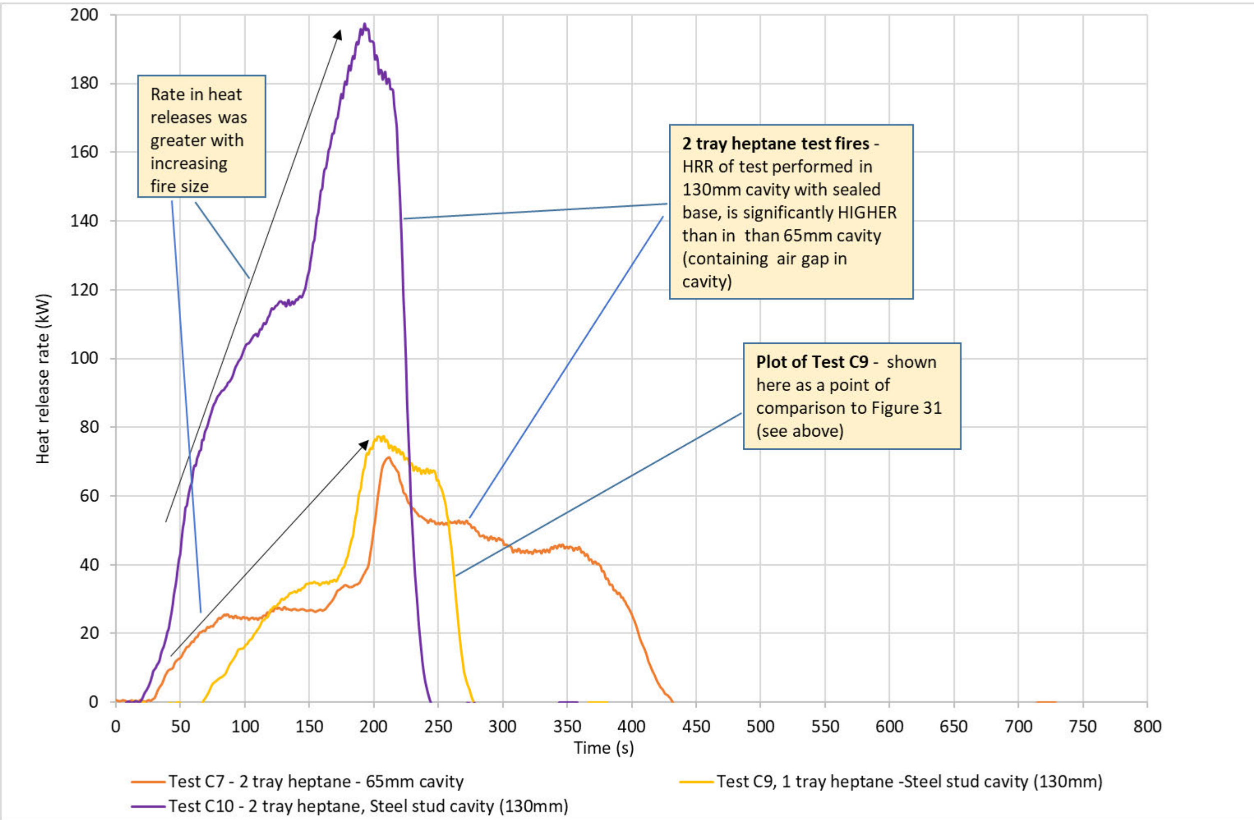


Figure 32: Two tray heptane fire cavity characterisation tests performed inside 65mm cavity (with air gap within cavity base) and 130mm cavity (with sealed cavity base). No two-tray heptane fire was performed outside the cavity

Effect of Cavity Base and Instrumentation on the Characterisation of HRR

The cavity characterisation tests C3 to C7 were performed using the Load Cell. The Load Cell was adopted due to the limitations of the Oxygen Analyser to record HRR <10kW. An opening at the centre, base of the cavity was created accommodate for the Load Cell. Steel studs cut to size were placed on either side of the Load cell to seal the remaining sides of the cavity base (see Figure 33). These tests were conducted within a cavity width of 65mm.

Cavity Characterisation tests C8 to C10 were conducted in a larger, 130mm cavity with a sealed cavity base. The load cell was removed for these experiments and the Oxygen Analyser was used to measure HRR. A piece of fire resistant (FR) plasterboard was cut to size and installed to seal the base (see Figure 33). The larger 130mm cavity was created to accommodate for the steel studs installed.

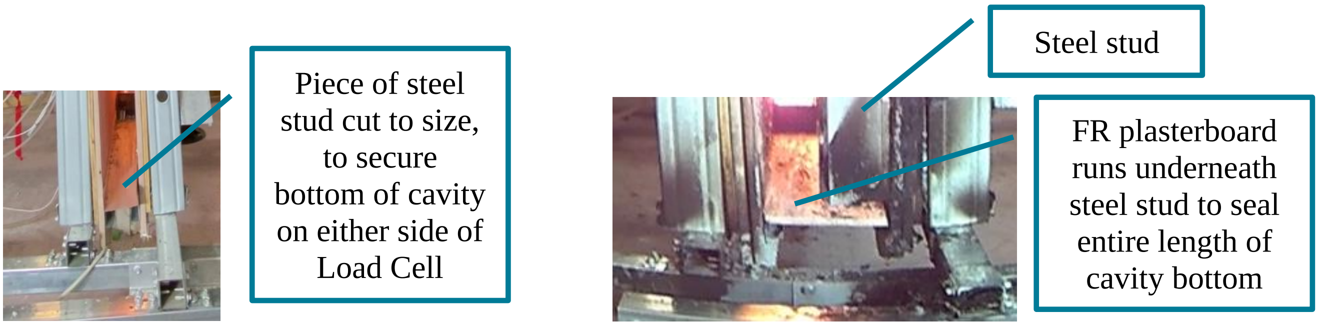


Figure 33: Left - ~65mm Cavity Characterisation test with steel studs at cavity base, Right: FR plasterboard sealing cavity base for larger ~130mm cavity

For the larger 1- and 2-tray heptane fires, it is clear that the closed base of the 130mm cavity was effective in insulating the fire, causing a greater increase in HRR than those tests performed in smaller, 65mm cavity with a partially open cavity base. The air gap created for the Load Cell in the smaller 65mm cavity would have allowed for cool air to flow and cool the tray, while the steel studs used to seal either side of load cell would have been effective in removing radiant heat from the fuel fire via conduction.

The smaller, one tray methylated spirits fire measured a lower HRR for the closed base, 130mm steel cavity. The Oxygen analyser was used to record the HRR for and therefore most likely underestimated the HRR due to the limitation of the oxygen analyser in capturing the HRR of fires <10kW. It is possible that the burn rate of the methylated spirits fire was more sensitive to the reduction in incident heat flux between vertical surfaces caused by the increase cavity width (from ~65mm to ~130mm), however more tests will need to be conducted to confirm this.

Thus, the following HRR measurements will be used to characterise the following ignition sizes:

- One tray, ~6-8 kW methylated spirits fire (measured using Load Cell)
- One tray, ~80kW heptane fire (measured from Oxygen Analyser)
- Two trays, ~200kW heptane fire (measured from Oxygen Analyser)

In summary, the Load Cell measurement are relied upon to characterise methylated spirits tray fires, however air gaps surrounding the tray impacted tray temperature and thus the HRR of the burning fuel. One and two tray heptane fires achieved peak HRR well within measurement range of oxygen calorimeter. Therefore, HRR measurements from the Oxygen Analyser will be used to characterise heptane tray fires used in the combustible material experiments.

Effect of metal fuel tray boundary conditions on HRR

The fuel tray is made of thin steel sheet and can readily conduct heat. For the larger fuel source fires (1 tray and 2 tray heptane fires), the heat generated from the burning fuel was conducted to the metal fuel tray holding the fuel, which in turn subsequently increased the burn rate of the fuel over the test period (see Figure 31and Figure 32) This phenomenon occurred regardless of whether the fuel tray was within or outside the cavity. The smaller, methylated spirits fire experienced a relatively even gradient burn suggesting that amount of conducted to heat to the fuel tray is not as significant to affect an increase in burn rate.

4.7.3 Severity (exposure conditions) of Ignition sources

Three severities of ignition sources were chosen:

- Reduced scale - 1 tray methylated spirits with peak HRR of ~30kW (Test C8)
- Base scale - 1 tray heptane with peak HRR of ~80kW (Test C9)
- Sensitivity scale - 2 tray heptane with peak HRR of 200kW (Test C10).

Figure 34 below graphically compares and depicts the range in exposure conditions in terms of radiant heat within the middle and top of the cavity of the above three ignition sources. Peak flame heights of the above three ignition sources are also stated (also shown in Table 20).

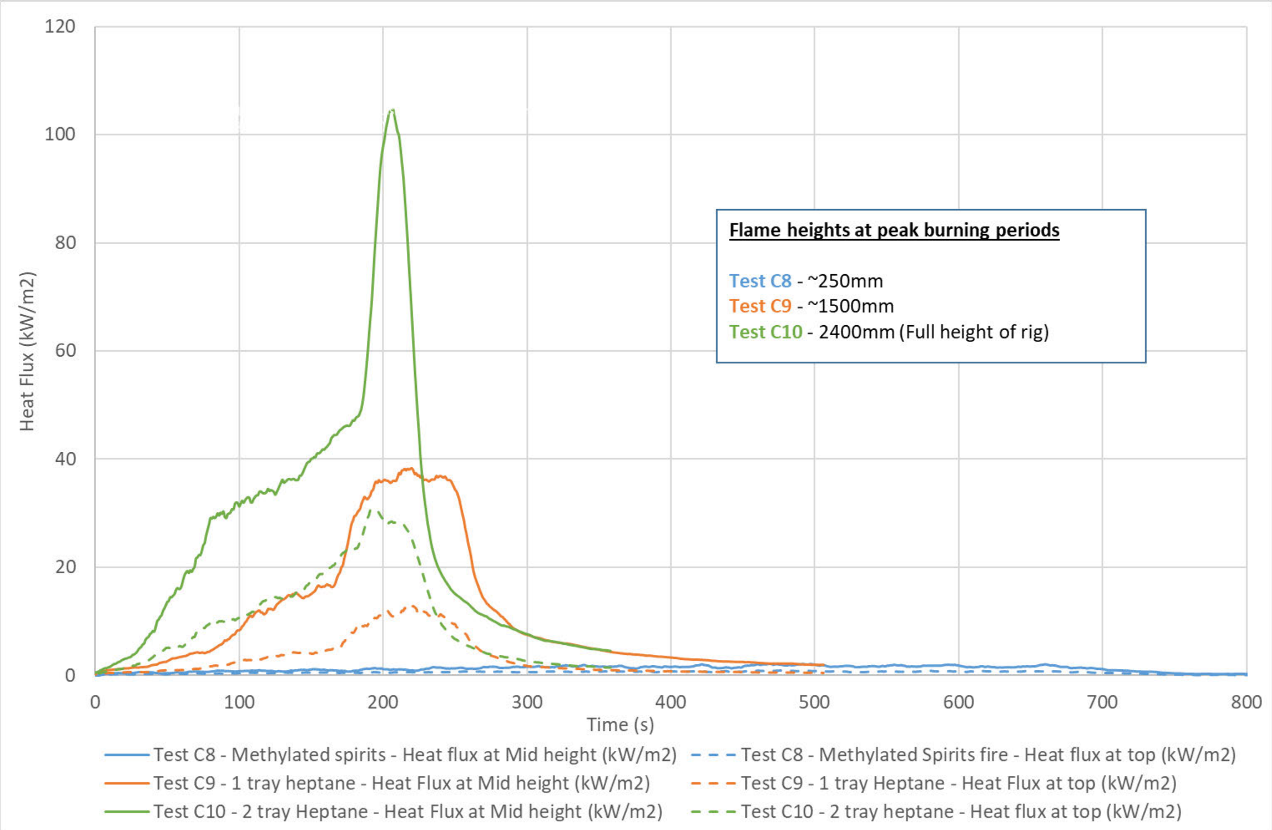


Figure 34: Exposure conditions between the ignition source sizes in terms of incident radiant heat flux at mid-height and top of cavity. Flame heights at peak burning period for each ignition source is also stated.

The maximum radiant heat for the mid height and top of cavity using a reduced scale fire source was 2.19kW/m^2 and 0.97 kW/m^2 respectively. The fire size and exposure conditions of the methylated spirits ignition source is similar to the one adopted for the FM Global Cavity Fire Test (see Section 4.7.4for more detail). For the combustible materials tested in this study, the methylated spirits tray ignition source did not promote fire spread for most materials (except for paper facing on phenolic board and some limited spread on PIR). However, the fire size and exposure conditions created by the one tray heptane fire tests was enough to induce fire spread for all the combustible materials, except sarking.

It is clear that the flame height and exposure conditions (>100kW/m^2) of two-tray heptane fire represents a significant step up from the one-tray heptane fire source and thus proved to be a too severe of a size to be utilised as an ignition source.

4.7.4 Comparison of ignition source Exposure Conditions against FM Global Cavity Fire Test

For the FM Global Cavity Fire Test [49] (see Section 3.3.3). datapoints of the controlled gas burner heat output (chemical HRR) to corresponding measured incident heat flux (to panels) were obtained for specified heights of 152mm and 305mm. Trendline between these datapoints were drawn to estimate the resulting heat flux to panels from any given Chemical HRR (see Figure 35**Error! Reference source not found.**). Cavity widths of 51mm and 102mm were examined for the FM Global Cavity Test method.

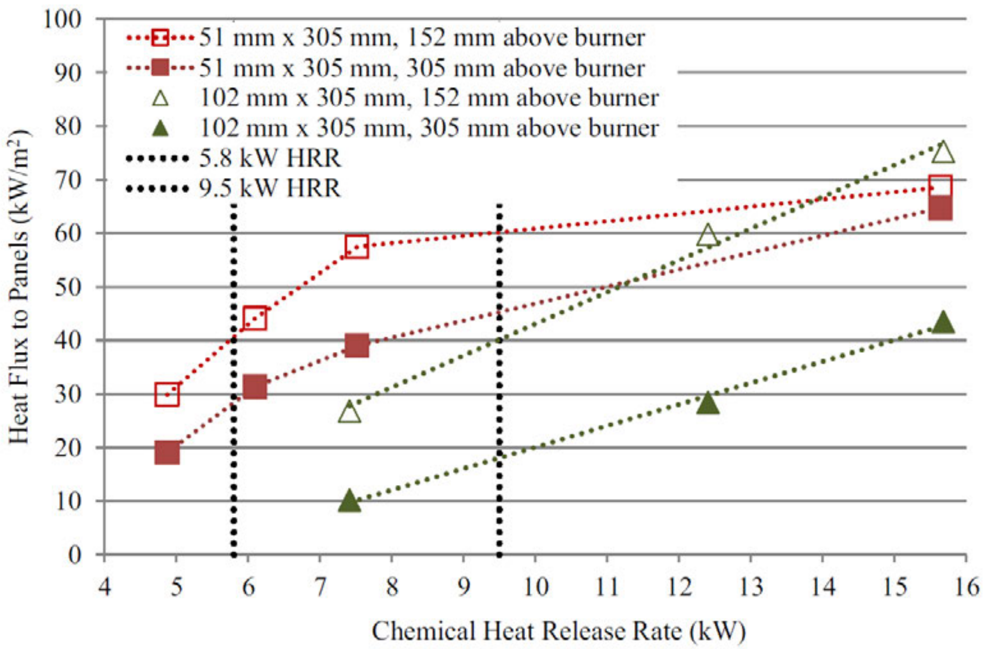


Figure 35: Incident Heat flux measurements depending on set cavity width or gas burner set HRR (Chemical HRR)

A chemical HRR that would deliver similar thermal shock (incident heat flux) to the two different cavity widths was desirable. Through this plot, it was found that a target HRR of 5.8kW and 9.5kW would deliver a uniform heat flux of 40kW/m^2, 152mm above the burner, for the 51mm and 102mm cavity widths respectively.

These exposure conditions were compared to incident heat fluxes recorded for the three fire ignition sizes utilised for this experimental study: reduced scale (1 tray methylated spirits), base scale (1 tray heptane) and severity scale (2 tray heptane) – see Table 25 and Table **26** below. Please note, that the corresponding incident heat fluxes 305mm above burner for both cavity widths were extrapolated from the graph plot of Figure 35.

Table 25: Incident Heat fluxes (kW/m^2) at 152mm above burner

152mm above burner				
FM Global		Experiment (Cavity Width of 65-70mm)		
51mm cavity width	102mm cavity width	Methyl. Spirits (1 tray)	Heptane (1 tray)	Heptane (2 trays)
40	40	45.9	56.9	66.3

Table 26: Incident Heat fluxes (kW/m^2) at 305mm above burner

305mm above burner				
FM Global		Experiment (Cavity Width of 65-70mm)		
51mm cavity width	102mm cavity width	Methyl. Spirits (1 tray)	Heptane (1 tray)	Heptane (2 trays)
30	20	25.3	57.6	64.0

Based on Table 25 and Table **26** above, the exposure conditions produced by the reduced scale (1 tray methylated spirits) is similar with the FM Global Cavity test, however the heptane tray fires result in severer exposure conditions.

Cavity characterisation tests with sealed cavity base (~130mm) did not measure at heights of 152mm and 305mm. Therefore, no comparison of these tests has been made with the FM Global Cavity Test.

FM Global conducted eleven (11) demonstrative tests using rigid extruded polystyrene foam and sprayed polyurethane foam when developing their Cavity Fire Test (detailed within Literature Review, see Section 3.3.3). For all six tests conducted with Rigid XPS (extruded polystyrene), fire spread up the full height (2.4m) of the rig. However, Test 14 - EPS with a M/S fuel source, did not cause any fire spread despite having similar exposure conditions to the FM Global test. Instead, the M/S ignition source caused the EPS to shrink and melt away from the flames. This suggests that the EPS supplied for this experimental study most likely contained Hexabromocyclododecane (HBCD), a common fire retardant found in EPS insulation boards (see ‘Fire Retardant Expanded/Extruded Polystyrene’ under Section 2.1.2 for more information on HBCD). HBCD reacts with oxidised gases of EPS, causing the surface of the EPS to shrink and contract away from the flame. This occurs for relatively smaller ignition sources such as Methylated spirits fuel fire, however for larger ignition sources and continuous flame impingement can overcome the fire retardancy offered by HBCD and cause fire spread. This reaction to fire behaviour of EPS was evident from the visual inspection of Test 13 (EPS + 1 hep) and Test 14 (EPS + M/S). The ignition source used for Test 14 (EPS + M/S), induced melting of localised impingement area, however the larger ignition source used for Test 13 (EPS +1 hep), applied severer heat fluxes to the area of flame impingement that was enough to overcome the fire retardancy of HBCD.

4.8 Discussion of Tested Specimen

This section discusses the events and associated test measurements in detail. Please refer to Appendix D for all graph plots for each test.

4.8.1 Sarking (Tests 1 & 2)

Both the one tray and two tray heptane fire applied to sarking did not promote any ignition or fire spread on the sarking. The sarking tore and melted away at the edges from flames, without any significant burning.

Table 27 and Table 28 show the flame progression of Test 1 (sark + 1 hep) and Test 2 (sark + 2 hep) respectively.

Shortly after ignition, the flames tore the sarking up the centreline for both Test 1 (sark +1 hep) and Test 2 (Sark +2 Hep). As the flames tore the sarking, white smoke is seen emitting at the torn edges, indicating the involvement of the blue, polypropylene layer of the sarking. The centreline flame of the ignition source split the sarking into two sections (with no indication of any lateral spread). For Test 1 (sark +1 hep), the hot gases of the fire pushed the sarking 'flaps' (created by the centreline tear) towards the RHS, sealing the side of the cavity. This did not occur for Test 2 (Sark +2 Hep), however the torn edges of sarking for Test 2 were more shrivelled due to the plastic propylene melting and deforming when in contact with flames of a larger heat source. At the test's conclusion, molten polypropylene droplets were sparsely spread on the bottom of the cavity, including some found in fuel tray.

Table 27: Test 1 – Flame progression on sarking – 1 tray of heptane

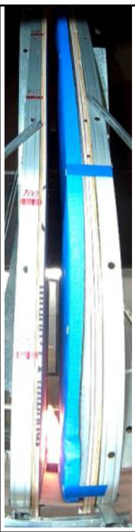
Images of Fire Progression					
Test time	t = ~0 mins	t = 1 min	t = 1 mins 21s	t = 3 mins	t = 4 mins
Comments	Ignition flame height at ~250mm	Flames and hot gases have teared open sarking.	Flames and hot gases push sarking (flap created from tear) to close off cavity at RHS.	Period of Peak HRR. Flames and hot gases tear through top edge of cavity.	Flame has extinguised. Cavity still remains relatively sealed.

Table 28: Test 2 – Flame progression on sarking – 2 trays of heptane

Images of Fire Progression				
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 4 mins
Comments	Ignition flame height at ~250mm	Flames and hot gases tear open sarking. Flame height is ~1000mm.	During Peak HRR period - Flames reach top of cavity.	Final stages of fire. Single drops of molten polypropylene are found in tray. Drops are also found in floor of cavity.

Figure 36 compares the HRR (kW) of Test 1 (sark +1 hep) and Test 2 (Sark +2 Hep) with Characterisation Tests within steel stud cavity, Test C9 (C test - Steel Stud + 1 hep) and Test C10 (C test - Steel Stud + 2 Hep).

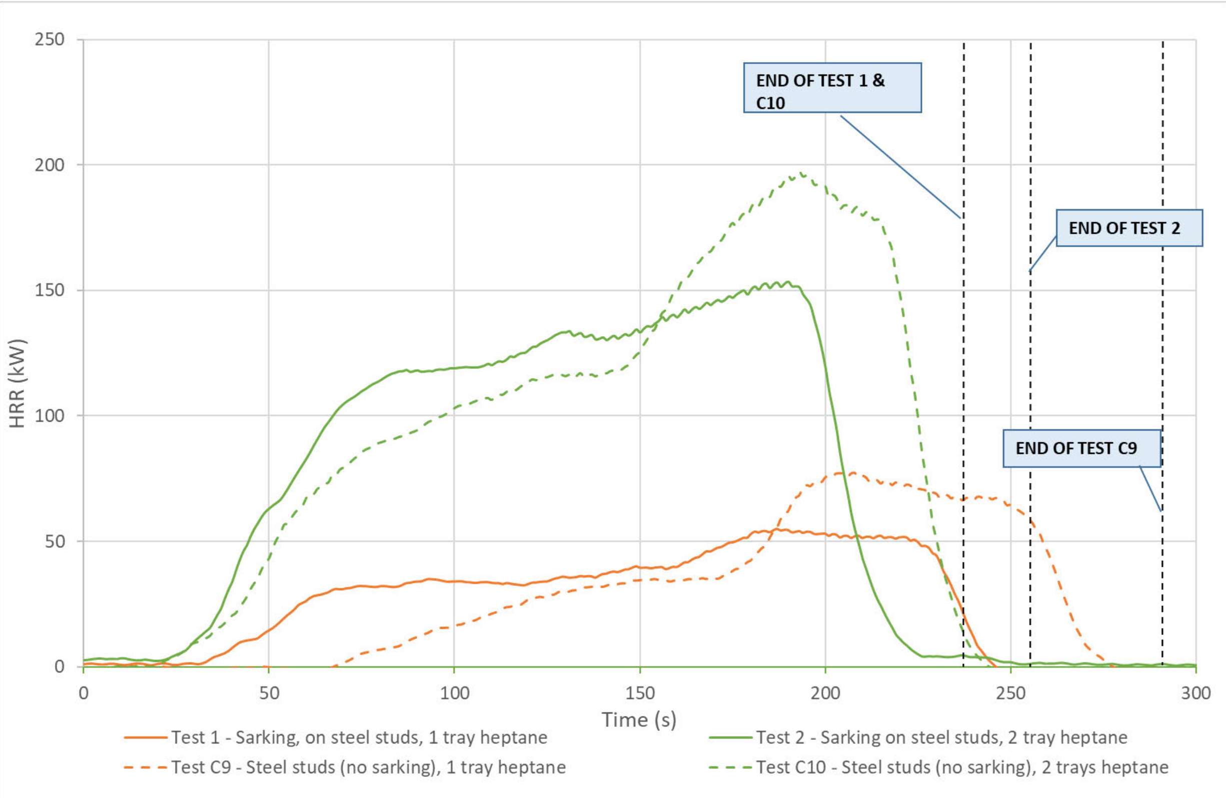


Figure 36: HRR - Sarking tests (Test 1 & 2) compared with characteristic burning of empty steel stud cavity

During the initial and middle stages of each test, the increase in HRR is greater for sarking tests compared to the characterisation tests. The installation of sarking reduces the steel stud cavity from ~130mm to a width of ~65mm – creating greater radiant heat feedback between the vertical surface. Furthermore, the sarking material itself is effective in insulating the flame, heating up the fuel tray, causing the fuel to burn faster. The localised burning of the polypropylene at the splitting edge of the sarking may have also contributed to the increase in HRR (in comparison to the characterisation tests), however this would have contributed minimally.

For the Characterisation tests, a steady increase in HRR gives way to a pronounced increase at ~175s for Test C9 (Steel Stud + 1 hep) and at ~150s for Test C10 (Steel Stud + 2 Hep), see Figure 36. The culmination of the fuel tray reaching a certain temperature and the reduced (remaining) volume of fuel, caused an increase in the burning rate. This pronounced increase exceeded the peak HRR reached by the sarking tests.

Figure 37 depicts the temperature distribution within the cavity for Test 1 (sark + 1 hep). The effective seal created by the sarking 'flap' to the RHS of cavity caused a surge in temperature (as evidenced by temperature readings for T/C 1 and T/C5, located on mid and top RHS of the rig). The trapped heat from rising gases from heptane fires and lack of air entrainment from sides of cavity caused the surge in temperature. At the same time, centreline temperatures T/C 2, 4, 6 and 8 experienced a dip in temperatures as flame heights were reduced (due to lack of air supply).

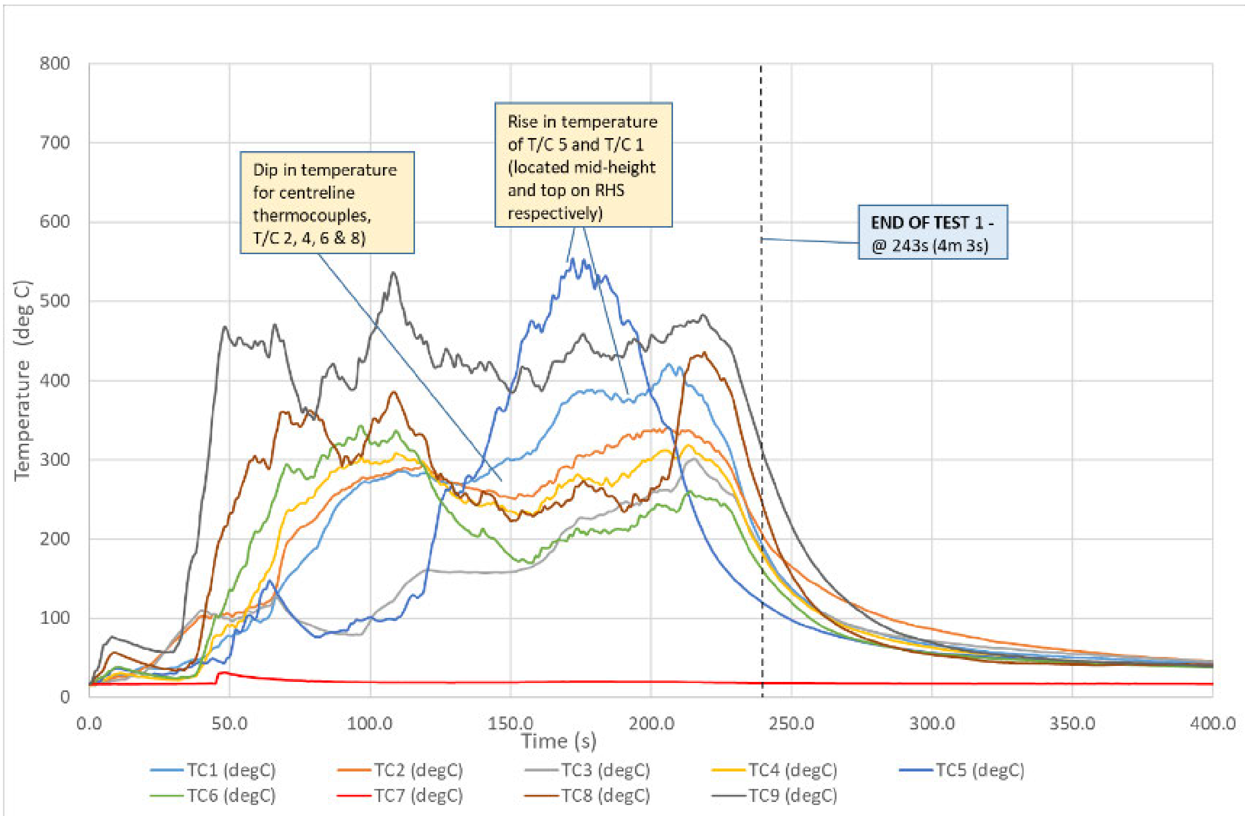


Figure 37: Test 1 (sark + 1 hep) temperature distribution within cavity (Note - T/C 7 dislodged from rig)

During this period, overall radiant heat at the centre mid-height and top also dipped (see Table 38). Apart from Test 1 (sark + 1 hep), the increase and decrease in temperature and radiant heat readings followed the general HRR curve (refer to for all graph plots for sarking test series)

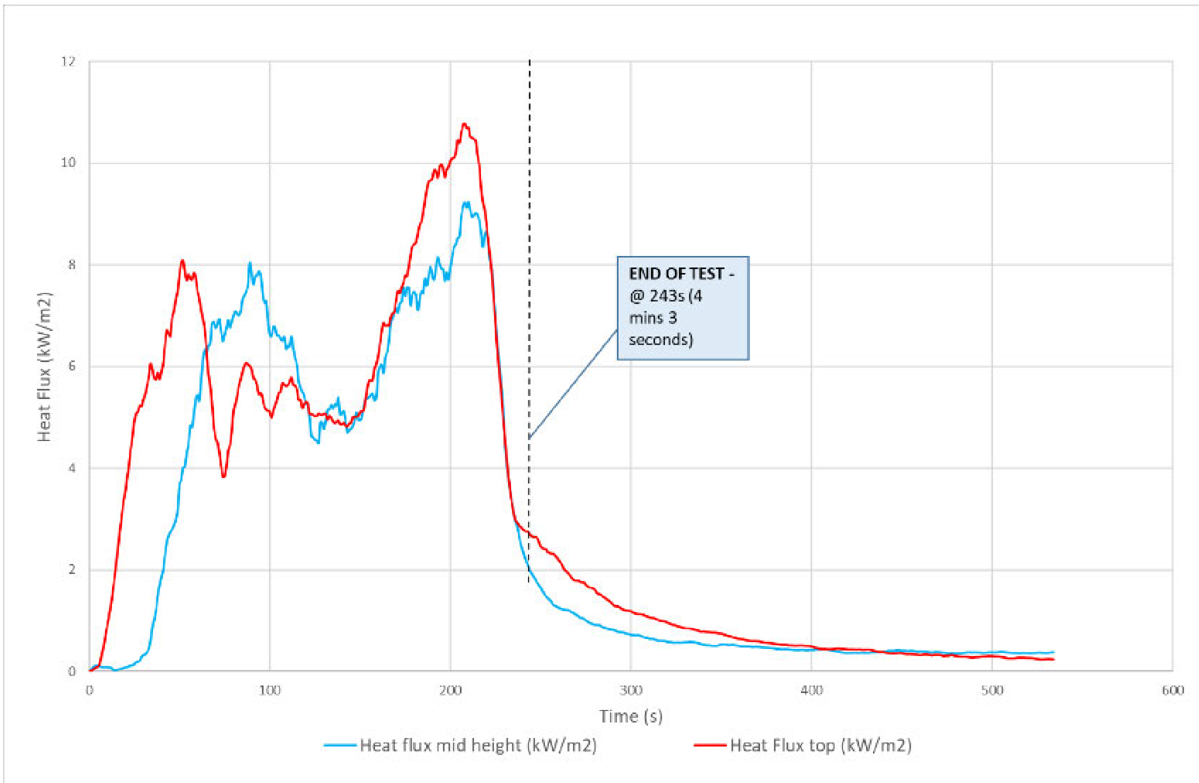


Figure 38: Test 1 radiant heat data (kW/m^2)

The post-test damage for both Test 1 (sark + 1 hep) and Test 2 (sark + 2 hep) show the split in sarking created by the ignition source flame and the shrivelling of the split edge (as the polypropylene melted away from the split edge). A greater split was created for Test 2 due to the larger ignition source (see Test 1 and 2 under Section 4.6.3 – Post Test Damage).

4.8.2 Polyester Batts – PB (Tests 3, 4 &5)

The one tray heptane fire resulted in ignition, fire spread, formation of a pool fire and complete consumption of the polyester batts. Retesting the one tray heptane fire on polyester batts combined with sarking did not significantly change this result. The sarking did not significantly contribute to the cavity fire. Instead, the sarking may have marginally delayed fire spread by providing some temporary protection to polyester batts located within adjacent stud spacings.

The one tray Methylated spirits fire caused the PB to melt and shrink away the ignition source flame. No ignition or flame spread was established on the surface of the material or within the small molten pool formed at the base of the cavity.

Table 29 and Table 30 describe the flame progression of Test 3 (PB + 1 hep) and Test 5 (PB + sark + 1 hep) respectively. The tests involving a single heptane tray ignition source (Test 3 and 5) produced molten polyester that flowed down to the base of the cavity and laboratory floor (beneath the rig)., creating secondary pool fires.

For Test 3 (PB + 1 hep) – the heat during initial stages of the heptane fire melted the surface layer of the polyester, causing long drips of molten polyester to flow. The hot gases from the flames melted polyester beyond the flame impingement zone. The increase flow of molten polyester to towards the ignition source allowed for the fire to propagate up the surface. Just prior to reaching peak HRR, the fire had spread to the top (2400mm) of the cavity, with large ‘balls’ of molten polyester flowing down on either side of the centre vertical fire zone, rapidly collecting at the cavity floor, and developing into pool fire.

Table 29: Test 3 – Fire progression on polyester batts – 1 tray of heptane

Images of Fire Progression							
Test time	t = ~0 mins	t = 1 min	t = 2 mins	t = 3 mins	t = 5 mins	t = 8 mins	t = 16 mins
Comments	Ignition flame height at ~250mm	Flames start melting surface of polyester. Flame height ~250mm.	Molten Polyester is rolling down either side of fire ('black dots' seen in image), accumulating on cavity floor, creating a pool fire.	During Peak HRR period. Heavy, dark smoke and flames being emitted at top edge of rig.	Cavity walls are bare as most of polyester is now contributing to pool fire on cavity floor. Molten polyester has flowed onto lab floor causing secondary pool fire near rig (seen in bottom LHS of image).	Majority of burning in cavity. Pool fire on lab floor manually extinguished (with F/R PB) to protect test rig from potential damage.	Flaming continuing in cavity at same similar intensity. End of test is called and fire extinguisher is applied to flames to prevent further damage to test rig.

Table 30: Test 5 – Fire progression on polyester batts with sarking – 1 tray of heptane

Images of Fire Progression							
Test time	t = ~0 mins	t = 1 min	t = 1 min 45s	t = 3 mins	t = 4 mins	t = 8 mins	t = 13 mins
Comments	Ignition flame height at ~250mm	Flames have torn sarking. Light smoke is being emitted out from top edge of cavity.	Hot gases from flames push sarking flap (created from torn sarking) to seal cavity.	Flames have reached top of cavity. Dark smoke and flames are being emitted from top part of cavity. Flaming molten EPS flow to lab floor and settles under cavity rig.	During Peak HRR period. Sustained flaming exit top edge of cavity. Pool fire created under and side of cavity rig burns. Flame height of pool fire reach ~250mm above base of cavity.	Minimal flaming in cavity. Most of burning occuring from pool fire on lab floor.	Intensity and flame height of floor pool fire has significantly reduced but continues to burn. Fire extinguisher is applied soon after, ending test.

During period of Peak HRR (at ~3 minutes into test), sustained flaming and significant amounts of thick dark smoke were emitted at the top edges of the rig. For most of the test duration – the fire continues to burn on the cavity floor (encompassing the full length of the cavity) and on the laboratory floor until manually suppressed by dry chemical extinguisher (at ~13 minutes). The Lab floor pool fire reached a maximum of height of 250mm above cavity base (a height of ~400mm in total).

Visual observations and reaction to fire of the PB for Test 5 (PB + sarking + 1 hep) were similar to Test 3 but were delayed due to the temporary barrier created by the sarking, protecting the PB from immediate involvement to the ignition source. In comparison to Test 3, time to reach peak HRR for Test 5 (PB + sarking + 1 hep) was delayed by ~45s, with slight increase in peak HRR (Peak HRR for Test 3 was ~252 kW and Test 5 was ~268kW). The rate to reach peak (FIGRA) was also slightly less for Test 5 (Test 3 @ ~1.37 kW/s and Test 5 @ ~1.14 kW/s). The peak incident heat flux to the top of cavity for Test 5 (24.7kW/m^2) was approximately half of that recorded for Test 3 (41.4 kW/m^2). This data provides evidence that the sarking provided a temporary barrier to flames, delaying PB involvement.

Table 31 describes the flame progression of Test 4 (PB + M/S).

Table 31: Test 4 – Fire progression on polyester batts – 1 tray of methylated spirits

Images of Fire Progression						
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 4 mins	t = 8 mins	t = 12 mins 30s
Comments	Ignition flame height at ~250mm	Flame height remains at ~250mm. Light surface melting of polyester batts occurs at flame impingement area.	Flame height remains at ~250mm. Molten polyester on surface of material has ignited.	During Peak HRR period - flame height reached ~750mm to 1000mm. Long, thin drips of molten polyester flow down are seen sorrounding flame impingement area.	Flame height reduces back to ~250mm. Molten polyester collected in tray continues to burn.	Minute flame persisting for long period before end of test was called.

For this Test, average flame height of ~500-600mm, with a maximum flame height of ~750mm. No surface melting of polyester occurred beyond the region of direct flame impingement. A peak HRR of 10.1 kW was reached at ~250s after ignition (a slow FIGRA of ~0.041kW/s). The molten polyester under the flame impingement area flowed into fuel tray and continued to burn 330s (5.5 minutes) after fuel fire had extinguished.

Error! Reference source not found. Figure 39 graphs the HRR for Test 1 (sark + 1 hep) with Test 3 (PB + 1 hep), Test 4 (PB + M/S) and Test 5 (PB + sark + 1 hep).

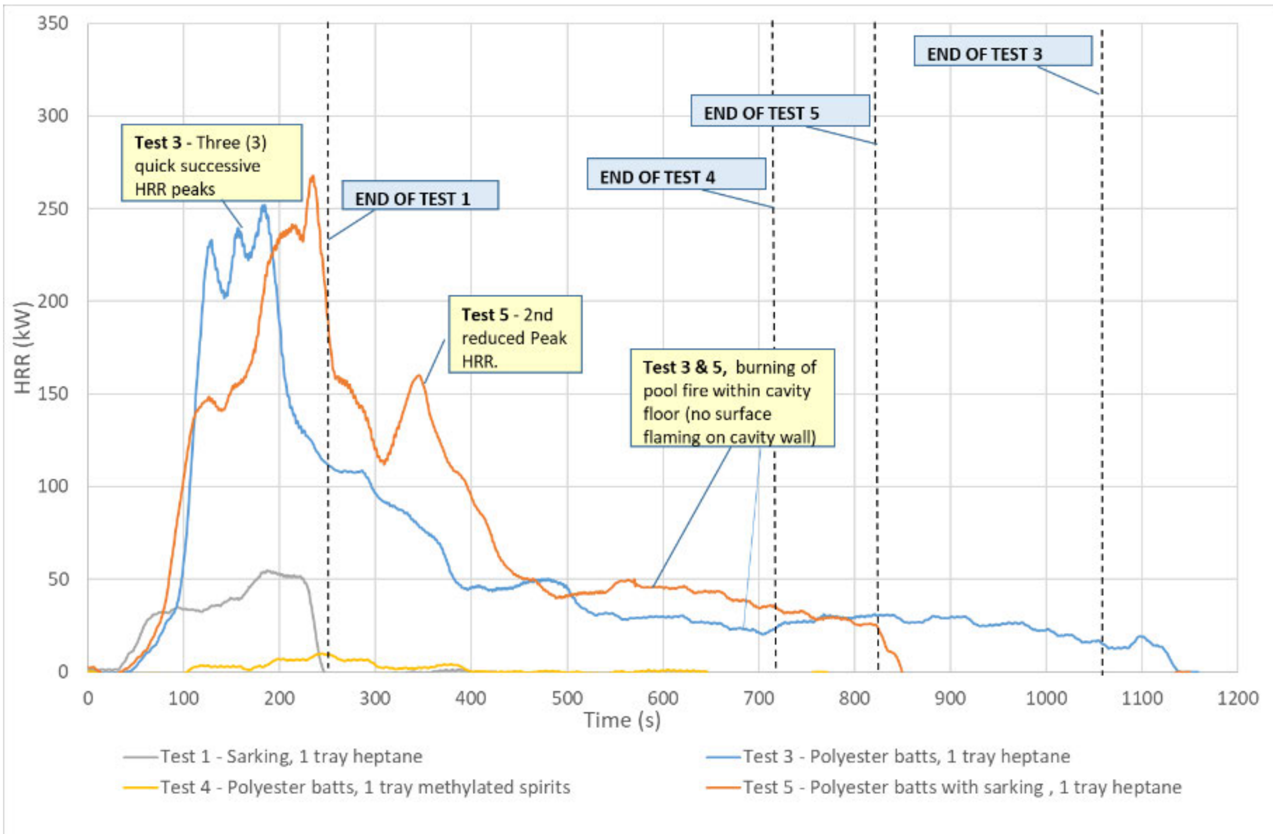


Figure 39: HRR chart of polyester batts series of tests – Test comparison of Test 1, 3, 4 & 5

Test 3 (PB + 1 hep) has three HRR peaks in quick succession (within 80s), which each subsequent peak slightly higher than the previous. Observation of test video show the rapid burning of polyester leading up to the peak HRR period produces copious amounts of dark black smoke that effectively starve off the fire as peak HRR is reached, causing the flames to momentarily retreat. The momentary retreat in flames allows a rush of air to enter the cavity and replenish oxygen levels causing the hot, dense smoke to reignite and produce flash flames. This process was repeated, causing intermittent 'pulsating' of flames out of top of rig. The phenomena were not seen with Test 5 as the rate of HRR growth was not as rapid, due to presence of sarking inhibiting full immersion of flames with polyester surface.

The lack of sarking for Test 3 (PB + 1 hep) allowed for greater air entrainment to support rapid fire spread to occur. The cool air entering the sides were able to shield mid-height LHS and RHS portions of polyester batts – which did not become involved in the fire (see Table 23).

Figure 40 compares the mid height (1200mm) at centre thermocouple, T/C 6 with the mid-height RHS thermocouple, T/C 5) and mid-height LHS thermocouples T/C 7, for Test 3 and Test 5. The mid-height, centre thermocouple (T/C 6) recorded maximum temperatures of between 800 - 900°C with similar RHS (T/C 5) and LHS (T/C 7) for test 5 however, the temperatures at the mid-height RHS and LHS for test 3 (PB + 1 hep) were significantly less (at 400 - 500°C). The sarking in Test 5 was effective in insulating the sides of the cavity during the peak HRR period, causing a rise in temperatures within the cavity. Apart from Test 3 (PB + 1 hep), the increase and decrease in temperature measurements and radiant heat readings for Test 4 (PB + M/S) and Test 5 (PB + 2 hep), followed the measured HRR curve (see Appendix D).

All the PB was consumed for Test 5 (PB + sarking + 1 hep). For test 3 (PB + 1 hep), a small portion of polyester batts remained at a mid-height edge of rig (with melted surface) - see Section 4.6.3 – Post Test Damage. Post-test observations of Test 4 (PB + M/S) show damage to a triangular shaped area with a 410mm base length and 530mm height (the approximate height and width of fuel fire impingement area. The peak period flame height for methylated spirits was ~500mm (see Characterisation Test flame heights for Methylated spirits).

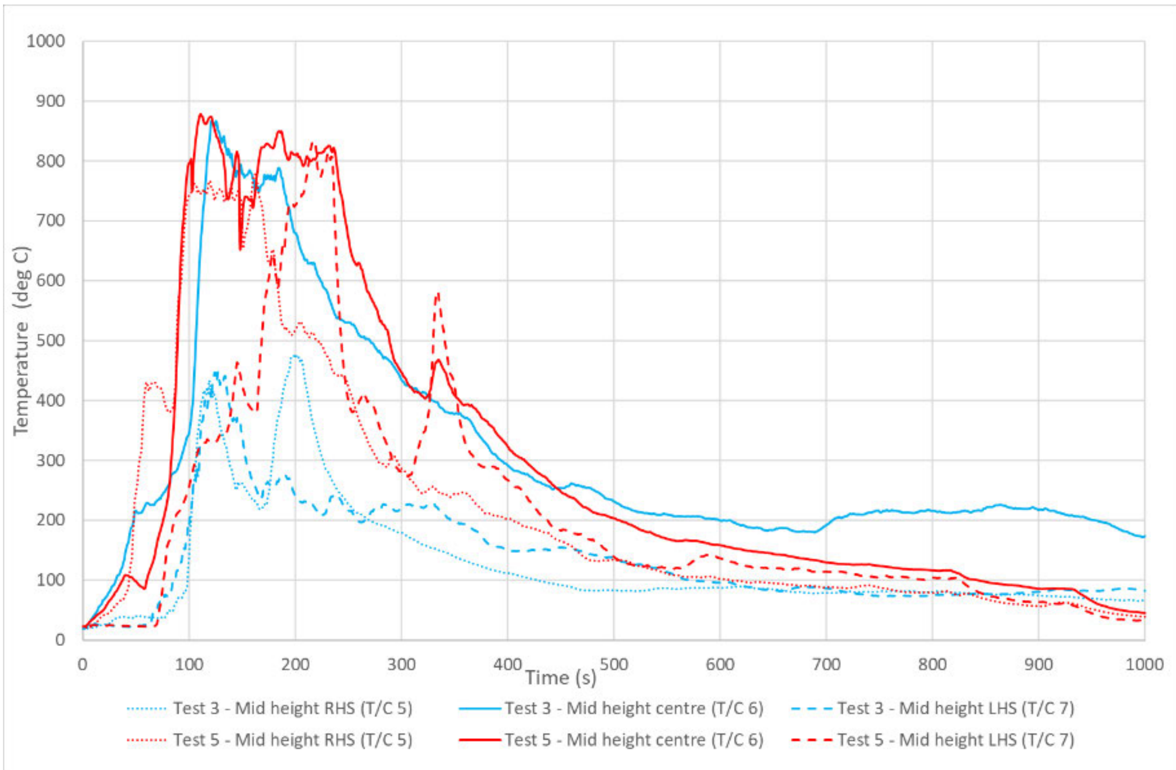


Figure 40: Mid-height, RHS and LHS cavity temperatures compared to centre mid-height cavity temperature for Tests 3 and 5.

4.8.3 Phenolic foam (PF) – Tests 6, 7, 8 and 9

Table 32, Table 33, Table 34 and Table 35 describe the flame progression for Test 6 (PF facing + 1 hep), Test 7 ((PF facing + 2 hep), Test 8 (PF facing + M/S) and Test 9 (PF exp + M/S)

The phenolic foam is manufactured with a thin aluminium foil paper facing adhered to the foam. The presence of this combustible facing aided flames to rapidly spread up the surface of the foam, reaching the top of the cavity within 1 minute of ignition. This occurred for all PF with facing tests (Test 6, 7 and 8) regardless of the ignition source size. Although fire spread to the top of the specimen occurred for all tests (including the test conducted without the combustible aluminium foil facing), the charring behaviour of the phenolic foam prevented significant horizontal fire spread.

Table 32: Test 6 – Fire Progression on phenolic foam with facing - 1 tray of heptane

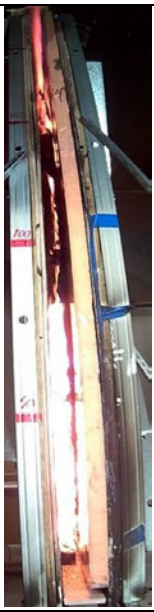
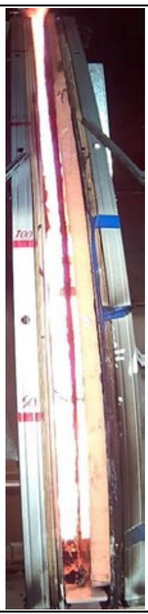
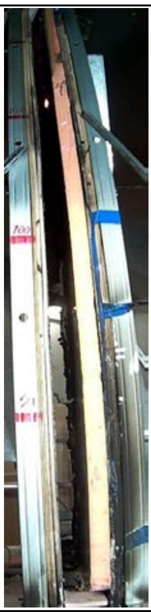
Images of Fire Progression					
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 4 mins 19s	t = 8 mins
Comments	Ignition flame height ~250mm	During 1st HRR Peak period involving paper skin of PF.	Intensity of flames have reduced, however flames still remain at full height (2400mm).	2nd peak HRR involving PF foam.	End of test has been called. Small flame still persisting above.

Table 33: Test 7 - Fire Progression on phenolic foam with facing - 2 trays of heptane

Images of Fire Progression						
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 7 mins, 11s	t = 8 mins	t = 10 mins
Comments	Ignition flame height at ~ 200-250mm.	During 1st Peak HRR period involving paper face of PF.	Flames retreat as PF skin has been consumed and newly formed char layer temporarily inhibits further fire spread.	During 2nd HRR peak period. Initial char layer is penetrated involving PF foam.	Flames have retreated to a height of ~250mm. Smouldering combustion continues above.	Fuel in tray has burnt out - debris in tray still burning.

**Note – Test 7 - re-ignition of flaming to upper surface of cavity (after end of test was called) was not captured in test video, as the video had been turned off at time of occurrence.*

Table 34: Test 8 - Fire Progression on phenolic foam with facing - 1 tray of methylated spirits

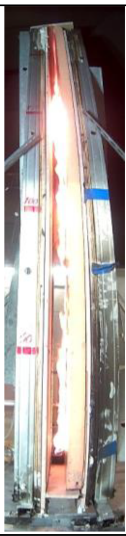
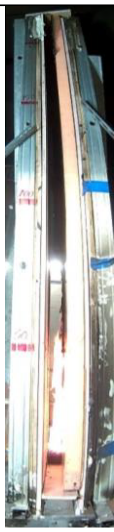
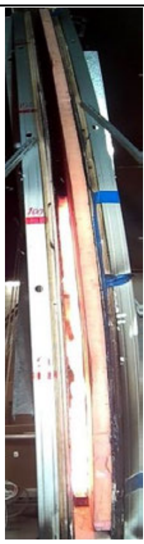
Images of Fire Progression						
Test time	t = ~0 mins	t = 1 min	t = 1 min 15s	t = 3 mins	t = 8 mins	t = 8 mins 40s
Comments	Ignition flame height at ~ 200-250mm	Flames have reached top of cavity, involving paper skin of PF .	During Peak HRR, flames exit top edge of rig. (Flame begin to exit top of rig ~1 min 5s).	Flames have retreated as paper skin of PF has been consumed. Fire has extinguised to top half of cavity, except for spot flame (seen at top edge of cavity).	Spot flames have extinguised and no smoldering combustion to top half of cavity. PF at flame impingment zone becomes involved.	Fuel flame out and fire to PF surface has extingished. Small amounts of debris (consisting paper and small fragments of PF) continues to burn in tray.

Table 35: Test 9 – Fire Progression on exposed Phenolic foam (facing removed) - 1 tray of heptane

Images of Fire Progression						
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 5 mins, 14s	t = 7 mins	t = 8 mins
Comments	Ignition flame height ~250mm.	Flames have reached ~1000mm.	Flames have reached top of cavity.	Peak HRR burning period - flames exit out of top edge of cavity.	Fire has extinguised. Smouldering combustion continues at top half of cavity.	Small flame re-igniting after end of test was called - persisting for ~2 minutes plus.

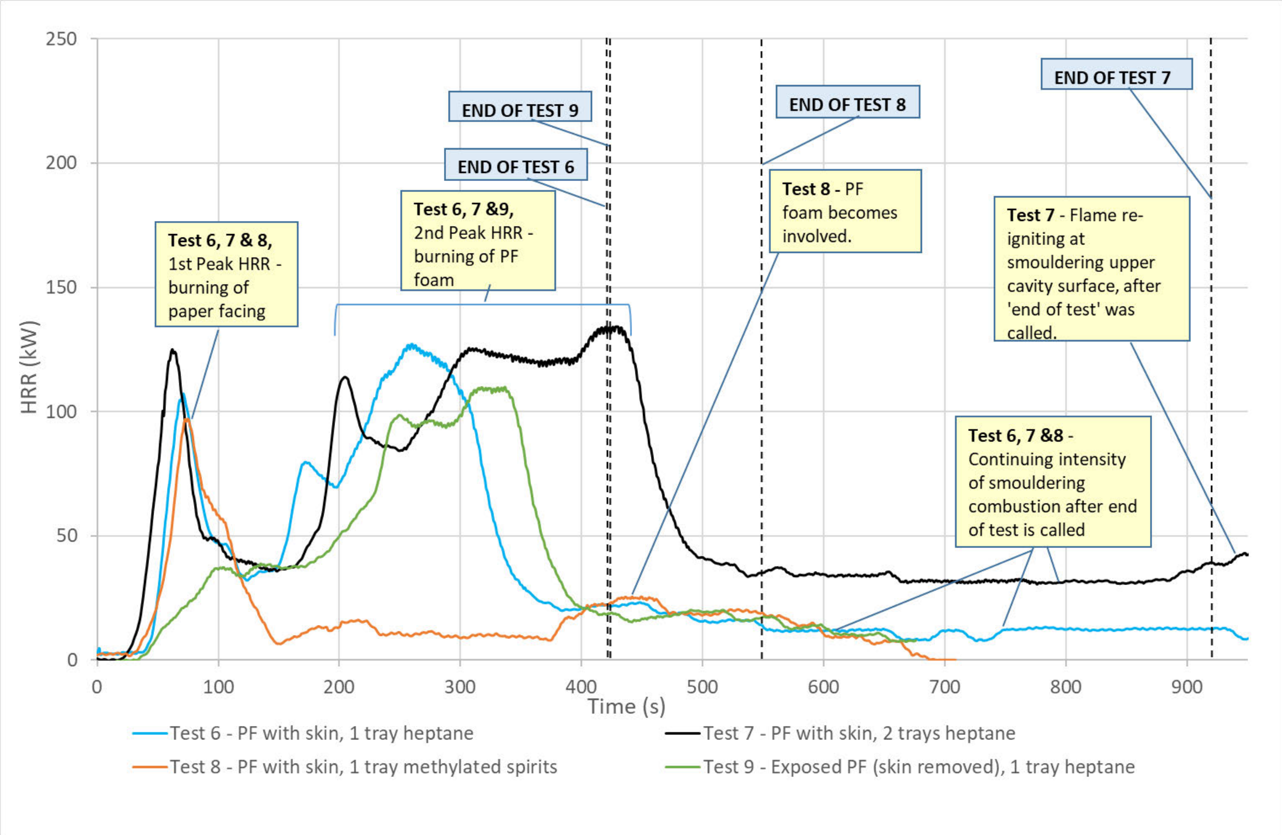


Figure 41: HRR chart of phenolic foam series of tests– Test comparison of Test 6, 7, 8 & 9

The two peak HRR periods are evident for Test 6 (PF facing + 1 hep) and Test 8 (PF facing + 2 hep) and a single peak HRR for test 7 (PF + M/S) and Test 9 (PF exp + 1 hep). The first Peak HRR period involves the paper facing. The time to first peak HRR occurs approximately at the same time for all three tests conducted with the paper facing (regardless of the size of the ignition source):

- Test 6 (PF facing + 1 hep) - 1st Peak HRR of 113.2kW @ 71s
- Test 7 (PF facing + M/S) - 1st Peak HRR of 125kW @ 62s
- Test 8 (PF facing + 2 hep) – Peak HRR of 97.1kW @ 75s

After the first peak HRR period, the flames begin to retreat as the paper facing is consumed and an initial char layer has formed. However, the heat intensity of the heptane fuel fire was able to penetrate the initial char layer to give rise to a second peak HRR period, mainly involving the PF foam. A second peak HRR was witnessed for Test 6 (PF facing + 1 hep), Test 9 (PF exp + 1 hep) and Test 7 (PF facing + 2 hep) and was 130.5kW, 109.8kW and 134kW respectively. Comparison of Test 9 and Test 7 indicate that doubling the ignition source did not result in further fire spread the ignition size of 1 tray of heptane was adequate in depicting the extent of PF behaviour.

For all tests, the burnout of the fuel source significantly reduces the flame heights and intensity of the fire within the cavity. Upon burnout of the heptane test fires – a mixture of spot flaming and smouldering combustion continues to the top ½ of the cavity surface and flames of < 500mm in height (involving PF foam and paper facing debris) continues to burn within the tray or cavity floor. Apart from reignition occurring for Test 7 (several spot flames on upper surface) and Test 9 (single flame near top RHS edge of cavity), all flaming generally ceased shortly after the ignition source had burnt out. Test 8 (PF facing + M/S) did not involve the PF until close to the end of test, with the flaming along the material surface extinguishing at time of fuel burn out.

The temperature profile for Test 6 (PF facing + 1 hep), Test 7 (PF facing + 2 hep) generally followed HRR trendline (having two peak temperature periods). Both mid-height RHS T/C 5 and mid-height LHS T/C 7 recorded the coolest temperatures (indicating air entrainment.)

The temperature profile for Test 7 (PF facing + 2 hep) and generally following HRR trendline (having two peak temperature periods), with the top thermocouples (T/C 1, 2, 3 and 6) of Test 7 following trend of HRR. Mid-height RHS T/C 5 and mid-height LHS T/C 7 remain coolest at 2^{nd} peak period. Note T/C 4 not inserted.

Both Test 8 (PF facing +M/S) and Test 9 (PF exp + 1 hep) had the top and centreline thermocouples following HRR curve. Again, RHS T/C 5 and T/C 7 recorded lowest temperatures.

Peak radiant heat data generally followed time of peak HRR. Refer to Appendix D5 for temperature and radiant heat (incident heat flux) graphs for Test 6 to Test 9. Refer to Table 19 for peak radiant heat values.

Post-test surface damage of Test 9 (PF exp + 1 tray hep) was greater than Test 6 (PF facing + 1 hep) however the centreline char depths (apart from the top measurement) were less (see Table 24), indicating that the PF paper facing did not protect the raw PF foam and may have aided in flame penetration of the material. Extent of surface post-test damage Test 8 (PF facing +2 hep) is greater in comparison to Test 6 (PF facing + 1 hep) due the larger ignition source. However measured lengths of charred area and depth at given points of panel were similar. For Test 7 (PF facing + M/S), no charring occurred (only surface damage) above 1.2m of cavity, with a recorded char depth of ~1-2 mm at centreline mid height. The charred area of panel was mainly within flame impingement zone.

4.8.4 Polyisocyanurate (PIR) foam -Tests 10, 11 & 12

Test 10 (PIR exp + 1 hep) resulted in fire spread on PIR to top of the specimen and burn through and consumption of the majority of the top half of the specimen. The reduced scale one methylated spirits tray fire (Test 11- PIR exp + M/S) resulted in some fire spread up the centreline of the specimen resulting in a brief period of intermittent flames reaching the top of the specimen. However, as the PIR charred it formed a protective layer which halted further fire spread from this ignition source.

Test 12, one tray heptane fire with PIR with aluminium facing in place resulted in fire spread to the top of the specimen. However, the aluminium facing offered some protection, delaying the onset of the fire spread and significantly reducing horizontal fire spread within the cavity compared to Test 10.

Table 36: Test 10 – Fire Progression on exposed PIR foam (facing removed) - 1 tray of heptane

Images of Fire Progression						
Test time	t = ~0 mins	t = 35s	t = 1 min	t = 3 mins	t = 8 mins	t = 11 mins
Comments	Ignition flame height ~250mm.	Initial peak HRR period (initial peak HRR < 2nd peak HRR).	Flames momentarily retreat as excess black smoke production suffocates flames within top of cavity.	During 2nd Peak HRR period - large flames exit out of top edges of cavity.	PIR has delaminated from rig. Significant smouldering combustion occuring at top half of cavity.	Small spot flaming and smouldering combustion occuring to top half of cavity. Flames out but Smouldering combustion occurs at time end of test is called.

Table 37: Test 11 – Fire Progression on exposed PIR foam (facing removed) - 1 tray of Methylated Spirits

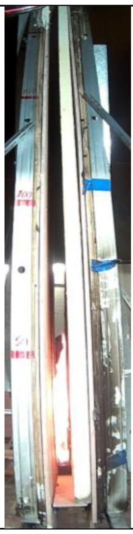
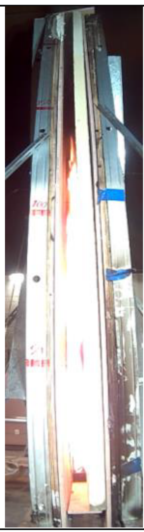
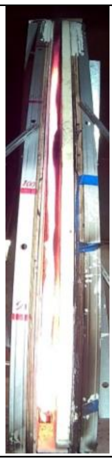
Images of Fire Progression							
Test time	t = ~0 mins	t = 1 min	t ~ 2mins 40s	t = 3 mins	t = 3 mins 20s	t = 6 mins 33s	t = 8 mins
Comments	Ignition flame height ~250mm.	Flames have reached ~500mm.	Flames have raced up surface of PIR. HRR significantly rises. Grey smoke is emitted out of top of cavity as flames raced up.	Flames height retreats to 500mm as char layer has formed to cavity surfaces above. Initial Peak HRR is maintained. Smouldering to above surfaces	Initial Peak HRR with flame height is hovering at ~500mm.	2nd Peak HRR. 2nd HRR peak > initial HRR Peak.	Flame is out in tray. Spot flames continues to areas within bottom half of cavity.

Table 38: Test 12 – Fire Progression PIR foam with facing - 1 tray of heptane

Images of Fire Progression							
Test time	t = ~0 mins	t = 1 min	t = 3 mins	t = 4 mins 20s	t = 8 mins	t =11 mins	t = 13 mins
Comments	Ignition flame height at ~250mm	Flames reach height of ~ 500mm.	Flames have reached the top of cavity.	During period of peak HRR. Continues flames exit out of top edge of cavity.	Flaming concentrated at top of rig. Minimal flames within bottom half of cavity. Fuel tray has burnt out.	Flames have extinguished as flaming and smouldering combustion continues to top half of cavity.	Nearing end of test, with smouldering combustion continuing above.

Within 35s into Test 10 (PIR exp +1 hep), flames reach the top and exit top sides of cavity. However momentarily retreat at the top as the initial char layer forms and quantity of black smoke collected at top of cavity suffocate flames. After the fuel tray extinguishes flames continue to burn at full height with flames and heavy black smoke exiting the sides of the cavity. Flames encompass the full width of the cavity from ~1000mm to top. At 8 minutes – the flames have significantly reduced with flames continue to burn to top 1000mm of cavity. No flaming or smouldering combustion occurring below 1000m. The majority of PIR on the top ½ of cavity is consumed destroying the integrity of the board and causing it to delaminate from the test panel and lean into the cavity.

The initial char layer formed in Test 11 (PIR exp + M/S) was successful in delaying initial fire spread. At ~ 3 minutes into Test 11, the flame height was still at ~500mm, reaching an initial peak HRR of 26.5kW (see Figure 43). Extended exposure allowed flames to penetrate initial char layer resulting in a second peak HRR of 66.2kW. Surface flame spread occurred (above the initial flame impingement zone) to reach top, with intermittent flaming exiting sides of cavity. The flames soon retreated as char layer was formed (above the initial flame impingement zone) and after the fuel source burnt out (at ~433s).

In Test 12 (PIR facing + 1 hep), flames reach the top around 3 minutes into test. In comparison to Test 10 (PIR exp + 1 tray hep), this is a delay of ~2.5 minutes (see Figure 43). Test 12 reached a peak HRR of 249.3kW with a calculated rate of fire growth (FIGRA) of 0.974 with Test 10 having a peak HRR of almost double (403.4kW) and FIGRA of 2.861. The PIR board was manufactured with the raw PIR foam sandwiched in between two layers of embossed aluminium facing. The purposes of the aluminium facing are to protect the integrity of PIR during the construction process. The video observations and test data show that this aluminium facing provides some form of fire protection by delaying and limiting its involvement in the fire.

Post-test damage observations for all PIR tests showed that the material not only chars, but swells upon exposure to heat and flames. The swelled areas become more brittle and therefore more susceptible to fire damage. The brittleness of the fire damaged PIR causes to the PIR to lose its integrity and fall away from test panel. Post damage photos of heptane fire tests, Test 10 (PIR exp + 1 tray hep) and Test 12 (PIR with facing, 1 tray hep) missing PIR board from top half (see Post-damage swelling is most significant to Test 10 (PIR exp + 1 hep) – see Figure 42. Reduced scale showed deep charring to bottom half of cavity (within flame impingement area), with minimal charring beyond this area.

Figure 42: Close-up view of post-test swelling of PIR foam - Test 10 (PIR exp + 1 hep)

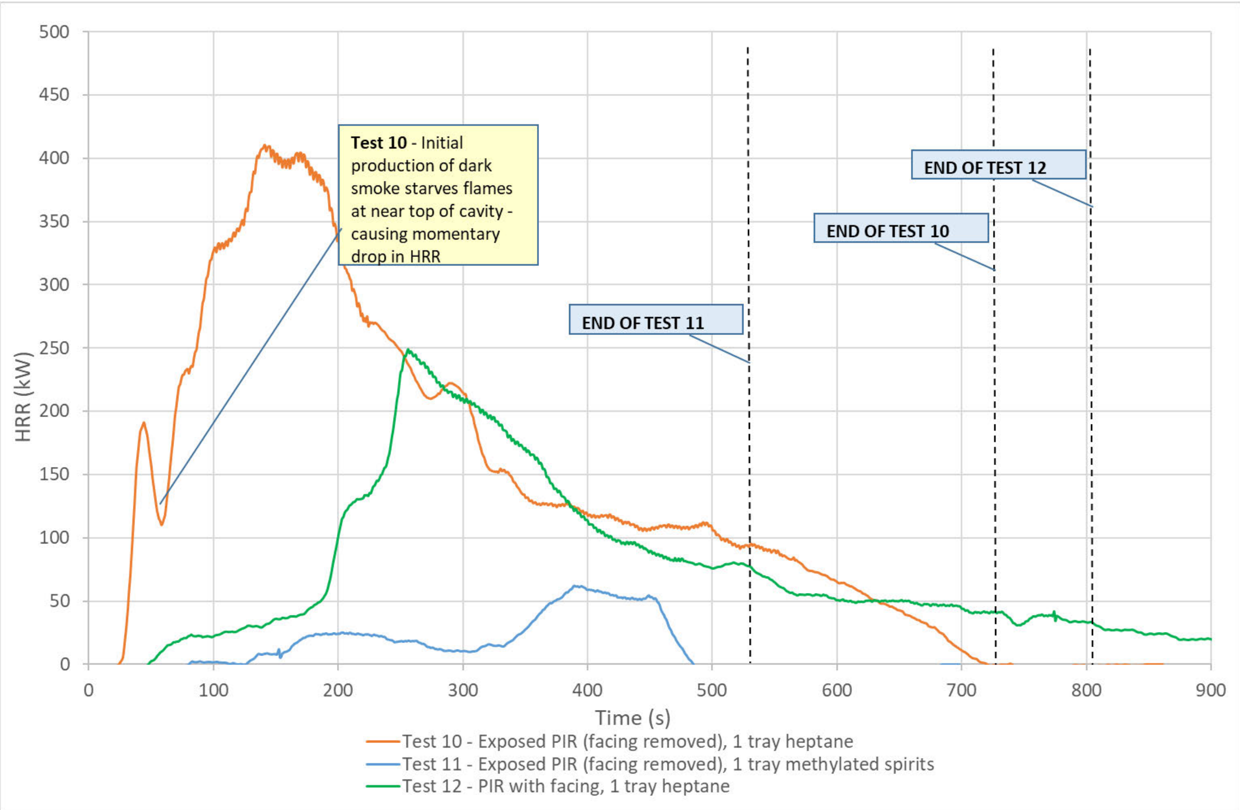


Figure 43: HRR chart of PIR series of tests– Test comparison of Test 10, 11& 12

Figure 44 shows the cavity temperature profile of Test 10 (PIR exp +1 hep). Peak temperatures within cavity are reached after Peak HRR, with peak temperature at top of cavity (recorded by T/C 1, 2 and 3) recording above 1000℃. As the ignition source burns out – temperatures within top and mid portions of cavity remain high as smouldering/flaming combustion continues within top half of cavity. Near the end the delaminated PIR board impinges on cavity thermocouples, showing burning at top half of cavity within temperature range of 750 – 1020 ℃, that continues until the end of test is called. Radiant heat for top of cavity peaks at 157.6 kW/m^2 with a second peak of 101kW/ m^2 during the flaming/smouldering combustion period, after ignition source burn out.

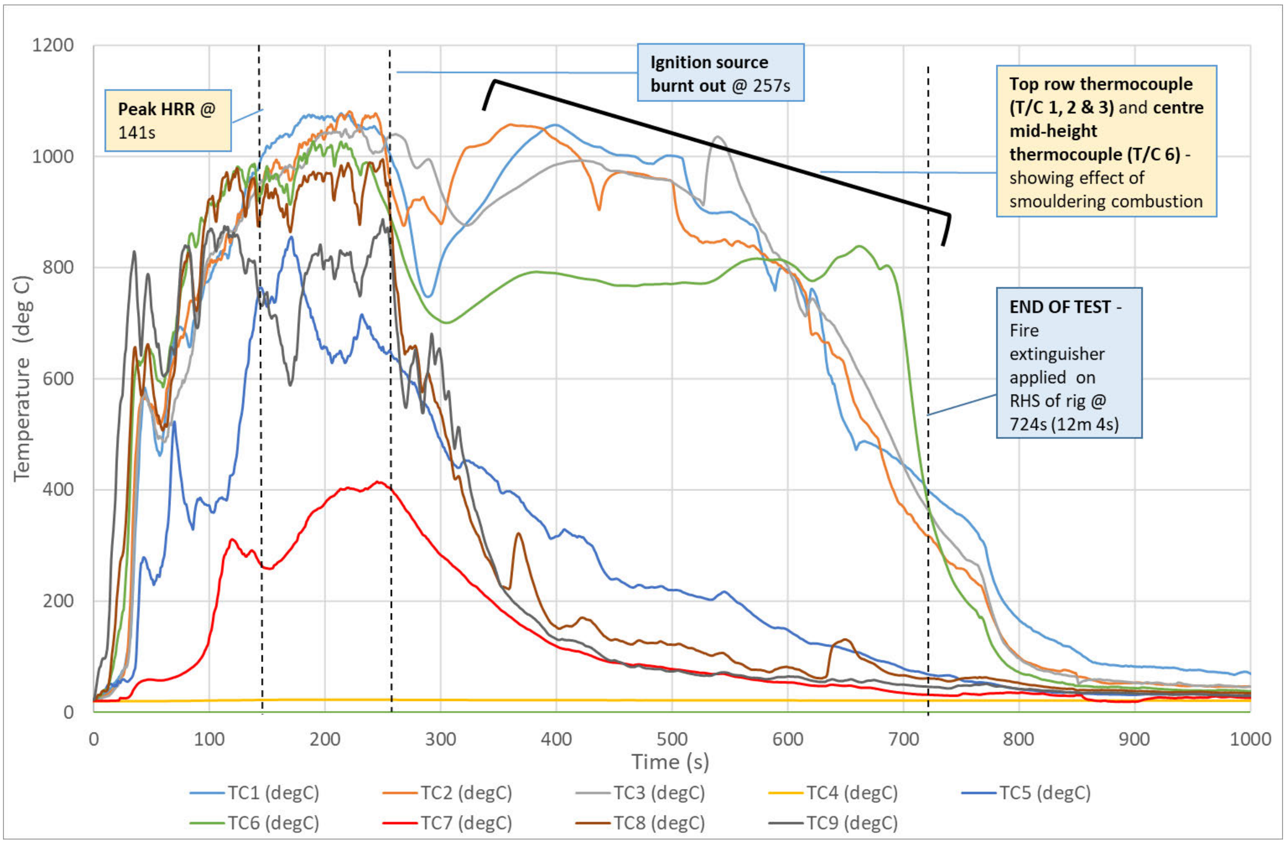


Figure 44: Test 10 (PIR exp +1 hep) - Temperature Profile (Note: T/C 4 had dislodged from instrumented panel during test)

For Test 11 (PIR exp + M/S), an initial temperature peak of 358.6℃ to centre, mid height (T/C 6) and 176.3℃ to centre, top (T/C 2), as flames penetrate PIR surface and momentarily spread to top. Before second peak temperatures are reached, there is a momentary drop in temperature as grey smoke collated at top of cavity cause flame front to retreat (~375s). Second peak temperatures occur at ~ 433s, at the time of ignition source burns out. At this time, centre top thermocouple (T/C 2) records a second peak temperature of 550.5℃, before dropping significantly. Unlike, Test 10 (PIR exp +1 hep), no significant flaming/smouldering combustion occurs after fuel burnout, with only few spot flames continuing at bottom half of cavity. Peak heat flux recorded to centre, top and centre, mid height, during second peak temperature period are 17.1 kW/m^2 and 65.1 kW/m^2 respectively. 17.1 kW/m^2 is ~ 5 times less than the peak heat flux recorded for Test 10 (PIR exp + 1 hep), after ignition source burn out.

Test 12 (PIR with facing + 1 hep) temperature profile within cavity is similar to Test 10 (PIR exp + 1 hep), with peak temperature to top row thermocouples (T/C 1, 2 and 3) reaching just below 1000℃. After ignition source burn out however, there is a distinct gradient drop in temperature from top to mid height of cavity (compare Figure 44 and Figure 46). Unlike in Test 10, the integrity of PIR board does not delaminate from test panel to impinge on cavity thermocouples.

For Test 12, peak incident heat fluxes recorded at top (131 kW/m^2) and mid-height (132.9 kW/m^2) occur during peak HRR period, see Appendix D . After ignition source burnout, incident heat flux fluctuated from 32 kW/m^2 and 94 kW/m^2 (with 94 kW/m^2 being the peak incident heat flux). As evident in previous tests – lowest temperature recorded for mid height RHS T/C 5 and LHS T/C 7, with T/C 7 exhibiting lower temperatures, indicating more air being entrained from on LHS of cavity. LHS T/C 7 are recorded to be near ambient temperatures for Test 11 (PIR exp + M/S).

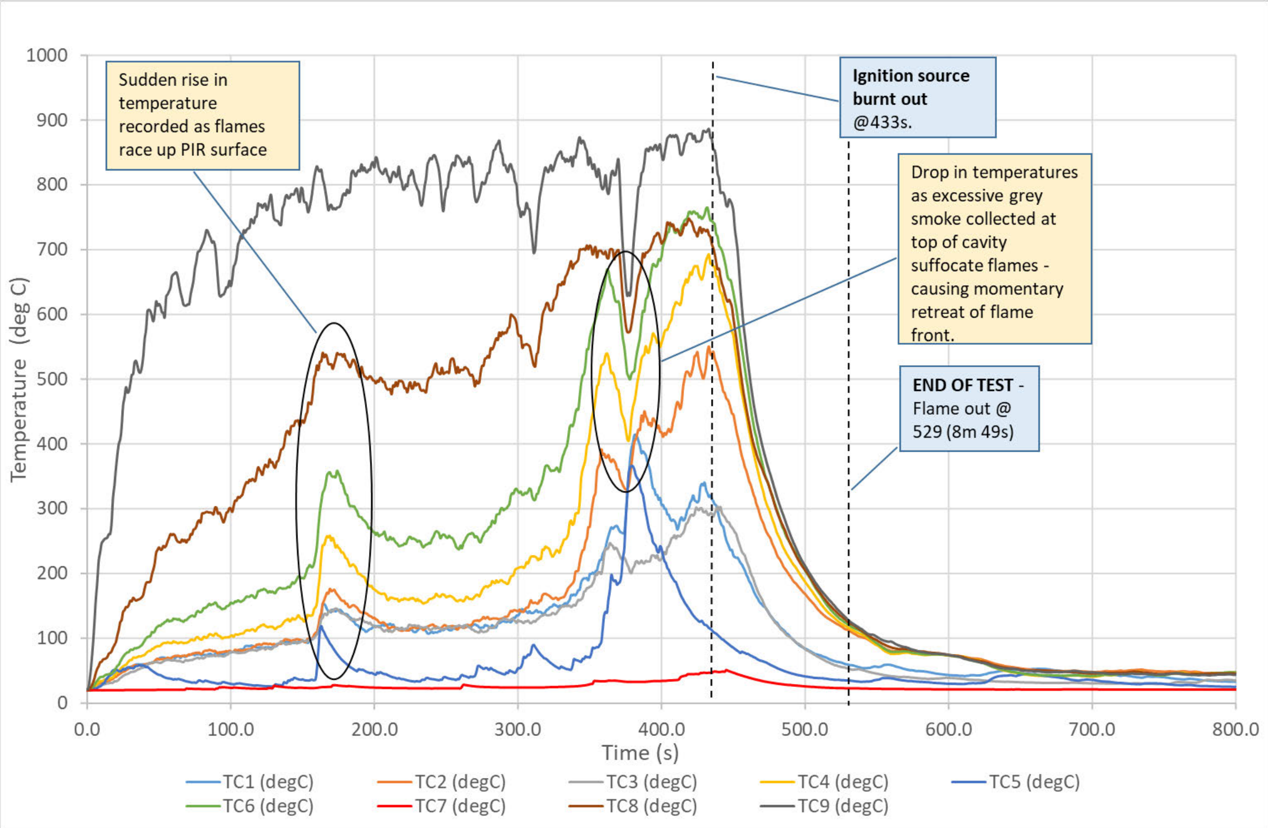


Figure 45: Test 11 (PIR exp + M/S) - Temperature Profile

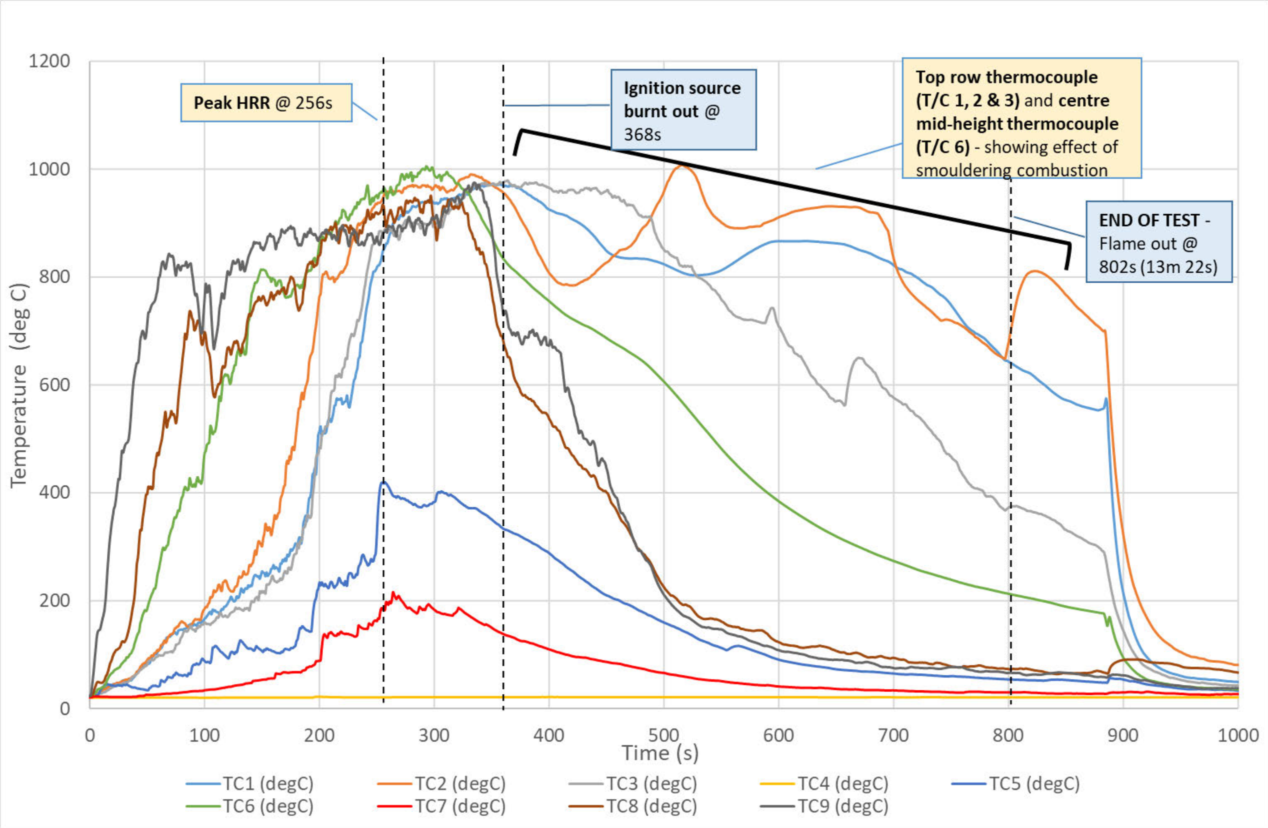


Figure 46: Test 12 (PIR with facing + 1 hep) - Temperature Profile

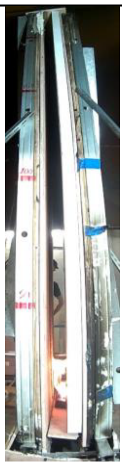
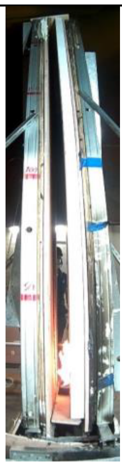
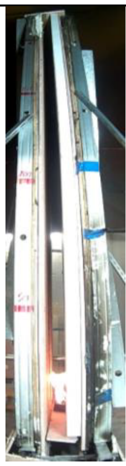
4.8.5 Expanded polystyrene Insulation board (EPS)

Test 13 (EPS + 1 hep) on EPS resulted in fire spread to the top of the specimen. A significant pool fire encompassed the entire cavity floor base (that also spread onto the lab floor) was formed, with most of the EPS being consumed. From all the tests performed, this test resulted in the largest peak HRR of ~700kW. In contrast, Test 14 (EPS + M/S) experienced no fire spread with the EPS only shrinking/receding away from the ignition source. A small pool of molten EPS mainly collected within the fuel tray and did not cause further lateral spread. It is hypothesised that EPS may have contained HBCD fire retardant due to the shrinking behaviour and lack of ignition witnessed in the test.

Table 39: Test 13 - Fire Progression on EPS - 1 tray of Heptane

Images of Fire Progression							
Test time	t = ~0 mins	t = 1 min	t = 1 min 30s	t = 2 mins	t = 3 mins	t = 8 mins	t = 12 mins 30s
Comments	Ignition flame height at ~250mm	Flame height increases to ~500mm. EPS melts and contributes to fuel fire (ignition source).	Flames spreads to top of cavity, involving entire surface of EPS. Molten EPS has formed a pool fire on the floor of cavity.	During period of Peak HRR. Flames extend around and above cavity capping (made of FR plasterboard).	All of EPS has melted and formed pool fire on cavity floor. Minimal EPS remain within cavity wall.	Pool fire has reduced to few spot flames within floor of cavity.	Single, minute flame still persists, when end of test is called.

Table 40: Test 14 - Fire Progression on EPS - 1 tray of Methylated spirits

Images of Fire Progression						
Test time	t=0 mins	t=1 min	t=1 min 30s	t=3 mins	t = 8 mins	t= 11 mins 40s
Comments	Ignition flame height at ~ 200-250mm	EPS begins to melt at surface of flame impingement zone.	During Peak HRR of test. Flame are seen attaching to molten EPS surface.	Height of flames still at ~250mm, no further surface flame spread.	Fuel has extinguised but molten EPS collected in tray continues to burn.	Minute flame burns persistantly moments before flame extinction.

Within 1 minute of Test 13 (EPS + 1 hep), flames reach a height of 500mm. Molten EPS starts forming above and around fuel flames. Molten EPS flows down into fuel tray and within ~1.5 minutes, flames ignite molten EPS above and spread rapidly to the top of rig. Large, sustained flames exit and breach FR plasterboard capping on top. During peak period, rapid flow of EPS flow onto cavity floor creating a pool fire that flowed and encompassed the length of cavity. Molten EPS did not flow to floor. For majority of test duration, burning of the EPS occurred on the cavity floor with pool fire flames reaching a maximum of 1000mm.

Test 13 (EPS + 1 hep) was extinguished by application of dry chemical extinguisher to both sides rig, as further burning may have damaged plywood behind FR plasterboard, lining the rig's steel stud frame. A peak HRR of ~700kW was reached with a FIGRA of 5.344 kW/s.

The EPS in Test 14 (EPS + M/S) was consumed within flame impingement area only with superficial surface melting occurring immediately above. Molten EPS collecting in tray only and continued to burn as a small flame after fuel had been consumed. No lateral flame spread occurred. Flame height does not exceed ~250mm. A Peak HRR of 17.4 kW was reached.

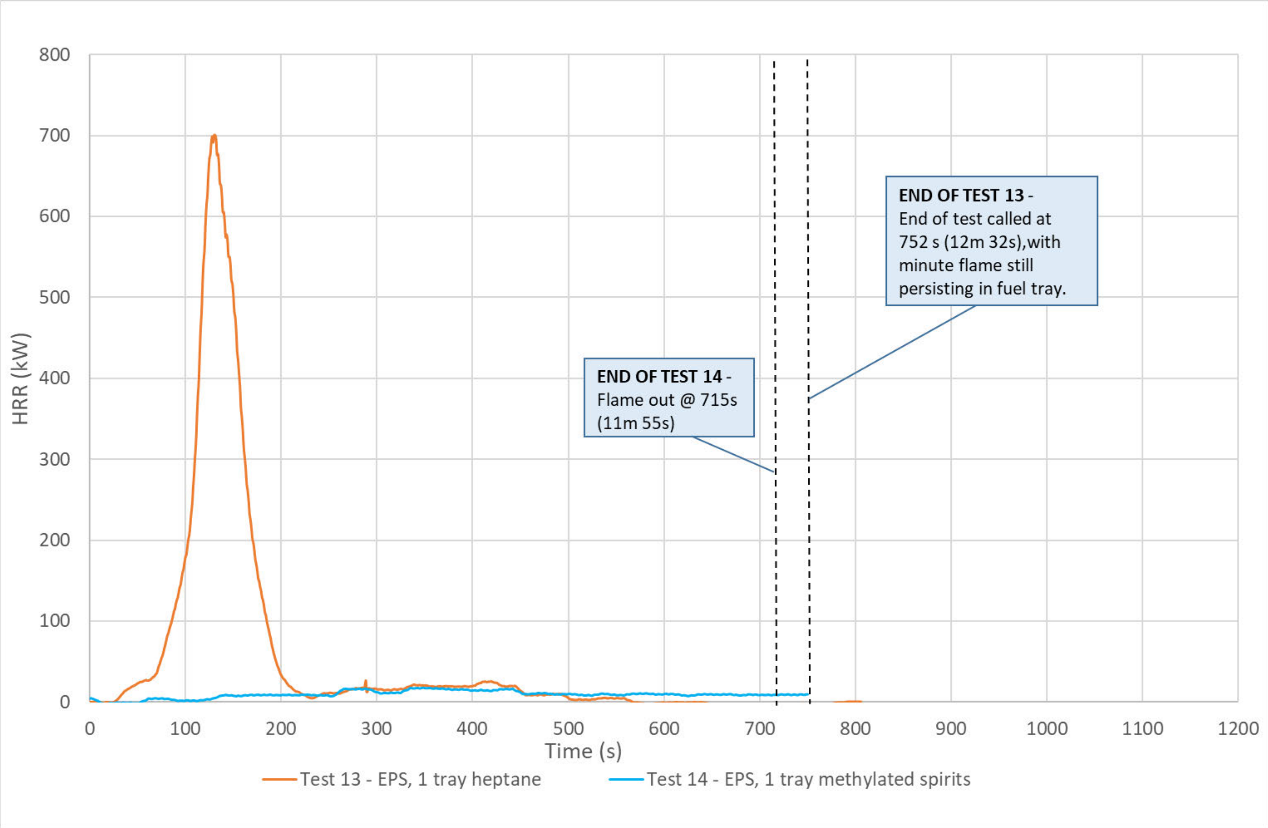


Figure 47: HRR chart of EPS series of tests– Test comparison of Test 13 & 14

The peak temperature readings for Test 13 (EPS + 1 hep) mirror the HRR curve (see Figure 48). The mid -height temperature (T/C 6) reached a peak 876.9℃, close to centreline peak temperature nearer to ignition source, TC/9 (300mm above fuel tray) at 886.7℃. As for other tests, the mid height RHS (T/C 5) and LHS (T/C 7) temperatures recorded the lowest temperatures (due to air entrainment), with the LHS (T/C 7) recording lower temperatures to RHS T/C 5. A second, lower peak temperature reading was recorded for T/C 9 and T/C 8 (see Figure 48). The top peak radiant heat temperature was a little less (84.7kW/m^2) with both top and mid height readings following peak HRR curve. Refer to Appendix D radiant heat graphs.

Test 14 (EPS + M/S) did not reach a distinct peak temperature recording for all thermocouple locations and followed the trend HRR shown in Figure 47. RHS and LHS mid height thermocouple recordings (T/C 5 and T/C 7 respectively) showed the lowest were coolest – indicating air entrainment. LHS T/C 7 recorded temperature close to ambient for entire test period. Radiant heat recordings also showed no distinct peak for both top and mid-height locations. Refer to Appendix D7 for temperature and radiant heat graphs.

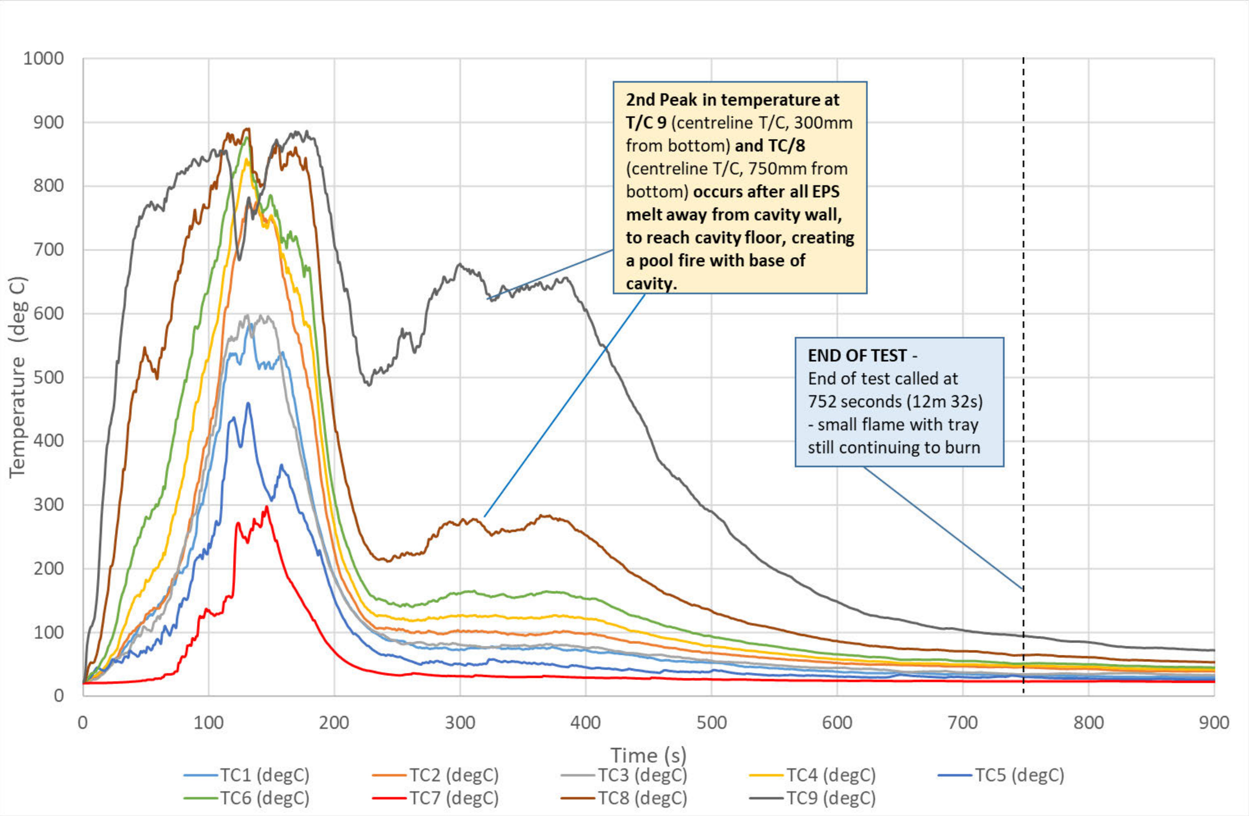


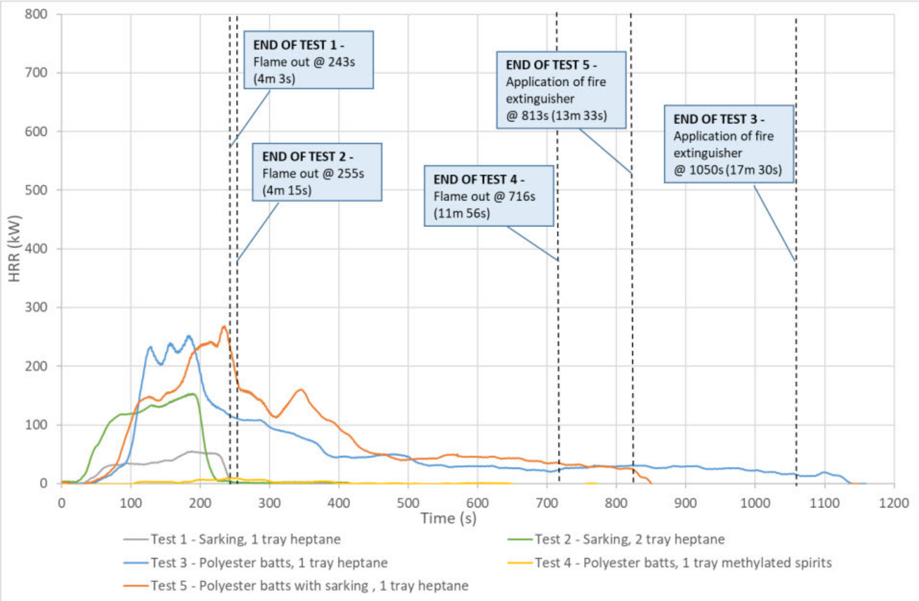
Figure 48: Test 13 (EPS + 1 hep) temperature profile within cavity.

4.8.6 Comparison of HRR between cavity materials

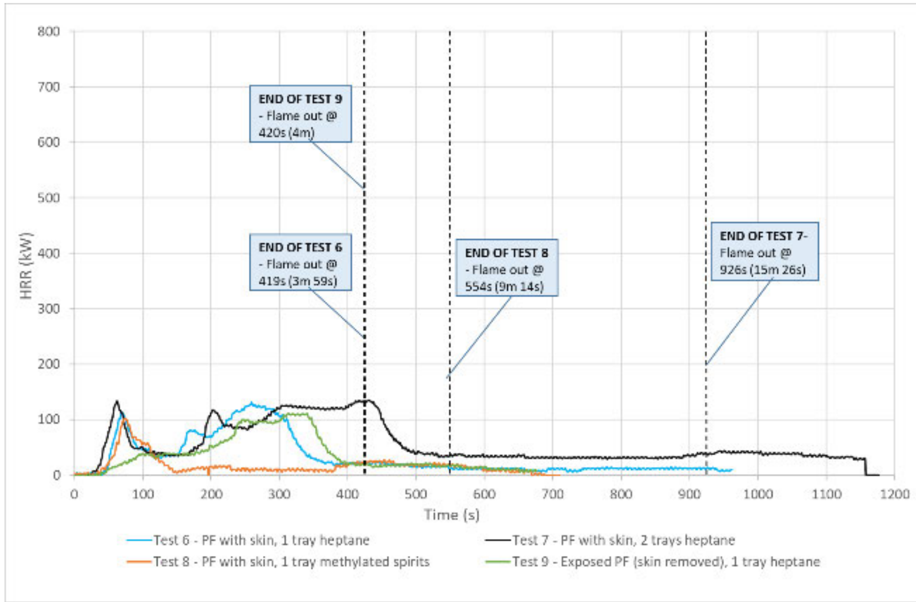
Figure 49 (next page) compares all plotted HRR completed for each test:

- All polyester batts and sarking tests (Test 1, 2, 3, 4 and 5)
- Phenolic foam (Tests 6-9)
- Polyisocyanurate tests (Tests 10-12)
- EPS tests (Tests 13-14)

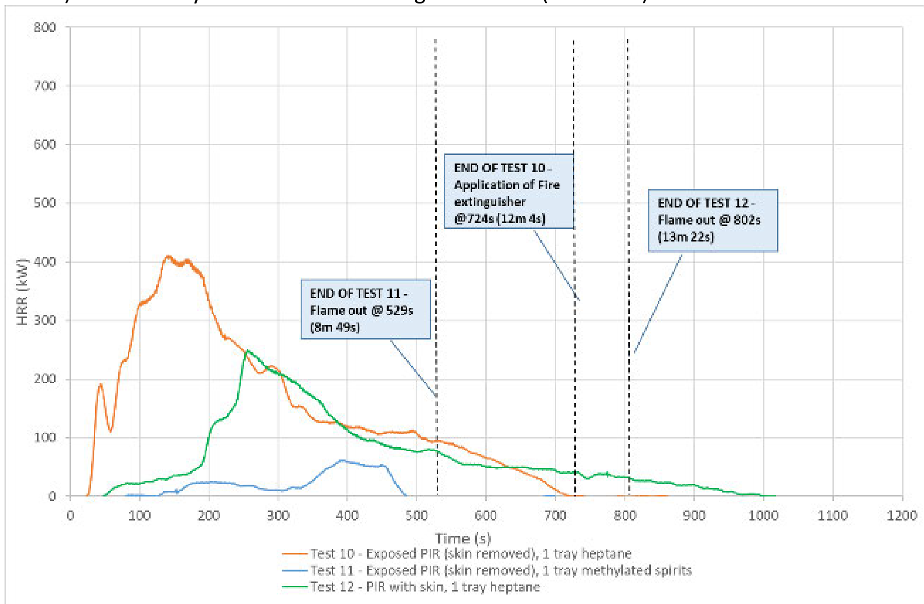
The scale of the x and y axis match between each set of plotted graphs in order to clearly show comparison between performance of each material.



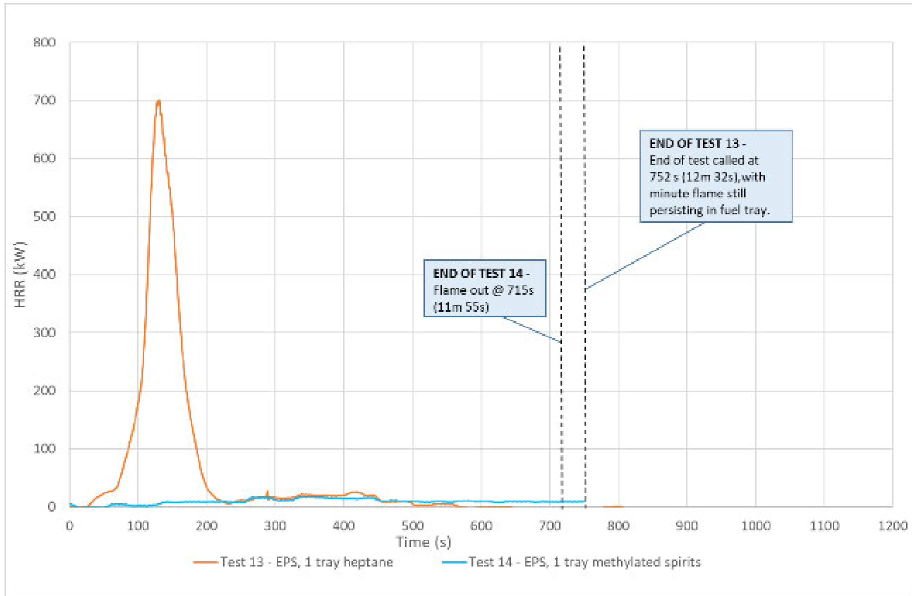
a) Polyester Batts and Sarking Test Series (Tests 1 -5)



b) Phenolic Foam Test Series (Tests 6 -9)



c) PIR Test Series (Tests 10 -12)



d) EPS board test Series (Tests 13 &14)

Figure 49: Comparison of HRR between test cavity materials (HRR charts of uniform scale)

The following summarises the performance in terms of HRR:

- Most tests reached the Peak HRR between 100s and 200s with the EPS board with 1 tray heptane (Test 13) reaching the greatest Peak HRR of 700.1 kW.
- For Tests 3, 5 and 13 (tests involving thermoplastic insulations with a one tray heptane fire), a significant amount of the burning occurred on the cavity floor. In the tests involving recycled polyester batts (Test 3 and 5), molten polyester flowed out of the cavity onto the laboratory floor. The laboratory floor pool fire reached a height of up to ~250mm above base of cavity. In an actual cavity fire scenario, the flow of molten Polyester will allow the fire to spread laterally via the cavity floor. Furthermore, flaming molten polyester has the potential to flow though gaps within the cavity floor construction and spread fire below area of origin. Molten EPS was more viscous than molten polyester batts and the material did not flow out of the cavity (Test 13). However, molten EPS fire also has the potential of spreading laterally and below area of origin.
- Although the thermosetting material of PIR recorded a peak HRR of 403.4kW (Test 10 – 1 tray heptane)is ~ two times more than peak HRR of polyester batts (252.0 kW), the risk of lateral or downward spread is significantly less due to its charring behaviour.
- The thermosetting materials phenolic foam resulted in the least HRR with only a slightly higher peak HRR for 2 tray heptane fire (134kW) than the single tray heptane fire (130.5kW).

5 CONCLUSION & FURTHER RECOMMENDATIONS

Fires on external wall systems that contain combustible components can spread rapidly, and severely compromise the fire safety of the building, presenting a unique fire risk. The most effective means of mitigating this risk is by regulating the fire performance of materials that make up an external wall. The fire performance of materials are intrinsically linked to their end use conditions.

Sarking and insulations are mainly installed within cavities of an external wall (EW) and thus understanding material fire performance within cavities plays an integral part in understanding overall external wall fire performance.

This study was completed to gain in depth understanding of typical properties of combustible materials found in an EW cavity, mechanisms of cavity fire spread and current knowledge base of building code requirements and associated test standards for EW, and experimental studies of materials found in cavities.

The experimental component of this study adopted and modified a cavity fire test rig that was based on the Cavity test rig described under Appendix B of FM Global Cavity Fire Test Standard, FM4411-2020.

The following summarises the fire spread and behaviours of the five materials tested:

- Sarking – No fire spread occurred under both one- and two-tray heptane fire tests. Comparison of the HRR and fire progression for Test 1 (Sark + 1 tray heptane) and Test 5 (PB + sark +1 tray heptane) showed that presence of sarking with polyester batts did not increase hazard of fire spread.
- PB batts – No spread occurred with a methylated spirits tray fire with only melting at the flame impingement zone. Exposure to a one tray heptane fire induced fire spread to the top of the specimen with flaming molten PB flow and spread onto the cavity floor and laboratory floor, forming pool fires. PB burnt on the floors for most of the test duration.
- PF – The test performed using methylated spirits fire induced fire spread up to the top of the specimen on the aluminium paper foil layer of the PF board, with limited penetration to the PF foam within the flame impingement zone only. For one tray and two tray heptane fires, flame spread to the top of the cavity, with no fire spread occurring after ignition source burnout. Significant smouldering and some spot flames to upper surfaces were observed after ignition source burnout.
- PIR – Extended exposure of the methylated spirits fire did result in surface fire spread with a brief period of intermittent flames to the top for exposed PIR, however burning on the PIR was reduced as surface char formed and no further spread occurred after ignition source burnout. For the 1 tray heptane fire, fire spread occurred to the top of the cavity with significant damage and consumption of the material occurring to the top of ½ of the cavity. PIR fire behaviour included significant swelling of the material upon charring, creating a more brittle char layer (in comparison to PF board). Upon flame burnout, no further fire spread occurred with only significant smouldering continuing. Test results showed that embossed aluminium facing of the PIR was able to protect and delay involvement of the raw

PIR however fire spread to top of specimen when the PIR with aluminium facing was exposed to the single heptane tray.

  - EPS – No spread occurred under a methylated spirits tray fire, with only localised melting and shrinking of the EPS at the flame impingement zone. Under a one tray heptane fire, fire spread to the top of the specimen, creating flaming molten EPS that flowed to the cavity floor, creating a cavity wide pool fire. The molten EPS was more viscous than the molten material witnessed in observed in the PE tests and thus did not flow further onto the laboratory floor. Majority of the burning occurred on the floor of the cavity for the duration of the test.

Note that only single product examples for each of the above types of cavity materials were investigated in this study and results may not generically represent other products. Reaction to fire of the above product types may potentially be influenced by variations in material formulation, fire retardant additives, thickness, density or facing materials. However, it was beyond the scope of this thesis to investigate this further.

The following summarises the main conclusions of this experimental study:

- The reduced ignition source (one tray methylated spirits fire) and base ignition source (one tray heptane fire) were adequate in representing a small and large cavity fire scenario. The one heptane tray fire size of ~80kW (representing a large pre-flashover or post flashover compartmental fire breach into the EW cavity), promoted ignition and fire spread on all test specimens except the sarking tested. This base ignition source enabled investigation in the differences of reaction-to-fire behaviour, HRR, cavity temperature and radiant heat between tested materials by being sufficiently severe enough to promote fire spread.
- Methylated spirits tray fire size of ~6-8kW was a comparable sized ignition source to FM Global Cavity Fire test study gas burner ignition source. This is a slightly larger fire compared to smaller point ignition size fires (such as match sized flames, an electrical or welding spark) and is adequate in identifying poor performing materials. In this study the methylated spirits tray ignition source did not promote fire spread for most materials (except for paper facing on phenolic board and some limited spread on PIR). In the FM Global Cavity Fire test a similar sized ignition source did promote fire spread on different materials (such as XPS which was not stated to be fire retarded with HBCD). This ignition source represented a minimum size, suitable for discriminating fire spread on poorer performing, non-fire retarded combustible insulation.
- The sensitivity ignition source (two tray heptane fire) did not reveal a significant change in HRR or reaction-to-fire behaviour in comparison to one tray heptane tests of the same material. The fire size created by the one tray heptane fire tests were enough to show significant spread (as mentioned above). The two-tray heptane fire alone (within a non-combustible cavity with no insulation) experienced full height flame with intermittent flaming witnessed at top of rig. This behaviour would class a two-tray heptane fire as being too severe and not suitable for an ignition source for this intermediate scale test.
- The Cavity fire test rig design was practical representation of an EW cavity. The 2.4m high and 1.2m wide parallel panel arrangement, with a closed base and top was adequate in simulating similar air flow within a well-ventilated cavity. Ventilation conditions of EW cavities depends on construction and design of the EWS and can vary greatly from building to building however a well-ventilated cavity may represent a worst-case scenario.

The intermediate-scale Cavity Test is an elevated fire risk assessment tool that provides more realistic HRR and fire spread behaviour to current small-scale test methods namely due to the size and type of ignition source, and representation of end use conditions. In Australia, small-scale test methods such as AS1530.2 and AS1530.3 are used to control reaction-to-fire behaviour of cavity materials:

- AS1530.2 Flammability Test - uses small pilot flame to ignite vertically strips of materials to measure rate of fire spread. The test is used to rank sarking and some insulations (by allocating a Flammability Index) for regulatory purposes.
- AS1530.3 Simultaneous determination of ignitibility, flame propagation, heat release and smoke release - applies a relatively low radiant heat source, which is incrementally increased and uses a pilot flame (~15mm flame height) to ignite volatiles in order to rank insulations (and other specified materials) in terms of their Fire Hazards (see Section 3.1.1 for more details).

Both of these tests do not adequately identify and rank thermoplastic insulations that shrink and melt from a heat source and therefore, the potential of flaming molten material to flow and spread laterally within the base of cavity (behaviour shown within the intermediate scale test method) is not captured from these small-scale test methods. The radiant heat conditions of AS1530.3 does not simulate radiant heat feedback that may occur within a cavity, nor radiant heat feedback potential of pool fire (created by molten material).

Currently, large-scale EW test methods, such as AS5113:2016, provide the most reliable assessment of exterior wall fire performance and provide industry with an avenue to seek compliance to the NCC, however they are very expensive and onerous to conduct. Large-scale test methods incorporate cavity materials in combination with external wall cladding to assess the fire performance of complete systems. For cases where the external wall cladding either,

a) supports rapid fire spread and dictates overall outcome or
b) is non-combustible and securely encapsulates the combustible cavity materials beneath,

the large-scale test method may not identify reaction-to-fire behaviour of cavity materials that can otherwise be understood, when exposed to a test method specifically designed to represent cavity fire scenarios.

Furthermore, outcomes of large-scale test methods are only applicable to the complete EWS tested. Intermediate scale tests are not commonly used to assess material or system fire performance for regulatory purposes, however, have scope to produce further fire test data to either extend full-scale outcomes, or screen poor performing materials or systems. The intermediate scale cavity fire spread test method presented in this study addresses a gap in understanding and assessing fire behaviour of cavity materials that is not currently addressed by either the small-scale tests or the full-scale façade tests. FM Global’s Cavity Fire Test method is the only standardised intermediate scale test method used to simulate cavity fire scenarios where the performance criteria is used to support certification (FM Approvals) issued by FM Global to provide third party insurance for building owners.

Recommendations for future research

In summary, this experimental study has applied different test parameters compared to FM Global Cavity Fire test, which include:

- Liquid fuel based ignition source,
- Main cavity width of 65mm (a 130mm cavity width was used to conduct Cavity Rig characterisation tests only),

- Varying ignition size (base, reduced and sensitivity scales) and
- Four insulation types (with and without protective facing), ranging from poor to good fire performance and one type of foil faced polypropylene sarking.

to study the influence of these parameters on test outcomes and has provided valuable data on fire performance and behaviour of combustible insulations within an EWS that is otherwise non-combustible.

Further Research into developing the Cavity Fire Test method may consider the following:

- **Fuel trays ignition source produced varied HRR.** Fuel trays were used in this study as a simple and practical ignition source. The burn rate of fuel within the tray was highly dependent on the surrounding environment. Factors such as the amount of ventilation and smoke influenced the radiant heat feedback to the tray, in turn dictated the burn rate of fuel. The FM Global Cavity Test method used a sand burner where the gas can be controlled to deliver a consistent HRR for the duration of the experiment. Use of a mass flow controlled, adjustable gas burner for any future research can allow for better control of the ignition source, and assist in further experimentation of fire sizes in between ~5kW, 80kW and 200kW; the discrete ignition sizes offered by fuels in this experimental study.

- **Cavity Test methods using lightweight timber stud construction** – Timber is another combustible material commonly found in EW cavities of buildings of low-rise construction. An experimental series that examines the burning behaviour of timber, in combination with insulations and/or sarking within a cavity may provide some useful insights. As timber can char and form a protective layer at ~300℃, it is likely possible that an ignition source equal to or greater than the 1 tray heptane (base scale) will be necessary to initiate fire spread.

- **Development of test Acceptance Criteria** – This experimental study has not focused on developing suitable acceptance criteria for this cavity fire test method. The aims of this study were to understand and investigate fire behaviours of typical combustible materials under varying test parameters at an intermediate scale.

  The FM Global Cavity Fire test study concluded that cavity fire materials that achieve; **a)** a peak HRR of <100kW and **b)** do not have a visible flame height of ≥1.8m, demonstrate good performance - when tested to an ignition source similar to the size and exposure conditions produced by the methylated spirits fire, used in the experimental study. All materials exposed to a methylated spirits fire in this experimental study did not experience fire spread beyond 1.8m or had a peak HRR 100kW and thus would pass the acceptance criteria set by the FM Global test method.

  Extruded polystyrene (XPS) performed poorly under the FM Global Cavity fire test. Fire retardancy of the XPS tested was not stated and given the result, it is possible that it did not contain a fire-retardant additive. However, EPS (an almost identical material to XPS in terms of material composition and reaction-to-fire behaviour) performed well under this experimental study and was likely to contain a HBCD based fire retardant. It is evident that variability in fire behaviour and fire performance exists between materials that are classed as similar or identical in terms of material composition and/or reaction-to-fire behaviour. Thus, to accommodate for this variability, formulation of performance criteria may require the following steps:

a) Test a significant variety of combustible cavity materials to the intermediate scale cavity fire test method,

b) Test the same materials under AS1530.2 and AS1530.3 small-scale test method and evaluate ranking of these materials under these standards,

c) Compare the ranking of these materials to outcomes of the intermediate scale Cavity fire test method,

d) Other small scale test methods such as AS3837 Cone calorimeter can be used to provide useful material fire performance data to extend understanding and

e) Based on the above analysis, develop acceptance criteria for the Cavity fire test method based on either:

   - height of flame spread and/or
   - peak HRR reached and/or
   - in conjunction with temperature and radiant heat measurements.

Alternatively, a test method that adopts a two or more ignition sizes may rank materials by assigning a classification where the allocated classification will dictate extent of end-use application in an EWS. A classification system is proposed for the large-scale European Harmonised Façade Test method – see Section B.3.1, under Appendix B

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Appendix A External Wall Fire Spread

A1 External Wall Fire Spread

There are several avenues or pathways of fire spread on EWS[1]:

1. **Initiating fire events (see** Figure 50**):**

   1.1. Pre or post flashover interior fire breaks out through unprotected openings (such as windows or wall vents)

   1.2. Pre or post flashover interior fire breaks and/or breach the interior wall and breaches into cavity or concealed spaces of an exterior wall,

   1.3. Exterior fire directly impinges on exterior wall (such as large car or bin fire)

   1.4. Exterior building fire radiate heats onto cladding of subject building for a period, supporting spontaneous ignition or

   1.5. Wind driven embers, burning debris and radiant heat from passing bushfire hits exterior wall surface causing ignition.

2. **Once ignition is established, there are several avenues of fire growth and spread within the external wall system:**

   2.1. Fire can spread up surface of combustible cladding,

   2.2. Incident radiant heat can damage and/or delaminate the cladding surface causing fire spread to cladding core,

   2.3. Fire spread up wall cavity and/or penetrate through to exterior surface of cladding or

   2.4. Fire spread to combustible items stored on balconies such as outdoor furniture.

3. **Once fully established, an advanced external wall fire can spread further by:**

   3.1. Re-entering floors above the compartment of fire origin via unprotected openings such as windows or vents and/or

   3.2. Falling flaming debris that ignite combustible cladding below the compartment of fire origin.

The presence of combustible materials, wind and network of cavities can accelerate fire spread up an EWS. Fire can cause secondary fires to floor above or below the compartment of origin, (via unprotected openings such as windows or vents or falling flaming debris respectively (refer to Figure 50).

The most credible worst-case external wall fire scenario are a post flashover interior fire[63, 64] breaking out and emitting flames onto the exterior cladding surface. It is for this reason that most full-scale façade standards simulate compartmental post flashover fire attack.

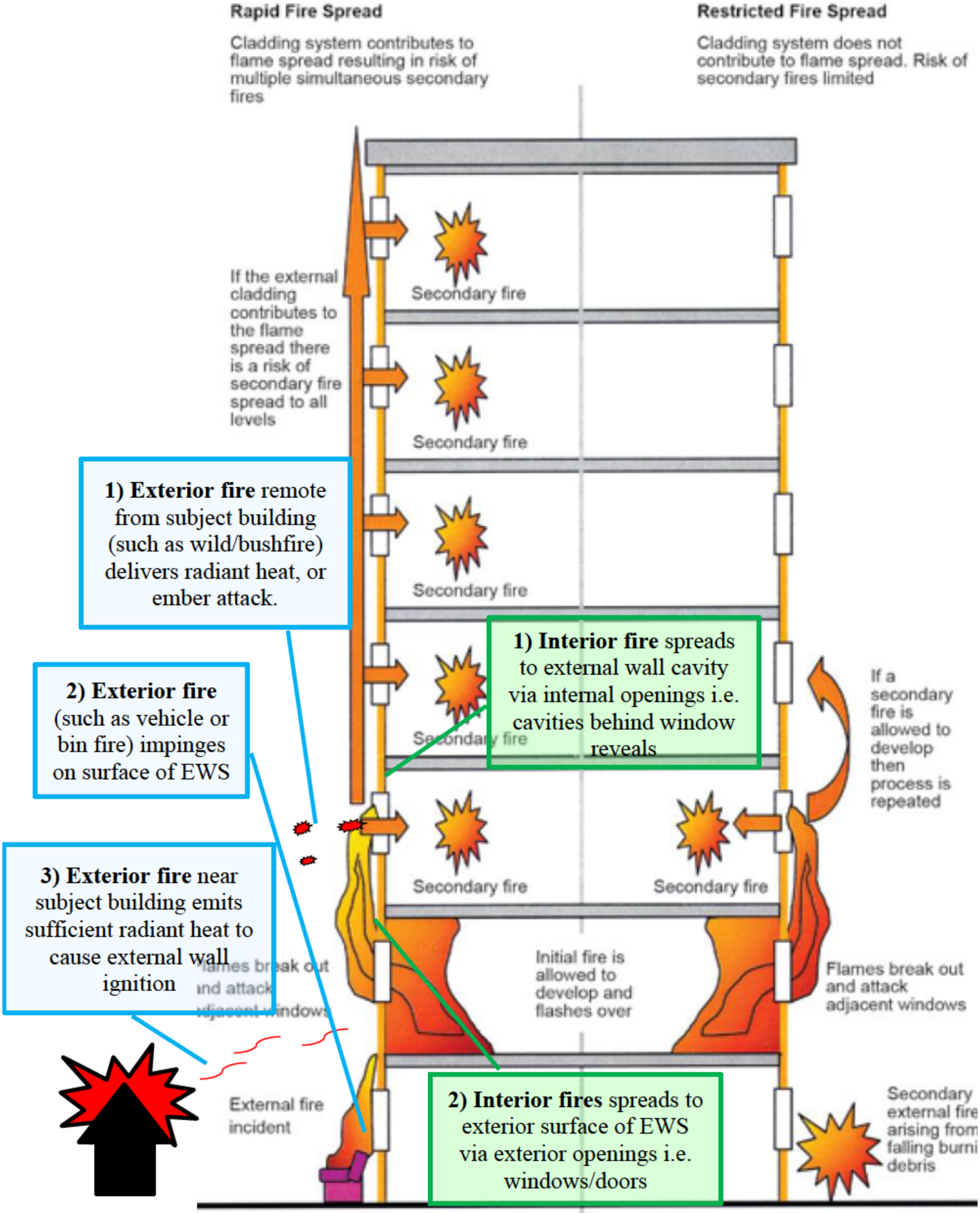


Figure 50: External wall sources of ignition that can occur within interior (green) or exterior (blue) of building. General image shows risk of rapid-fire spread (due to presence of combustible cladding) vs. restricted fire spread (limited to no combustible cladding present).

Vertical fire spread up the EWS can occur in the absence of any combustible components. Flames emitting from an opening of a post-flashover compartment fire can cause secondary interior fire by shattering the window (opening) located on the next level above. This phenomenon is referred to as 'leap frogging', or floor-to-floor fire spread via openings.

Appendix B Fire Test Methods

B1 Small-scale Testing Methods

The table below summarises the most common small-scale testing methods to classify building materials including materials within external walls.

Table 41: List of small-scale fire test methods applicable for external wall materials

Fire Characteristic Measured	Test Standards	Brief Description	Comments
Combustibility	**AS 1530.1**, ISO 1182, EN ISO 1182, BS 476 part 4, ASTM E2652, ASTM E136	Combustibility tests are similar in design to AS 1530.1 standard, Temperature exposure between tests are either 750°C or 835 °C with mass loss criteria not always applied.	Materials deemed combustible (such as plasterboard) are permitted to be used in areas of the building requiring non-combustible materials. Although deemed combustible they are shown not to significantly contribute to fire growth and spread.
Limited Combustibility	EN 13501-1 Class A2: EN1182, EN 120 1716 and EN 13823	Specimens are subjected to 750°C in small tube furnace with measurements taken to determine test criteria as above.	Used in UK Approved Documents B to classify materials with Limited Combustibility.
Heat Release rate (Cone Calorimeter). Other measurements include mas loss rate, effective heat of	ISO 5660, ASTM E 1354 and AS/ NZS 3837	A conical shaped radiator imposes radiant heat (between 0-100kW/m^2) on a 100mmx100mm square specimen. Flow, temperature, CO, CO_2	Measurement outcomes provide an indication of material performance only (as cone calorimeter does not represent complexities of real fire

Fire Characteristic Measured	**Test Standards**	**Brief Description**	**Comments**
combustion and smoke production.		&O_2concentration and smoke optical density of the combustion gases help calculate heat release rate, mass loss, effective heat of combustion and smoke production.	exposure conditions). Only the outer surface of material is exposed making it difficult to assess true behaviour of multi-layered, composite materials that may include protective outer layer.
Fire Propagation Test (UK)	BS476 part 6	255mm square by up to 50mm thick is heated within a combustion chamber. A gas tube burner is applied to the bottom of the specimen for 20 minutes. The measured gas temperatures are compared to a non-combustible material to derive a Fire Propagation index.	Used to determine flame propagation properties of internal wall linings.
Surface Spread of Flame	BS 476 part 7	925mm x 280 wide specimens, up to 50mm thick is vertically mounted on a frame perpendicular to 900mm square gas fired radiant heat panel.	Used to measure propensity of materials to support lateral flame spread.
Gross Calorific Value	NFPA 259 - Potential heat of building products	Materials placed either in a muffle furnace (a front-loading, insulated boxed oven) at 750°C for 2 hours. Unconsumed material is placed into bomb	

Fire Characteristic Measured	Test Standards	Brief Description	Comments
		calorimeter to determine heat of residue.	
Small Flame Screening Tests	ASTM D 635, UL94, IEC 60707, IEC 60695-11, IEC 60695-11-20, ISO 9773, EN11925-2 and **AS 1530.2 Flammability Test**		Flame was originally used as a quick and cheap means of testing materials for ignitability and ability to sustain flaming. Complexities between test standards vary.

B.1.1 EN13501-1 European Reaction-to-fire Classification for Internal Wall Linings – Europe and UK

EN13501-1 test standard utilised four tests used to classify non-flooring linings in buildings are described in Table 42 below.

Table 42: Euro class Test methods used to classify internal wall linings - that is extended to External Wall systems

Test Method	Description	Scale
ISO 1182 - Non-combustibility Test	Similar to AS1530.1 and other combustibility test methods (see The table below summarises the most common small-scale testing methods to classify building materials including materials within external walls. Table 41)	Small
EN ISO 1716 – Gross Calorific value	A small-scale test using bomb calorimeter housing a specified mass of the grounded specimen is ignited to measure the heat of combustion (total calorific value) of the material. The test identifies	Small

	the potential heat release of a material when completely burnt.	
EN ISO 11925-2 Small Flame Test	Similar to AS1530.2 and other small flame test methods (see The table below summarises the most common small-scale testing methods to classify building materials including materials within external walls. Table 41). Specimens are exposed to a propane flame for either 15 or 30 seconds. Outcomes such as established ignition (flame ignition is >3s), distance of flame spread (flame tip reaches above 150mm from point of flame application) and the time in which this occurs are recorded.	Small
EN 13823 Single Burning Item (SBI)	A 30kW gas burner is placed in the corner of a 1m (W) by 1.5m (H) long wing wall and 0.49m (W) by 1.5m (H) short wing wall. The setup is under an exhaust hood fitted with oxygen consumption calorimeter. Total test period is 21 minutes and observations of flame spread and material behaviours are noted. HRR (kW), total HR (MJ) and smoke production rate (m^2/s) are recorded.	Intermediate

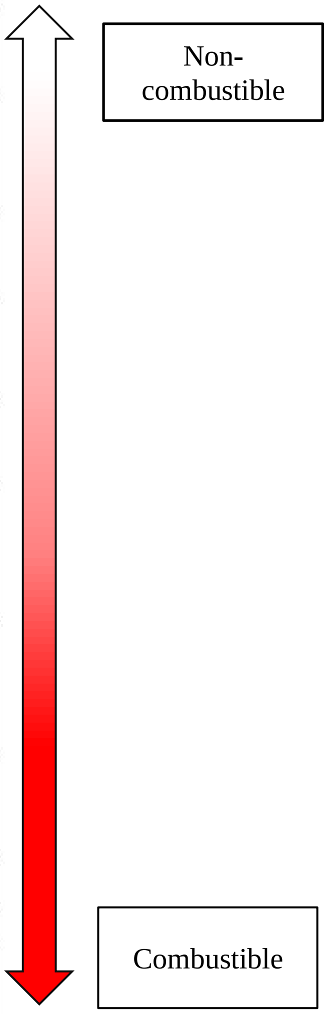
The outcomes of the above four tests are used to classify the material as per Table 43.

EN 13823 SBI test method is used to classify materials from A2 (limited combustibility) to D. An Aluminium Composite Panels (ACP) core categorised under the Insurance Council of Australia (ICA) risk category ‘C’ (core with an inert mineral filler content percentage of 93-99%) can be deemed equivalent to EN 13501-1 classification of ‘A2’ – limited classification. Specimen core with ICA Category D (ACP core with 100% inert mineral filler) can have the equivalent EN 13501-1 classification of ‘A1’ non-combustible.

Table 43: EN 13501-1 Classification of non-floor lining construction material

Class	Test method(s)	Classification criteria	Additional classification
A1	EN ISO 1182 [a] and	$\Delta T \leq 30$ °C; and $\Delta m \leq 50$ %; and $t_f = 0$ (i.e. no sustained flaming)	-
	EN ISO 1716	$PCS \leq 2{,}0$ MJ/kg [a] and $PCS \leq 2{,}0$ MJ/kg [b c] and $PCS \leq 1{,}4$ MJ/m^2 [d] and $PCS \leq 2{,}0$ MJ/kg [e]	-
A2	EN ISO 1182 [a] or	$\Delta T \leq 50$ °C; and $\Delta m \leq 50$ %; and $t_f \leq 20$ s	-
	EN ISO 1716 and	$PCS \leq 3{,}0$ MJ/kg [a] and $PCS \leq 4{,}0$ MJ/m^2 [b] and $PCS \leq 4{,}0$ MJ/m^2 [d] and $PCS \leq 3{,}0$ MJ/kg [e]	-
	EN 13823	$FIGRA \leq 120$ W/s and LFS < edge of specimen and $THR_{600s} \leq 7{,}5$ MJ	Smoke production [f] and Flaming droplets/particles [g]
B	EN 13823 and	$FIGRA \leq 120$ W/s and LFS < edge of specimen and $THR_{600s} \leq 7{,}5$ MJ	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i]: Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
C	EN 13823 and	$FIGRA \leq 250$ W/s and LFS < edge of specimen and $THR_{600s} \leq 15$ MJ	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i]: Exposure = 30 s	$F_s \leq 150$mm within 60 s	
D	EN 13823 and	$FIGRA \leq 750$ W/s	Smoke production [f] and Flaming droplets/particles [g]
	EN ISO 11925-2 [i]: Exposure = 30 s	$F_s \leq 150$ mm within 60 s	
E	EN ISO 11925-2 [i]: Exposure = 15 s	$F_s \leq 150$ mm within 20 s	Flaming droplets/particles [h]
F	No performance determined		

[a] For homogeneous products and substantial components of non-homogeneous products.
[b] For any external non-substantial component of non-homogeneous products.
[c] Alternatively, any external non-substantial component having a $PCS \leq 2{,}0$ MJ/m^2, provided that the product satisfies the following criteria of EN 13823: $FIGRA \leq 20$ W/s, and LFS < edge of specimen, and $THR_{600s} \leq 4{,}0$ MJ, and s1, and d0.
[d] For any internal non-substantial component of non-homogeneous products.
[e] For the product as a whole.
[f] In the last phase of the development of the test procedure, modifications of the smoke measurement system have been
introduced, the effect of which needs further investigation. This may result in a modification of the limit values and/or parameters for the evaluation of the smoke production.
s1 = $SMOGRA \leq 30$m^2/s^2 and $TSP_{600s} \leq 50$m^2; **s2** = $SMOGRA \leq 180$m^2/s^2 and $TSP_{600s} \leq 200$m^2; **s3** = not s1 or s2
[g] **d0** = No flaming droplets/ particles in EN 13823 within 600 s;
d1 = no flaming droplets/ particles persisting longer than 10 s in EN 13823 within 600 s;
d2 = not d0 or d1.
Ignition of the paper in EN ISO 11925-2 results in a d2 classification.
[h] Pass = no ignition of the paper (no classification);
Fail = ignition of the paper (**d2** classification).
[i] Under conditions of surface flame attack and, if appropriate to the end–use application of the product, edge flame attack.



B2 AS5113.1 Large-scale Façade Test (Australia)

External Wall Classification

A timber crib of dimensions ~ 1.5m W x 1m D x 1m H is assembled using either Pinus sylvestris or Pinus radiata wood. The crib has a nominal heat output of 4500 MJ in 30 minutes and a peak HRR of 3±0.5 MW. The base of the crib is offset from the ground by ~ 400mm.

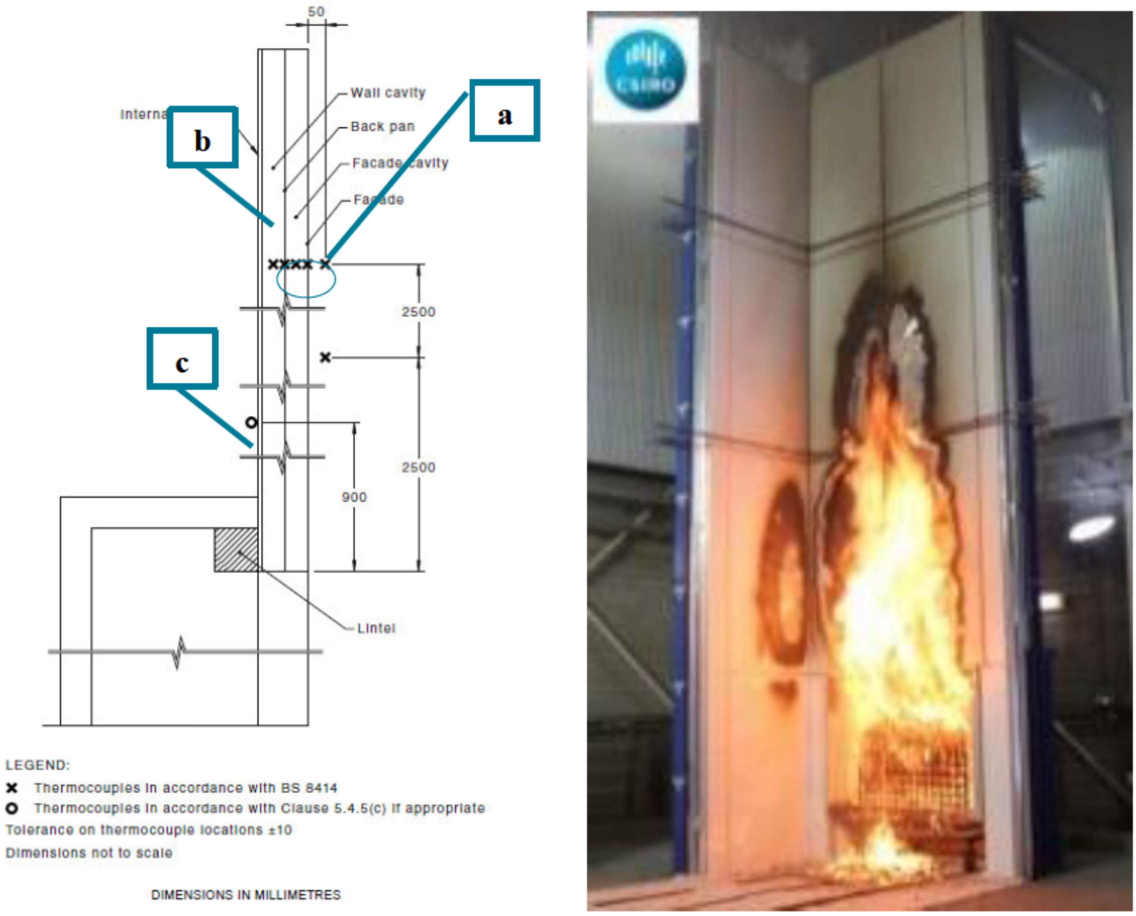


Figure 51: Cross-section of AS 5113.1 test rig, based on BS8414 (left) showing measurement requirements (see below) and BS8414 test rig at CSIRO laboratories (right)

The performance criteria for EWS tested using the BS 8414 rig under AS 5113 test standards is presented in the Table 44 below.

Table 44: Performance criteria for EW classification

Requirement	Element of measurement	Exact location	Measurement
a	Cladding surface	5m above opening, 50mm from cladding surface	Temperature shall not exceed 600°C for continuous period of 30s
b	Cavity or any combustible layer	5m above opening, at mid depth	Temperature shall not exceed 250°C for continuous period of 30s
c	Unexposed surface – for a EWS not attached to a wall required to have an	900mm above opening	Temperature difference shall not be >180K.

	FRL -/30/30 or FRL 30/30/30		
d	Unexposed surface – for a EWS not attached to a wall required to have an FRL -/30/30 or FRL 30/30/30	Area above opening	No flaming or openings to unexposed surface shall be observed.
e	Entire surface area and layers within EWS	-	Flame damage examined post-test must not occur past the minimum dimensions of the test specimen (as defined in BS8414). This includes melting and charring but does not include discolouration due to smoke.
f	Falling debris	-	Continuous burning of fallen debris >20s shall not occur
g	Mass of fallen debris	-	Post-test total mass of fallen debris <2kg.

All performance criteria must be met in order for the tested specimen to pass. These requirements are more stringent than that presented in UK's Building Research Establishment 135 (BRE 135) criteria applied to BS 8414 test.

B3 European Harmonisation Façade Test Method[46, 65]

A need to harmonise these requirements in order to streamline compliance and the introduction of products between countries was realised. In 2016, the Standing Committee of Construction (SCC) commenced a project to develop a common approach to test and assess fire performance of external wall systems. The initial stages of the project focussed on collecting existing regulatory requirements of all Member states (EU countries invited to submit information) and identifying which countries go beyond EN 13501-1 reaction to fire and fire resistance classification systems. The next stages focussed on establishing a common testing and classification methodology that can be applied to existing regulatory systems of respective EU countries that included:

- Two test method and classification of external wall fire performance to be based on DIN 4102-20 (for medium fire exposure test method) and BS 8414 (for large fire exposure test method). Each scaled test method would be applied to achieve a different façade fire classification level.
- A new classification system that can:
    1. Align with current regulatory requirements and historical experimental data of Member states using DIN 4102-20 or BS414, and
    2. Satisfy additional requirements of Member States that do not use either DIN4102-20 or BS414 test.

A new classification system that can satisfy both 1) and 2) can prove onerous as additional requirements (although optional) can lead to an increased number of tests required to allocate a classification. To fulfil the goal of reducing the number of tests – an **alternative assessment method** is developed. The alternate assessment is optional and will help align regulatory measures in countries that currently do not adopt either DIN 4102-20 or BS 8414. The new **proposed assessment method** will be applied in countries currently using either DIN 4102-20 or BS 8414.

Table 45: Differences between the Proposed Assessment and Alternate Assessment Method

DIFFERENCES IN TEST ASSESSMENT METHODS		
Aspect	**Proposed Assessment Method**	**Alternate Assessment Method**
Fire Scenario	Post-flashover fire scenario simulated in DIN 4102-20 (for medium fire exposure test method) and BS 8414 (for large fire exposure test method). The BS8414 (large scale) fire may simulate external fire impingement scenarios up to a certain fire load – but this needs to be further validated.	Same as Proposed Assessment Method

Size of Rig	Both DIN 4102-20 and BS 8414 test rig dimensions to remain the same. If falling debris is being assessed – then rig must be uplifted/extended to ensure radiation from combustion chamber does not interfere with falling debris.	DIN 4102-20 rig dimensions to be: main wall 3.5 x7.0m and wing wall 1.5 by 7.0m. BS 8414 rig dimensions to be: main wall 3.5 x8.0m and wing wall 1.5 by 8.0m. Heat exposure area is the same for both test methods as combustion chamber height is proportionally smaller for DIN 4102-20 (1m less than BS 8414). In addition to above – test rig needs to uplifted/extended as mentioned for the Proposed Assessment Method.
Fuel and Combustion Chamber	Both elements to remain the same as stated in both DIN 4102-20 and BS 8414 test standard; wood cribs within combustion chamber.	Same as Proposed Assessment Method
Secondary Opening (to assess performance of façade around openings)	Optional.	Mandatory.
Junction Between Façade and Floors (for specific façade systems only) – evaluate risk of fire spread within junction.	Optional.	Optional.
Measurements of Fire Spread	DIN 4102-20 and BS 8414 flame spread measurements to remain the same.	Similar to Proposed Assessment Method but extra thermocouples introduced for horizontal flame spread to replace visual observations.

Test Duration	DIN 4102-20 and BS 8414 test durations to remain the same.	After 22 minutes for DIN 4102-20 and 30 minutes for BS 8414, the combustion chamber will be extinguished. Further observations and measurements will be made; to bring the total test period of 60 minutes for each test.

B.3.1 Classification System

The large fire (LF) classification is attained using BS 8414 test standard and medium fire (MF) classification is attained using DIN 4102-20 test standard. The proposed assessment method contains six different characteristics (see Table 46) with only the type of heat exposure (either medium or large) being mandatory.

LF Large Fire Classifications (36 combinations)

LF	J	W	F1	D0
	NPD	NPD	F2	D1
			NPD	NPD
Example	*LF- NPD -NPD-NPD-NPD*			

MF- Medium Fire Classifications (18 combinations)

MF	S	F1	D0
	NPD	F2	D1
		NPD	NPD
Example	*MF-F-NPD-NPD*		

Table 46: Key for Classifications (Classifications in Asterix are optional)

LF	Large Fire	***F1**	Falling Parts are considered and test outcome successful. Parts are <1kg and0.1m^2
MF	Medium Fire	***F2**	Falling Parts are considered and test outcome successful. Parts are <5kg and 0.4m^2
***J**	Junction between façade and floor	***D0**	Burning debris are considered and test outcome successful. No burning debris.

***W**	If secondary opening (window) is present and test outcome is successful.	***D1**	Burning debris are considered and test outcome successful. Burning duration of debris is <20s.
***S**	Smouldering is considered and test outcome is successful	NPD	

For the Alternate assessment method – only four classifications are proposed.

	Both Flame Spread and Falling Debris requirements fulfilled	Flame Spread requirements fulfilled but not falling parts
Large Exposure	LS1	LS2
Medium Exposure	LS3	LS4

The next step towards harmonisation is to verify and validate all of the above proposed testing and classification characteristics by performing a test round robin.

Appendix C Building Code Reaction-to-fire Requirements

C1 New Zealand

The New Zealand Building Code (NZBC) is also a performance-based code. Section C of the NZBC deals with fire safety and protection, and contains six clauses, two verification methods and seven acceptable solutions based on the occupancy class in all or part of the building.

Document C/AS2 contains Acceptable Solutions for Buildings other than Risk Group SH (detached houses or multiple dwellings with dwelling having own egress path and building is ≤2 units high).

Table 47: Fire Test Methods referenced in NZBC C/AS that applicable for EWS

Test Method	Scale	Building Element	NZBC C/AS2 reference and comments
AS 1530.1: 1994 – Combustibility Test for materials	Small	All materials	Appendix C- Clause C 4.1.1 – defines combustibility of materials as determined under AS1530.1.
EN13501-1 – Group of tests to classify reaction-to fire behaviour	Small/Med	All materials	Clause 5.8.4 - For buildings with a height ≥25m, all elements of the EWS to be non-combustible (in accordance with either EN13501-1 or AS1530.1) or have limited combustibility (EN13501-1). If building EWS is ≥25m and contains some or all combustible components – then it must be tested to a large-scale test (see below).
AS 1530.2:1993 – Test for Flammability of Materials	Small	Flexible fabrics in EWS (may include sarking)	Clause 4.17.8 b) Suspended flexible fabrics (used as underlay to roofing or exterior cladding that is exposed to view) to have flammability index ≤5. It is unclear whether this includes sarking.
AS 1366 – Parts 1-3 (1993) and Part 4 (1989) – Test for Fire Propagation on rigid	Small	Foamed plastics	Clause 4.3 - Foamed plastics must comply with flame propagation criteria specified in AS1366.

Test Method	Scale	Building Element	NZBC C/AS2 reference and comments
cellular plastic sheets for thermal insulation.			These requirements do not apply to damp-proof courses*, seals, caulking, flashings, thermal breaks and ground moisture barriers.
AS/NZ 3837 or ISO 5660.1 Cone Calorimeter Test	Small	Cladding materials	Appendix C – Clause C7.1.1. Cladding materials are defined (in accordance with AS/NZ 3837 or ISO 5660.1) as either: -Type A (achieving Peak HRR of ≤ 100 kW/m^2 and total HR of or ≤ 25 MJ/m^2 within a period of 15 minutes) or - Type B (achieving Peak HRR of ≤ 150 kW/m^2 and total HR of or ≤ 50 MJ/m^2 within a period of 15 minutes)., when exposed to a heat flux of 50 kW/m^2.
Clause 5.8.4 - For buildings with a height ≥25m and EWSs contains all or some parts as combustible; the EWS may be tested to either:			
AS5113:2016	Large	EWS	Achieve EWS classification
BS 8414-1 or BS8414-2	Large	EWS	Satisfies BRE 135 acceptance criteria.
NFPA 285	Large	EWS	Passes

*Damp-proof course is defined in NZBC, document C/AS2 as '*a strip of durable vapour barrier placed between building elements to prevent the passage of moisture from one element to another'[66]*. This can be interpreted to mean any vapour barrier or weatherproof membrane (including sarking) used to protect building elements from moisture damage.

C2 USA

Examples of specific IBC requirements include the following:

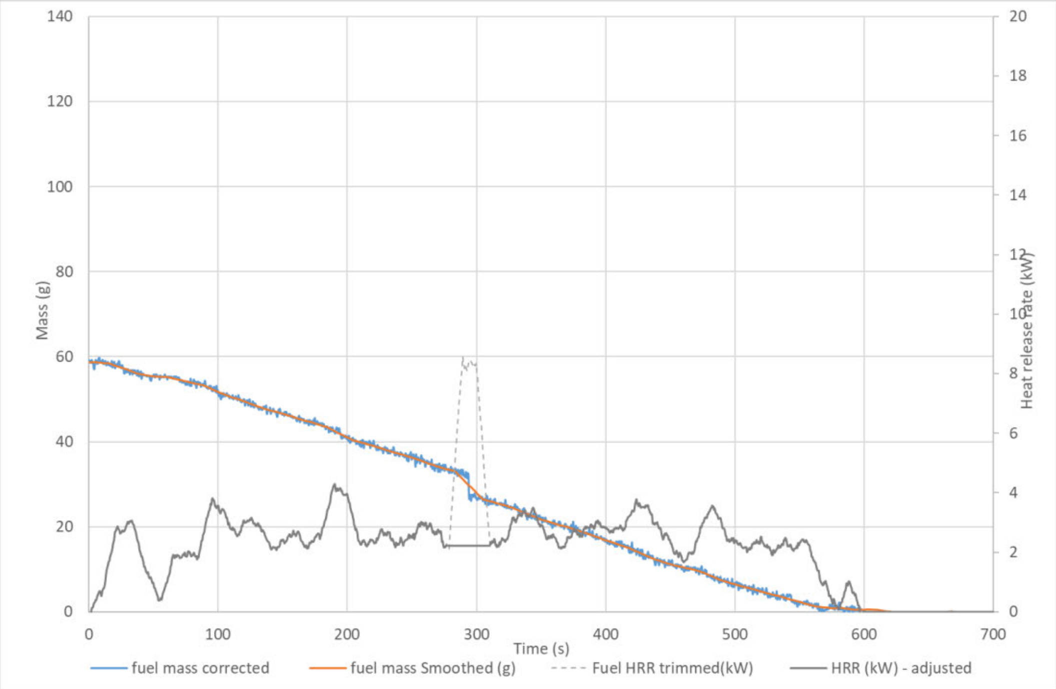
- Flame Spread Index and/or Smoke Developed index is required for all cladding or external wall systems and is determined in accordance with ASTM E84 or UL 723, i.e. Flame spread index of ≤75 and smoke developed index of ≤450 is required for Metal Composite Materials (MCM), such as ACP and High Pressure Laminates (HPL).

- Self-ignition temperature of ≤343℃ is required for MCM and HPLs tested under ASTM D 1929 (a test method used to determine ignition temperatures of plastics).
- Ignition resistance of materials tested in accordance with NFPA 268, specifying critical heat flux that does not clause sustained flaming. Critical heat flux levels are dependent on separation distances i.e., 12.5 kW/m^2 at a separation distance of 1525mm specified for combustible external coverings. Separation distance of 1525mm represents the minimum distance permitted for all cladding/EWS
- Separation of material from interior wall by approved thermal barrier or surface protected by non-combustible material i.e. foam plastic insulations maybe required to have either aluminium (≥0.81mm) or steel lining (≥0.41mm) or separated from building using 12.7mm gypsum board or equivalent (depending on height of application).
- Limitation in coverage of an EWS or a limitation in unprotected openings permitted (whichever is lesser). This requirement is applied to light transmitting plastic walls and MCM cladding.
- Limitation of EWS application in respect to height i.e., combustible coverings are limited to heights 12.192m.
- Installation of fire barriers to afford vertical separation distances between combustible EWS. This is one of many requirements introduced under 'option 2'; for buildings installed with MCM for a maximum height of 22.86m (75ft) or unlimited height if building is sprinkler protected.
- Additional concessions are permitted for sprinkler protected buildings.

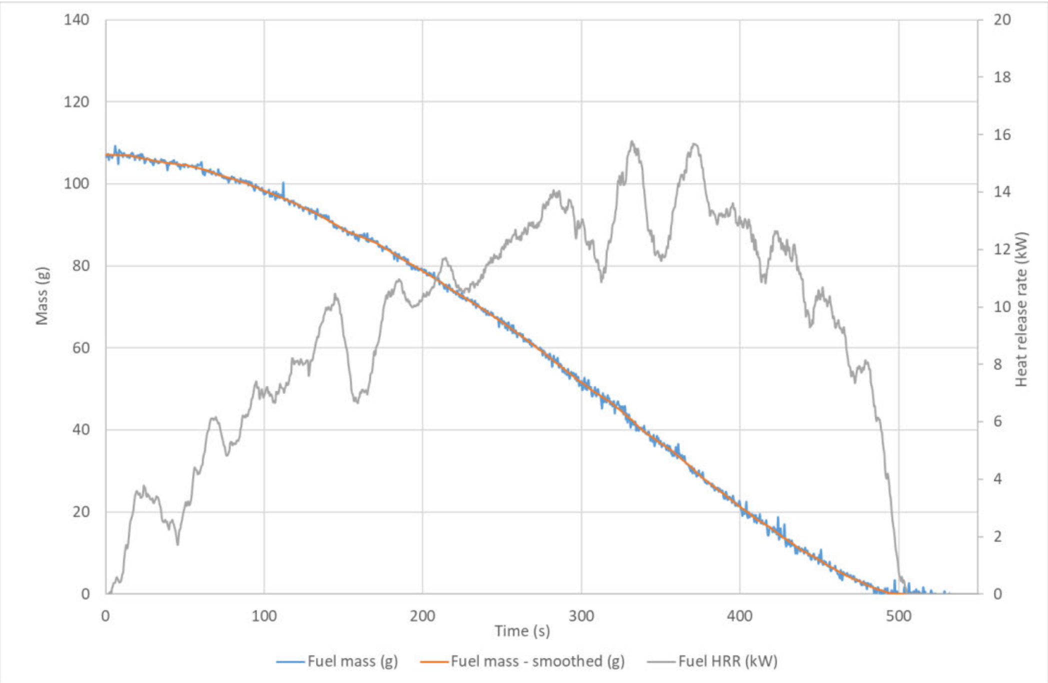
NFPA 5000 generally requires compliance with full scale NFPA 285 regardless of height however like IBC, specific requirements for different types of materials are also stated.

Appendix D - Test Graphs

D1 Test Graphs for Characterisation Tests

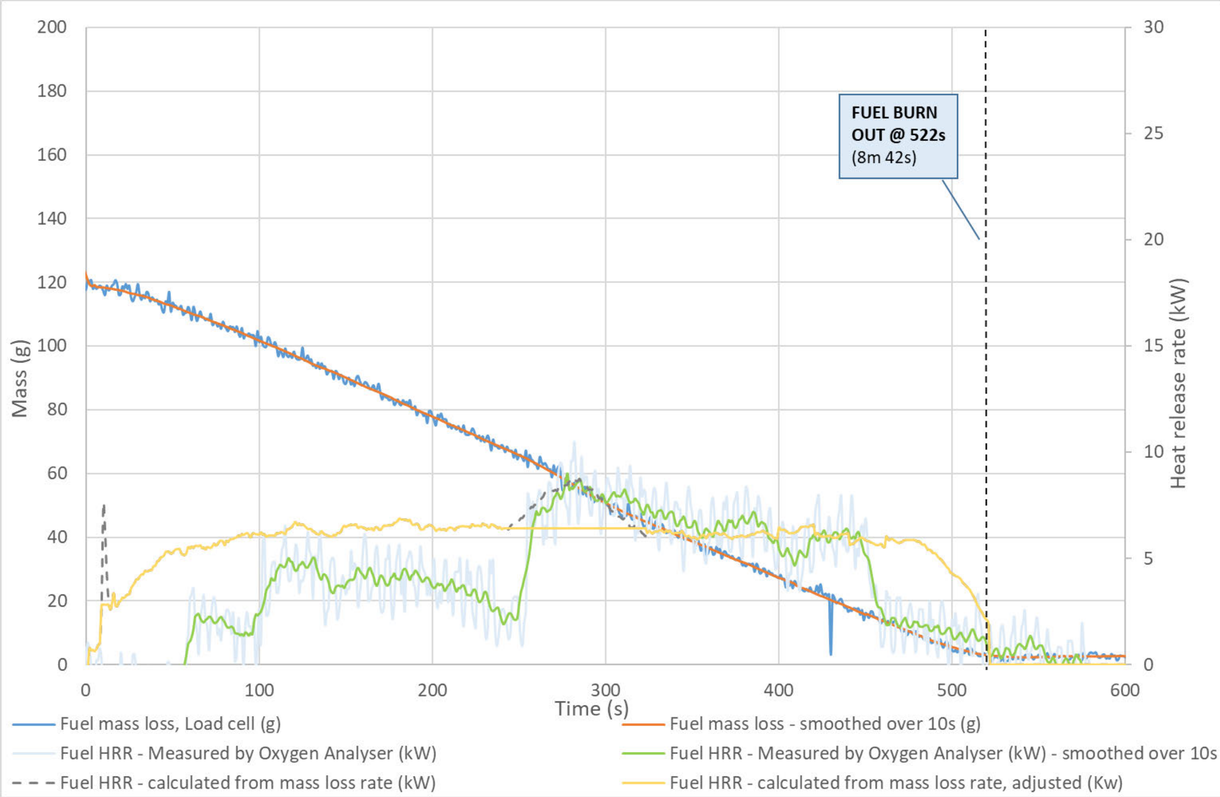


Apx D 1 - Test C1 – HRR graph (measured by mass loss rate) of 1 tray of 60g methylated spirits – burning outside of test rig (open burn)

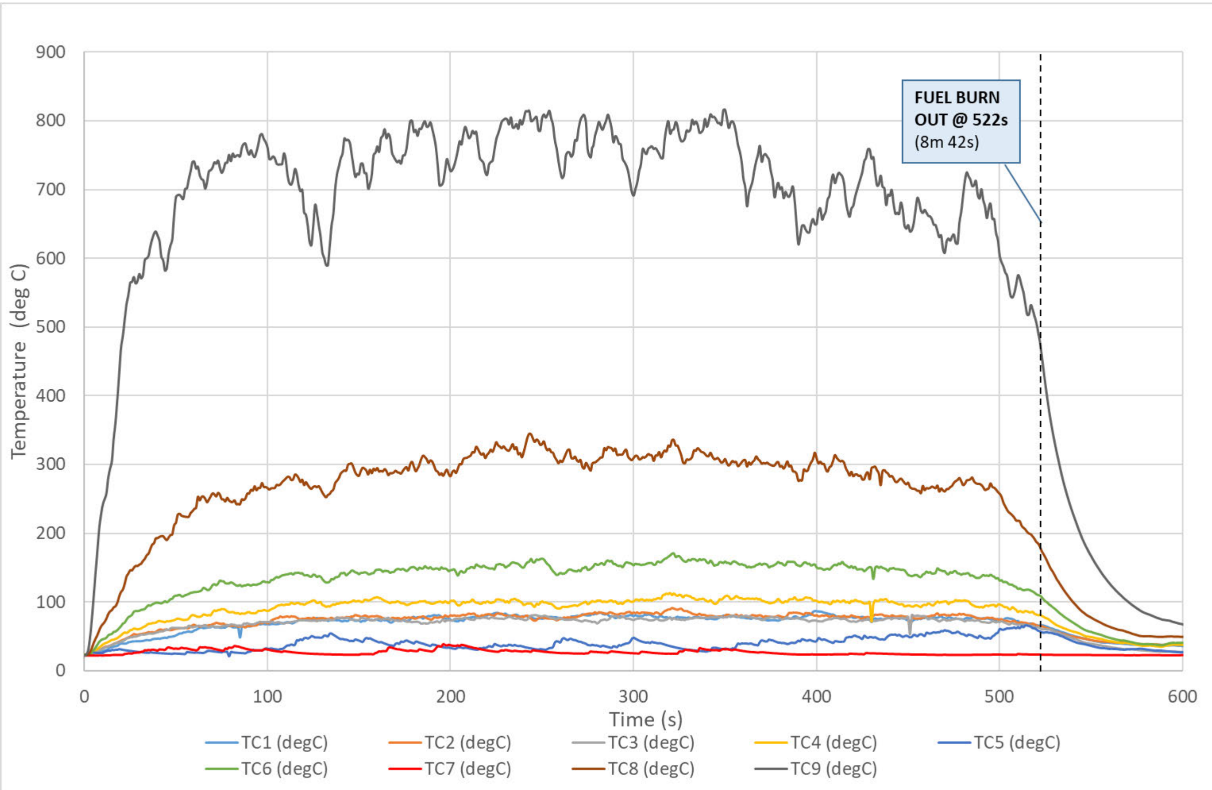


Apx D 2 - Test C2 – HRR graph (measured by mass loss rate) of 1 tray of 100g heptane – burning outside of test rig (open burn)

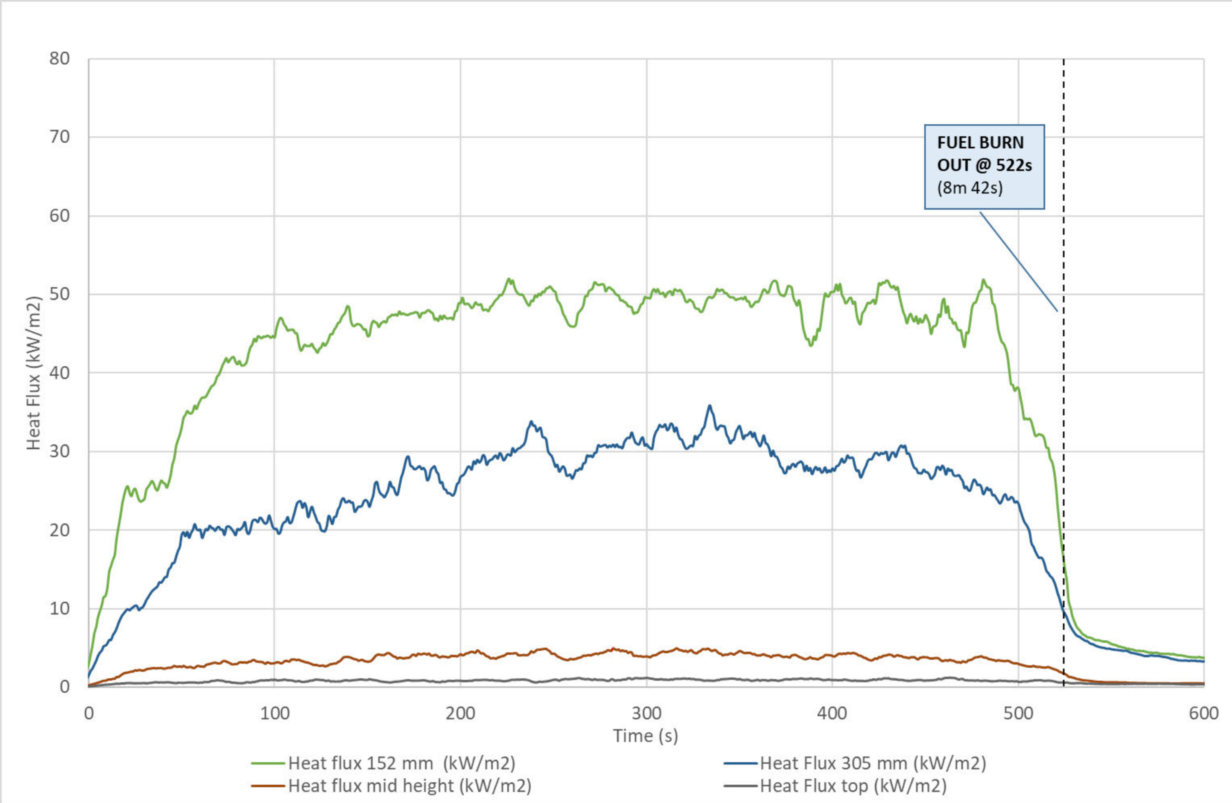
D.1.1 Characterisation Tests – (partial closed cavity base, ~65mm cavity width)



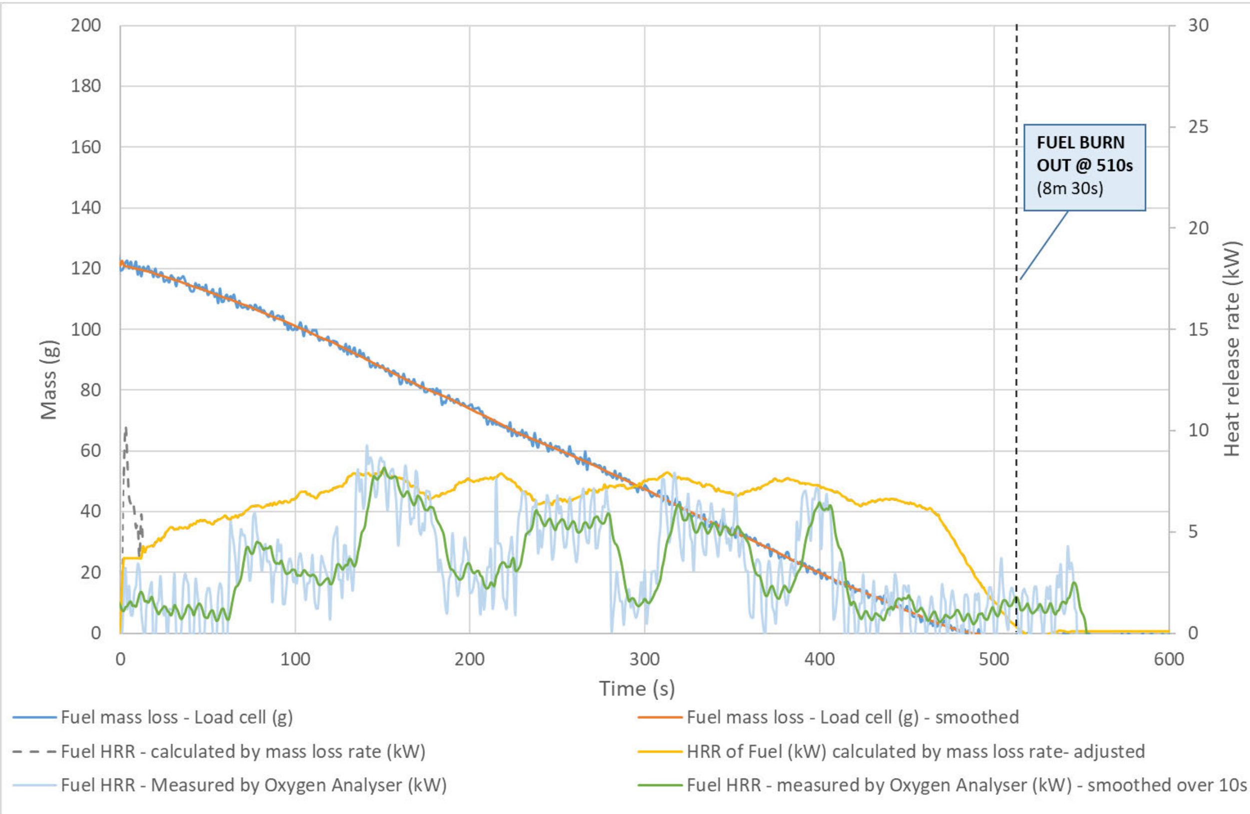
Apx D 3 - Test C3 – HRR graph of 1 tray methylated spirits test, inside rig (~65mm cavity), Test A



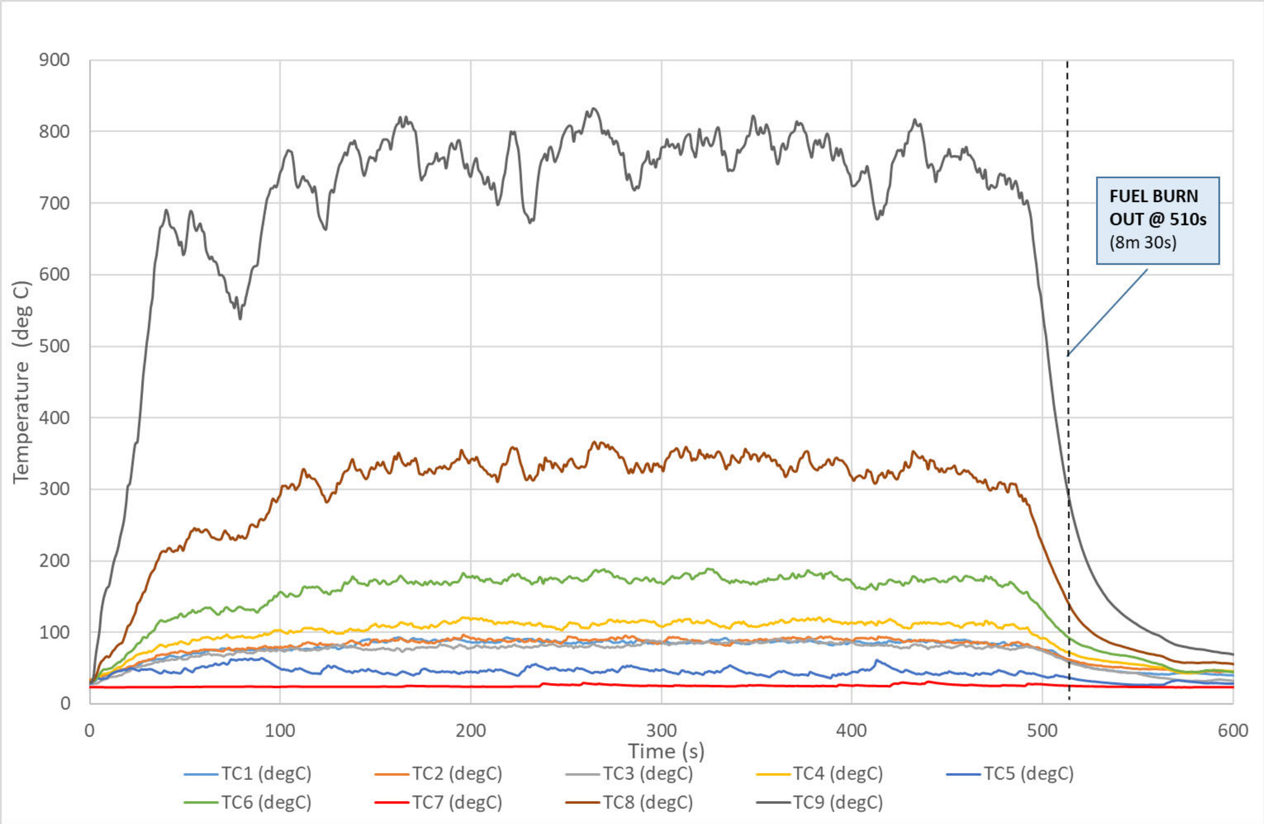
Apx D 4 - Test C3 – Temperature graph of 1 tray methylated spirits test, inside rig (~65mm cavity), Test A



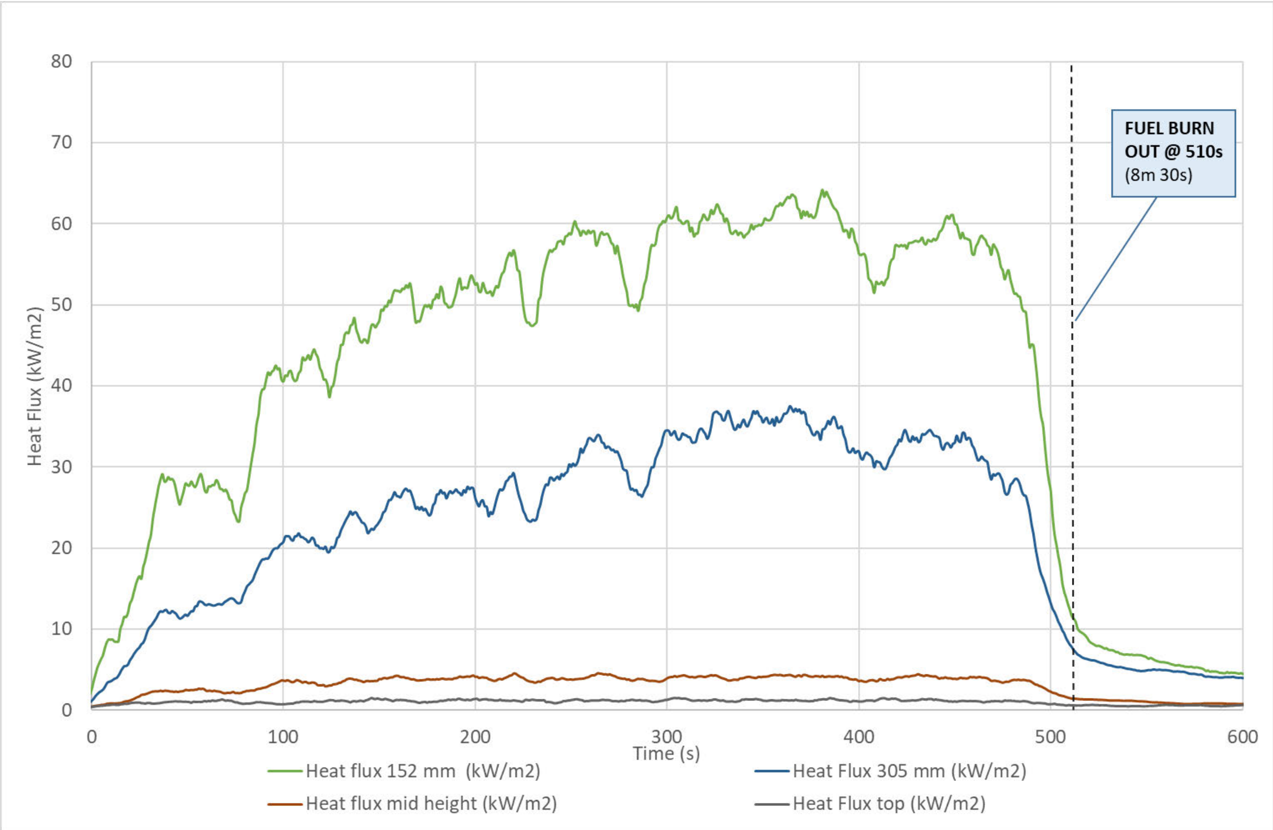
Apx D 5 - Test C3 – Incident heat flux graph of 1 tray methylated spirits test, inside rig (65mm cavity), Test A



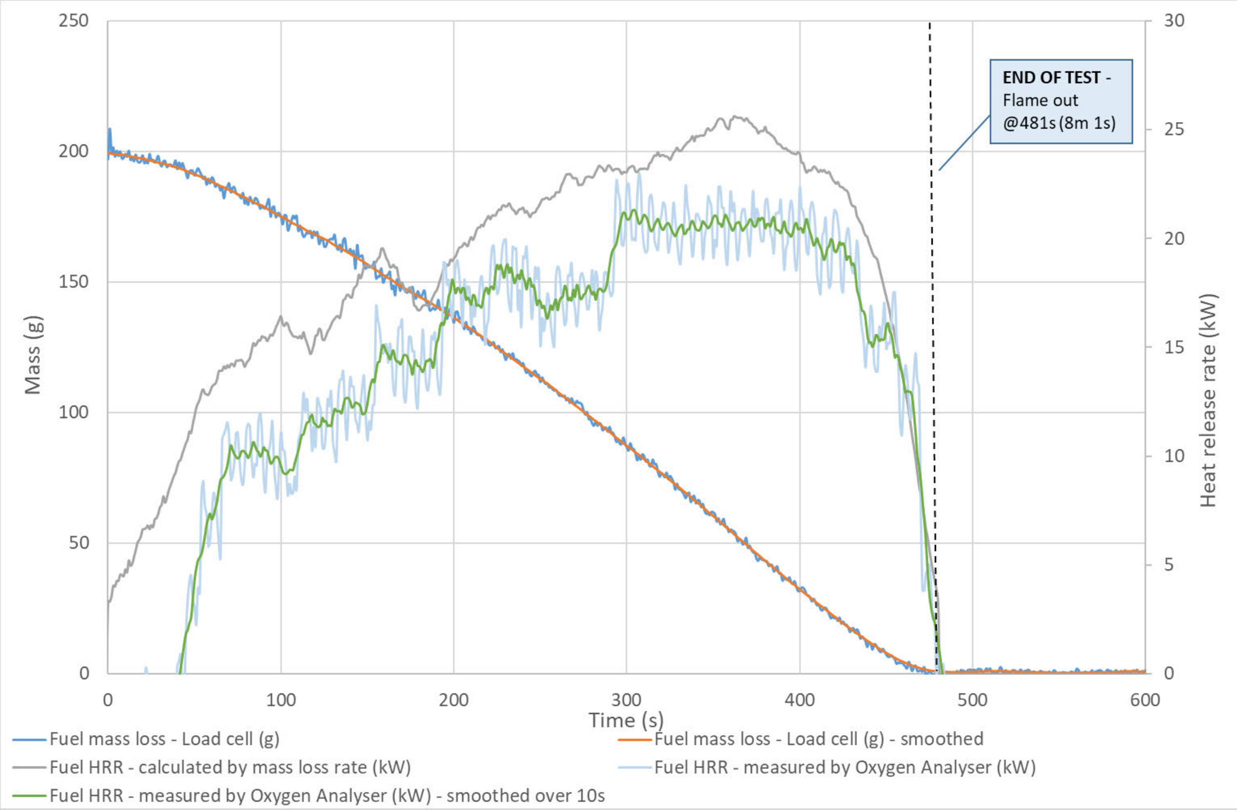
Apx D 6 - Test C4 – HRR graph of 1 tray methylated spirits test, inside rig (~65mm cavity), Test B



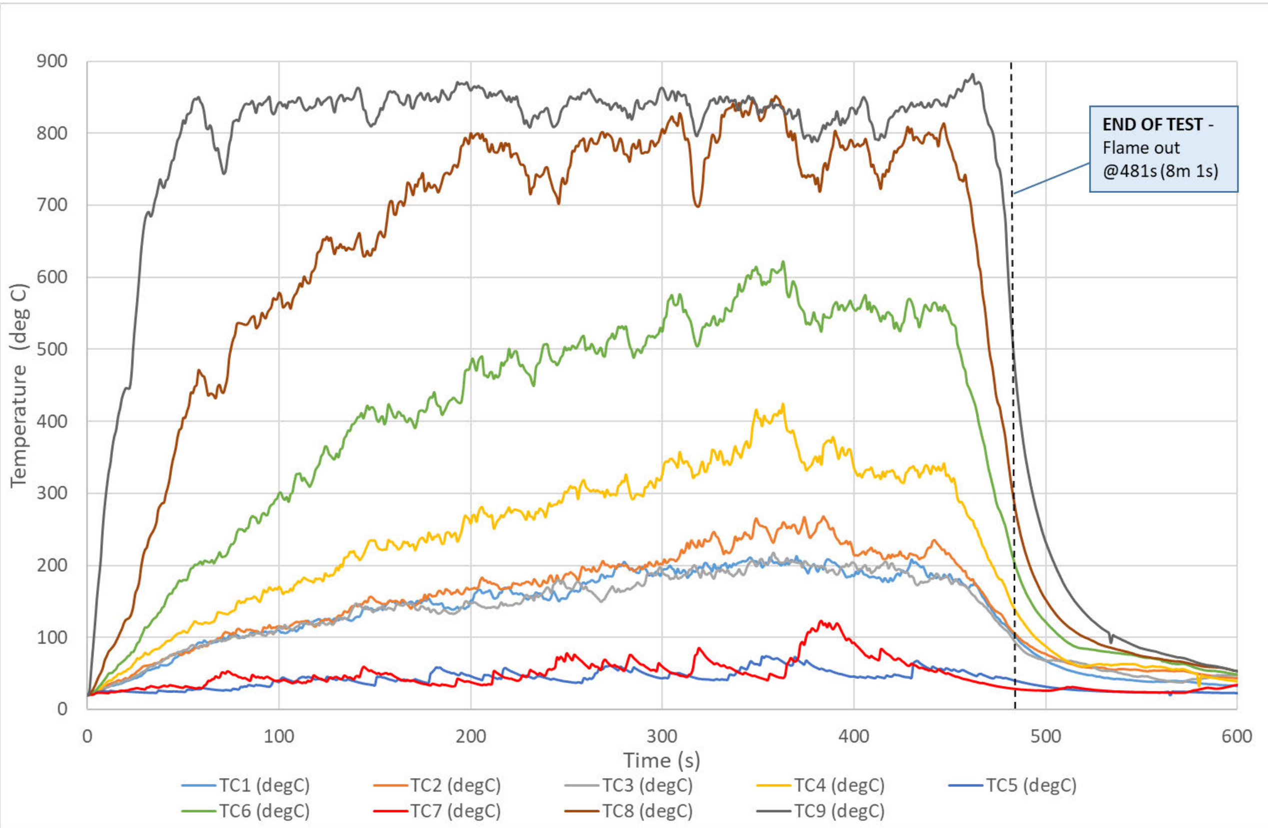
Apx D 7 - Test C4 – Temperature graph of 1 tray methylated spirits test, inside rig (~65mm cavity), Test B



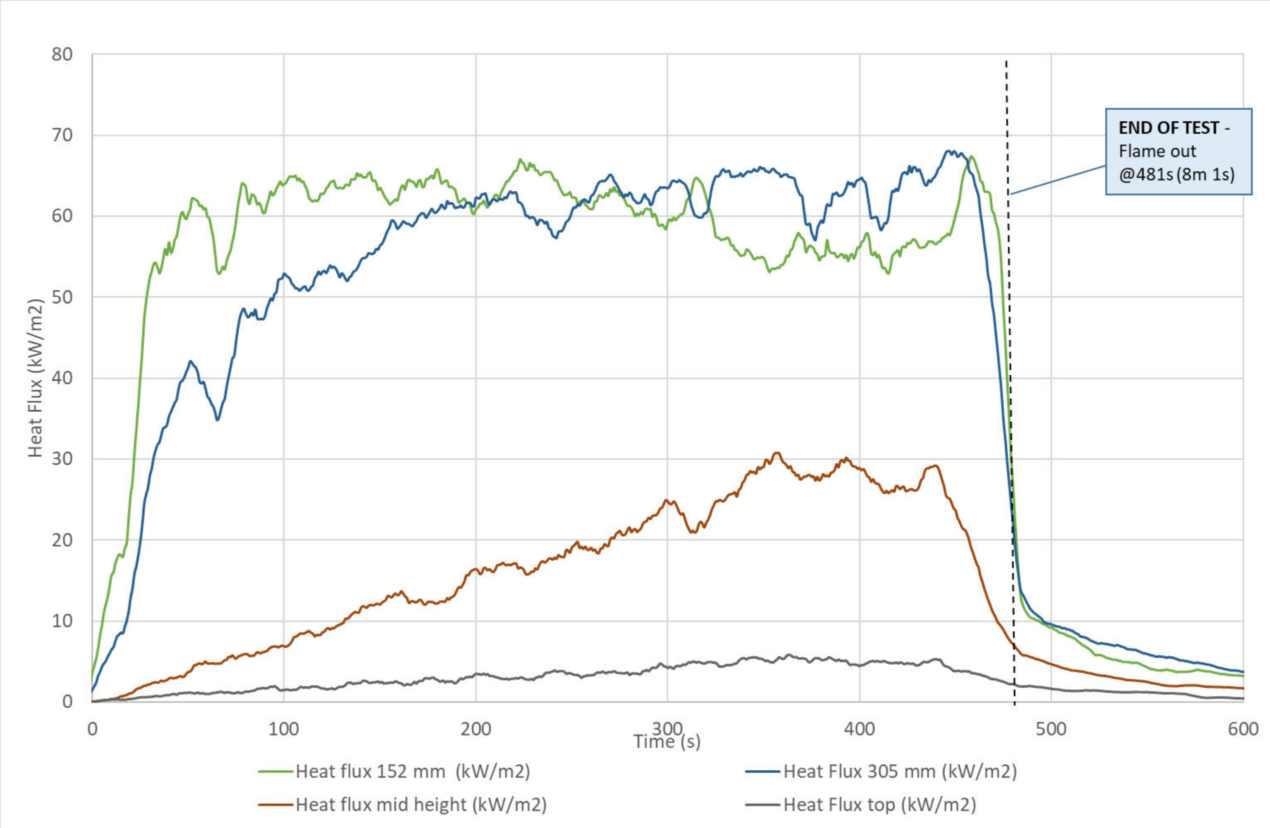
Apx D 8 - Test C4 – Incident heat flux graph of 1 tray methylated spirits test, inside rig (~65mm cavity), Test B



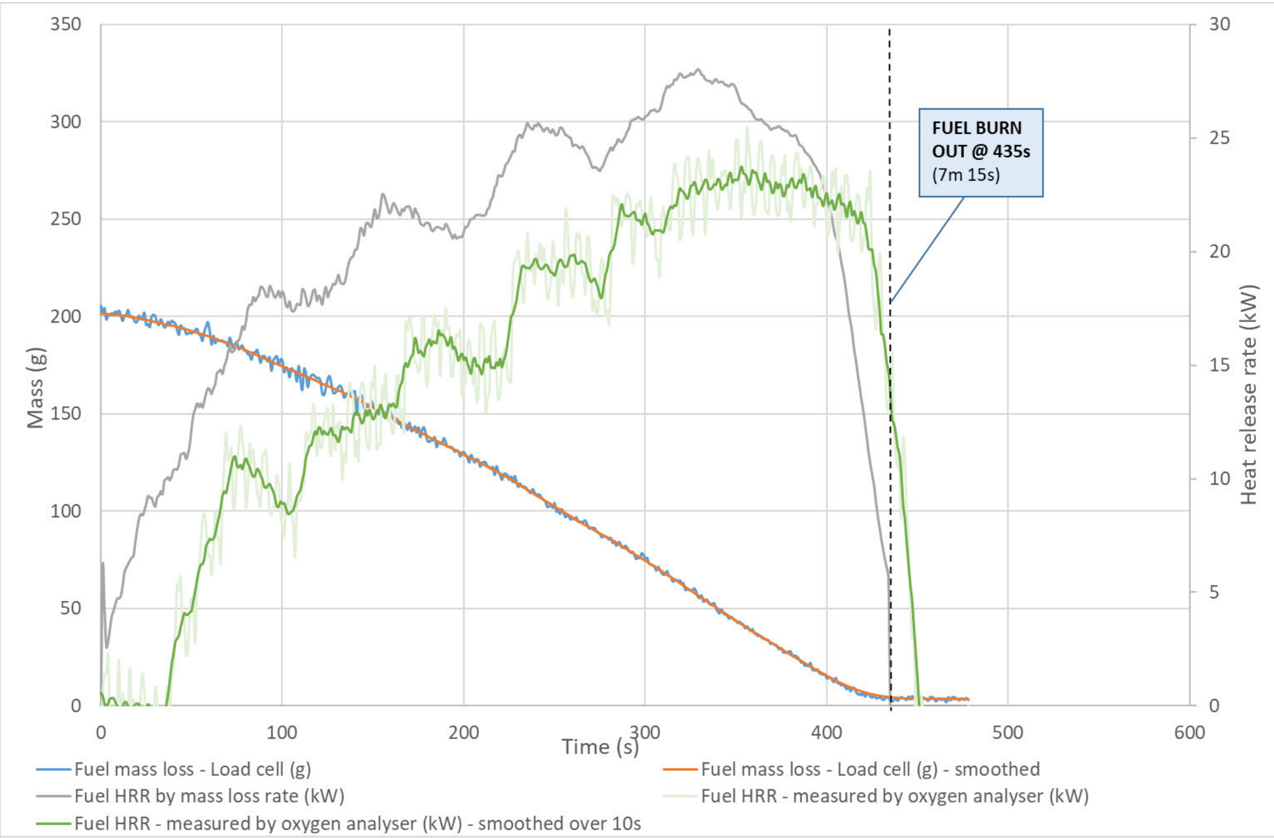
Apx D 9 - Test C5 – HRR graph of 1 tray heptane test, inside rig (~65mm cavity), Test A



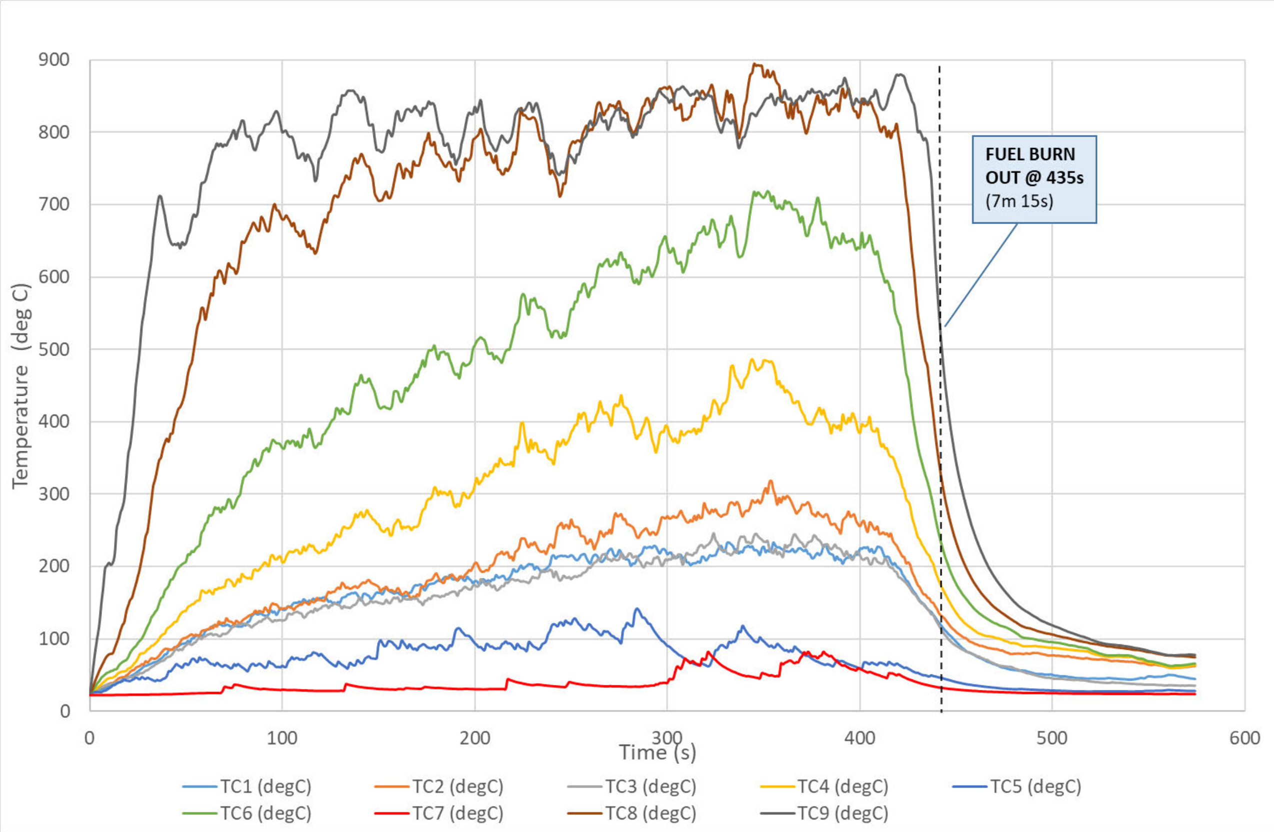
Apx D 10 - Test C5 – Temperature graph of 1 tray heptane test, inside rig (~65mm cavity), Test A



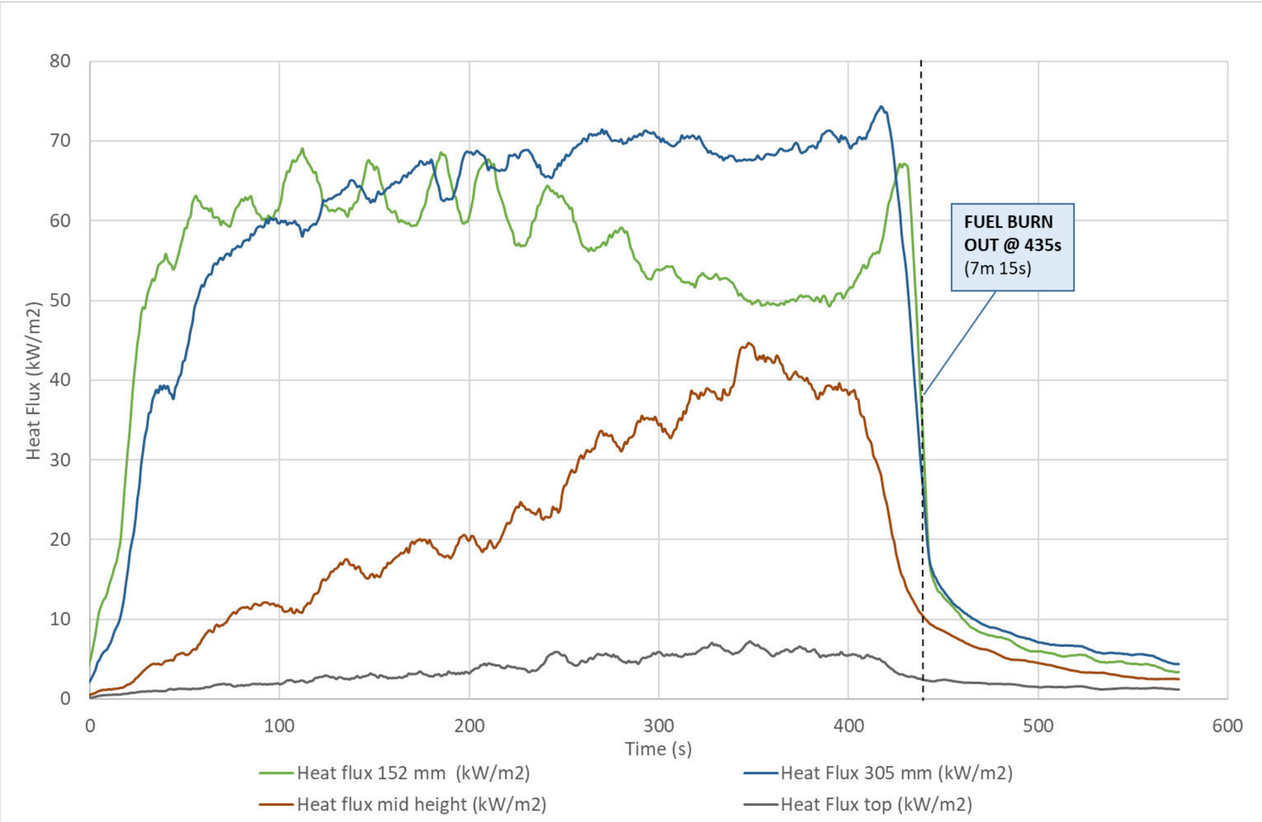
Apx D 11 - Test C5 – Incident heat flux graph of 1 tray heptane test, inside rig (~65mm cavity), Test A



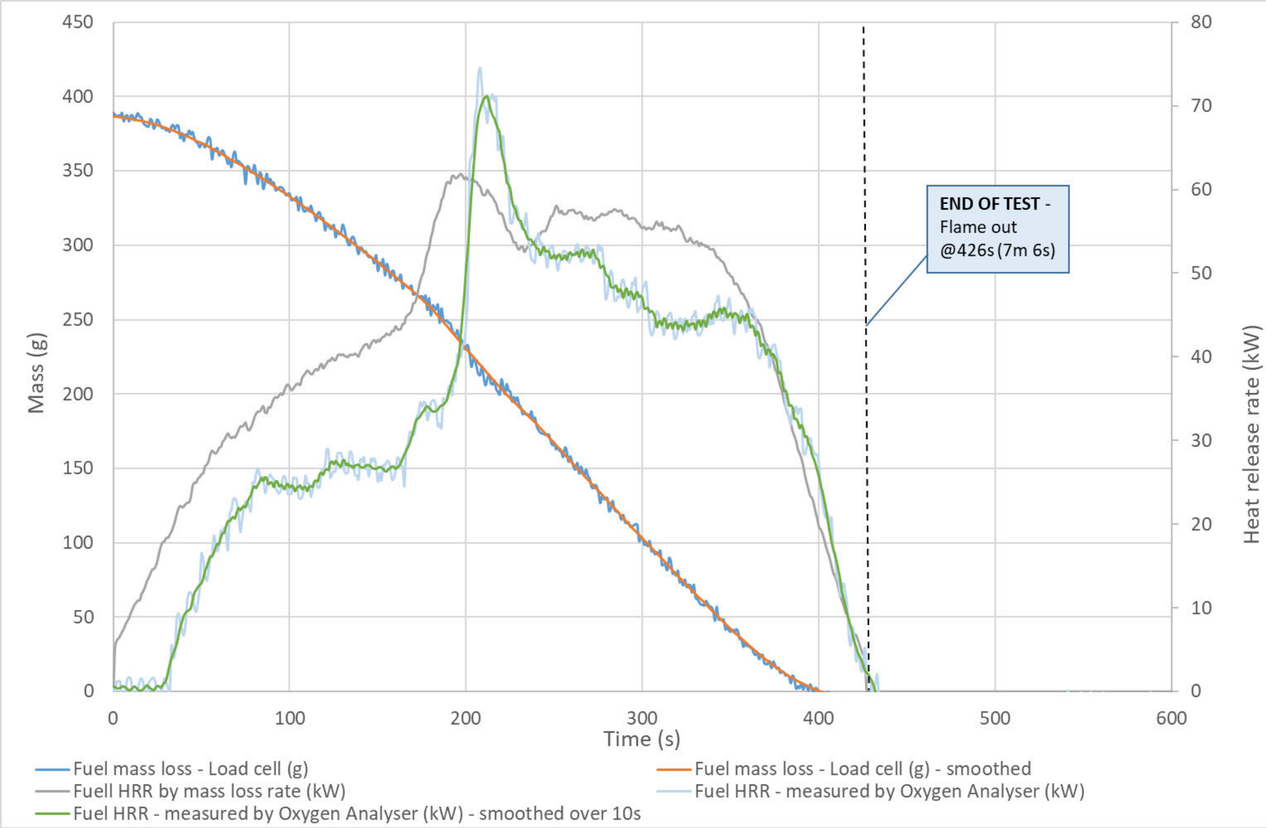
Apx D 12 - Test C6 – HRR graph of 1 tray heptane test, inside rig (~65mm cavity), Test B



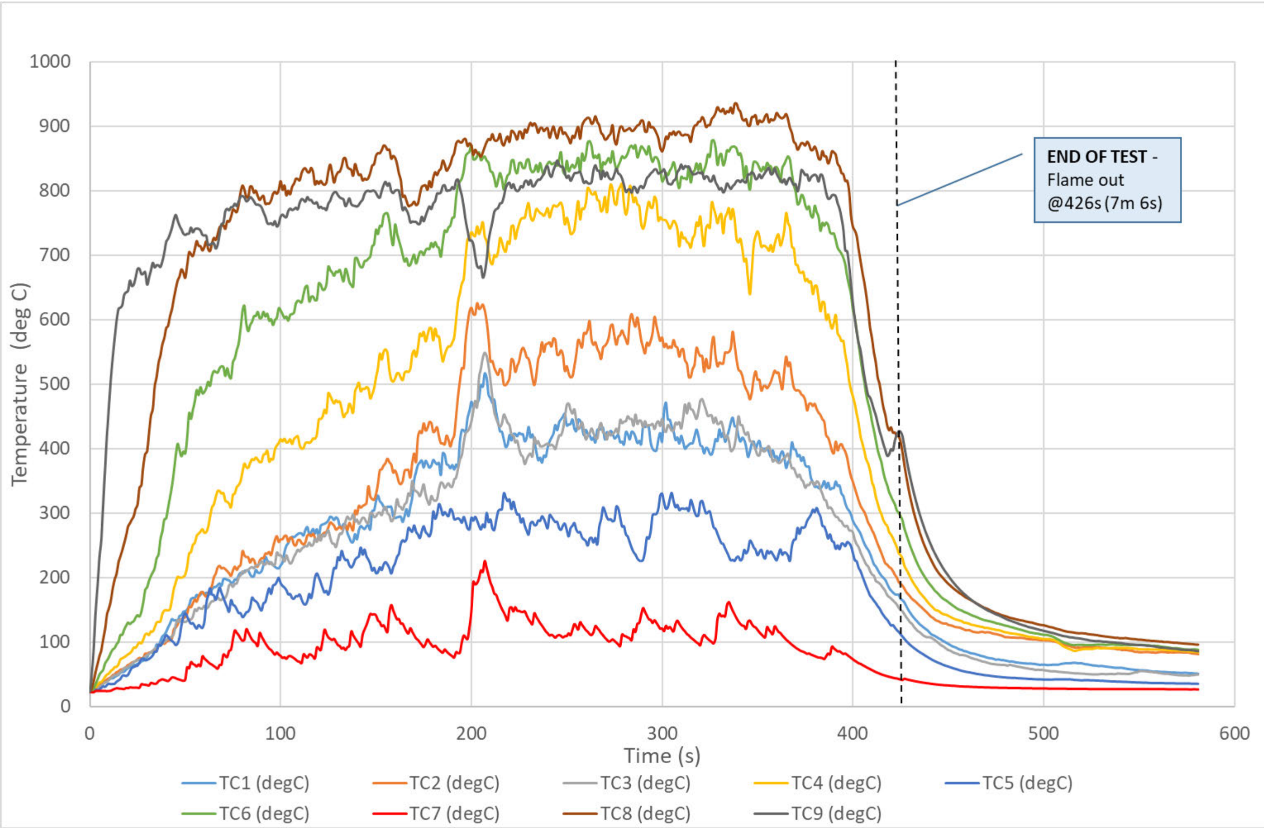
Apx D 13 - Test C6 – Temperature graph of 1 tray heptane test, inside rig (~65mm cavity), Test B



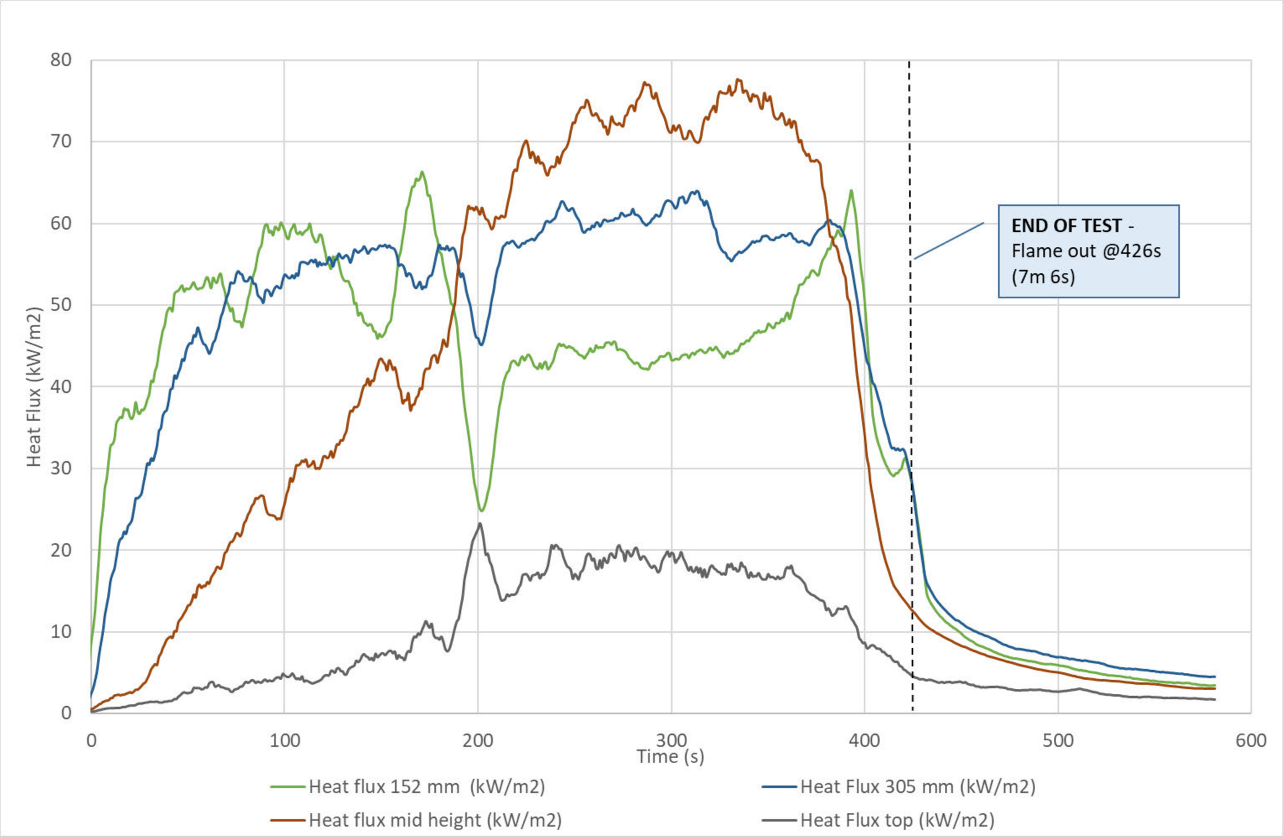
Apx D 14 - Test C6 – Incident heat flux graph of 1 tray heptane test, inside rig (~65mm cavity), Test B



Apx D 15 - Test C7 – HRR graph of 2 tray heptane tests, inside rig (~65mm cavity)

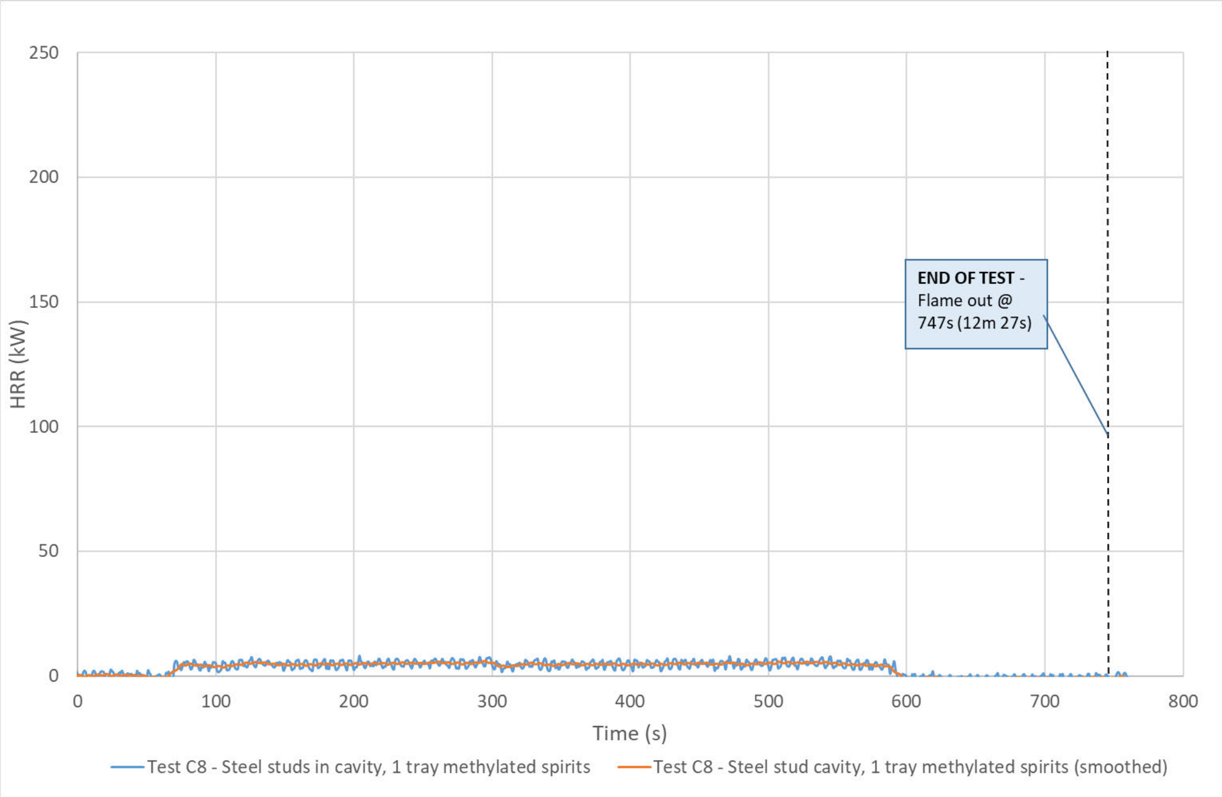


Apx D 16 - Test C7 – Temperature graph of 2 tray heptane tests, inside rig (~65mm cavity)

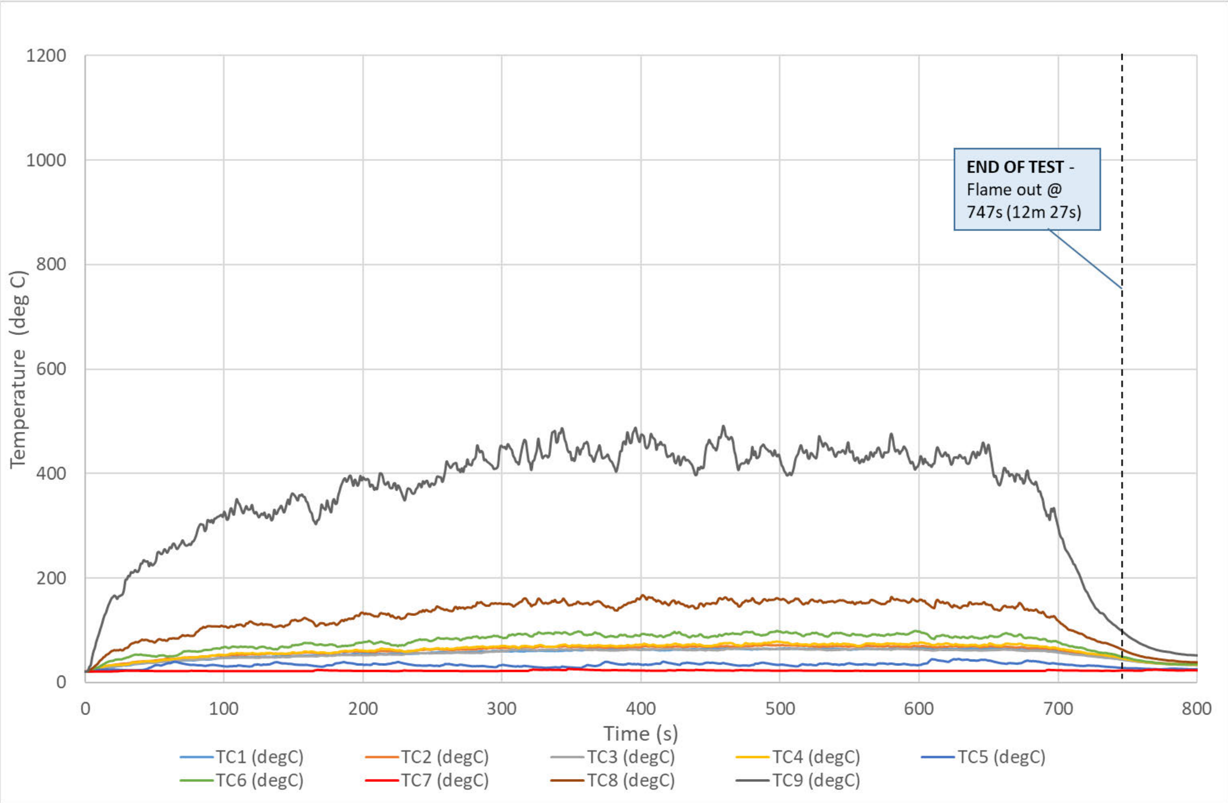


Apx D 17 - Test C7 – Incident heat flux graph of 2 tray heptane tests, inside rig (~65mm cavity)

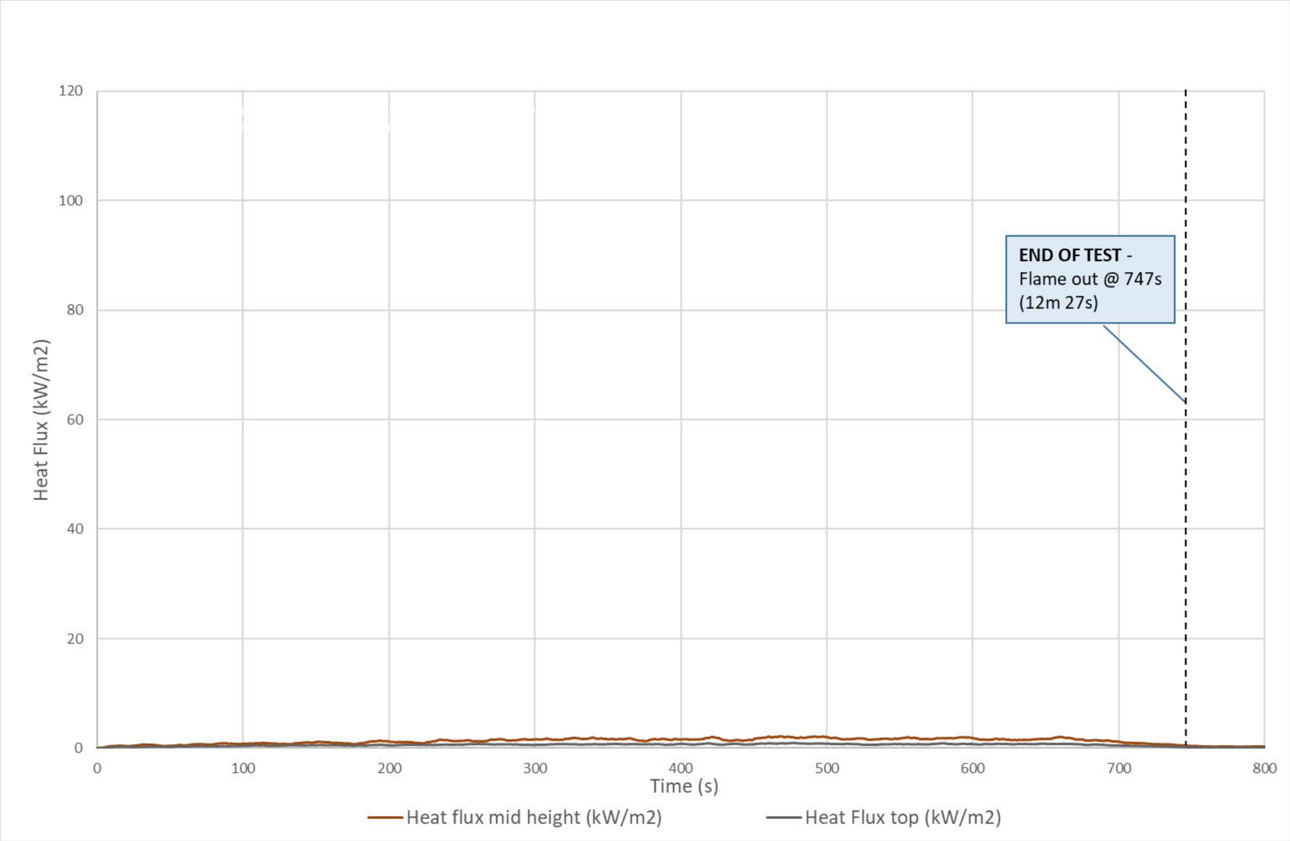
D.1.2 Characterisation Tests – with steel studs in cavity (closed base, ~130mm cavity width)



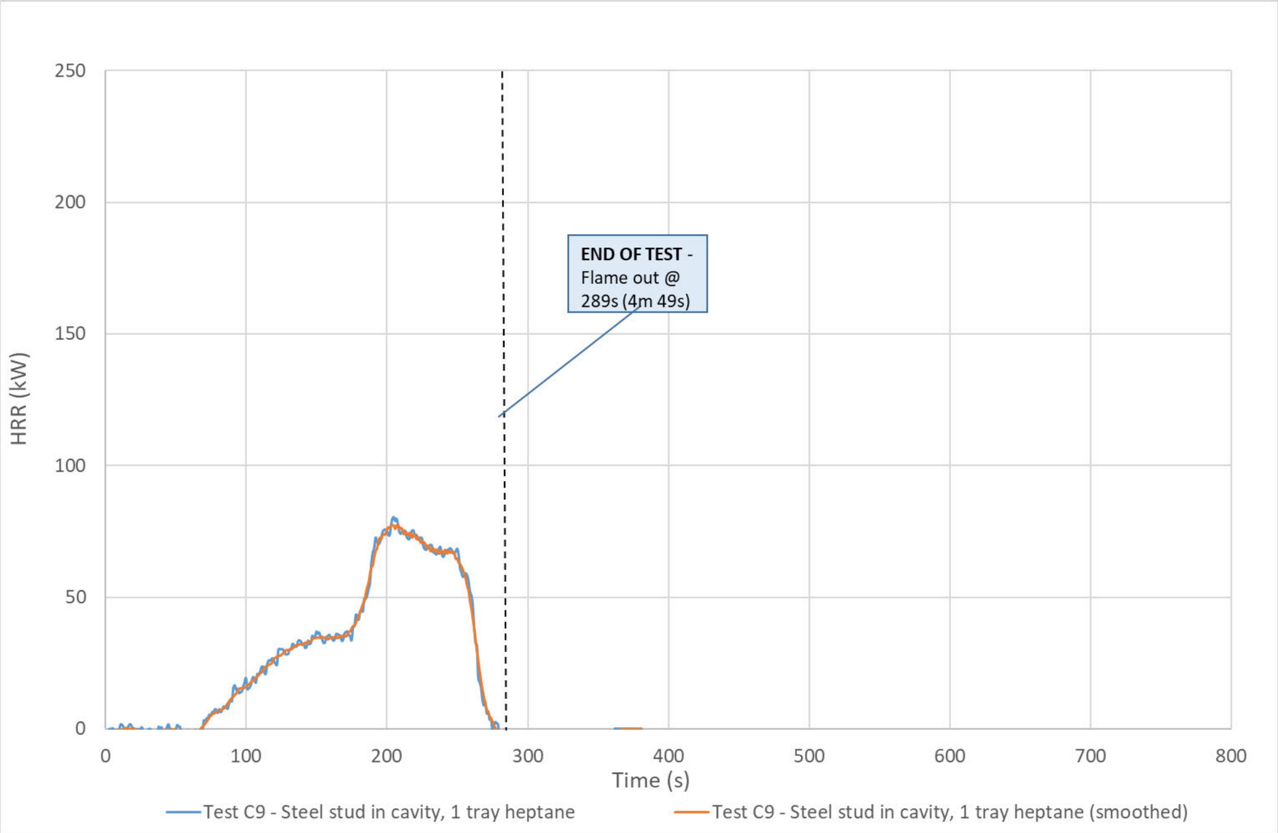
Apx D 18 - Test C8 – HRR graph of 1 tray methylated spirits test, with steel studs in cavity (closed base, ~130mm cavity)



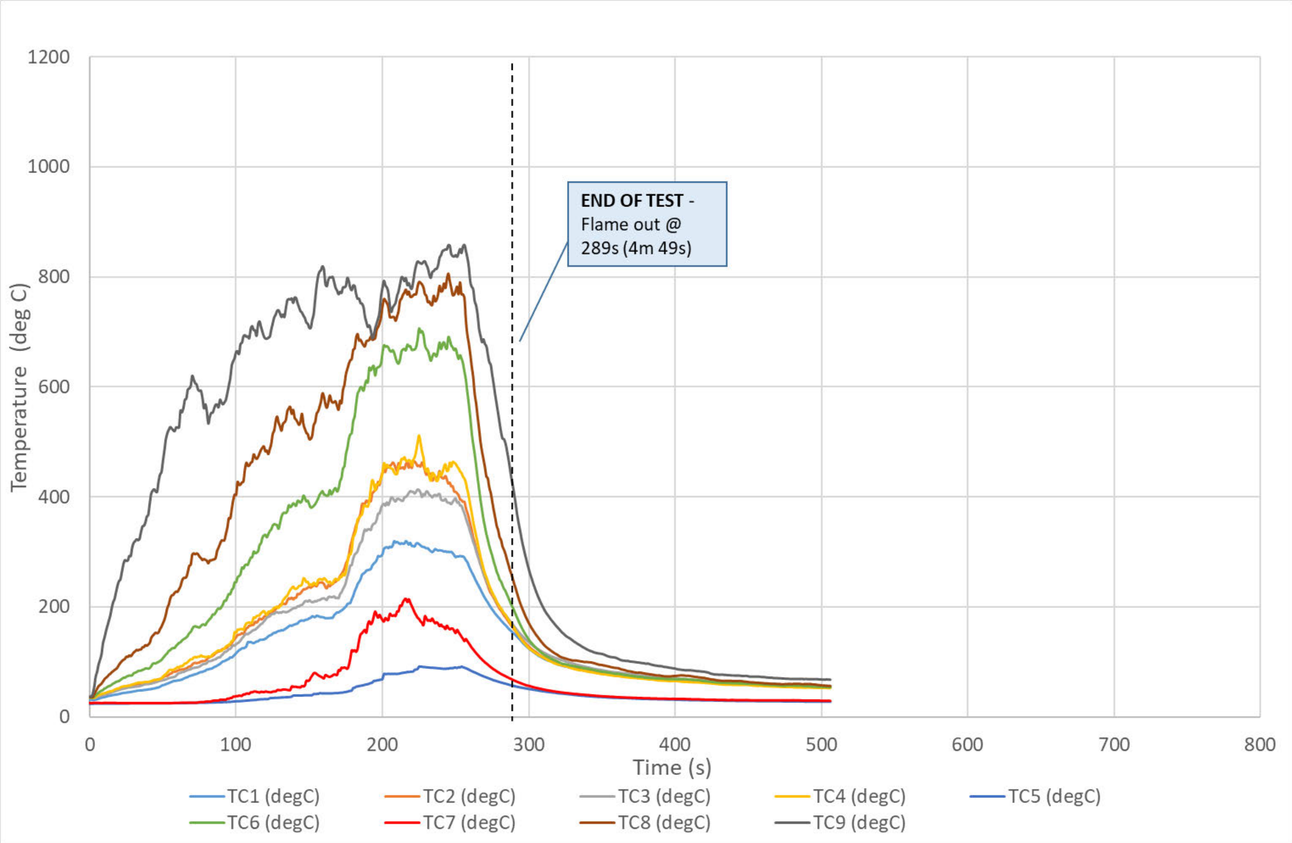
Apx D 19 - Test C8 – Temperature graph of 1 tray methylated spirits, with steel studs in cavity (~130mm cavity)



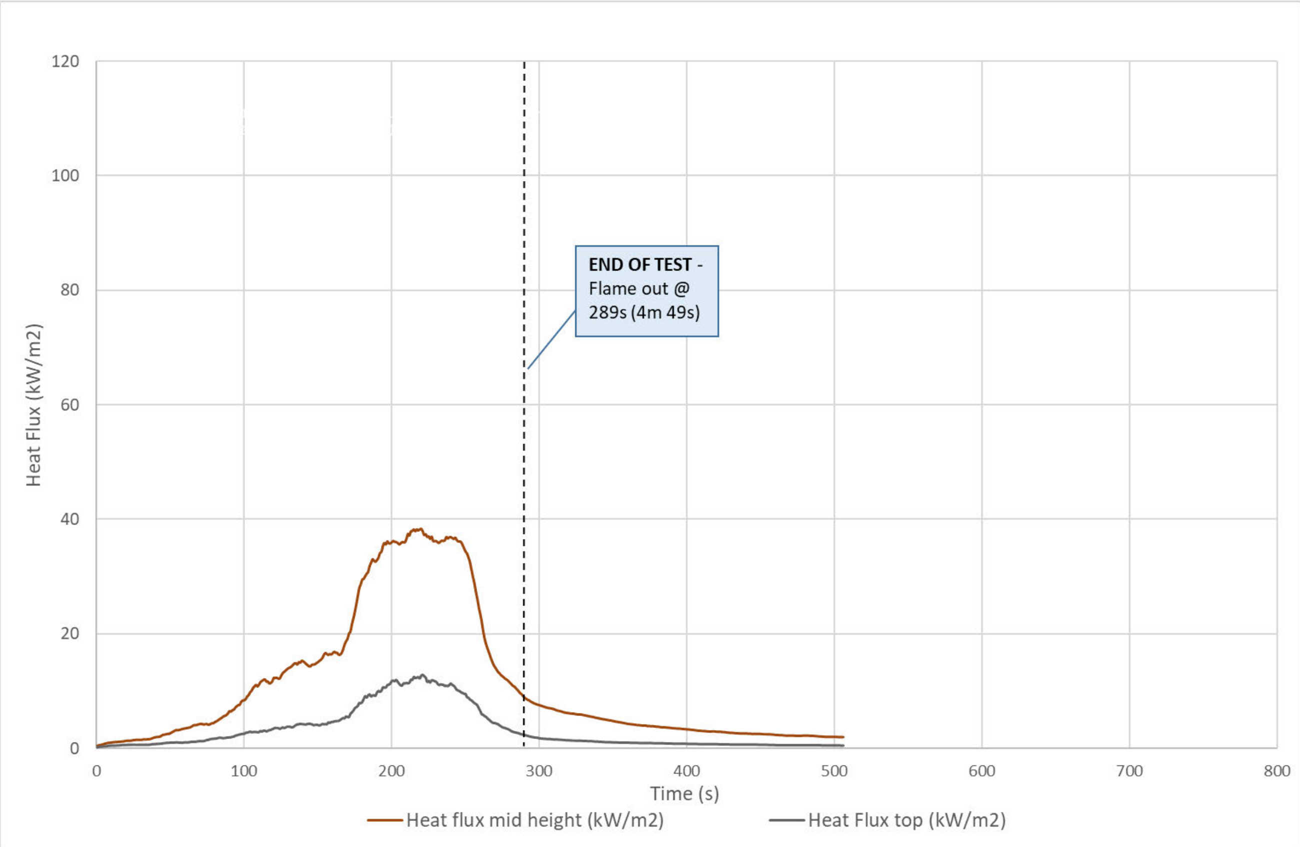
Apx D 20 - Test C8 – Incident heat flux graph of 1 tray methylated spirits, with steel studs in cavity (closed base, ~130mm cavity)



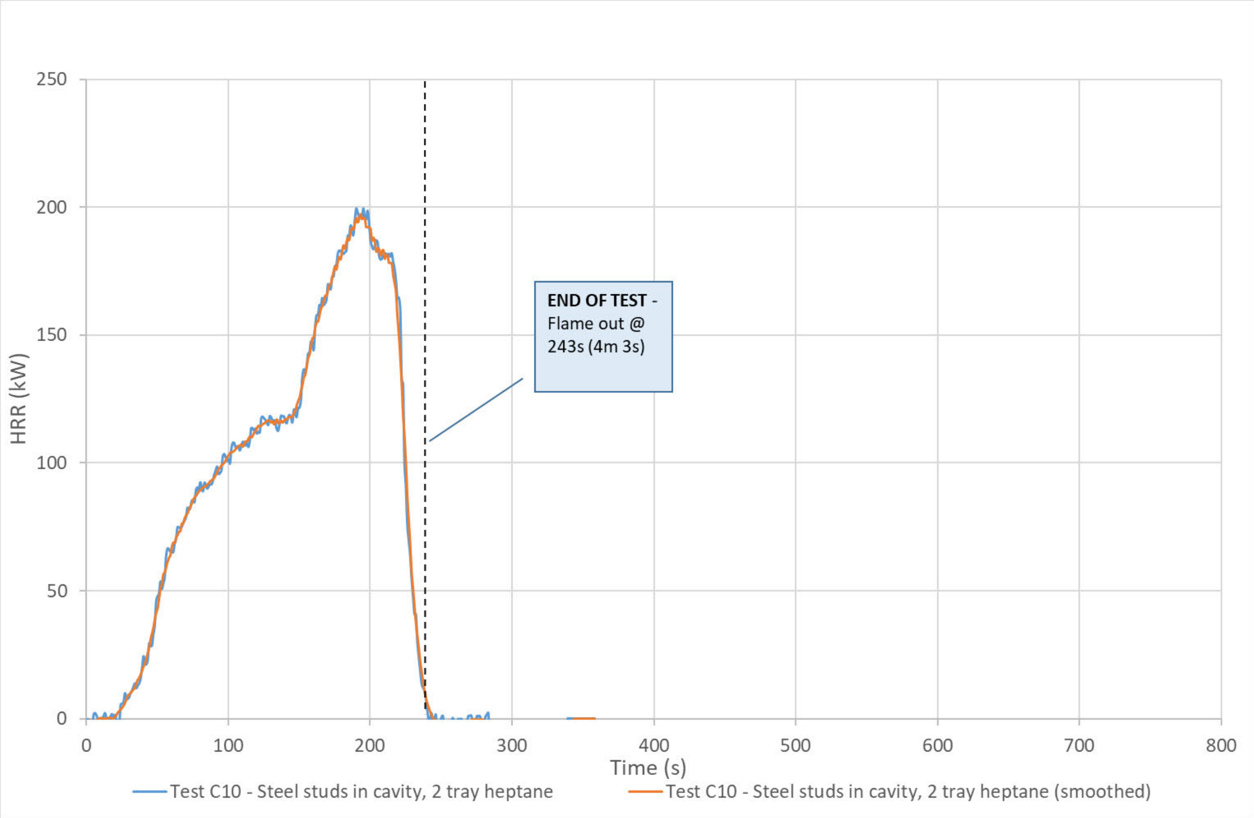
Apx D 21 - Test C9 – HRR graph of 1 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)



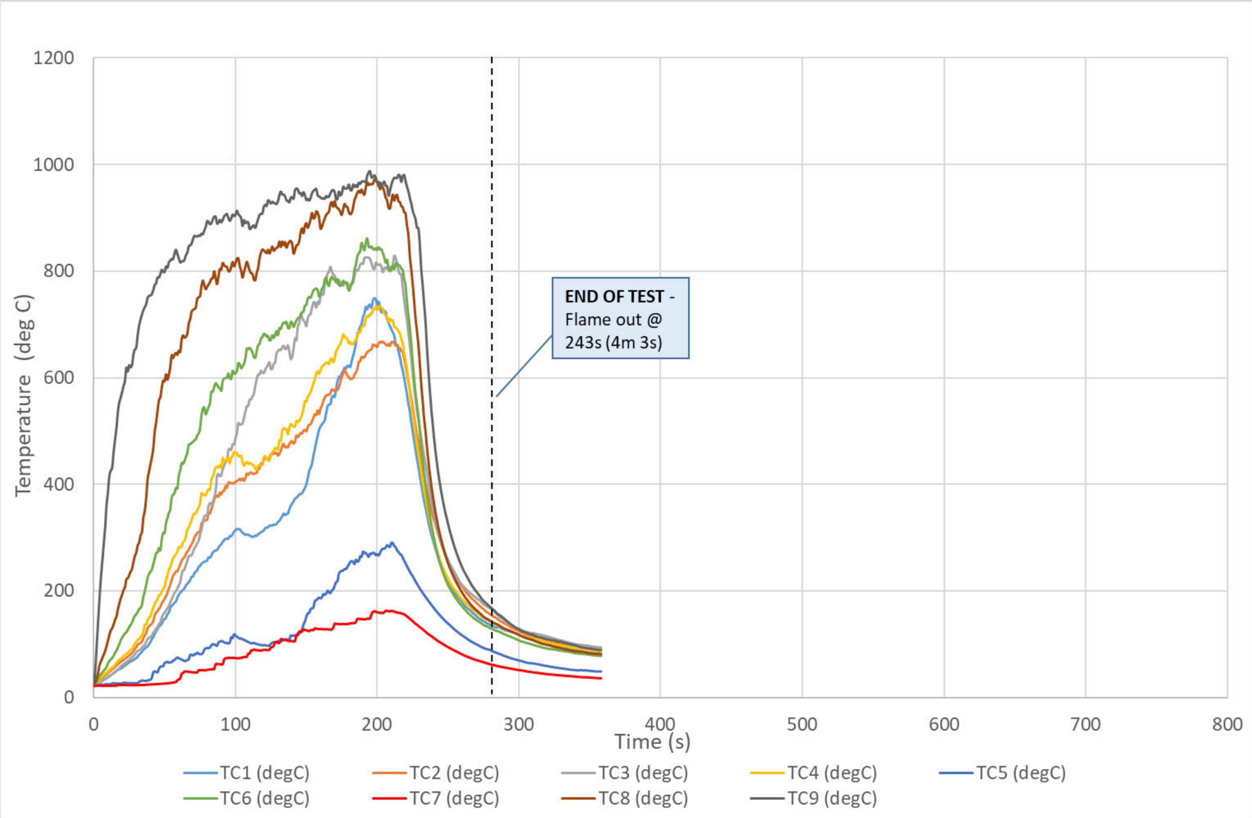
Apx D 22 - Test C9 – Temperature graph of 1 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)



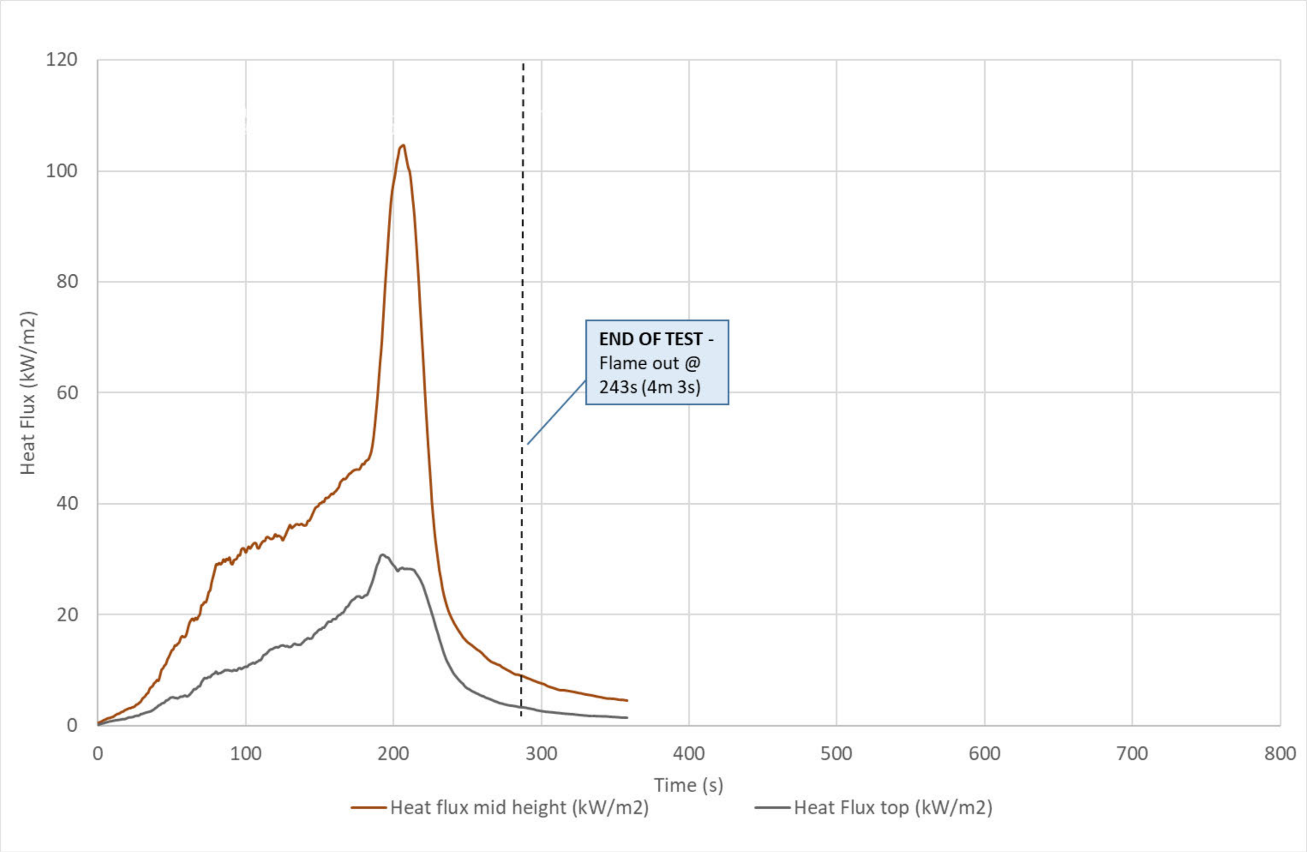
Apx D 23 - Test C9 – Incident heat flux graph of 1 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)



Apx D 24 - Test C10 – HRR graph of 2 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)

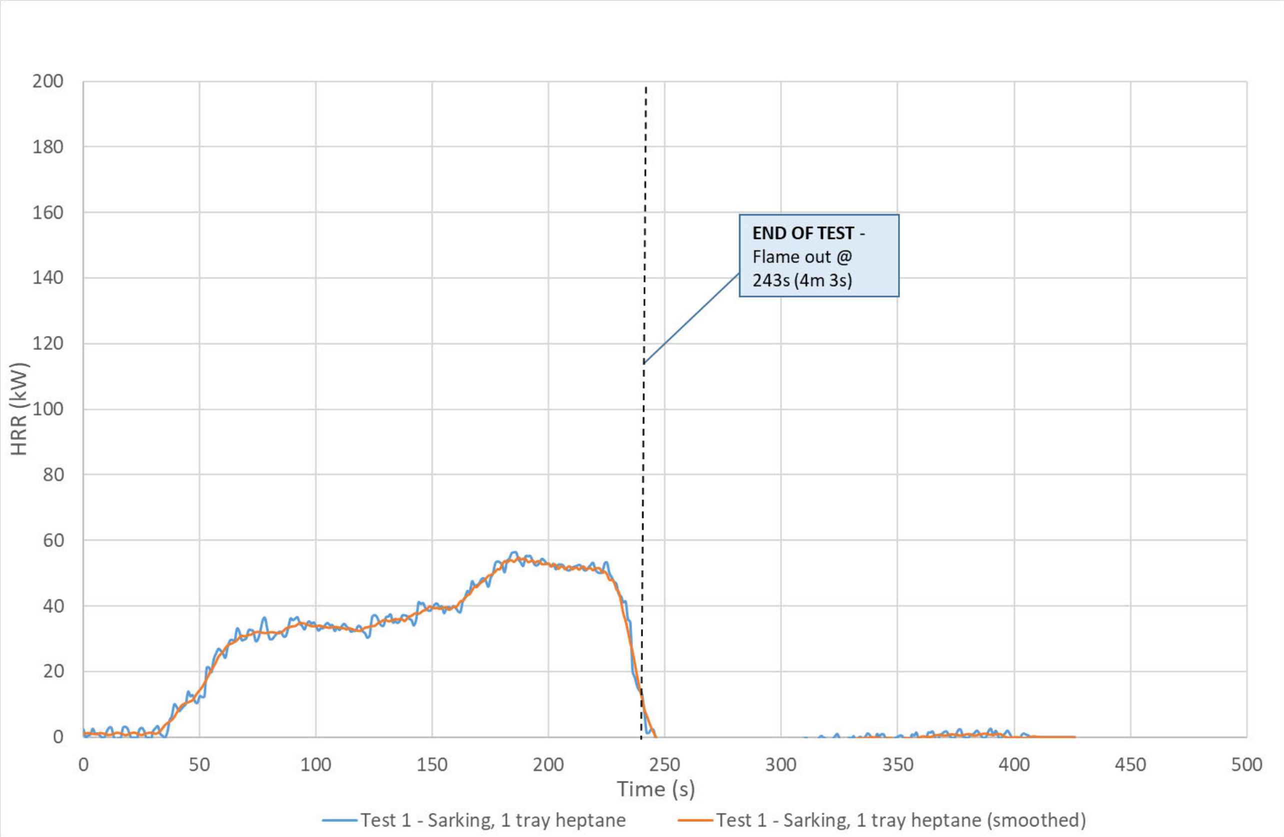


Apx D 25 - Test C10 – Temperature graph of 2 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)

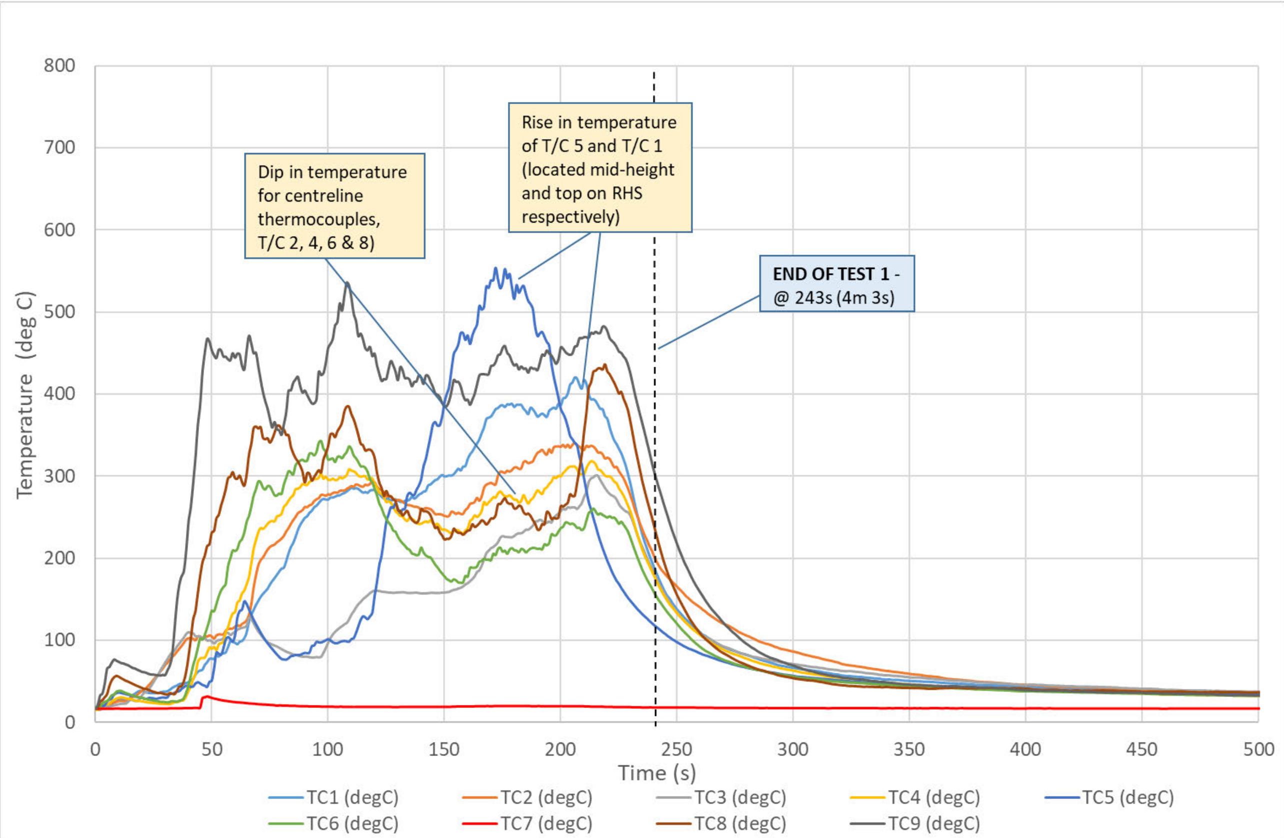


Apx D 26 - Test C10 – Incident heat flux graph of 2 tray heptane test, with steel studs in cavity (closed base, ~130mm cavity)

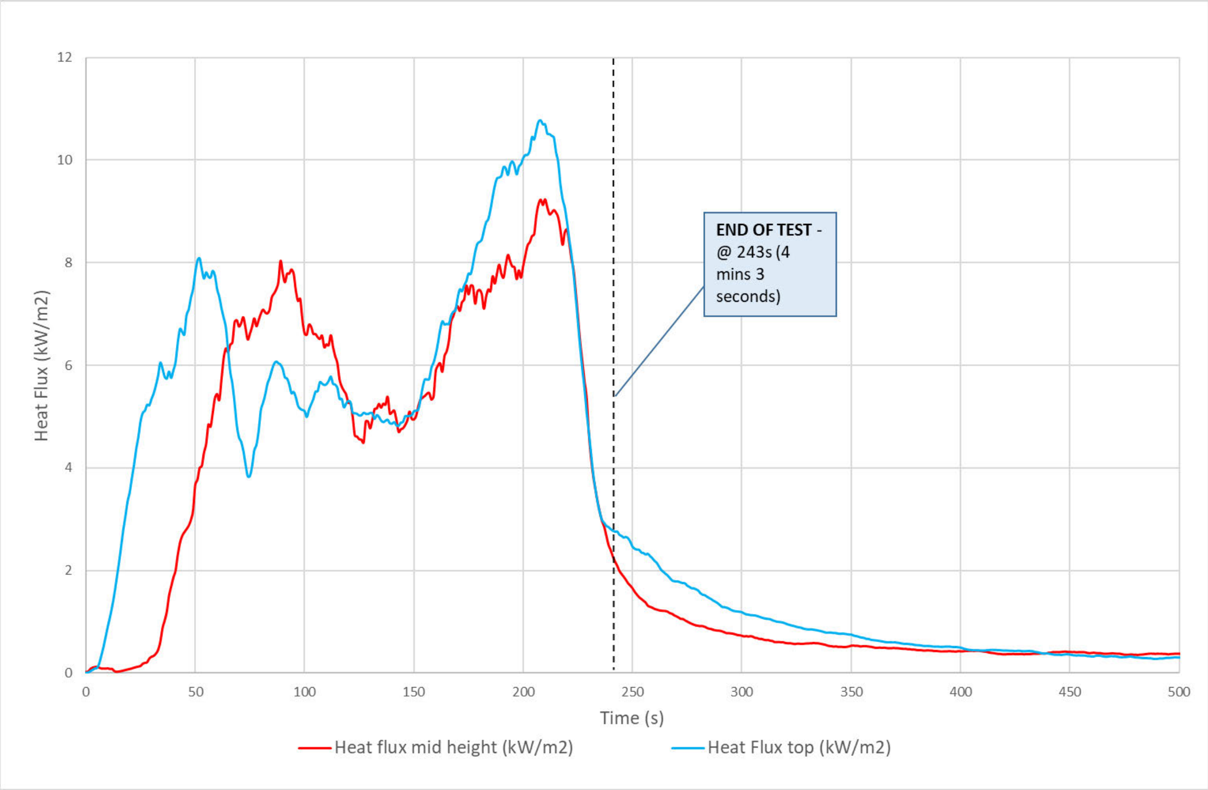
D2 Test Graphs for Sarking Tests



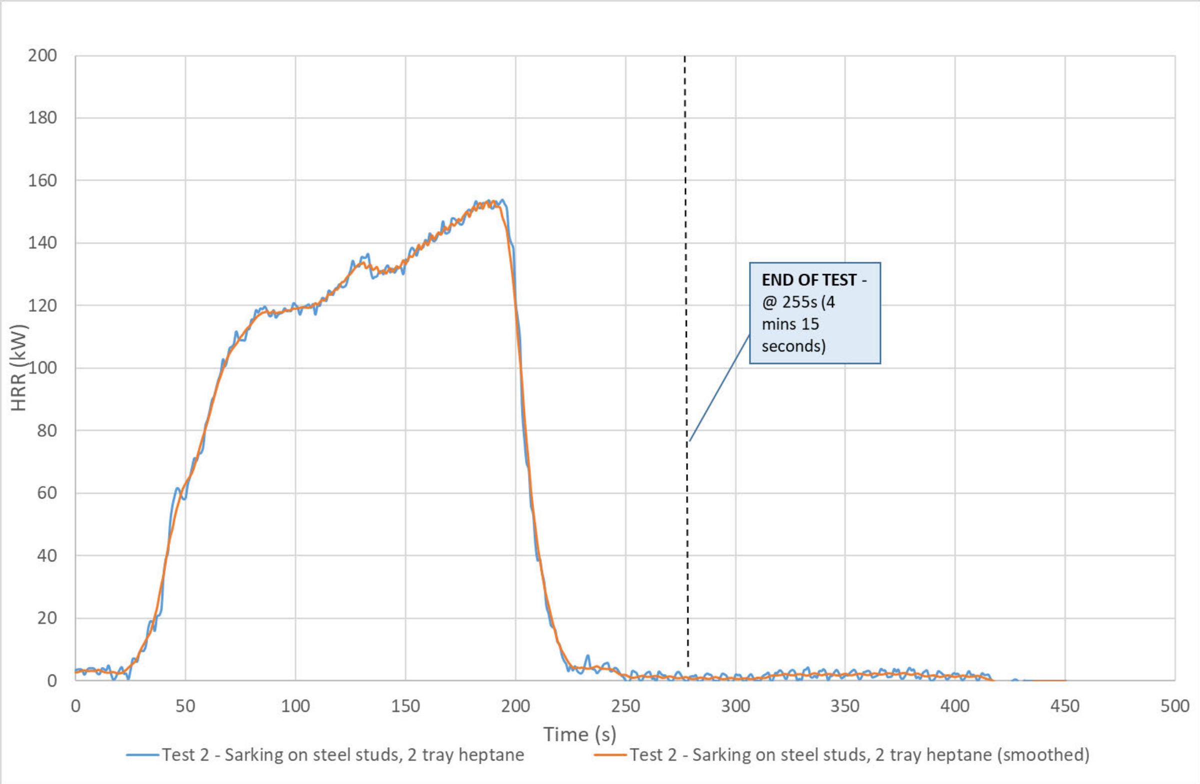
Apx D 27 - Test 1 –HRR graph of Sarking, 1 tray heptane test (base case)



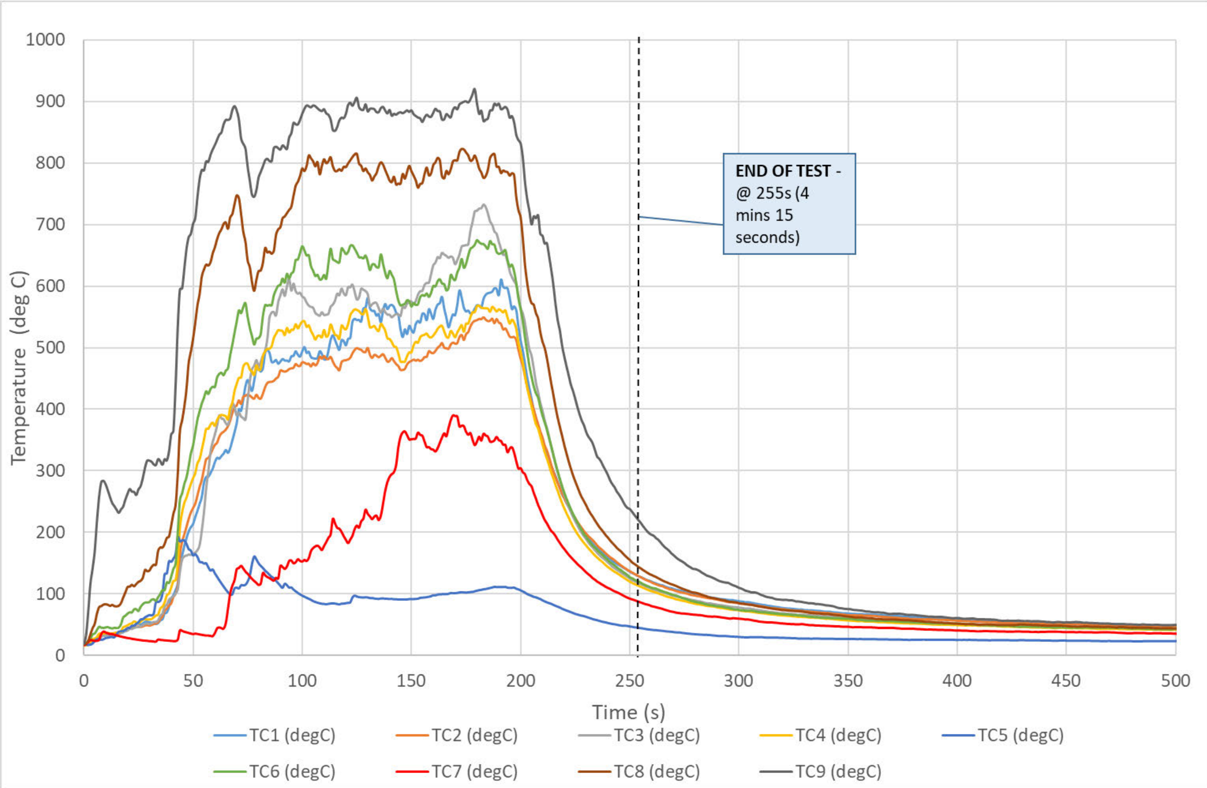
Apx D 28 - Test 1 – Temperature graph of Sarking, 1 tray heptane test (base scale)



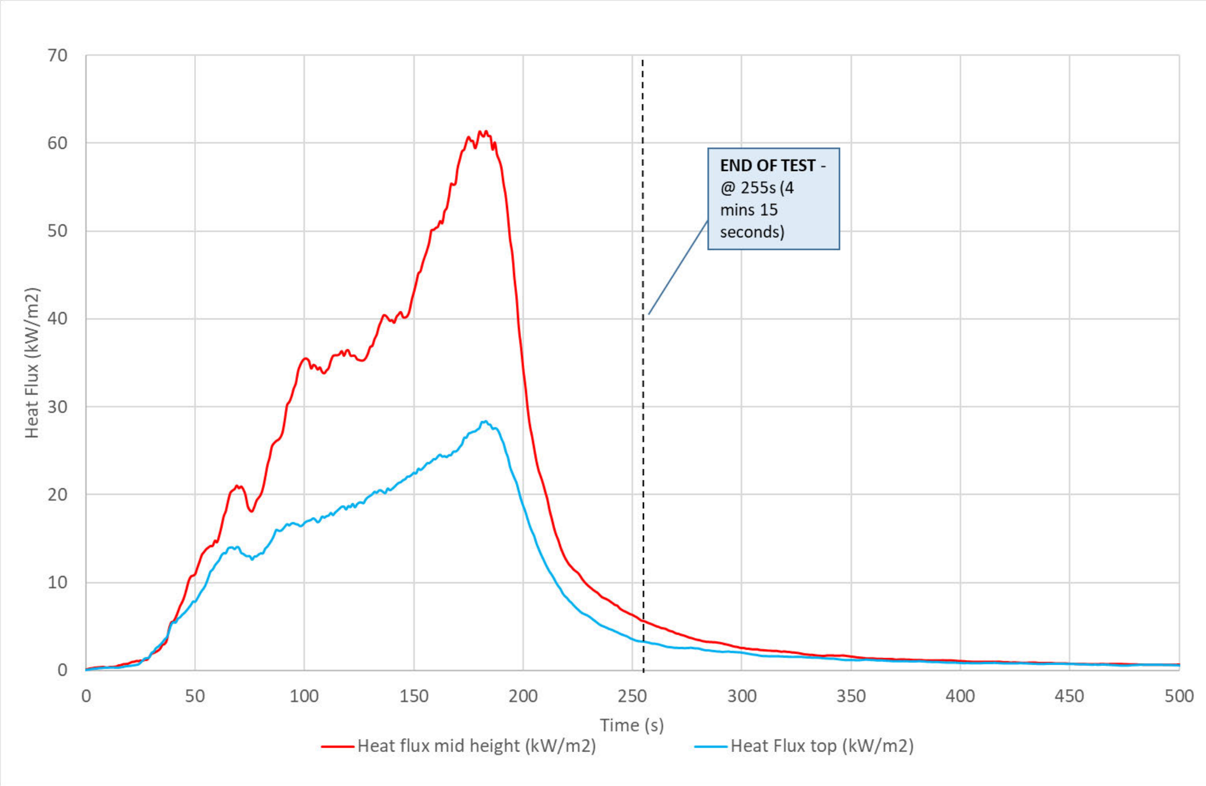
Apx D 29 - Test 1 – Incident heat flux graph of Sarking, 1 tray heptane test (base scale)



Apx D 30 - Test 2 –HRR graph of Sarking, 2 tray heptane test (sensitivity scale)

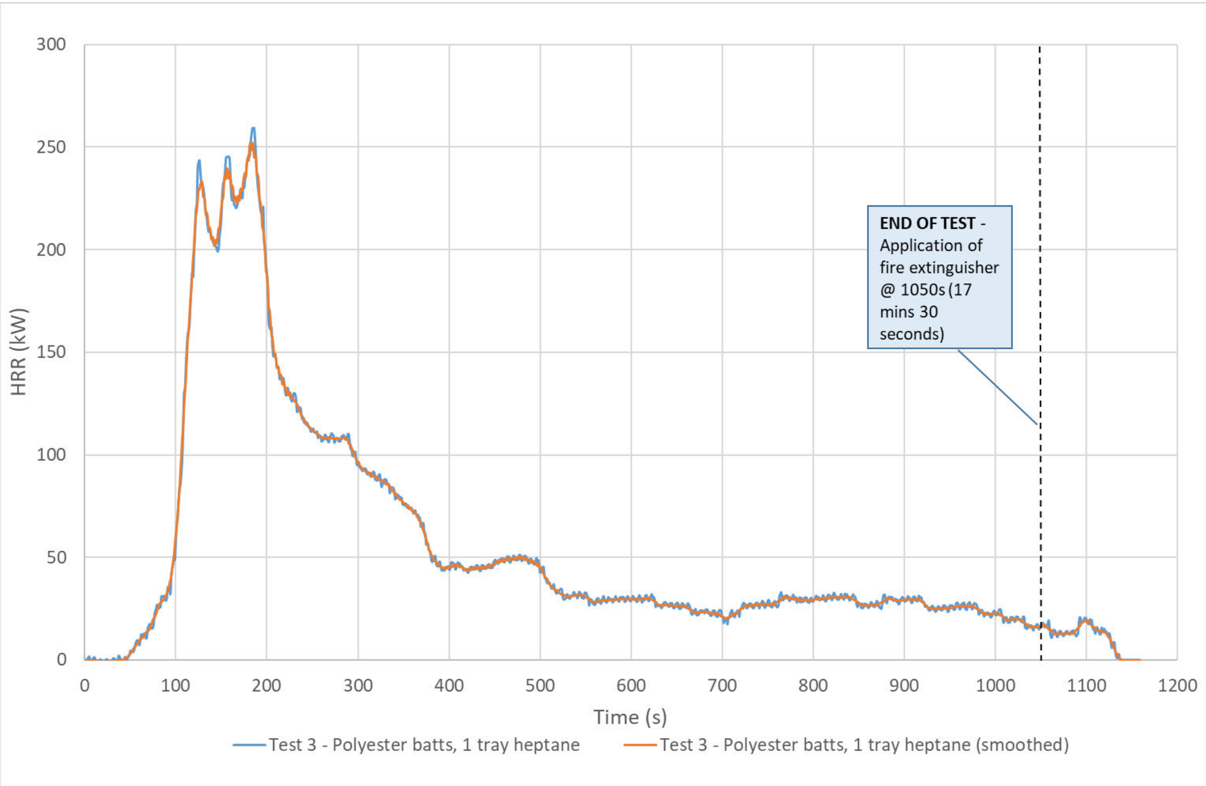


Apx D 31 - Test 2 – Temperature graph of Sarking, 2 tray heptane test (sensitivity scale)

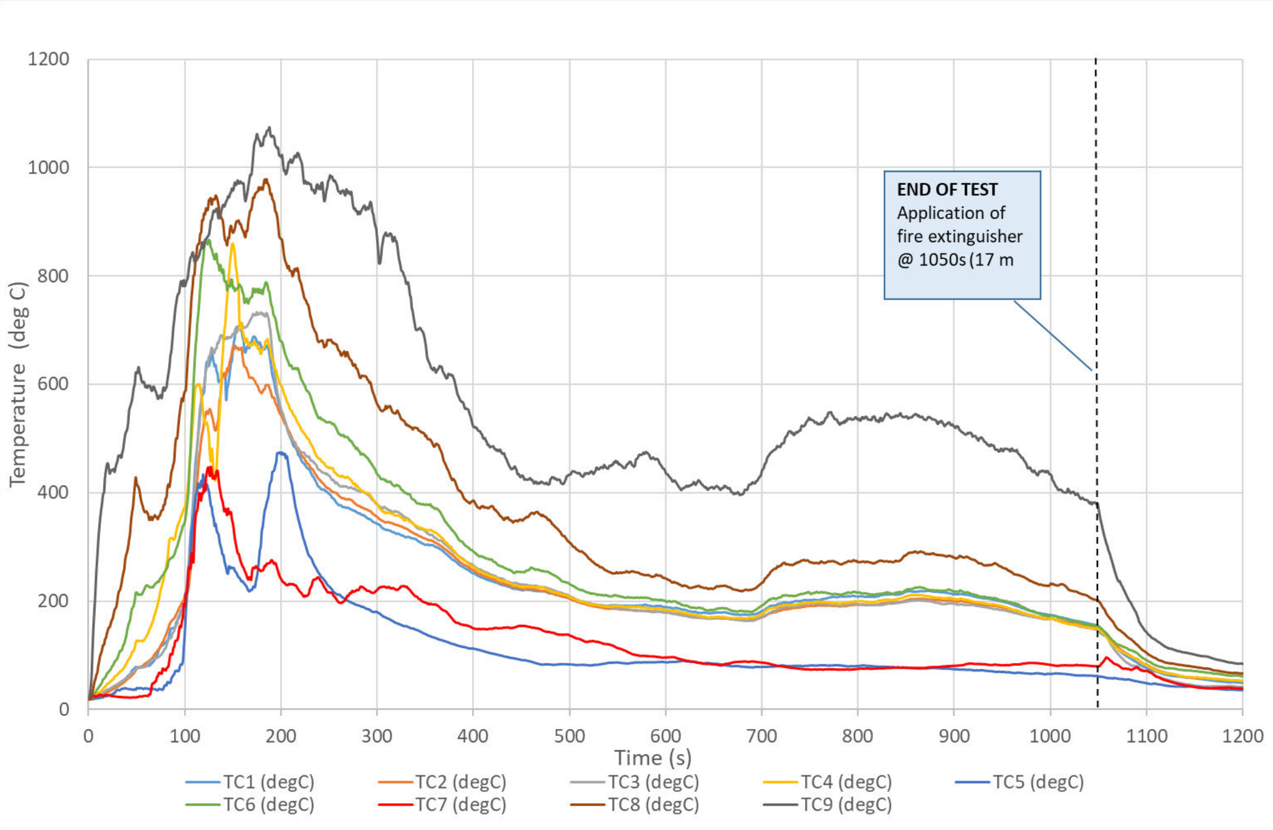


Apx D 32 - Test 2 – Incident heat flux graph of Sarking, 2 tray heptane test (sensitivity scale)

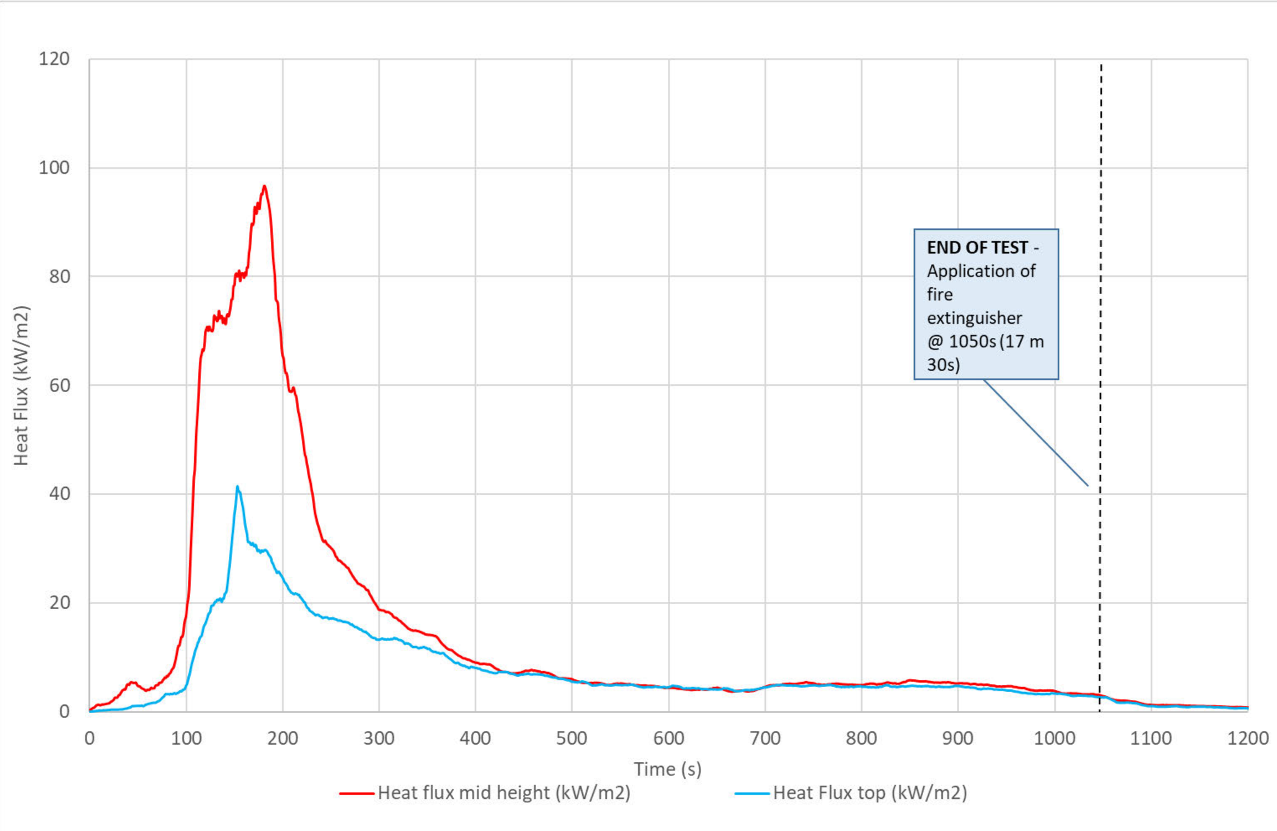
D3 Test Graphs for Polyester Batts



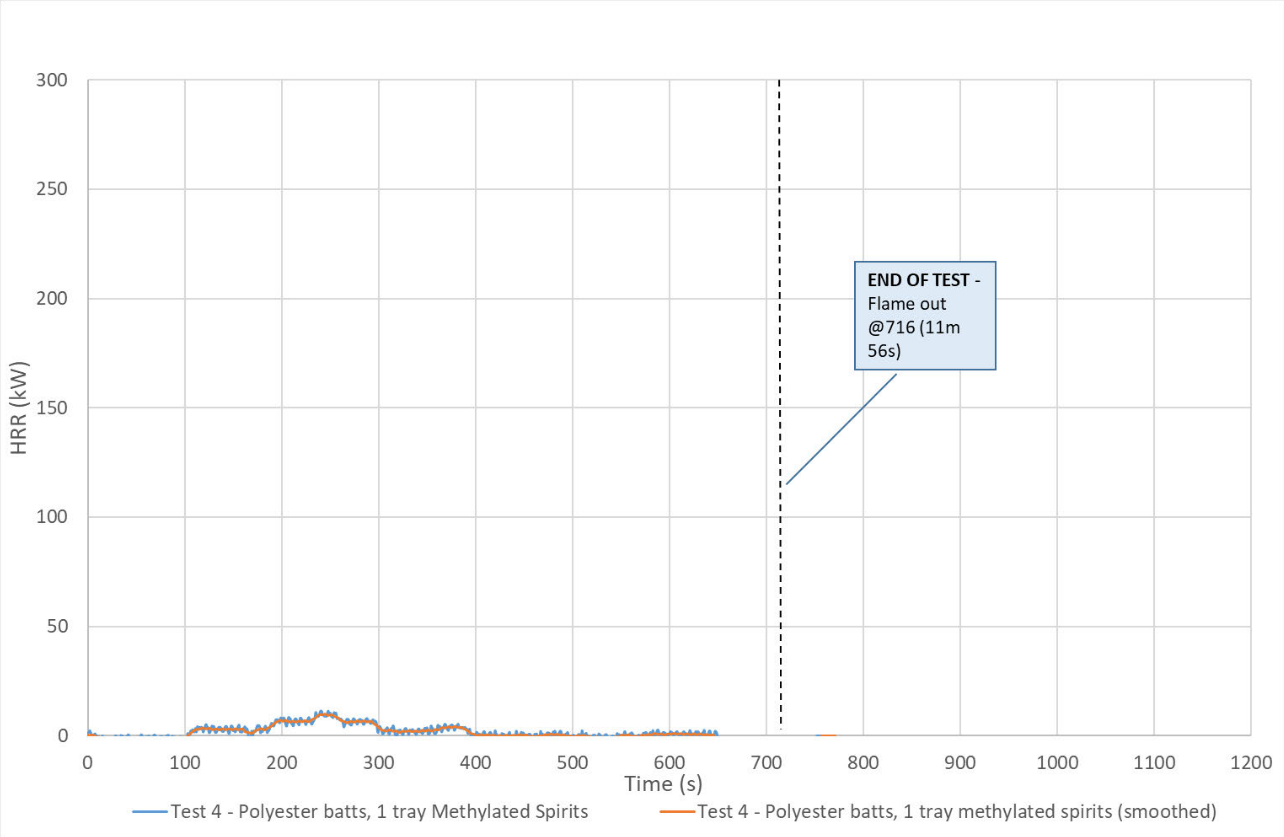
Apx D 33 - Test 3 –HRR graph of Polyester batts, 1 tray heptane test (base scale)



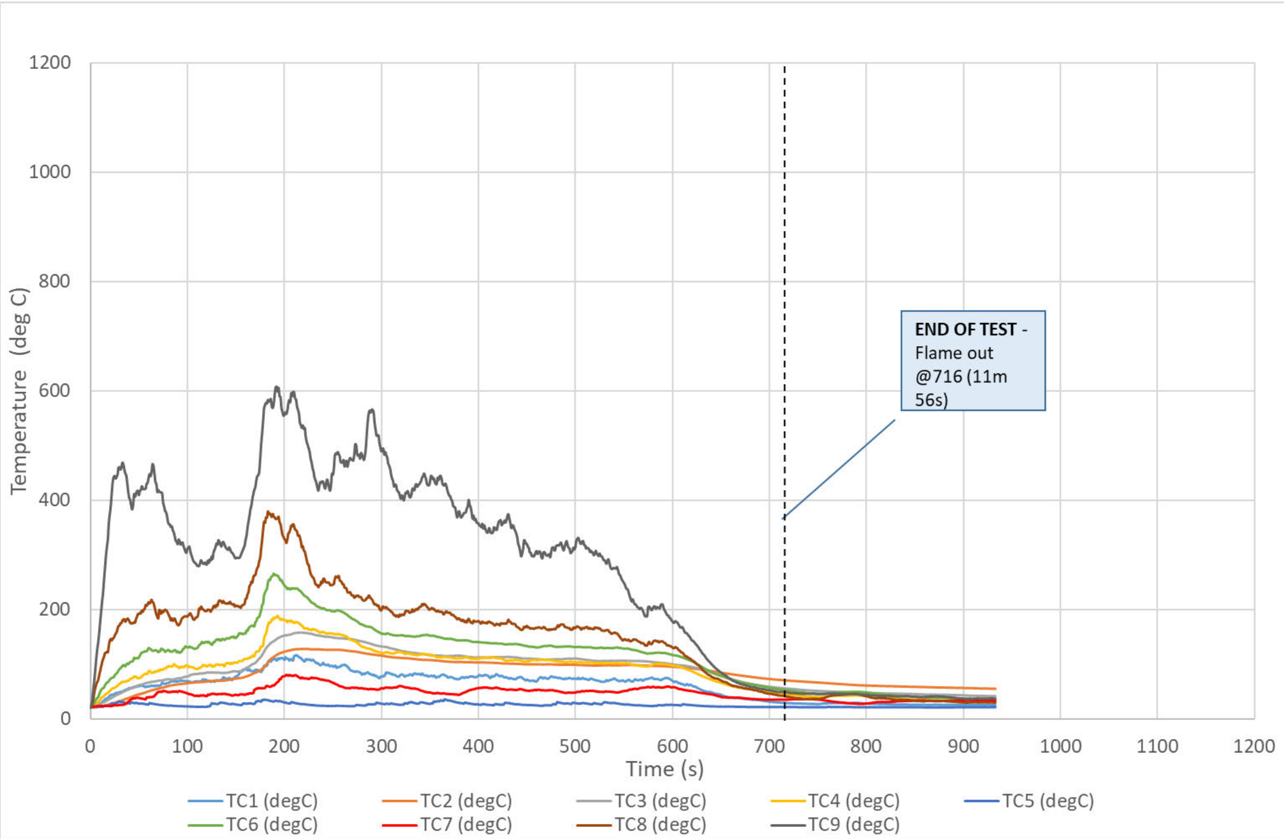
Apx D 34 - Test 3 – Temperature graph of Polyester batts, 1 tray heptane test (base scale)



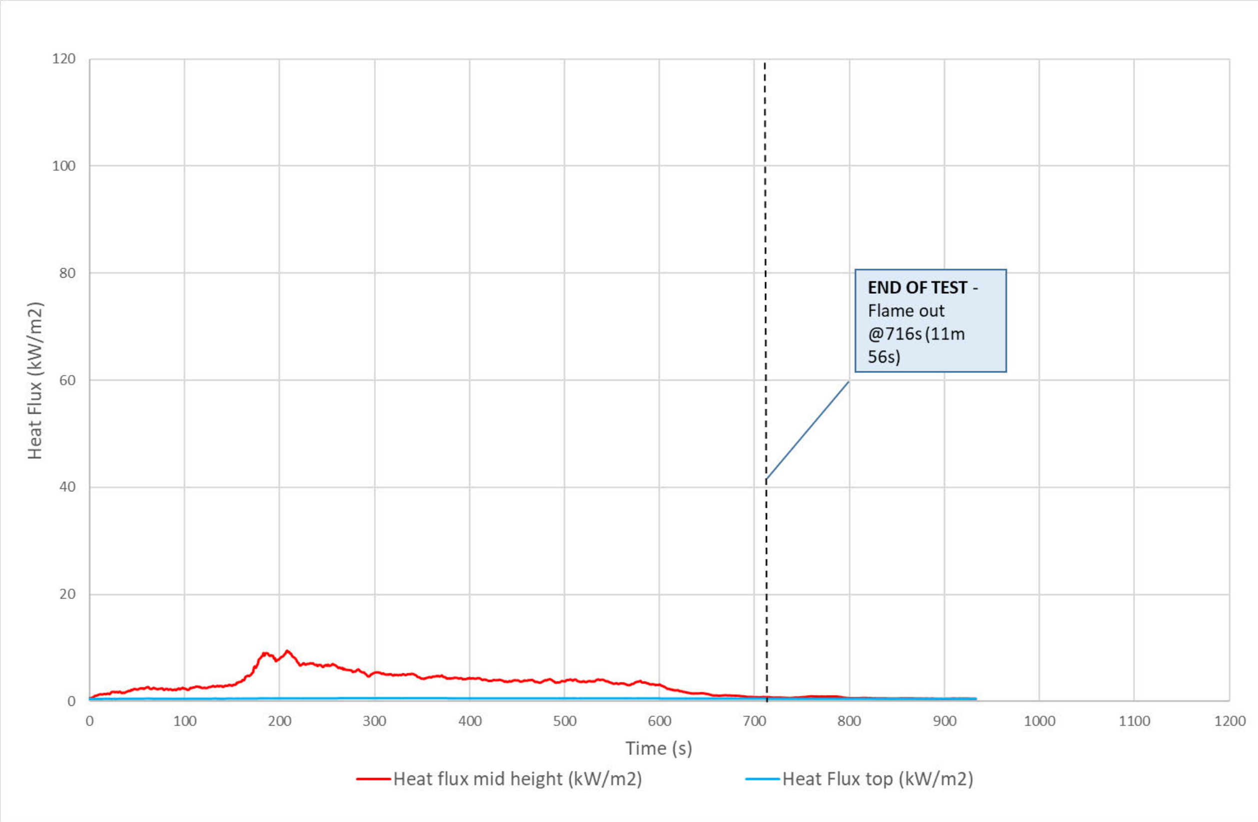
Apx D 35 - Test 3 – Incident heat flux graph of Polyester batts, 1 tray heptane test (base scale)



Apx D 36 - Test 4 –HRR graph of Polyester batts with methylated spirits test (reduced scale)

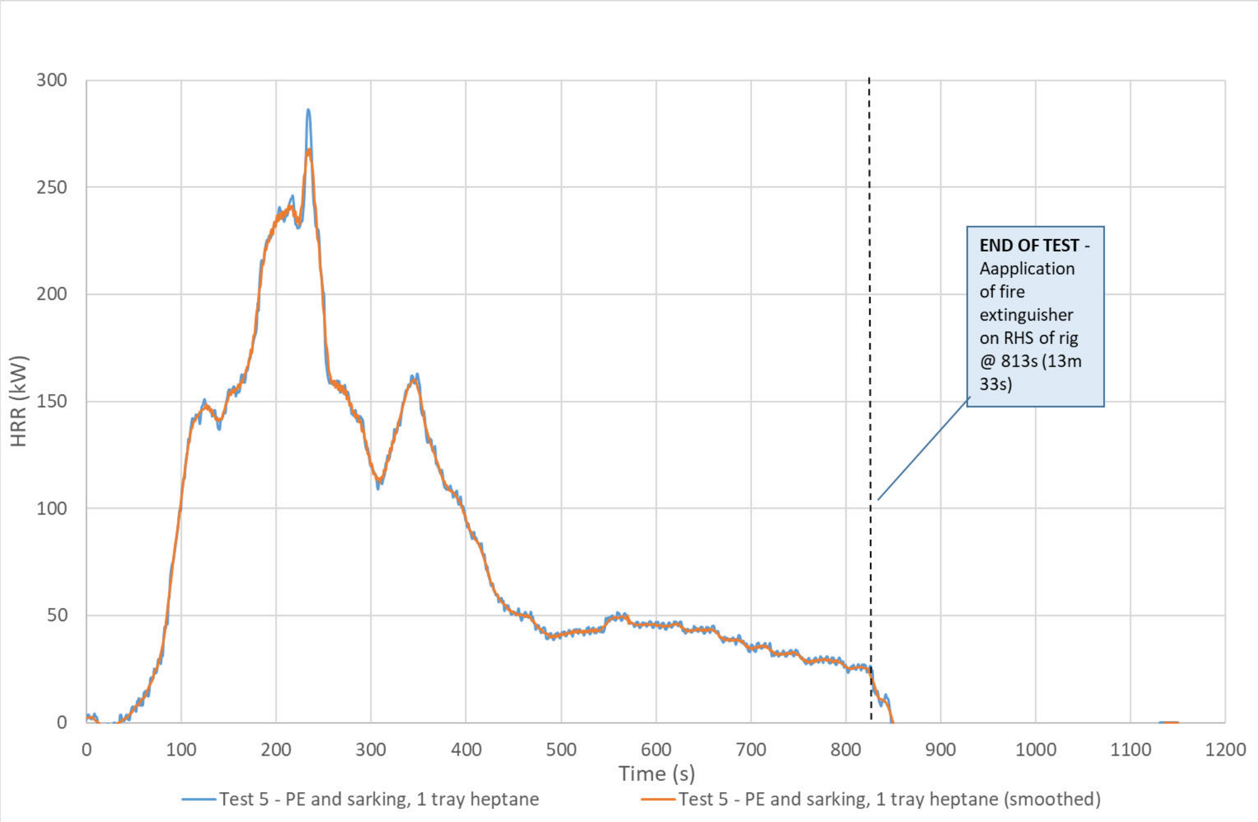


Apx D 37 - Test 4 – Temperature graph of Polyester batts with methylated spirits test (reduced scale)

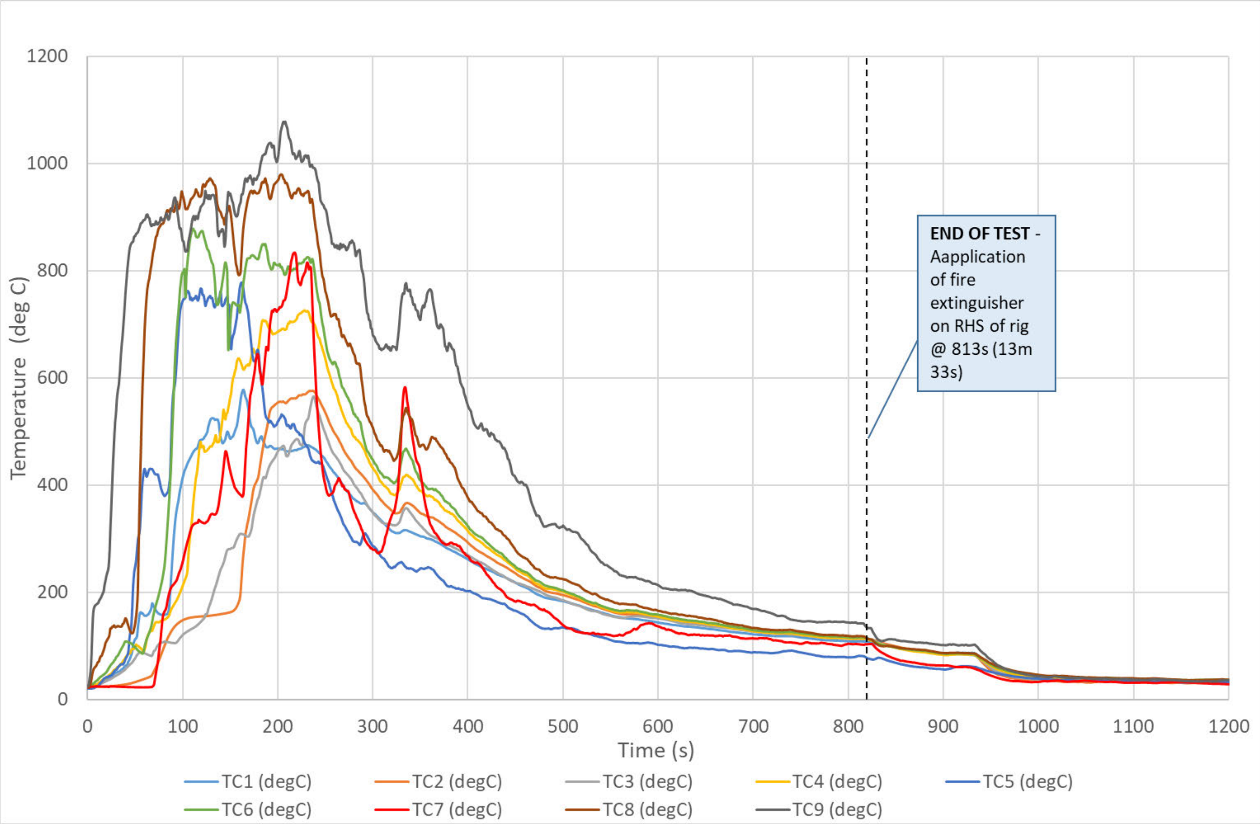


Apx D 38 - Test 4 – Incident heat flux graph of Polyester batts with methylated spirits test (reduced scale)

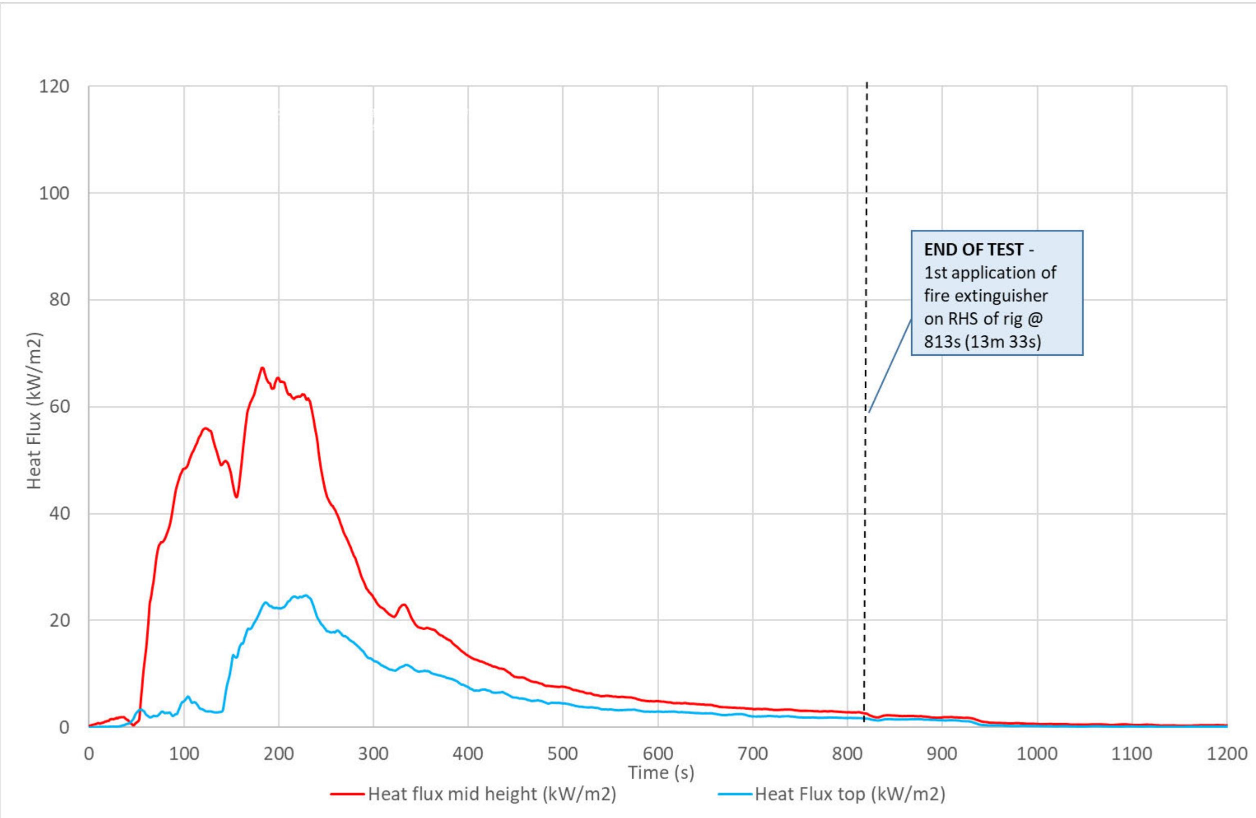
D4 Test Graphs for Polyester Batts with Sarking



Apx D 39 - Test 5 –HRR graph of Polyester batts and sarking, 1 tray heptane test (base scale)

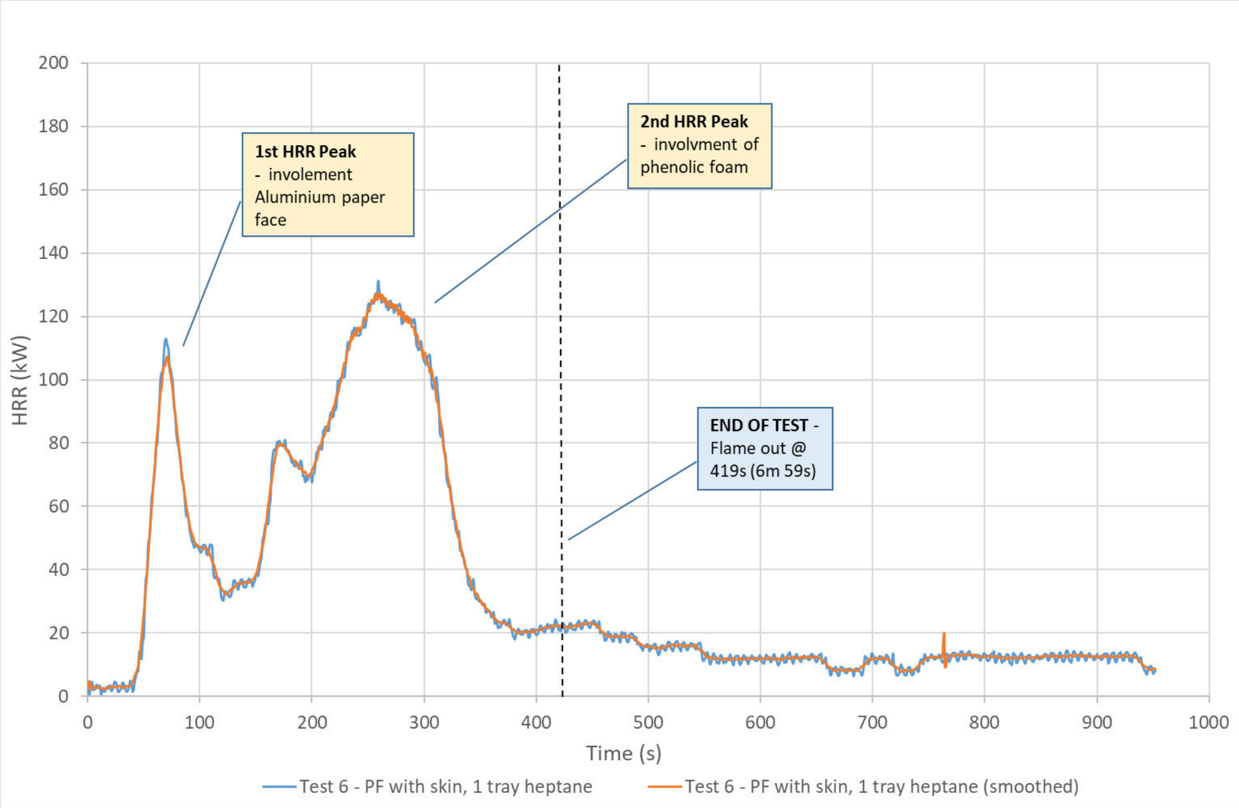


Apx D 40 - Test 5 – Temperature graph of Polyester batts and sarking, 1 tray heptane test (base scale)

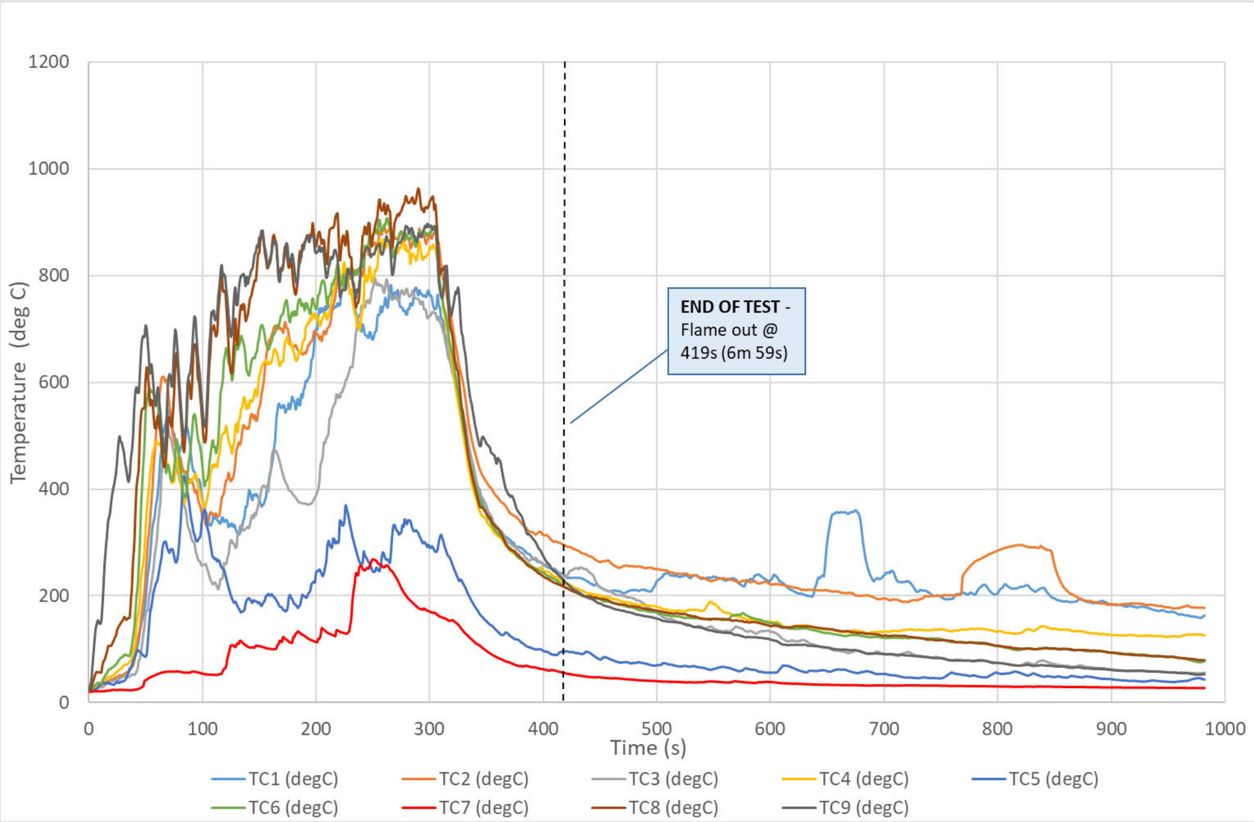


Apx D 41 - Test 5 – Incident heat flux graph of Polyester batts and sarking, 1 tray heptane test (base scale)

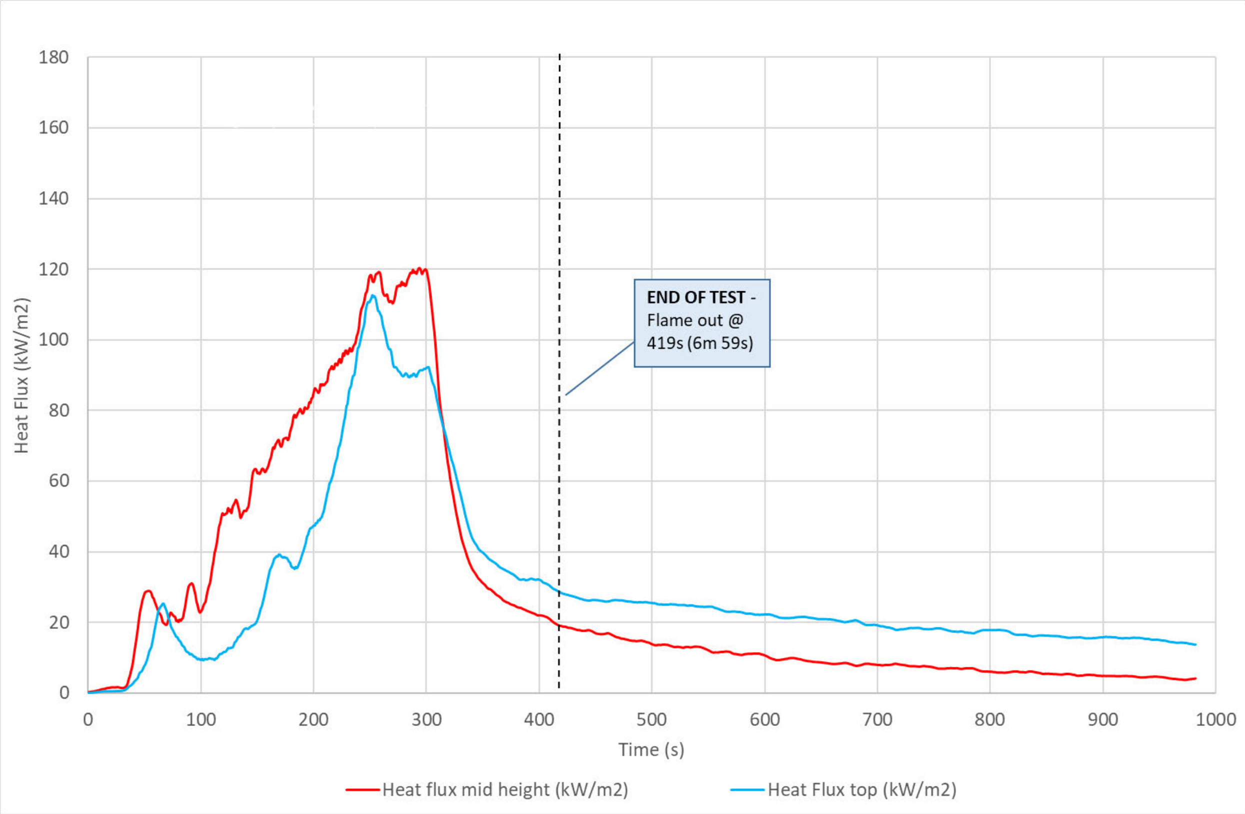
D5 Test Graphs for Phenolic foam



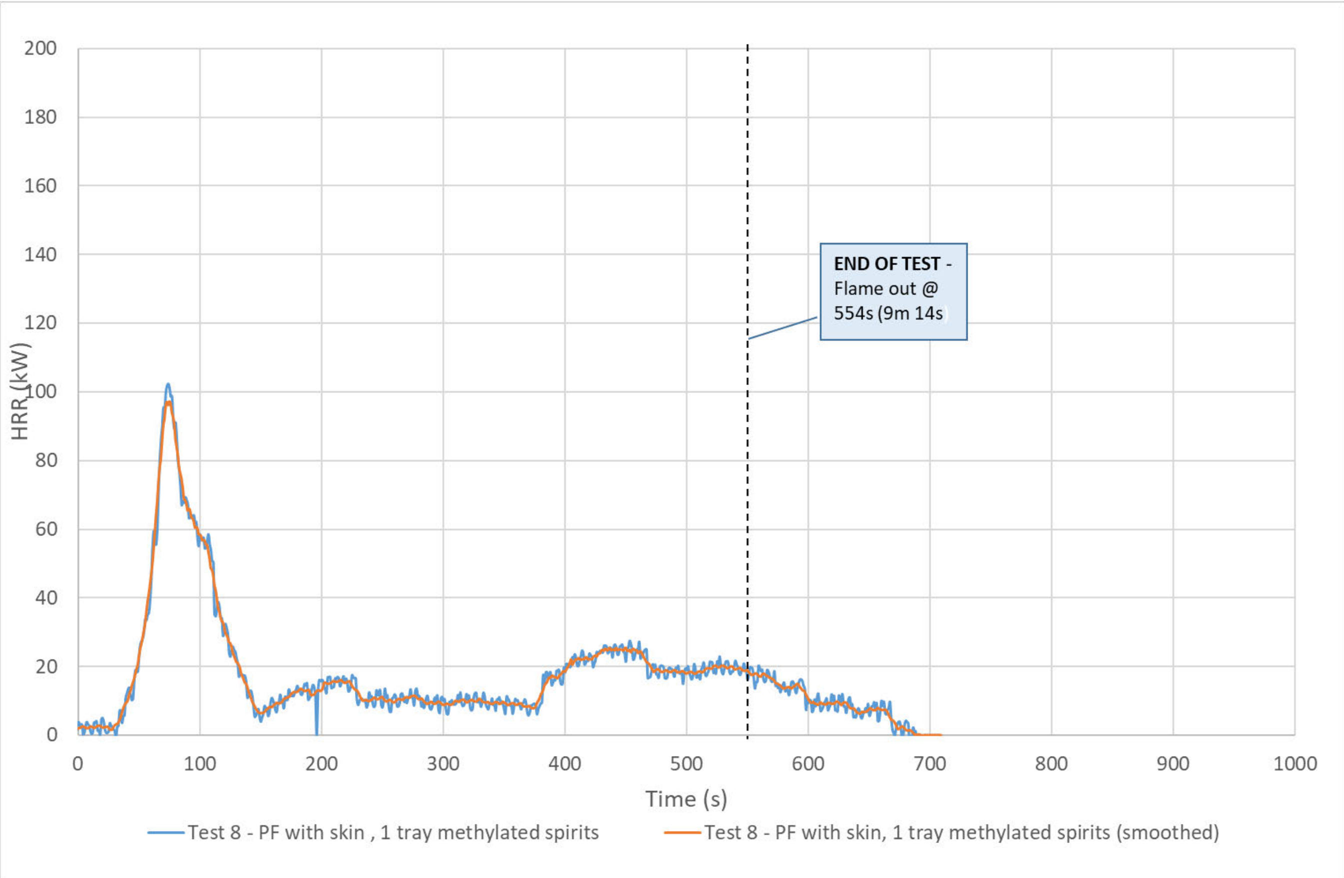
Apx D 42 - Test 6 –HRR graph of Phenolic foam with facing, 1 tray heptane test (base scale)

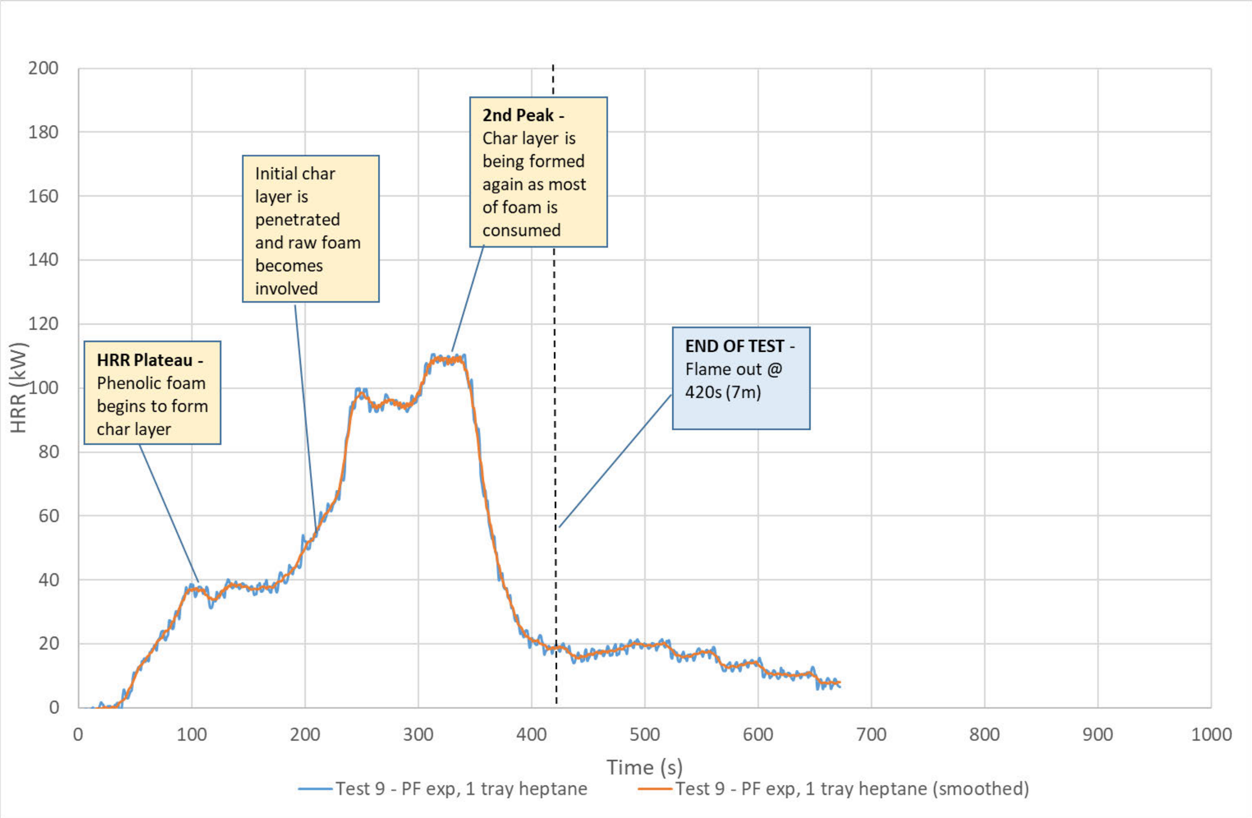


Apx D 43 - Test 6 – Temperature graph of Phenolic foam with facing, 1 tray heptane test (base scale)

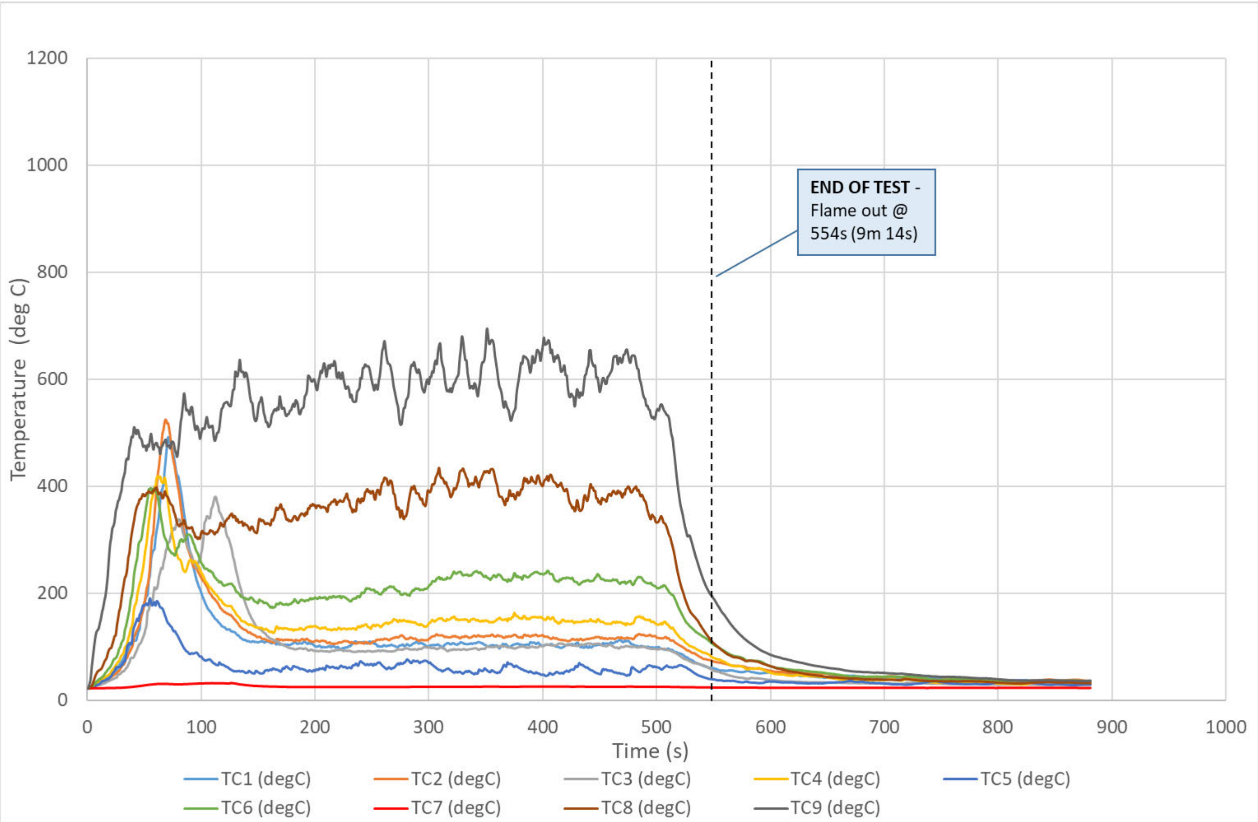


Apx D 44 - Test 6 – Incident heat flux graph of Phenolic foam with facing, 1 tray heptane test (base scale)

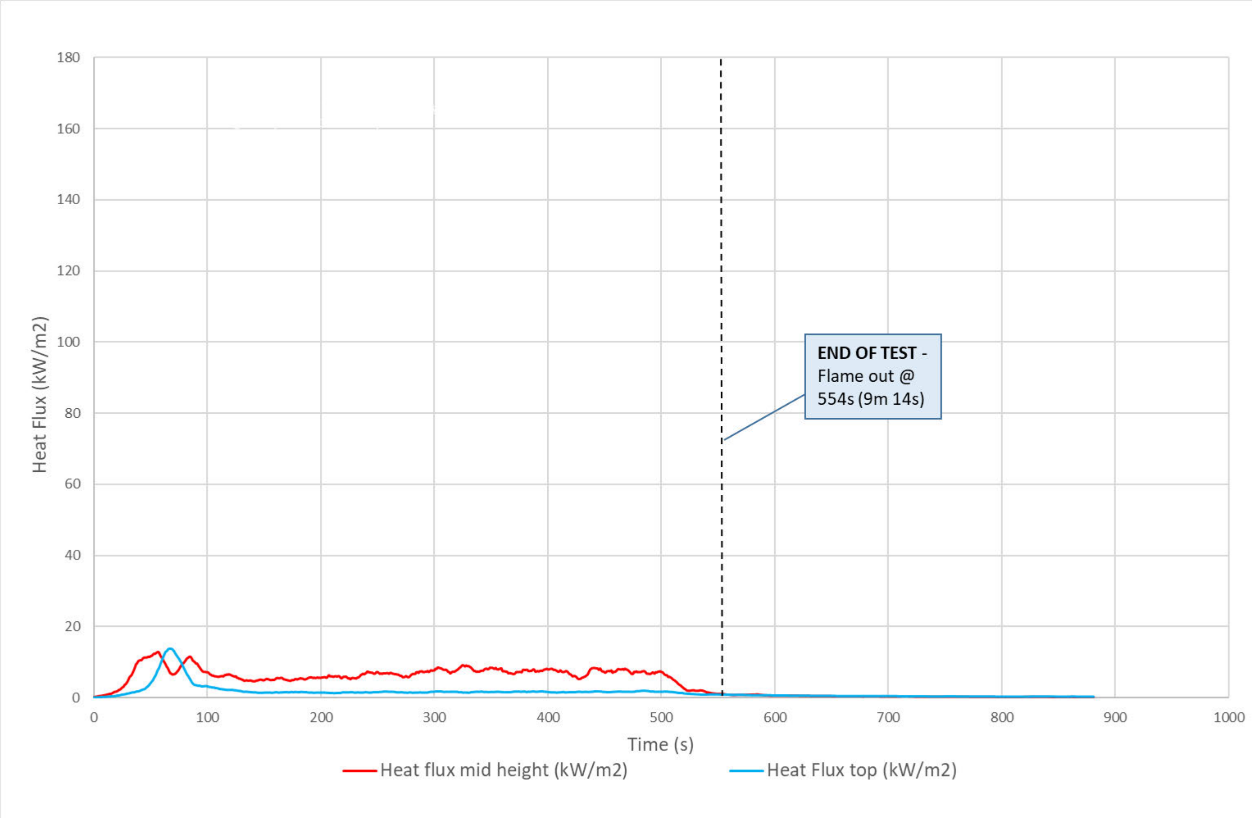




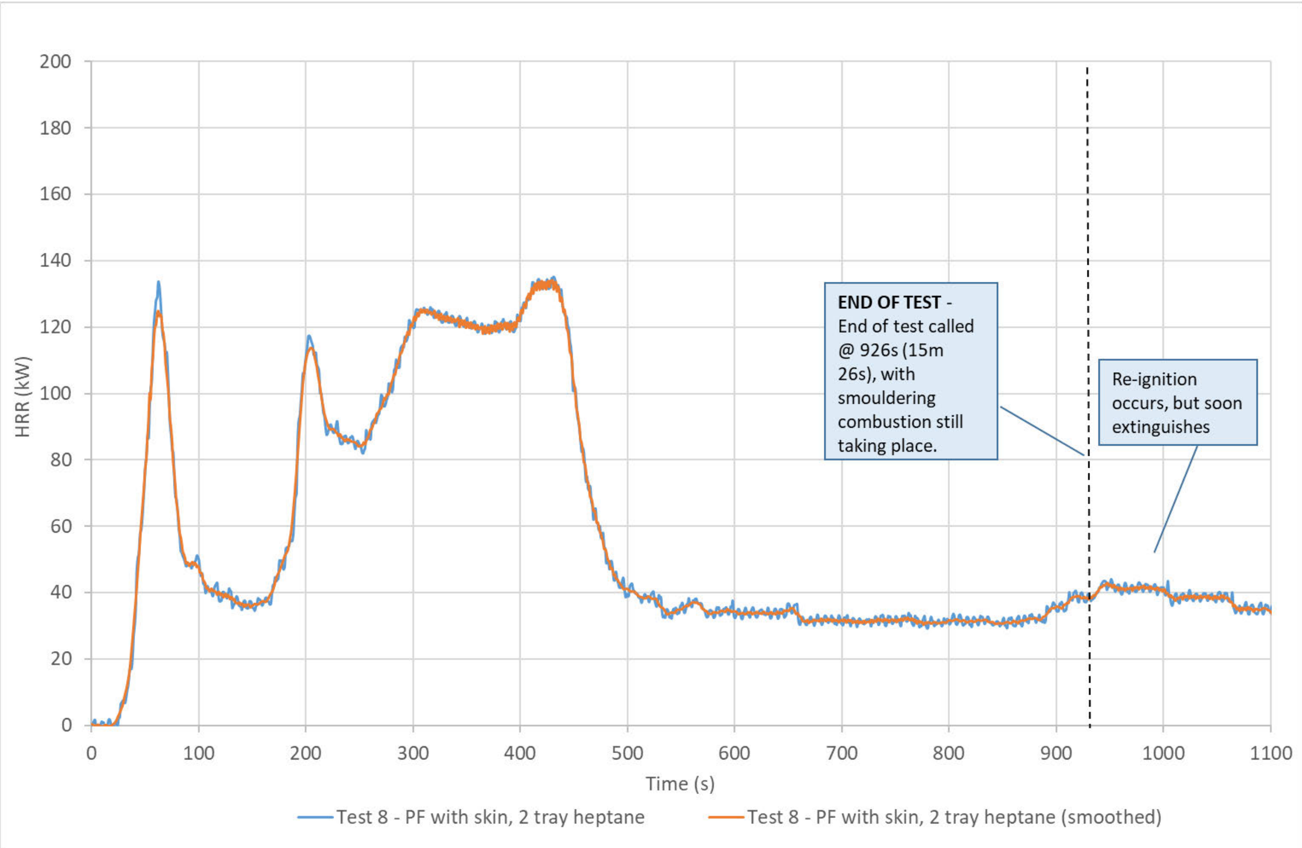
Apx D 45 - Test 7 –HRR graph of Phenolic foam with facing, 1 tray methylated spirits test (reduced scale)



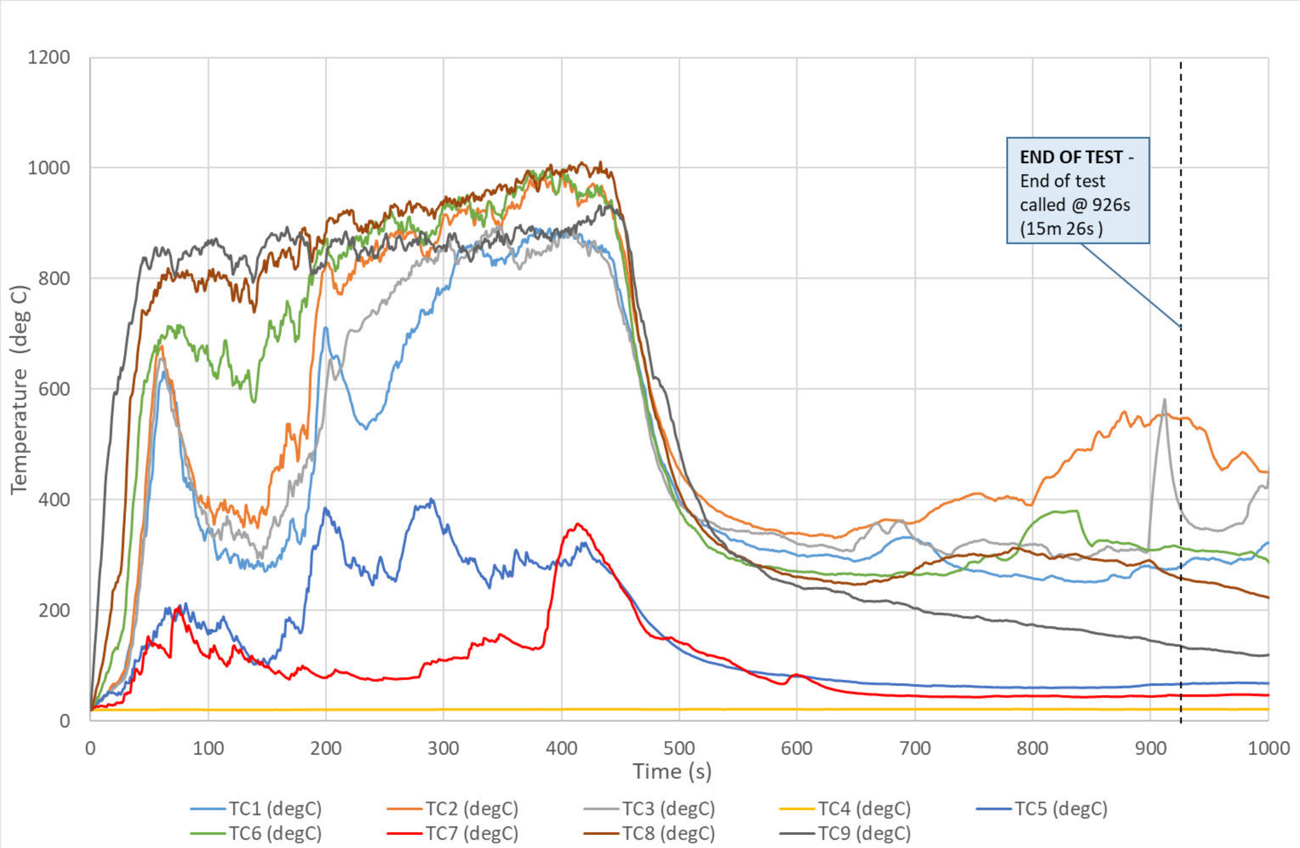
Apx D 46 - Test 7 – Temperature graph of Phenolic foam with facing, 1 tray methylated spirits test (reduced scale)



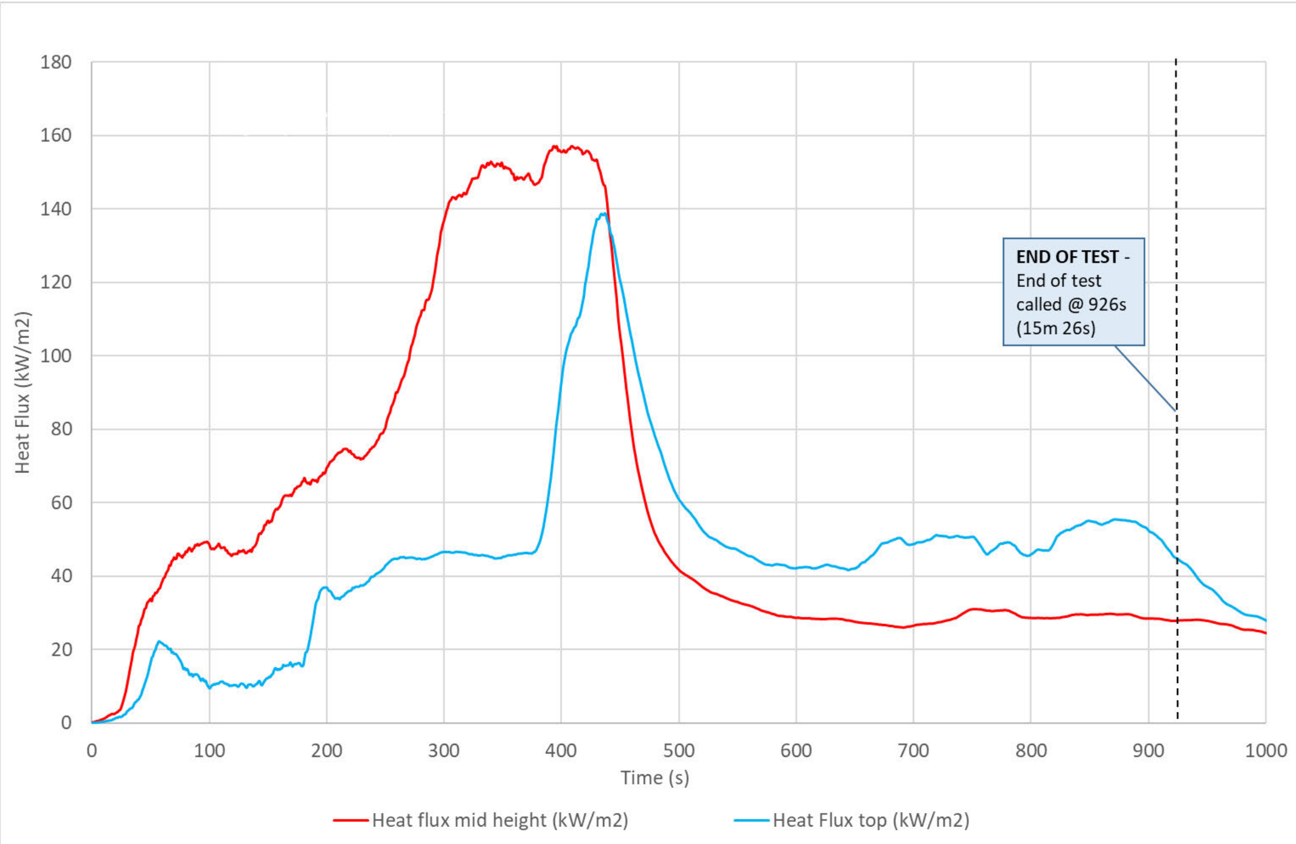
Apx D 47 - Test 7 – Incident heat flux graph of Phenolic foam with facing, 1 tray methylated spirits test (reduced scale)



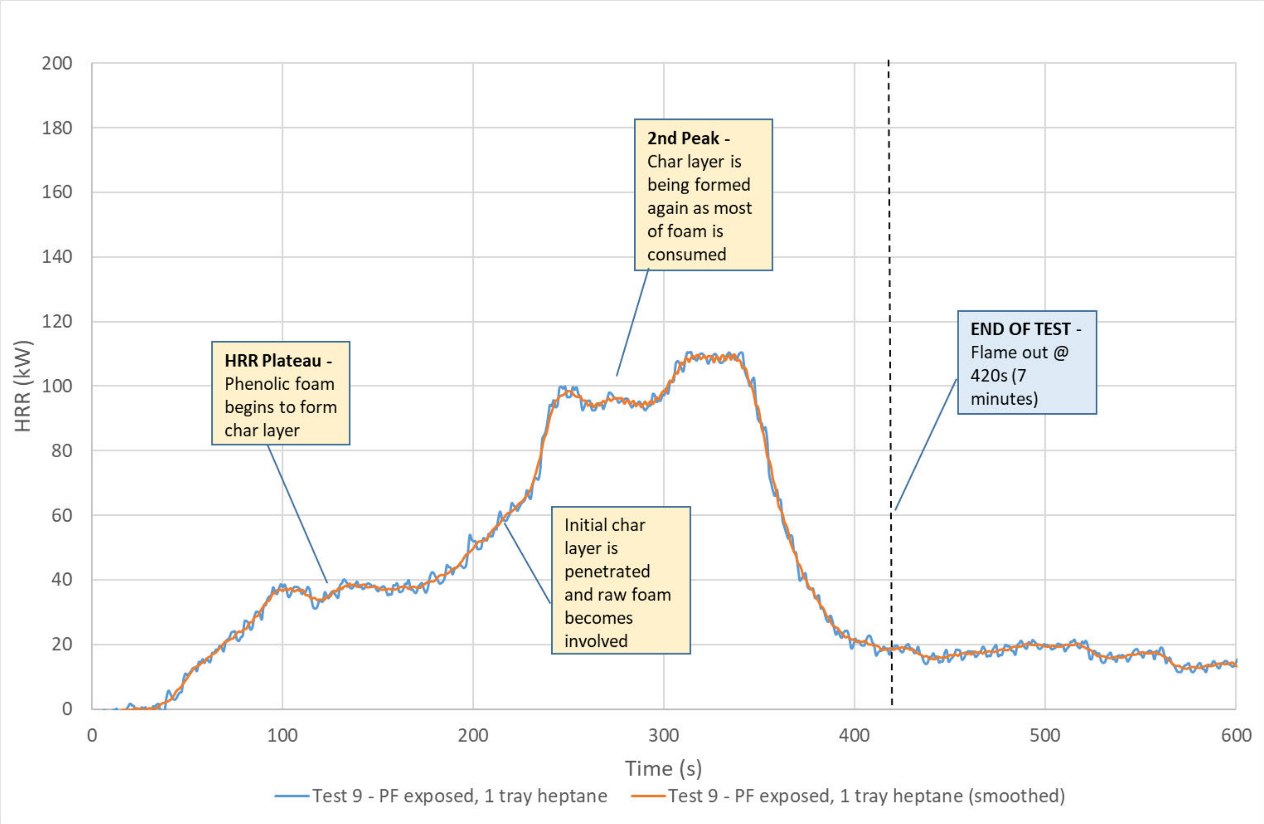
Apx D 48 - Test 8 –HRR graph of Phenolic foam with facing, 2 tray heptane test (sensitivity scale)



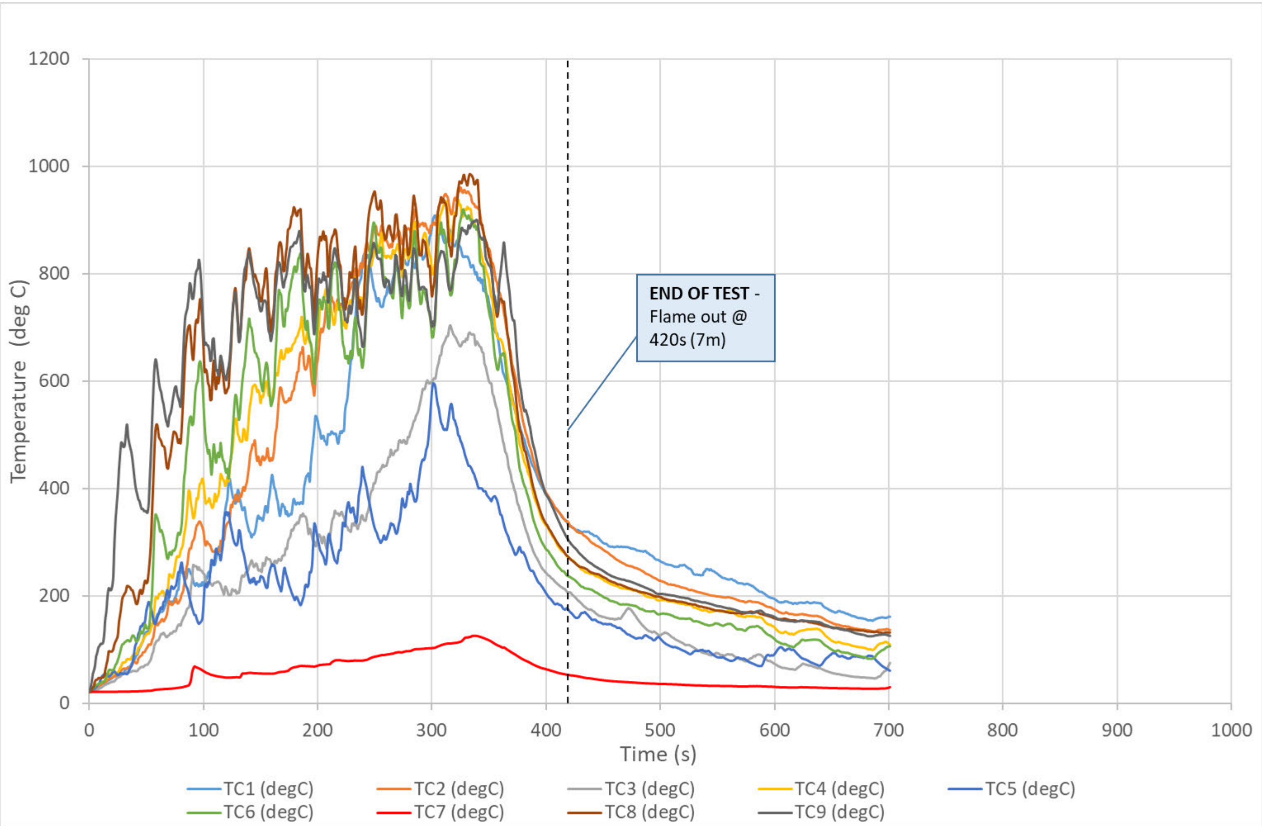
Apx D 49 - Test 8 – Temperature graph of Phenolic foam with facing, 2 tray heptane test (sensitivity scale)



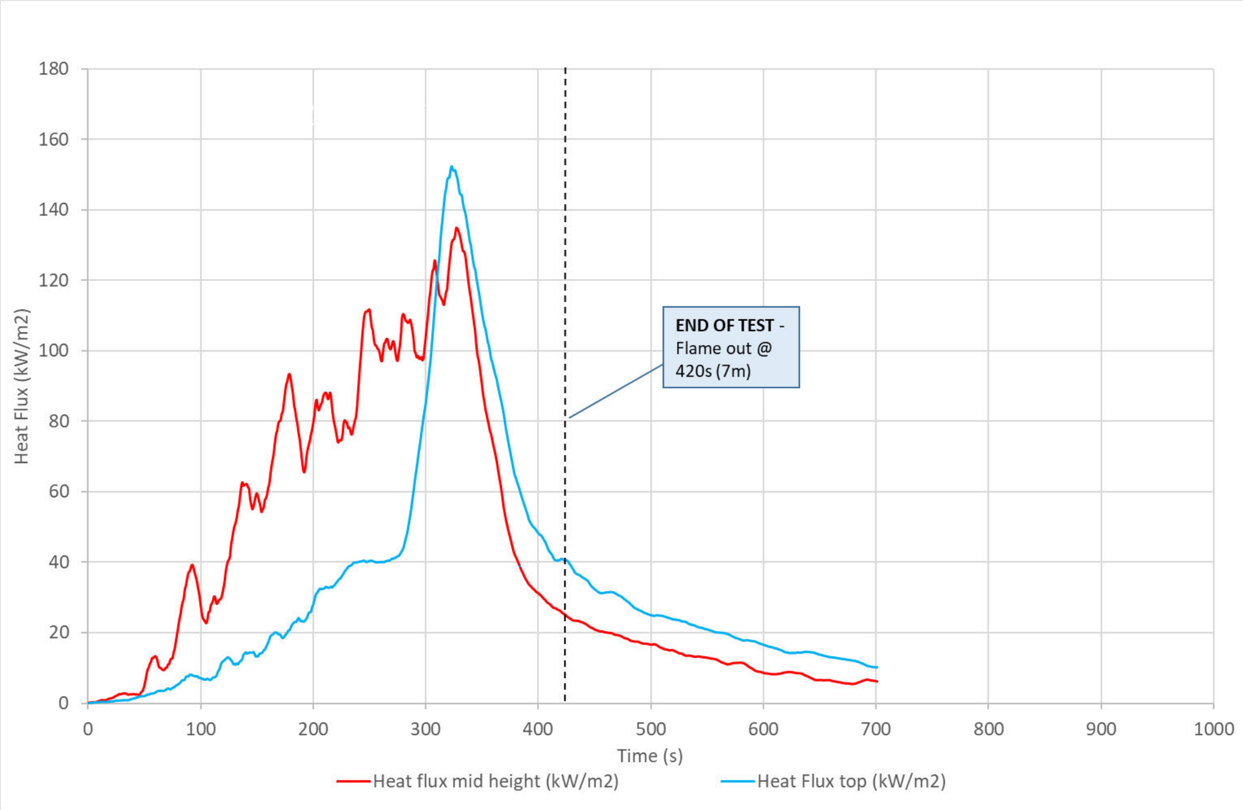
Apx D 50 - Test 8 – Incident heat flux graph of Phenolic foam with facing, 2 tray heptane test (sensitivity scale)



Apx D 51 - Test 9 – HRR graph of Exposed Phenolic foam, 1 tray heptane test (base scale)

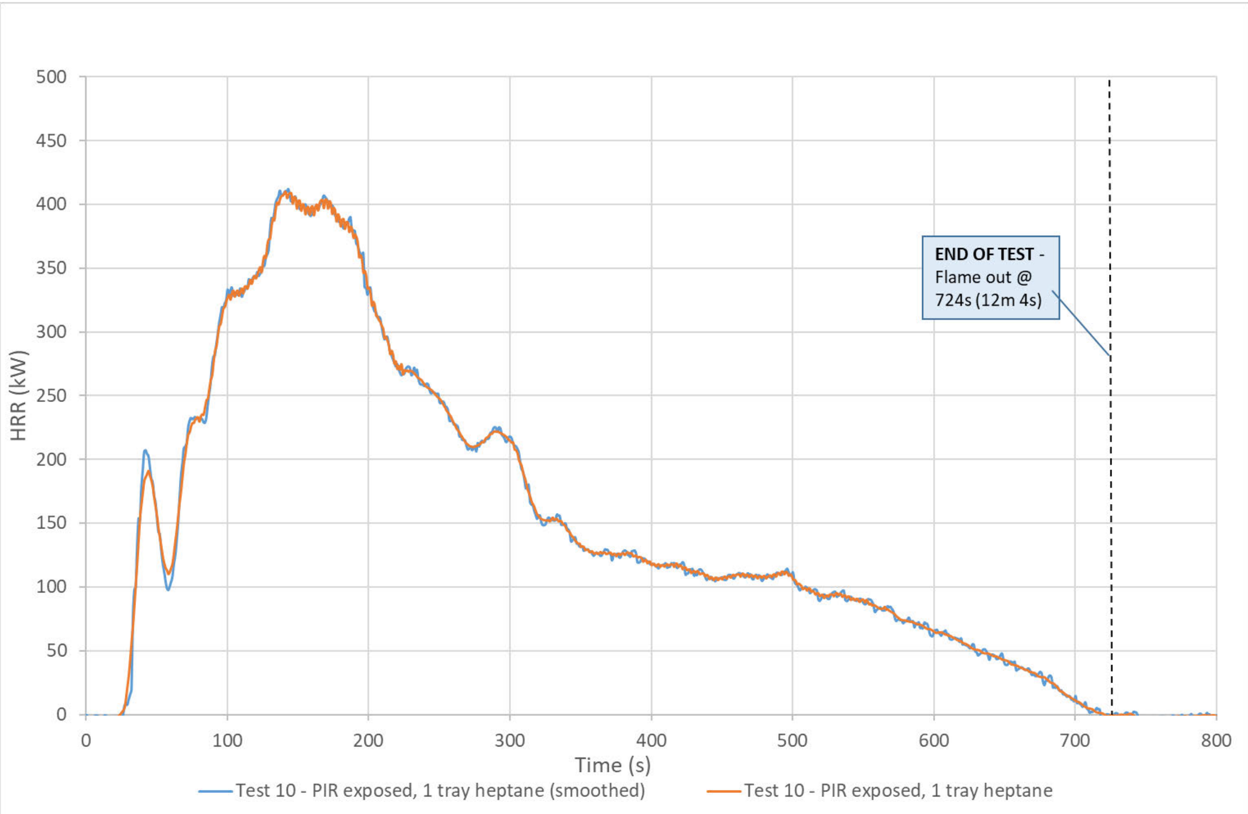


Apx D 52 - Test 9 – Temperature graph of Exposed Phenolic foam, 1 tray heptane test (base scale)

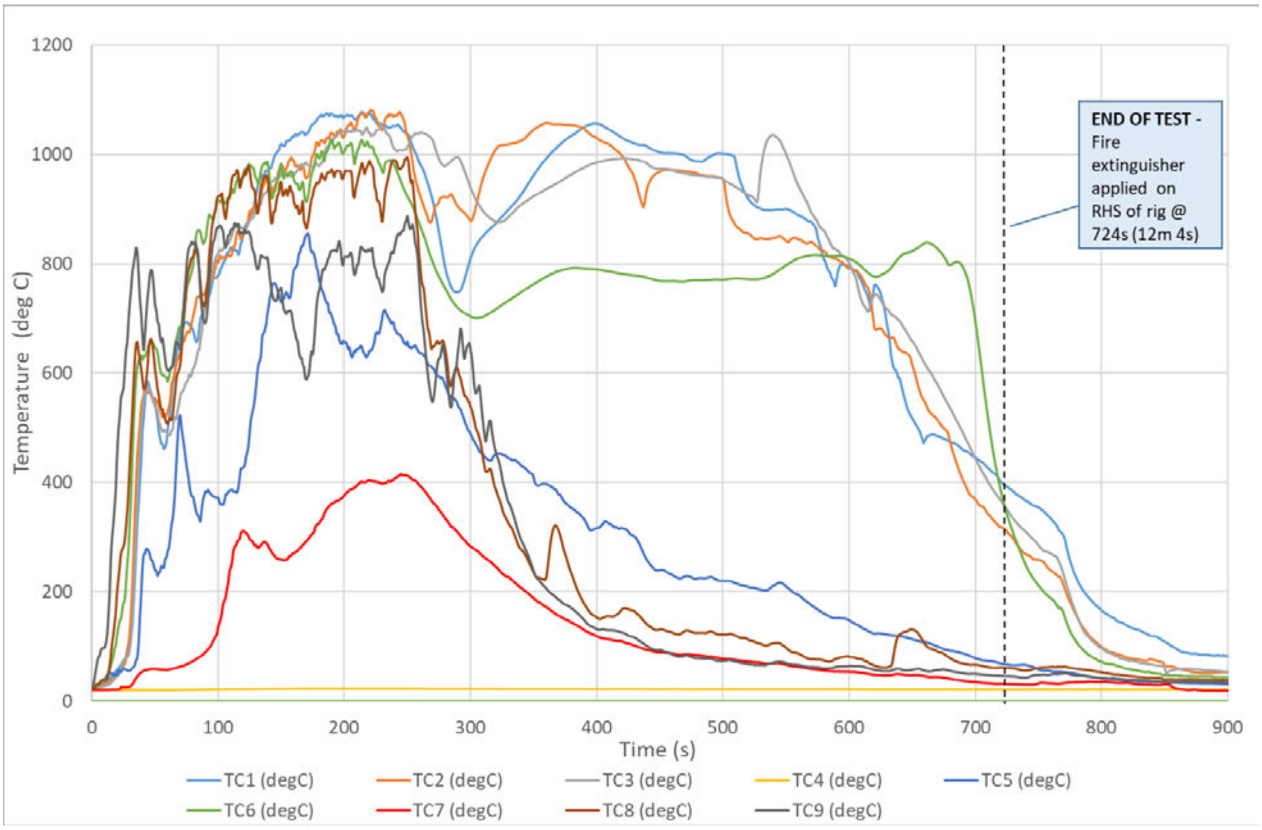


Apx D 53 - Test 9 – Incident heat flux graph of Exposed Phenolic foam ,1 tray heptane test (base scale)

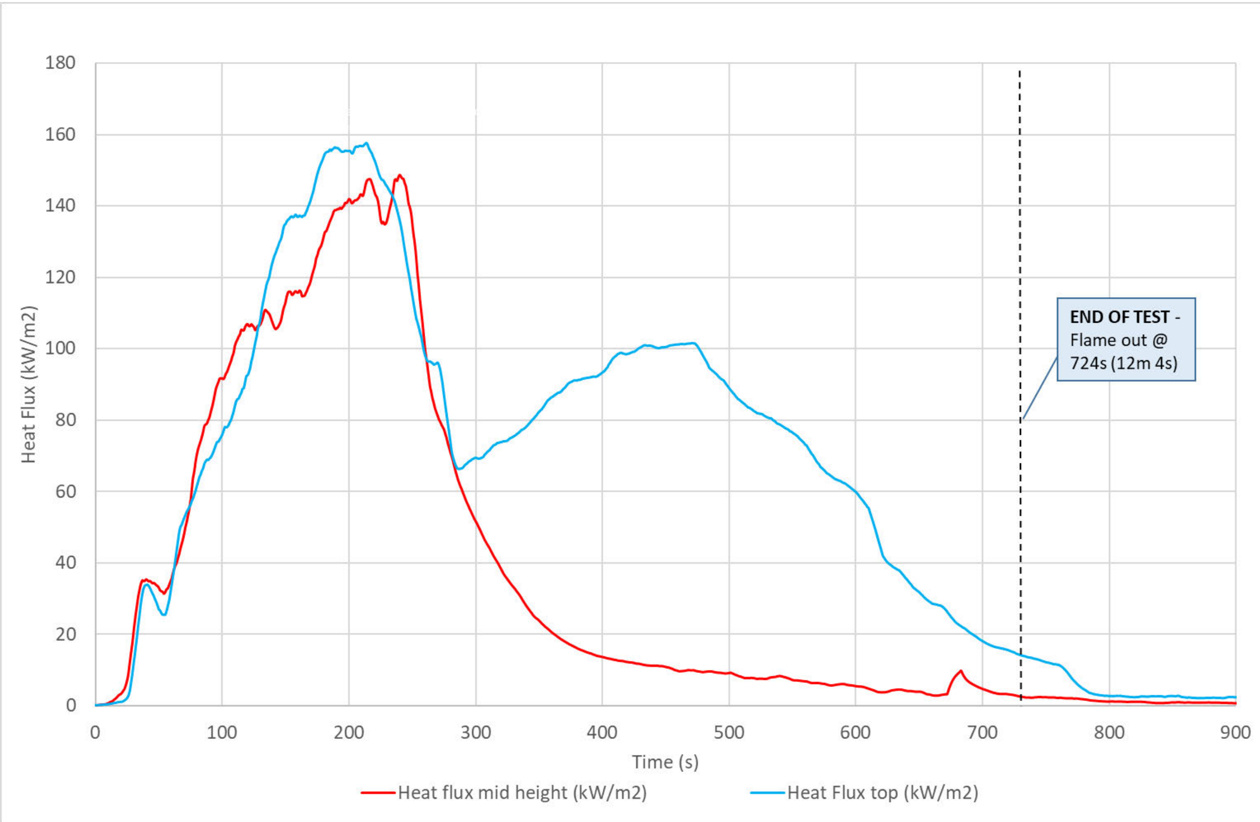
D6 Test Graphs for Polyisocyanurate



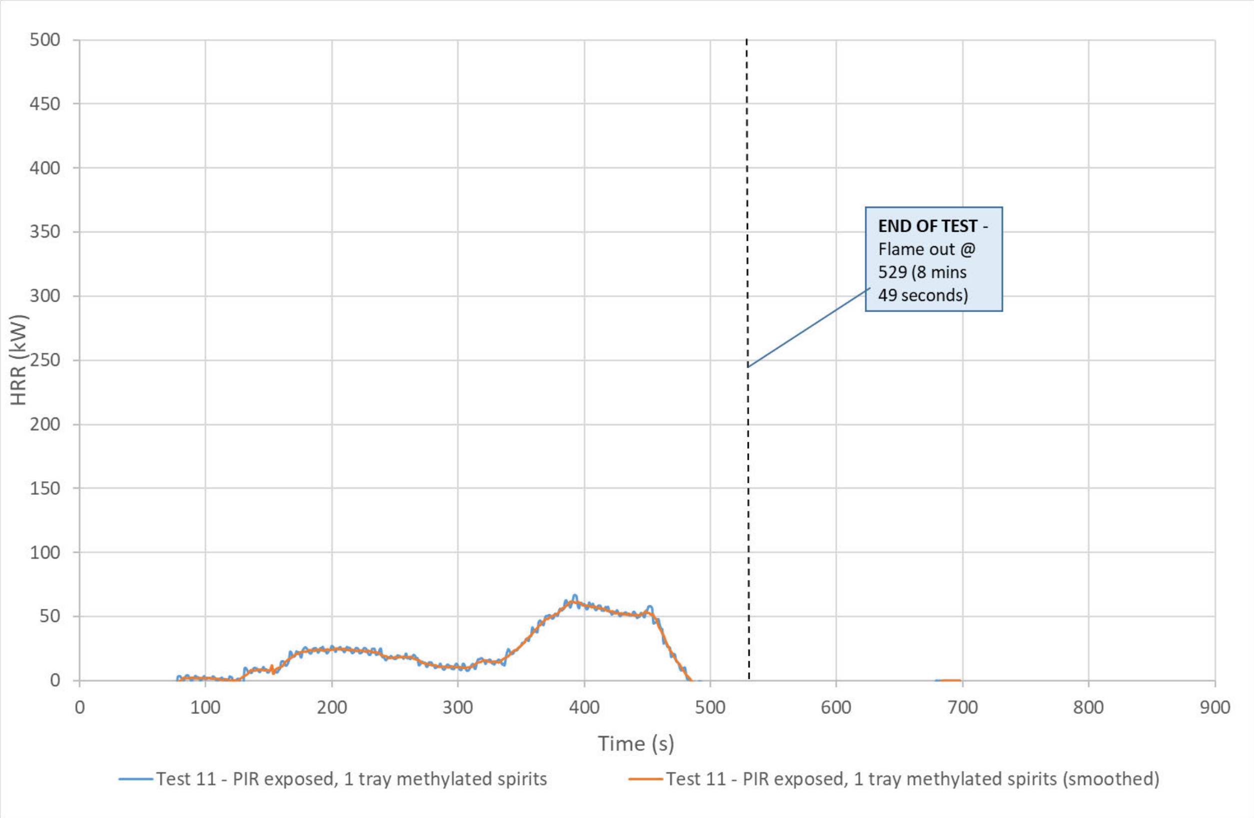
Apx D 54 - Test 10 – HRR graph of Exposed Polyisocyanurate board, 1 tray heptane test (base scale)



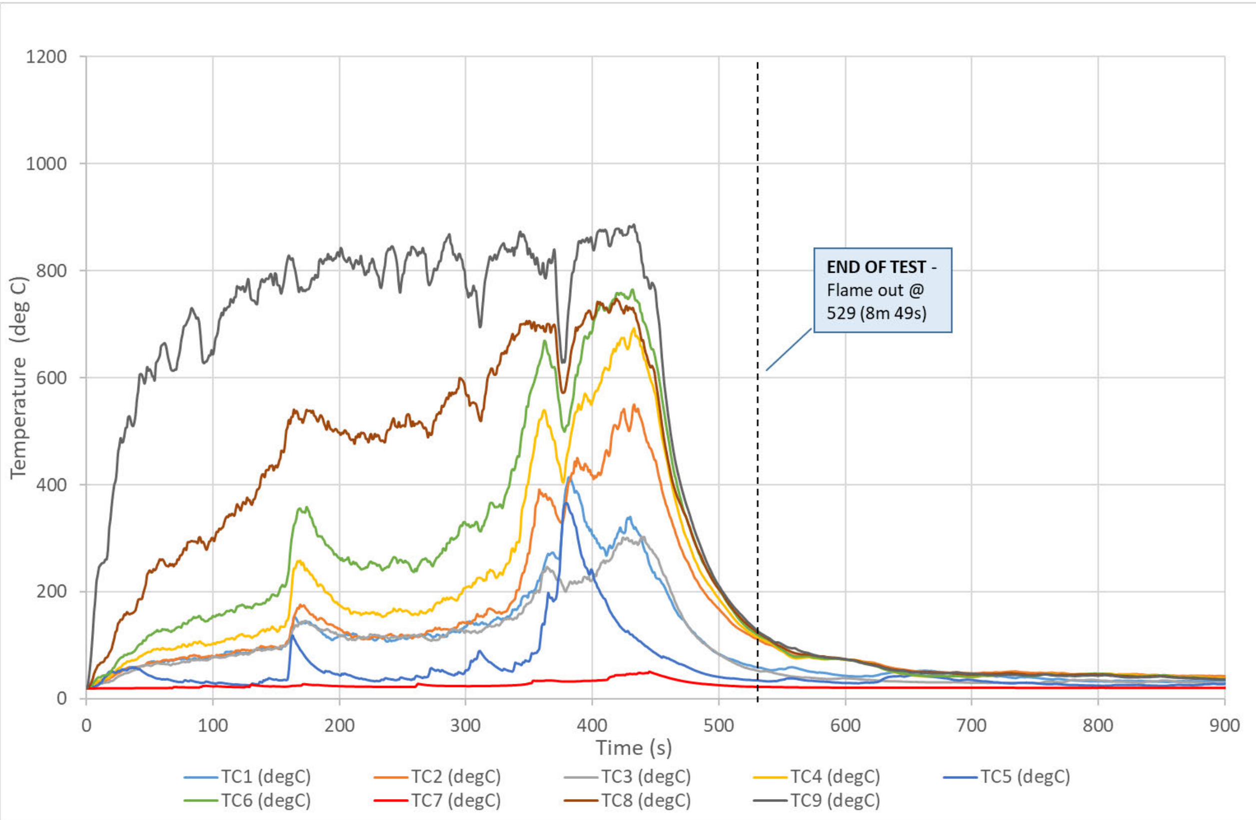
Apx D 55 - Test 10 – Temperature graph of Exposed Polyisocyanurate board, 1 tray heptane test (base scale)



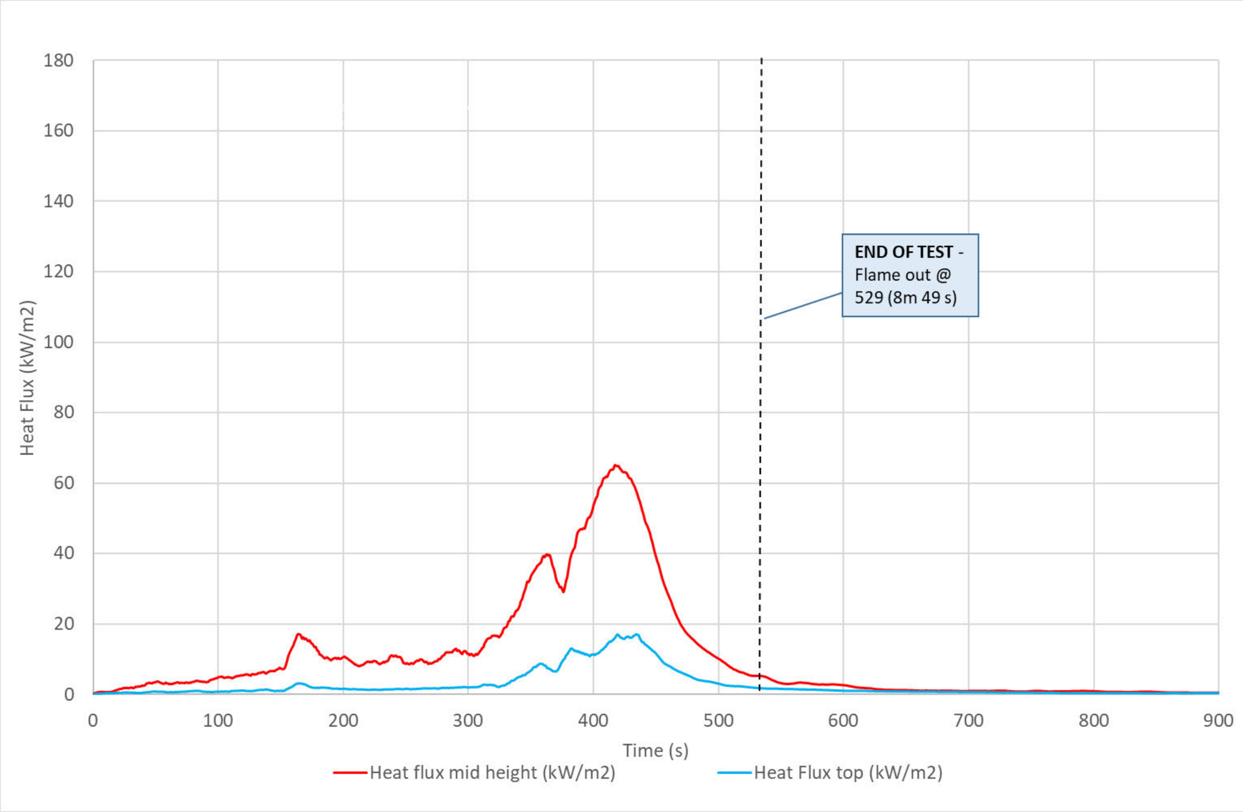
Apx D 56 - Test 10 – Incident heat flux graph of Exposed Polyisocyanurate board,1 tray heptane test (base scale)



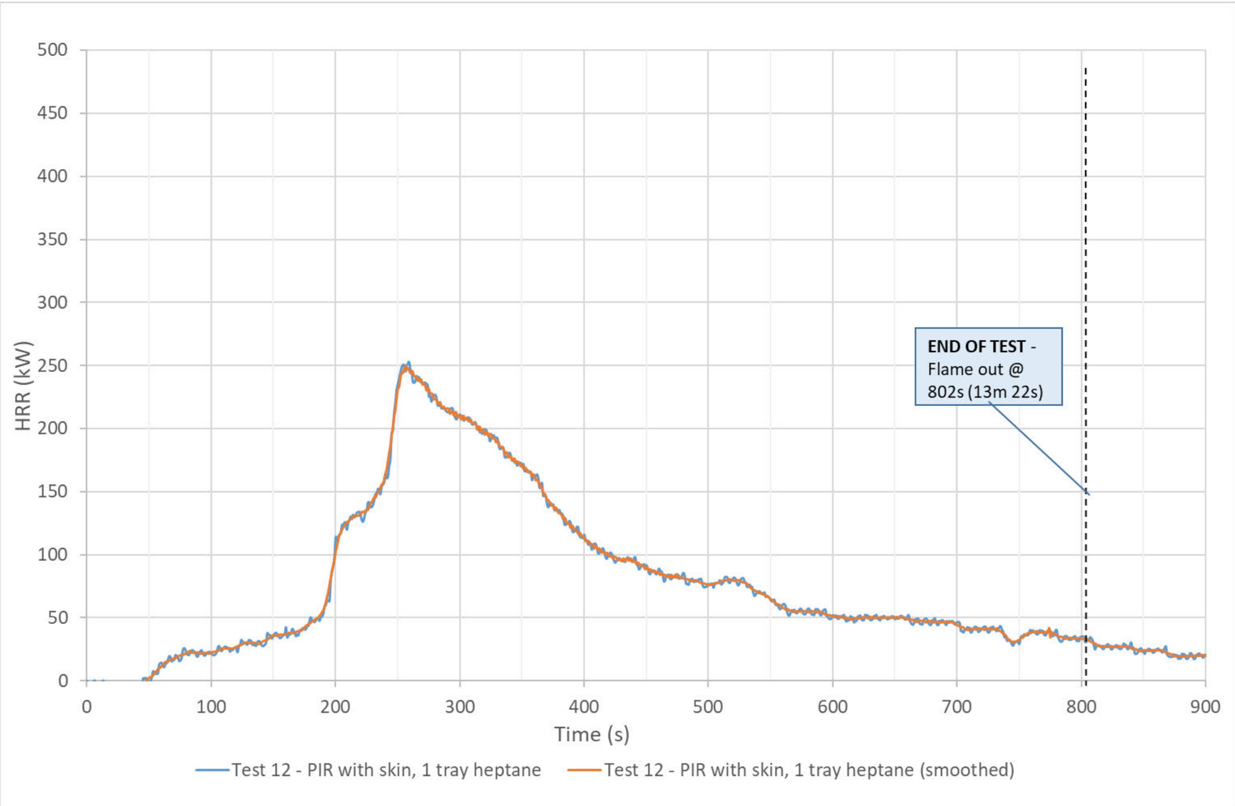
Apx D 57 - Test 11 –HRR graph of Exposed Polyisocyanurate board, 1 tray methylated spirits test (reduced scale)



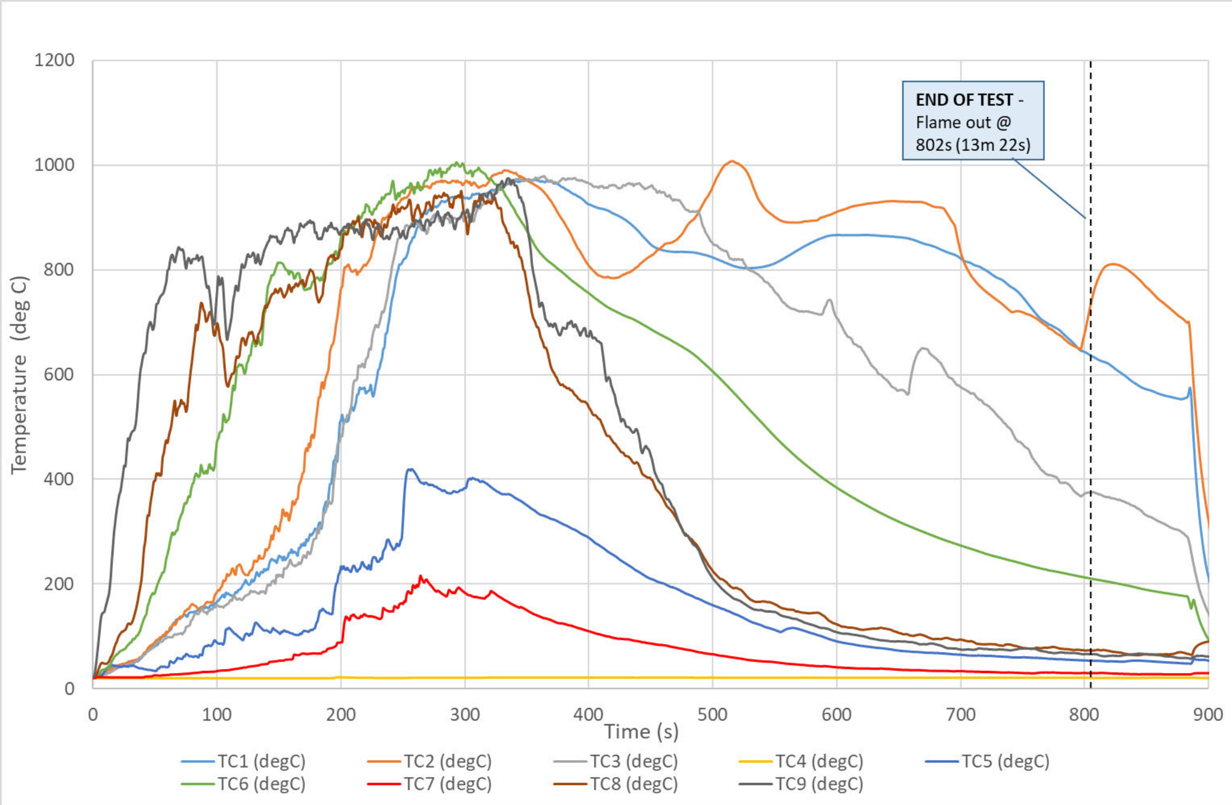
Apx D 58 - Test 11 – Temperature graph of Exposed Polyisocyanurate board, 1 tray methylated spirits test (reduced scale)



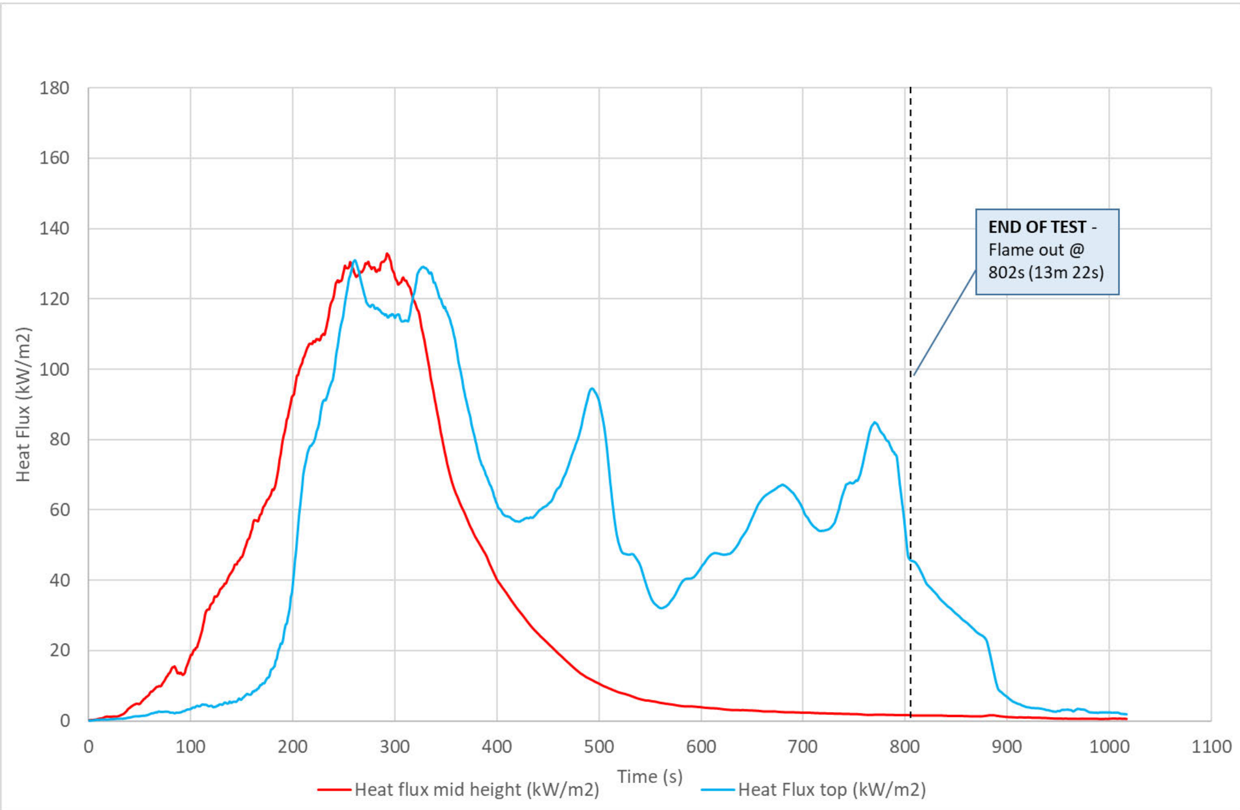
Apx D 59 - Test 11 – Incident heat flux graph of Exposed Polyisocyanurate board, 1 tray methylated spirits test (reduced scale)



Apx D 60 - Test 12 – HRR graph of Polyisocyanurate board with facing, 1 tray heptane test (base scale)

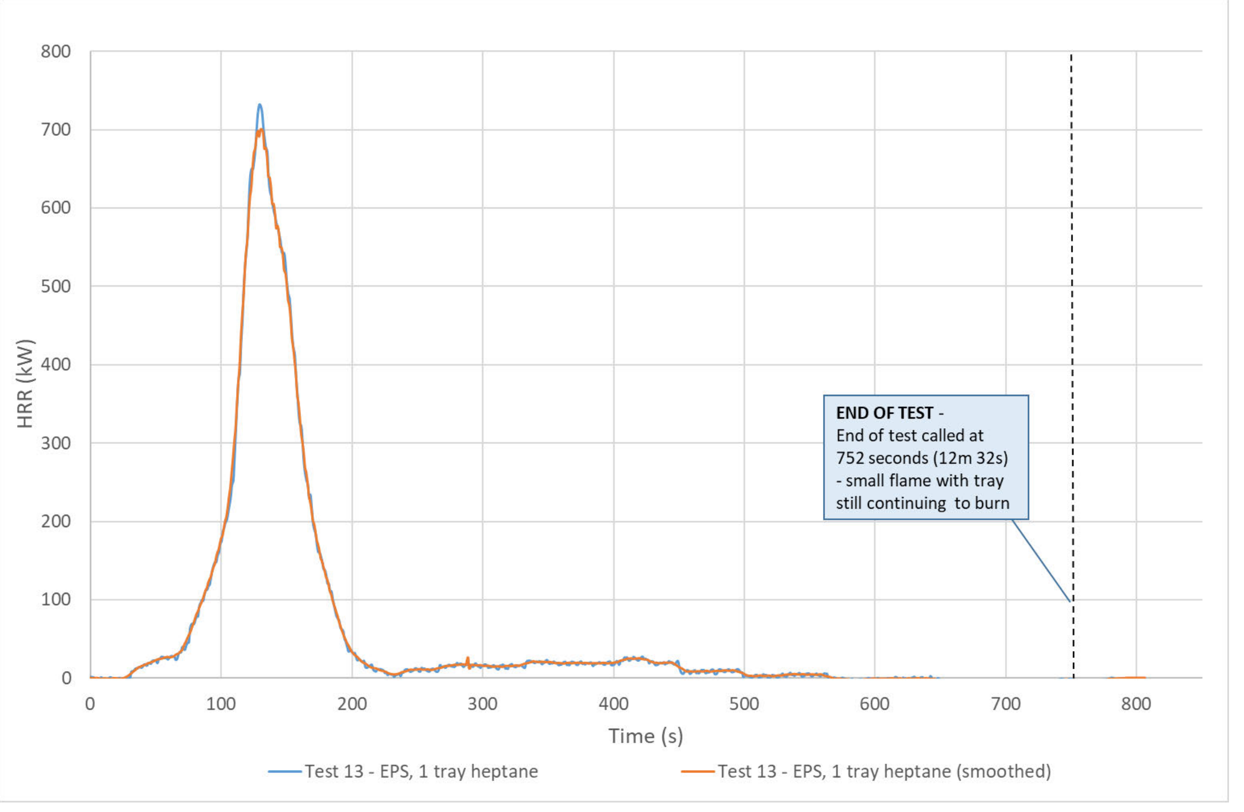


Apx D 61 - Test 12 – Temperature graph of Polyisocyanurate board with facing, 1 tray heptane test (base scale)

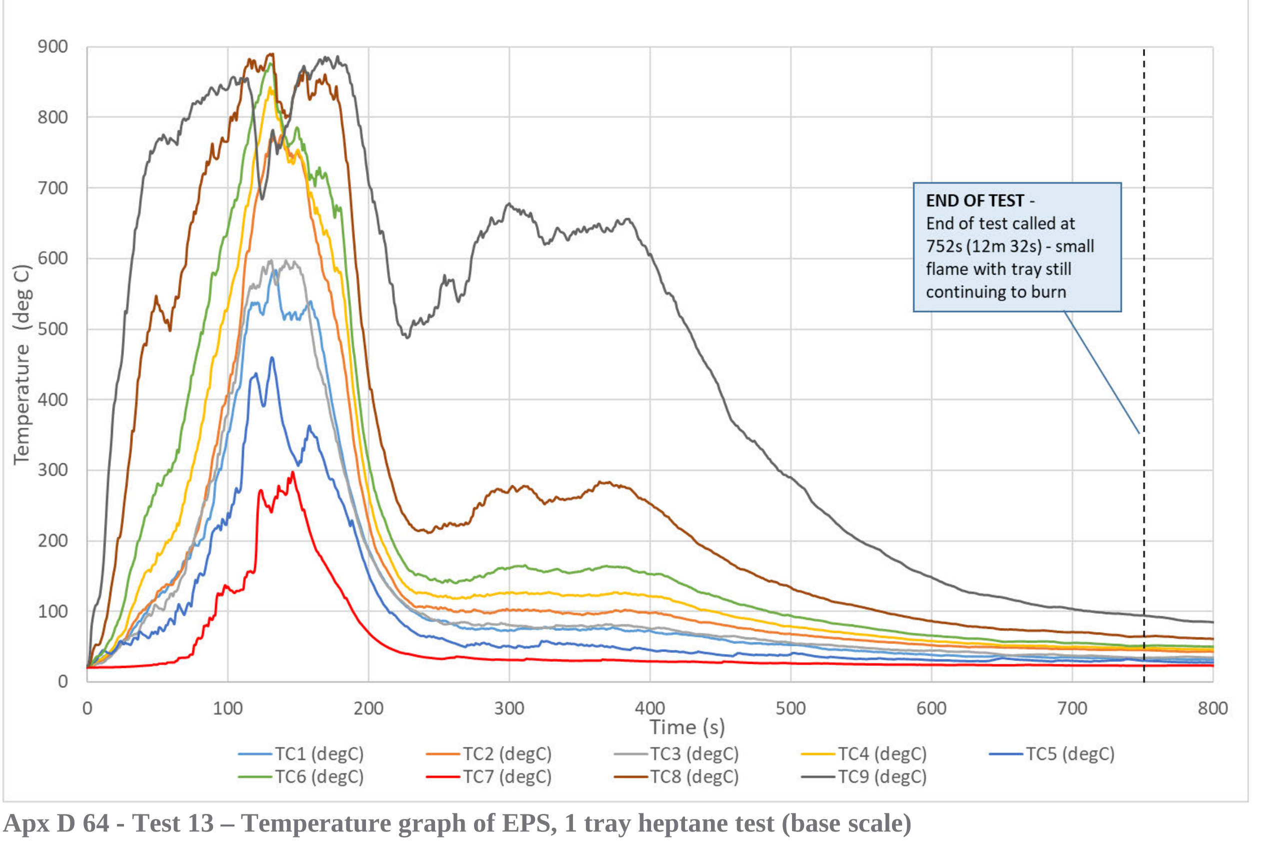


Apx D 62 - Test 12 – Incident heat flux graph of Polyisocyanurate board with facing, 1 tray heptane test (base scale)

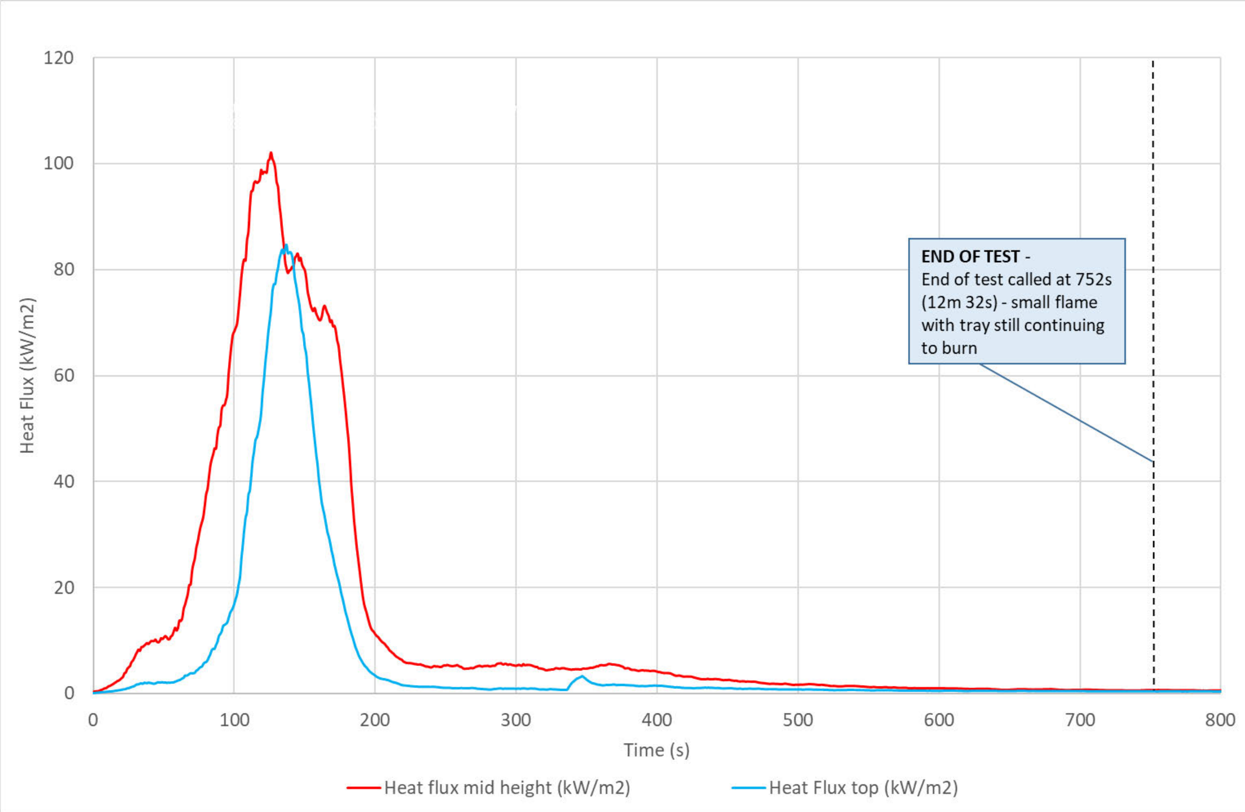
D7 Test Graphs for Expanded Polystyrene



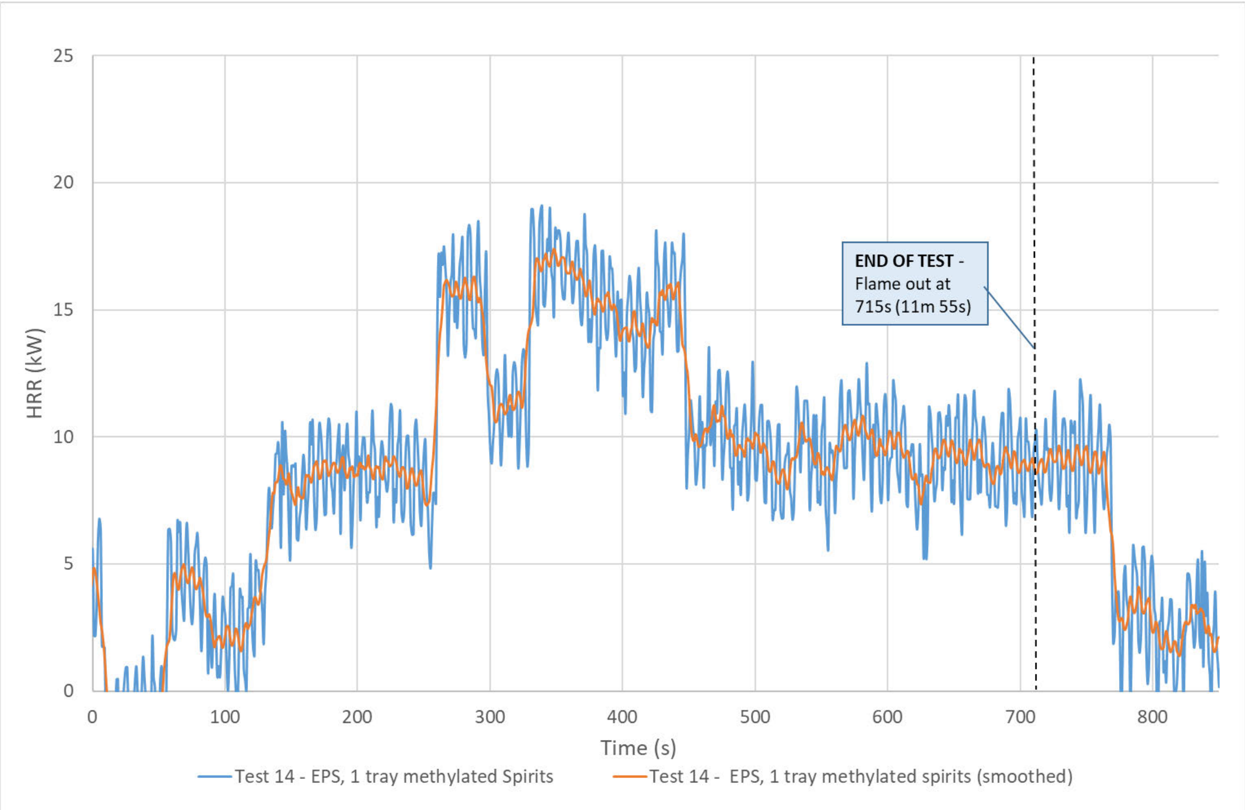
Apx D 63 - Test 13 – HRR graph of EPS, 1 tray heptane test (base scale)



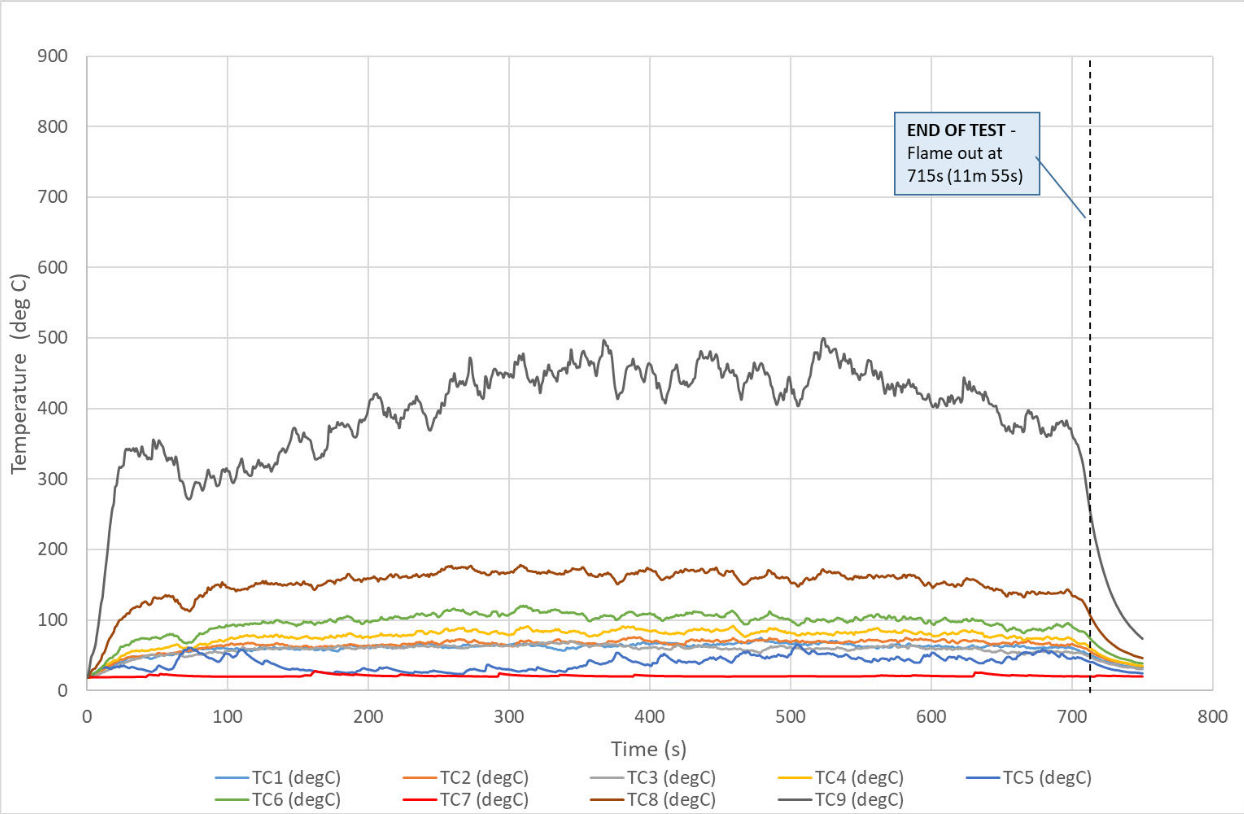
Apx D 64 - Test 13 – Temperature graph of EPS, 1 tray heptane test (base scale)



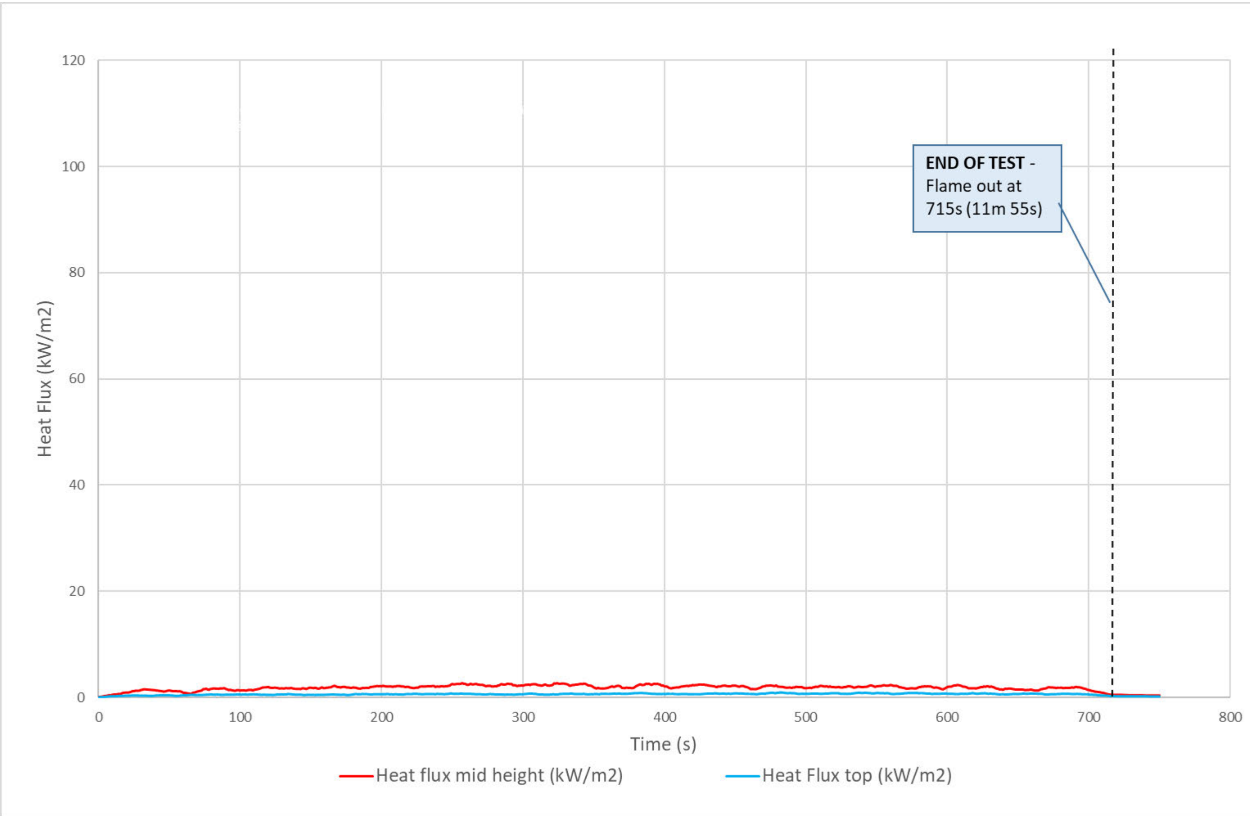
Apx D 65 - Test 13 – Incident heat flux graph of EPS, 1 tray heptane test (base scale)



Apx D 66 - Test 14 –HRR graph of EPS, 1 tray methylated spirits test (reduced scale)



Apx D 67 - Test 14 – Temperature graph of EPS, 1 tray methylated spirits test (reduced scale)



Apx D 68 - Test 14 – Incident heat flux graph of EPS, 1 tray methylated spirits test (reduced scale)