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Permanent Fire Load of the Building Envelope

(An examination of the Heat of Combustion in theoretical and realistic combustion processes using an increasing-scale testing approach)

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International Master of Science in Fire Safety Engineering

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Abstract

Fire load, the total thermal energy released by the combustion of a material, is an essential part of determining a building's fire performance and the associated fire protection strategies. Elements in a structure are typically categorized into two types of fire loads: permanent and temporary. Permanent fire loads represent the combustible materials in the building envelope. With the advent of energy efficiency, polymer-based materials with unique burning behaviors have been utilized more in the building envelope. These, and other materials that experience delamination, charring, melting, etc., can affect the way permanent fire loads are quantified.

National guidelines prescribe the use of the heat of combustion (HoC), which is derived from grams of material and tested in controlled conditions through calorimetry techniques when calculating fire loads. Micro-scale tests to obtain HoC, e.g., Bomb Calorimeter and Microscale Combustion Calorimeter, indicate that the specimens do not represent large-scale behaviors and physical factors such as end-use of the material, ventilation factors, layering of materials, etc. Additionally, it has been examined that the current literature values that are derived from Bomb Calorimeter tests are deemed outdated and report underestimation or overestimation when calculating permanent fire loads.

The aim of the project is two-fold: carry out a theoretical examination of how permanent fire loads are calculated per country, and; utilize traditional and alternative approaches to obtain the Hoc for building envelope materials. By utilizing an increasing-scale testing approach, theoretical (Microscale Combustion Calorimeter and Bomb Calorimeter) and realistic values (Cone Calorimeter and 1/3-scaled room corner test) for the Heat of Combustion were derived.

It was determined from the experimental design that the calculated fire load from the room corner tests results in the lowest fire loads, both permanent and temporary, because it considers systemic performance and material-to-material interaction. The presence of the non-combustible materials provided means to delay the burning of the combustible linings. Further, it was seen in the scaling of the tests from micro- to final form of the samples, that the Cone Calorimeter is an attractive starting point to accurately represent permanent fire loads since materials could be tested as composites or in larger sizes vs. microscale tests.

Abstract in Mother Tongue (Hiligaynon)

Ang fire load (karga sang kainitaan) ang kabug-usan sang thermal enerhiya nga ginapagwa sang isa ka nasunog nga materyal, amo ang isa ka labing importante nga bahin sa pag tukoy sang fire performance sang isa ka bilding kag ang mga na asosyar nga mga stratehiya parti sa proteksyon sa kalayo. Sa masami, duha ka klase gina kategorisar ang mga elementa sa estruktura: permanente kag temporaryo. Ang permanente nga karga sang kalayo nagarepresentar sa mga madali masunog nga mga materyales nga ara sa bilding. Sa pagsulong sang energy efficiency, ang mga materyales nga base sa polymer nga may mga unique nga behavior sa tion nga masunog mas ginagamit na sa building envelope. Ini nga mga materyales, kag iban pa nga naga eksperyensya sang delamination, charring, melting, kag iban pa pwede maka apekto sa paagi sang pagkuha sa permanente nga karga sang kalayo.

Ang national guidelines nagapatuman sang paggamit sang heat of combustion (HoC), nga nagahalin sa mga gramo nga materyal kag ginatest sa controlled nga mga kondisyon sa paagi sang calorimetry techniques sa pagkalkular sang fire loads. Ang mga micro-scale nga mga test para makuha ang HoC, pareho sang Bomb Calorimeter kag Microscale Combustion Calorimeter, nagapakita nga ang mga specimens wala nagarepresenta sang large-scale nga mga pagkabagay kag sang mga physical factors pareho sang end-use sang materyal, mga faktor sang ventilation, layering sang mga materyales, kag iban pa. Gin-examine man nga ang current literature values nga nagahalin sa Bomb Calorimeter tests ginakabig nga wala na sing kabagay ukon sobra ka gamay sa pagkalkular sang permanente nga fire loads.

Ang tuyo sang proyekto may duha ka bahin: una, ang paghimo sang theoretical examination sang paagi sang pagkalkular sang permanent fire loads sa kada pungsod, kag ikaduha, ang paggamit sang traditional kag alternative nga mga approach para makuha ang HoC sang mga materyales sa building envelope. Paagi sa paggamit sang increasing-scale testing approach, nagresulta sa pag-derive sang theoretical (Microscale Combustion Calorimeter kag Bomb Calorimeter) kag realistic nga mga values (Cone Calorimeter kag 1/3-scaled room corner test) sang Heat of Combustion.

Gin determinar sa experimental design nga ang gin kalkular nga fire load gikan sa room corner tests nagapakita sang pinakanubo nga fire loads, duha sila sang permanente kag temporaryo nga mga fire loads, bangod nagatugot ini sang systemic performance kag sang material-to-material interaction. Ang presensya sang mga materyales nga indi madabdab nagahatag sang paagi sa pagpaantala sang pagdabdab sang mga nagadabdab nga linings. Dugang pa, nakita sa pag-upang sang mga test gikan sa micro- asta sa katapusan nga porma sang mga sample nga ang Cone Calorimeter isa ka magamayon nga umpisa para sa pagrepresentar sing husto sang permanente nga karga sang kainitaan kay ang mga materyales mahimo ma-test bilang mga komposisyon ukon sa mas daku nga kadakuon kon ikumparar sa mga microscale nga mga test.

The strength of walls
depends on the courage
of those who guard them.

- Genghis Khan

Nomenclature

A	Area [m^2]
A_f	Fuel bed area [m^2]
b	Correction required for the combustion heat of the "fuels" used during the test [MJ]
c	Temperature correction factor required for the exchange of heat with the outside [K]
D	Pool diameter [m]
E	Water equivalent of the calorimeter, the bomb, their accessories and of the water introduced into the bomb [MJ/kg]
H	Height of the room opening [m]
H_{ui}	Heat of combustion value of the material *i* [MJ/kg]
K	Extinction coefficient [m^{-1}]
M / M_i	Total mass (loss) of the combustible material *i* [kg]
$\dot{M}$	Mass loss rate [kg/s]
$\dot{M}''$	Mass flux or mass burning rate per unit area [$kg/m^2.s$]
$\dot{M}''_\infty$	Limiting burning rate [$kg/m^2.s$]
m_i	Combustion factor [-]
q	Latent heat of vaporization of the condensed water [MJ/kg]
Q	Permanent fire load [MJ]
$\dot{Q}$	Heat Release Rate [kW]
Q''	Permanent fire load density [MJ/m^2]
t	Time [s]
T	Temperature [K]

Subscript

eff	Effective heat of combustion [MJ/kg]
gross	Gross heat of combustion [MJ/kg]
net	Net heat of combustion [MJ/kg]
FO	Flashover
fuel	Heptane and water in room corner tests
i	Initial

m	Maximum
T / total	Total
ui	Pertains to the combustible material

Greek Symbols

$k\beta$	Empirical constant [m^{-1}]
ψ_i	Protection factor, value between 0-1 [-]
ρ	Density [kg/m^3]
σ	Standard Deviation [-]

Terminology and Symbols

PCFC	Pyrolysis-combustion flow calorimetry
ISO	International Organization for Standardization
FTT	Fire Testing Technology Limited
CBUF	Combustion Behaviour of Upholstered Furniture
THR	Total Heat Released
EHC	Effective Heat of Combustion
EUREFIC	European Reaction to Fire Classification

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1. Introduction

1.1 Background

All fire engineers must and should be familiar with the concept of *design fire* since it is the building block of any effective fire protection strategy. As concerted efforts are placed to shift from a prescriptive to a performance-based mindset, a fundamental knowledge of fire behavior is imperative for all technical stakeholders - engineers, architects, and firefighters. Simply put, a design fire is a fire's characteristics described in terms that are easily relatable and understood by everyone: heat, smoke, and toxic gas production [1]. In incidents, a well-defined design fire paints a strong picture of what one fire scenario would presumably *look* and *feel* like in a closed compartment. For fire engineers to capture the most accurate and clearest picture of a design fire and its associated risks, they must have the proper tools at their disposal. This starts with identifying what factors could heavily influence the duration, severity, intensity, and size of a fire. Numerous studies agree that the *fire load* and *heat release rate (HRR)* are two of the most defining parameters [1–5].

Defined as the total heat or energy released from the combustion of materials [6], fire loads are classified as either permanent or temporary. Temporary fire loads pertain to the building contents [7], i.e., furniture, stored goods, etc. Permanent fire loads, on the other hand, are defined as the combustible components of the boundary elements or the building envelope [8,9]. In Performance-Based Design, permanent fire loads are identified as one of the factors to be highly considered in the fire safety design process. This is because the material and thermal properties of enclosure boundaries affect the design fire [1]. By identifying the possible amount of combustible materials in the compartment, fire development and possibly fire spread are quantified. Fire loads are instrumental for fire professionals to foresee the severity of fire scenarios. With the understanding that high heat and thick smoke are also likely with a large fire load, the need to add active fire protection like sprinklers and smoke extraction systems is evaluated [2].

In recent years, the call for energy efficiency has drastically influenced the way building envelopes are constructed with the increased use of polymers [10]. Polymer-based insulations, such as phenolic foams, are considered good thermal insulators because of their low thermal conductivity [11]. With these desirable properties, polymer-based insulations support energy efficiency in buildings, but at the risk of being combustible. Like any other ignitable material, the nature and burning behaviors of these polymer-based insulations strongly impact the fire load calculations of the building envelope.

Permanent fire load calculations rely on accurate values of heat of combustion (HoC). Heat of Combustion is defined as the heat released per amount of material burned. Most, if not all national guidelines, purport the use of Bomb Calorimeter HoC data. In obtaining the HoC of individual materials through micro-scale characterization techniques, e.g., Bomb Calorimeter, Microscale Combustion Calorimeter, etc., complete combustion occurs. Factors such as environmental ventilation conditions and system performance are not considered in these techniques. HoC values from micro-scale tests are seen to only represent ideal burning conditions and do not fully represent the real behavior of materials in real-life combustion processes and large-scale behavior. Research studies have questioned the limitations of these HoC values and the extent to which they consider the impact of physical behaviors of materials like charring, melting, dripping, swelling, shrinking, and delamination [12,13]. Despite the prevalent use of HoC from micro-scale tests for permanent fire load calculations, its viability to represent real-life combustion processes is subject to question.

Fire engineers are presently challenged to not only understand fire behavior from a Heat of Combustion perspective but also to take tangible steps to accurately quantify permanent fire loads.

1.2 State of the Art of Permanent Fire Loads

A web search in Scopus or Web of Science using the following keywords, “Permanent Fire Load” “Determination of permanent fire load” and “Calculation of permanent fire load”, results only in collective literature on total fire loads, both permanent and temporary. The literature does not give enough focus to research on permanent fire loads since the articles do not single out this topic. In Google Scholar, a web search conducted in the first week of February 2023, using the same keywords above on permanent fire loads results in five (5) relevant citations [2,8,14–16]. The literature does not examine the impact of HoC to fire load calculations, rather the studies revolve around the following topics:

- Definition of permanent fire load and its difference from temporary fire load. This is discussed in length in the chapter on Fire Load Density in the SFPE Handbook.
- The need to update fire load data and survey methods for high-rise buildings, schools, and offices.

Research on the building content however is well-studied, with the fire dynamics mapped out clearly for beds, upholstered furniture, etc. [17]. This is evident since building content, rather than the building envelope, composes a significant portion of the fuel in a compartment [18].

Experimental programs on envelope materials, however, are not novel endeavors since research is imperative to understand their performance in fire.

Sundström and Magnusson instigated research in the 80s on fire behaviors of wall linings [17]. The paper maintains that there is an untapped potential for research on compartment linings since it is not as explored as building content. The research that was carried out addressed three main points: derive flammability characteristics from small-scale tests for the basis of material classification, propose a standard for full-scale testing, and develop mathematical modeling to correlate small-scale combustion processes and full-scale fire growth.

In the following years, Wickström and Göransson [19] would continue to contribute to building envelope research by also using scaling techniques and finding correlations between full-scale and bench-scale methods for wall and ceiling linings. The research, supported by the Swedish National Testing and Research Institute, proposed prediction models of Heat Release Rate and Time to Flashover in full-scale tests using Cone Calorimeter results.

Past and present studies have since then put forth work to better understand the behavior of envelope materials by performing increasing-scale experiments, sometimes coupled with numerical simulations. The authors acknowledge the limitations surrounding micro-scale experiments, therefore, they sought to explore alternative methods in Cone Calorimetry and large-scale experiments.

A study conducted by Carpenter et al [20] looked into the nature of characterization methods that use relatively smaller specimen sizes, e.g., Vertical Tube Furnace. The study proposed improved methods such as bench-scale tests to better represent material ignitability. The research was conducted with a Cone and Larger-capacity Cone Calorimeter in a round-robin fashion among seven participants. Each participating institution was given a set of common building envelope materials, ranging from untreated timber to rubber foam insulation. Results showed that the cone calorimeter is better to represent combustibility of materials through heat release rate and is more suitable to test these materials because the samples could be layered or tested as composites, thus representing the end-use form of materials.

Some studies also investigated different components of building envelopes like façade systems. In the wake of the Grenfell incident, McKenna et al. carried out micro- and bench-scale experiments to understand the performance and behavior of façade materials. Their study is a strong starting point for

this research project since they also sought to quantify the effects of performing increasing scale testing on the total heat released by materials [21].

Although tests that only require a few grams of the material are highly reproducible and repeatable compared to bench and full-scale tests, the challenge of characterizing materials that are non-uniform in content remains. Materials that are laminated, composed of mixed content, and coated are difficult to characterize in micro-scale calorimetry techniques. Full-scale testing is a viable option to test irregular building geometries or joints in the construction that have an impact on flame spread [19]. These full-scale tests, however, are too costly and time-consuming to execute. Thus most, if not all, national guidelines determine fire loads through a gram of material, tested in idealized environments. De Sanctis [9] postulates that particularly for timber materials in structural elements, where charring is likely to occur, careful consideration must be put into permanent fire load calculations. Yet, his research does not elaborate further on the best approach to establish the behavior of timber building elements during a fire.

The argument for increased complexity of testing to enhance the understanding of building envelope materials is established in other studies [22,23], including the studies mentioned above. These studies highlight the value of understanding materials using different techniques and various levels of complexity of sample specimens. However, most of the cited studies looked to apply the scaling technique for material classification only. These mainly looked to study fire properties based on Ignitability, Combustibility, Flame Spread, and Surface Flammability. Little evidence was seen that results for increasing the scale of testing were used to analyze the resulting HoC values and their impact on the permanent fire load.

1.3 Problem Statement

This research project is motivated by the state of the art to answer the following question: With the occurrence of charring and the burning nature of novel building envelope materials, is utilizing micro-scale experiments still the ideal approach to quantify the permanent fire loads from the building envelope?

1.4 Aim and Objectives

The overarching aim of this project is to gain a wider understanding of the behavior and performance of building envelope materials of industrial structures in theoretical combustion vs. actual combustion processes.

First, a comprehensive review will be conducted as to how selected countries determine permanent fire loads for industrial structures. This exercise aims to establish state of the art in national policies.

Secondly, an experimental program will be designed and conducted on an increasing scale (See Sec 3. Methods and Materials): micro-scale experiments → bench-scale experiments → scaled room corner experiments.

The following objectives are presented to support the aim of this project:

- **Objective 1:** Establish how permanent fire loads are determined in Sweden, Belgium, Netherlands, and the UK through the gathering of design guidelines and presenting a summary of how different countries motivate and calculate permanent fire loads.
- **Objective 2:** Conduct tests on a Microscale Combustion Calorimeter (MCC) and Bomb Calorimeter to obtain theoretical heat of combustion values; Conduct Cone Calorimeter and 1/3-scaled room tests to replicate more realistic fire scenarios and obtain values of the *effective* heat of combustion in small and medium scale level. From the results of the experiments, a comprehensive analysis shall be conducted.
- **Objective 3:** Calculate and analyze a worked example of the total permanent fire loads based on the heat of combustion values obtained from the MCC, Bomb Calorimeter, Cone Calorimeter, and the 1/3-scaled room corner test.

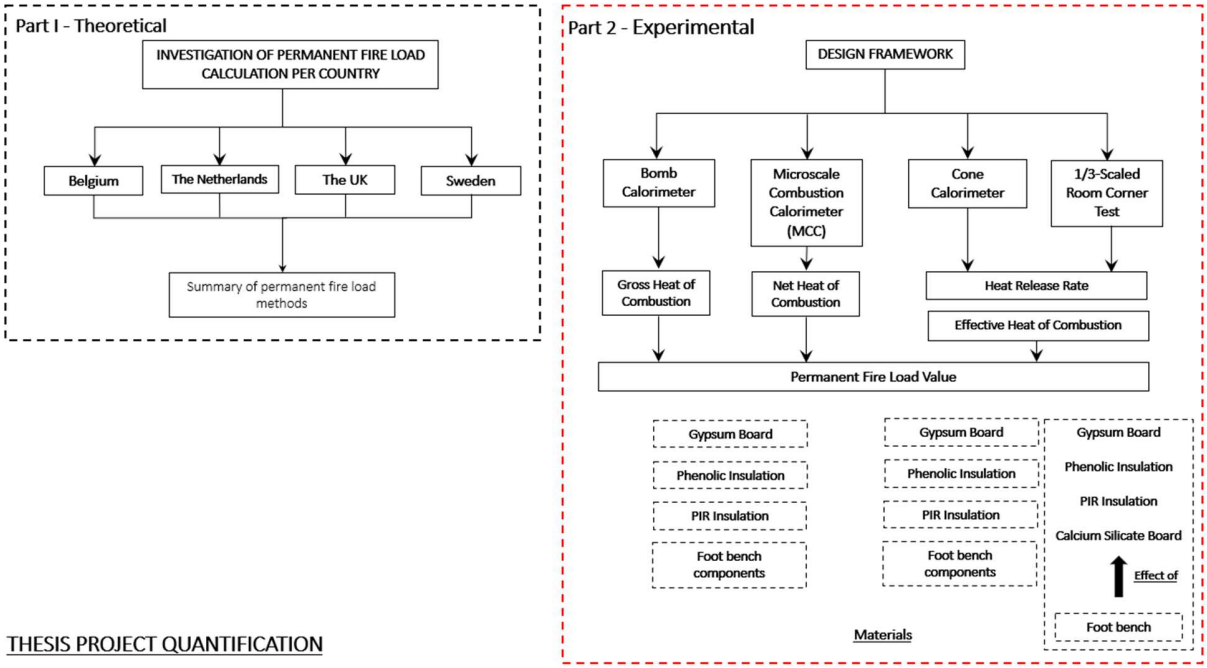

Figure 1. Summary of the thesis quantification to address the stated aims and objectives. Part 1 – Theoretical addresses Objective 1, while Part 2 – Experimental addresses Objectives 2 and 3.

1.5 Limitations

Conducting full-scale experiments is the ideal solution to obtain the actual behavior of envelope systems as stated in the previous section. However, due to the scope limitations of the project, 1/3-scaled room corner tests will be performed instead. While empirical correlations may not accurately depict a relationship between a full-scale and a 1/3-scaled room corner, scaling relationships for Heat Release Rate can be obtained from the study by Ingason et al. on a model scale of tunnel fires [24]. The study also references other experiments that examine scaling theories. Additionally the research by Wickström and Göransson, as part of the EUREFIC project, is also a strong basis for the prediction of heat release rates in large-scale fire tests based on the results of the cone calorimeter [25].

For fire in compartments, significant phenomena that occur are radiative/thermal feedback back to the fuel source and the effect of the ventilation opening [6]. These phenomena, as well as heat losses to the environment, will not be analyzed in the 1/3-scaled room corner tests. Several fire properties such as smoke production, toxic product emissions, flame spread, etc. can be studied in enclosure combustion, but the focus of the research will be to obtain only the effective heat of combustion values from the 1/3-scaled room corner tests.

The scope of the project is restricted to the materials listed in Sec. 3.1 Materials due to the thesis duration. The researcher, with the motivations stated for each material, deem the materials selected as appropriate representations of permanent, and even temporary fire loads, in practical applications.

The methods to conduct micro-, bench-, and scaled room testing can be done using several instruments, but the selected techniques were restricted to the available equipment in and near Lund University. Microscale Combustion Calorimeter, Cone Calorimeter, and Open Calorimeter tests were done at the fire lab in LTH, Lund University; Bomb Calorimeter tests were done in Kingspan's testing facility in Holywell, UK; the 1/3-scaled room corner test at the Danish Institute of Fire and Security Technology (DBI).

2. Literature Review

This Chapter presents the principles and supporting topics related to the concept of permanent fire loads. Relevant works of literature were identified based on the proposed sections below. Literature was gathered from sources like Google Scholar and Scopus. The sections are divided into: Heat of Combustion, Fire Load, and Permanent Fire Load Calculations per Country. The review of related literature starts by defining Heat of Combustion, transitioning to its importance in Fire Load calculations, and culminating in the difference in Permanent Fire Load calculations and definitions for selected countries.

2.1 Heat of Combustion

Heat of Combustion (HoC) or the calorific value is a broadly used term not just in fire engineering but in other fields like chemistry. It represents the energy released when a *quantity of material* (kilograms, liters, moles, etc.) undergoes chemical processes like thermal decomposition. In fire engineering, the standard unit to describe the heat of combustion is **Megajoules/kilogram (MJ/kg)** [12]. An exothermic reaction, where energy is released from the test specimen, is represented by a negative HoC value.

Fire design standards and related literature frequently mention the terms *gross*, *net*, and *effective* when describing HoC. The difference between these three can be best summarized by the following:

<table>
<tr><td colspan="3">Total energy released</td><td>Gross heat of combustion</td></tr>
<tr><td colspan="2">Energy released by material in complete combustion</td><td>Energy required to evaporate water in the material</td><td>Net heat of combustion</td></tr>
<tr><td>Energy released by material in incomplete combustion</td><td>Efficiency factor to burn a material (100% for materials that burn entirely)</td><td>Energy required to evaporate water in the material</td><td>Effective heat of combustion</td></tr>
</table>

Figure 2. The highlighted cell in gray represents either the gross, net, or effective heat of combustion [8,26].

The *gross* heat of combustion is taken to be the absolute value when a material is completely oxidized in a closed system [26]. Since there are no presumed heat losses to the outside environment, all energies are preserved and measured within the apparatus. In practical engineering, heat loss is highly likely. This is seen when combustion products are lost to the environment as steam and flue gases. Thus, the energy absorbed by water in the material is rarely or never recaptured. This phenomenon is best characterized by the *net* HoC, which is obtained by subtracting the energy needed to convert water to

vapor from the gross value [12,27]. A lower value for the *net* HoC vs. the *gross* HoC is expected because of the difference represented by the heat of vaporization. For practical applications such as fire load calculations, the SFPE Handbook strongly recommends the use of the *net* HoC since it closely reflects the reality of fire processes [28].

Effective heat of combustion is derived by multiplying the net HoC with an efficiency factor which is used to describe how well a material burns. Simply explained, clean fuels have an efficiency factor of 100% or 1, meaning they undergo complete combustion and do not leave soot or residue. Whereas for materials that undergo charring, or produce soot like in the case of Acetylene which has an efficiency to burn at 75%, the efficiency factor is less than 100% [29]. Alternatively, the effective heat of combustion can be obtained directly through experiments using oxygen consumption measurements or by measurement of the convective and radiative heat released by burning of the material [30].

2.2 Standard Methods to obtain the Heat of Combustion

2.2.1 Theoretical values of HoC

Calorimetry – the physical science of measuring heat – has been a long-standing technique to quantify thermal energy from materials [31]. The invention of the first calorimeter apparatus in the 1800s, the Bomb Calorimeter, assisted in quantifying heat released from explosives. The apparatus was later extended to the testing of organic materials [26]. In the 1940s, the method was improved in the universities of Lund in Sweden and Bartlesville in the U.S.A. to be able to assess inorganic and combustible materials. The applications of calorimetry in fire science were established early on in the 80s by proponents like Hugget [32] but it was later in 1995 at the 50th Calorimetry Conference that Richard Lyon highlighted the importance and applications of calorimetry in fire science [29]. Headlining 27 other presentations, Lyon and other notable names like Quintiere, Babrauskas, and Delichatsios successfully illustrated the midpoint of Fire and Calorimetry. The authors identified calorimetry as a central technique to determine flammability properties and fire predictions and aid in fire research. Lyon also emphasized the flexibility and repeatability of small-scale calorimetry when full-scale tests proved to be expensive to replicate when certain variables must be changed immediately in the experimentation process [29].

Both the gross and net heat of combustion can be derived from micro-scale calorimetry techniques. One universally popular means is via the Bomb Calorimeter, in recent years, the Microscale Combustion Calorimeter (MCC). The working principles of a Bomb Calorimeter and MCC are based on temperature

rise and oxygen consumption, respectively. In a Bomb Calorimeter, a specimen measured in known grams is placed in a tightly closed and thermally insulated vessel. After the specimen is ignited in a controlled oxygen atmosphere, the temperature change is recorded and used to calculate the gross heat of combustion through Equation 1 [12]:

$$H_{ui,gross} = \frac{E\ (T_m - T_i + c) - b}{M_i} \qquad \textit{Equation 1}$$

The gross heat of combustion $H_{ui,gross}$ is influenced by the following parameters: E, the water equivalent of the calorimeter and accessories introduced to the bomb, the difference between the recorded max temperature T_m and initial temperature T_i, temperature correction factor c, correction required for the combustion heat of the "fuels" used during the test b, and the total mass of combustible material M_i.

The net heat of combustion $H_{ui,net}$ has a direct relationship with the gross value through the latent heat of vaporization q of the condensed water. Mathematically, this is expressed as Equation 2 [12]:

$$H_{ui,net} = H_{ui,gross} - q \qquad \textit{Equation 2}$$

In the early 2000s, a new micro-scale method to determine the Heat of Combustion was developed based on oxygen consumption. The principle behind oxygen consumption in a Microscale Combustion Calorimeter is that there is a direct relationship between the oxygen consumed by the material to the energy that it releases. This theory is similar to the techniques developed in the Cone Calorimeter and Room Corner tests done in the 80s. It has been concluded that for every kilogram of oxygen consumed by the material, approximately 13.1 MJ of heat is released [33]. The Thornton's constant, 13.1 MJ/kg·O_2, was observed for a range of tested organic materials and represents an average of the experimental results. This has been discussed in length in Janssens' classic paper on the oxygen consumption principle [34]. The paper provided calculation procedures to determine the rate of heat release in full-scale tests. The calculation procedures are based on the known element that was measured in tests, e.g., calculations when only O_2 is measured, a combination of O_2 and CO_2, etc.

Through the MCC, the heat of combustion is obtained via two methods: Method A or Method B. Specimens tested in Method A are decomposed in an inert gas to mimic real-life fire scenarios. It was observed that oxygen is not present on the surface of the pyrolyzing material, as represented in Figure 3 [35,36]. The specimen and purge gases are then mixed with sufficient oxygen in the combustor to

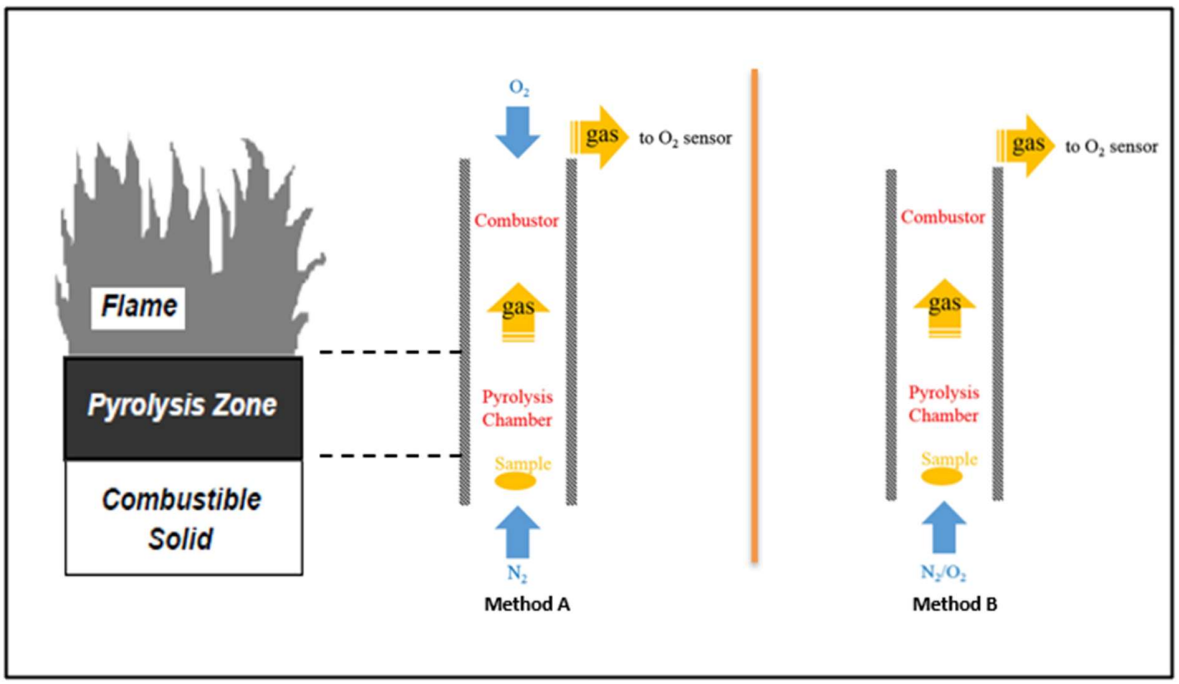

Figure 3. Schematic diagram of the combustion conditions in a Microscale Combustion Calorimeter and compared to real fire scenario, modified from [35,36].

ensure complete oxidation of the specimen gas. The obtained Heat of Combustion represents only that of the volatile gases for this method. In Method B, the sample is exposed to dry air (80% N_2 / 20% O_2) in the pyrolysis chamber to effectively decompose the material before the specimen enters the combustor. Thus, all the possible pyrolysis gases from the volatile gas and solid residue are measured. A *net* Heat of Combustion results from both methods. A study conducted by the Federal Aviation Administration reports that the obtained HoC from MCC Method B shows good agreement with the HoC values of the Bomb Calorimeter. It was reported that MCC Method B values are within the 2% error range from Bomb Calorimeter HoC [37].

Sec 2.4 Permanent Fire Load Calculations per Country discusses intensively the use of ISO 1716 - Reaction to fire tests for products with a Bomb Calorimeter to be the conventional method to attain the Heat of Combustion. All the national guidelines require that heat combustion values be derived from experimental results from ISO 1716. Based on sample preparation and repeatability, the MCC provides a faster method to obtain HoC. With a 1.0 g sample, it has been observed that a Bomb Calorimeter analysis can take up to 25 minutes, while milligrams of samples only take up to 5 minutes to test in an MCC [38]. However, the relative weakness of using MCC lies within the working principle of oxygen consumption itself. Studies [35,39] investigated the applications and limitations when using an MCC. Several factors are seen to affect the quality of data obtained. One identified factor is the sample mass,

which affects the consumed oxygen level. As the sample mass is increased, more oxygen is needed in the test process and quickly depletes the Oxygen source [35]. Increasing the sample mass is further limited by the system supply of Oxygen at only 20cc/min, as seen in Figure 4.

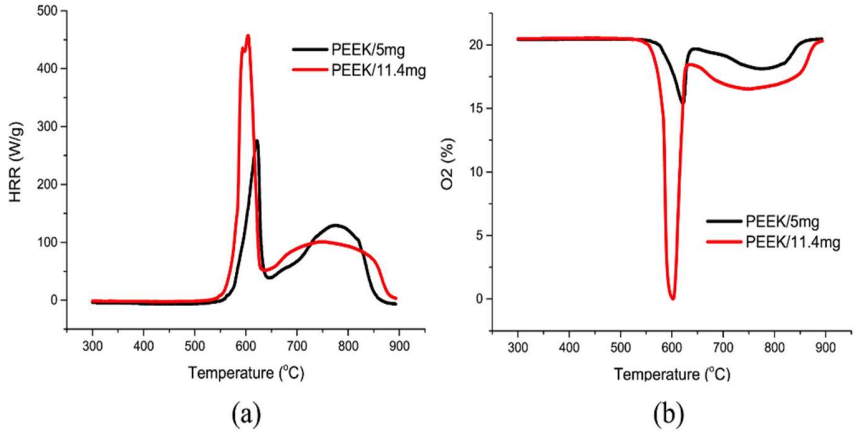

Figure 4. For samples with larger mass, more oxygen is consumed as seen in (b). The tests conducted by Zhuge et al show that the Peak HRR can be higher (a) or lower in the case of Flame-Retardant Polyethylene, modified from [35].

Since the Bomb Calorimeter operates on a constant temperature and pressure reaction, it eliminates the variability that arises from an introduction of an external oxygen source to the test. The Bomb Calorimeter test also occurs in the closed space of the vessel proper and thus allows for highly accurate readings [26].

2.2.2 Realistic values of HoC

The Bomb Calorimeter and MCC reference standards present clear limitations when tests are executed using these techniques. The design standards put forth provisions that due to the controlled nature of the experimental conditions, care must be taken when using the resulting HoC for fire design and assessments. To reiterate ASTM D7309, the results from Microscale Combustion Calorimetry do not inherently represent the specimen behavior in actual fire conditions [13]. Both MCC and Bomb Calorimetry according to ISO 1716 state that these methods do not consider the specimen size as illustrative of the end use of the product, or its final form [12]. In cases where external factors such as the thickness of the material, system performance, the presence of joints or gaps, and ventilation conditions are crucial, calorimetry methods fall short.

While the techniques discussed in Sec. 2.2.1 allow for rapid testing using only grams of materials, bench- and full-scale methods present more realistic methods of defining a fire. The fire development is represented through the rate at which heat is released in these tests. These techniques also have the

advantage of using larger samples that can test system configurations or final forms of the products. However, care must be taken when using the results from these bench- and full-scale methods. The examined product or system must be equivalent to the samples used in the experimental design. Additionally, other factors such as the experimental conditions and fuel source must be considered [40]. An effective HoC $H_{ui,eff}$ can be derived from the ratio between the Heat Release Rate $\dot{Q}$ and the Mass Loss Rate $\dot{\mathrm{M}}$ as shown in Equation 3.

$$H_{ui,eff} = \frac{\dot{Q}}{\dot{M}} \qquad \textit{Equation 3}$$

Additionally, the effective heat of combustion can also be derived from the total heat released Q, a result of integrating the area under the Heat Release Rate $\dot{Q}$, divided by the total mass lost M_i.

$$H_{ui,eff} = \frac{\mathrm{Q}}{M_i} \qquad \textit{Equation 4}$$

2.2.3 Updating literature calorific data

In Section 2.3, the dependence of fire load calculations on the heat of combustion is discussed. Literature values are used extensively when experimental values for the actual product are not available. While the focus of the thesis project is to quantify the effects of increasing-scale experiments on permanent fire load calculations, it is of interest to further motivate the thesis project by presenting case studies that argue for the outdated assumptions on fire load calculations. Since a product tested some years ago may not be the same as the products of today, there is ambiguity on whether the literature values are still valid.

- *A Survey of Fire Loads for Different Room Types found in a Third Level Educational Building [2]*

A study on fire load estimation for a third level educational building shows that there are overestimations and underestimations of total fire load values calculated using the Heat of Combustion values from existing reference literature. Experiments were conducted to compare the theoretical vs. experimental fire load densities in canteens and classrooms. Results showed that the actual fire load should be less than the published values. This led to the conclusion that modern guidelines take a conservative approach. This extra margin of safety is used in cases when fire loads can vary over time [41] and there is a lack of calorific data [1]. On the other hand, fire load values in computer rooms and

administrative offices are greater in experiments vs. published values. This underestimation could render the current fire protection strategies inadequate.

- *Enhanced Fire Severity in Modern Indian dwellings* [42]

The study conducted by Khan and Srivastava suggested that the changes in the socioeconomic and cultural landscape in India have led to the increased use of plastics, built into composite partitions, core panels for walls, false ceiling panels, etc., in modern office and residential buildings. In the study, it was discovered that modern buildings possess fire load values that are three times higher than the value prescribed by building codes in India and those reported by outdated studies conducted from 1970 to 1990. As an example, the authors reported that the fire load density they obtained for office and dormitory buildings is 1400 MJ/m^2 vs. the value of 487 MJ/m^2 which was determined in the '90s. Another conclusive statement worth mentioning is that the authors have noticed that plastics, with high calorific values, replaced the decline in the use of cellulosic materials.

With the above studies, we can see that there is a need to update the calorific values for all types of buildings and in parallel, update our understanding of the fire behavior of building envelope materials.

2.3 Fire Load

Fire or fuel load is used to describe the total heat or energy from the complete combustion of burnable materials in the compartment/s of a fire origin [6]. Fire loads or fire load density can affect fire safety design as a high value can dictate increased potential severity and damage within a compartment. The burning duration in a fire development is also proportional to the value of the fire load [7]. The concept of fire load is not to be interchanged with 'loads in fire situations', which are associated with the loadbearing capacity of structural elements. Fire loads are expressed in megajoules **(MJ)**. The general equation to calculate fire loads, as stated in the SFPE Handbook and related studies [3,7,40,43], is expressed as:

$$Q = \Sigma M_i \, x \, H_{ui} \qquad \textit{Equation 5}$$

Fire load density is another commonly associated term when discussing fire loads because it signifies the fire load per reference area **(MJ/m^2)** [40]. There are many ways to define a reference area, but the most common notion is by dividing the total energy by the floor area of the compartment [44].

Loads are classified as either permanent or temporary. Temporary fire loads, also called contents [7], variable [40], or movable fire loads, pertain to the building contents. These are represented by furniture,

any stored goods, or features of the structure that are not part of the construction [18]. Permanent fire loads, on the other hand, are defined as the combustible components of the building structure or boundary elements. Some examples of permanent fire loads are, but not limited to, waterproof membranes, façade systems, and insulation linings [9,40].

2.3.1 Determining fire loads

Fire loads are determined traditionally via two methods: 1. statistical values associated with the building use 2. in-situ survey methods [2,7,8,43]. In method 1, fire loads are prescribed based on the estimated use of the building space, e.g., dwellings, hospitals, schools, entertainment centers, etc. These prescriptive values are averaged for 80% of historical data of similar occupancies. However, it has been stated in both the SFPE Handbook and EN 1991-1-2 [8,43] that the determined fire load per occupancy does not consider the permanent fire loads in the values. As such when determining permanent fire loads, in-situ survey methods shall be applied and the permanent fire load value is calculated using Equation 5, $Q = \Sigma M_i \, x \, H_{ui}$.

The SFPE Handbook recommends an in-situ survey as the preferred method when considering industrial use, e.g., warehouse or storage facility, due to the high variability of stored goods. Compared to offices and homes that have relatively predictable content, industrial structures are much better quantified by the actual contents when calculating fire loads. In-situ survey methods are recommended to be combined with the direct weighing of the combustibles since survey methods can have uncertainties due to the level of accuracy and competence of the surveyor [40].

Fire load determination depends on local regulations and how each country implements them. A theoretical study of the applicable design standards and national guidelines is carried out in the subsequent section. This presents a comparison of the similarities and differences in how permanent fire loads are determined in Belgium, the Netherlands, Sweden, and the UK.

2.3.2 Fire load and the Heat Release Rate

The concept of fire loads is strongly linked to the heat release rate. Heat release rate illustrates how a fire develops over time and shows the critical phases in a fire, i.e., when the fire will ignite all combustible materials or when it starts to decay. As the heat release rate is shown as a fire development curve, the area under this curve is equal to the effective total fire load for specific conditions of a fire test. The effect of a large fire load can either increase the duration or heighten the intensity of the heat release curve as shown in **Error! Reference source not found.**.

Essentially, a high value for the total fire load not only impacts the duration of the fire but can also be used to estimate the fire-resistance rating of the elements of a structure. As an example, Belgium recommends the highest fire resistance of the common wall (e.g., EI 120) between two compartments with different fire loads.

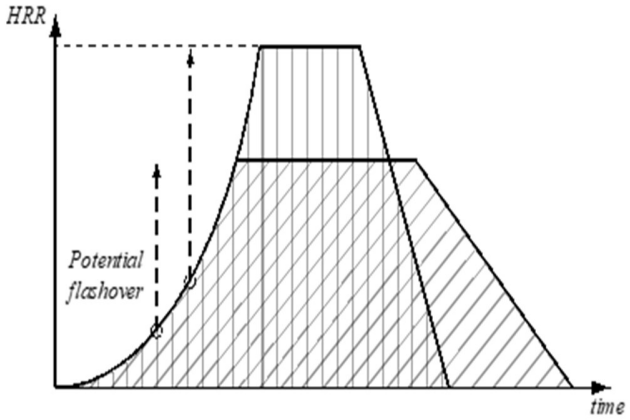

Figure 5. The shape of the heat release rate curve is influenced by the fire load, modified from SFPE Handbook [8].

2.4 Permanent Fire Load calculations per country

2.4.1 Belgium

Belgium references De klassering van industrie-gebouwen (Classification of industrial buildings), a supplementary document to Annex 6 to the Royal Decree of 7 July 1994, as the guideline for determining fire loads in industrial buildings [45]. Industrial buildings are defined as any closed structure that is intended for the commercial processing of goods and is not normally for public use.

This document emphasizes fire loads as the basis of the building class of a structure and its subsequent fire protection. The strictest requirement is Class C, for a normative fire load density of >900MJ/m^2, and is the default class for unclassified buildings. Once a building class (A, B or C) is determined for an industrial structure, the maximum permissible area is limited by the classification. Alternatively, a building can obtain a maximum permissible area by dividing a total fire load of 5700 GJ (for unsprinklered) or 34,200 GJ (sprinklered) by the calculated fire load density.

The fire load does not only affect the maximum permissible area but also imposes the fire resistance requirements of the compartment walls. For example, when two compartments with different classes share a common wall, the highest requirement (EI 120) is applied.

As stated in the document, building elements are not considered in the permanent fire load calculation for any of the following requirements:

- Material is deemed non-combustible (e.g., masonry, steel, concrete, etc.);
- Structure is equipped with a sprinkler system;
- Floor covering is classified as C-s2 and above, and ceiling and wall covering are classified as B-s3 and above;
- Construction elements are indirectly exposed to the fire. However, in the case of sandwich panel systems, the underlying material must also meet the minimum ratings of the surface materials as stated in point 3.

Combustible materials shall be automatically included when they are *directly exposed to the fire and heavily contribute to the initial fire development*. The overall value contribution must be greater than 100 MJ/m^2.

Unlike building contents that have prescribed values in the guideline, permanent fire loads are only obtained by calculation. Permanent fire loads, referred to as the shell of the building, can be calculated using Equation 6. In this equation, a protection factor ψ_i is a significant consideration. This means that a multiplier between 0 and 1 is factored in, 0 if the material is fully protected like in the case of a material stored in a fire-resistant container, or 1 if the protection is inconsequential. How to determine a protection factor between 0 and 1 however is not stated. Additionally, a combustion factor m_i is used to correct for the HoC value, to represent real fire scenarios. The correction or combustion factor is 1 for materials that ignite completely or if the m_i is unknown, 0 for materials with no contribution to the fire development, and 0.8 for cellulosic materials. M_i is the mass of material.

$$Q = \sum H_{ui}\, x\, M_i\, x\, m_i\, x\, \psi_i \quad \textbf{[MJ]} \qquad \textit{Equation 6}$$

The guideline stresses the use of the *net* Heat of Combustion H_{ui} derived from Bomb Calorimetry in NBN EN ISO 1716 [46] since it is deemed to correspond to the actual energy available in a compartment fire. According to the guideline, HoC values can be derived from various literature such as DIN 18230-3, NEN 6090, NBN EN 1991-1-1, NIBRA, and the NFPA Handbook.

No reference guideline is provided for residential and commercial buildings since permanent fire load is not a factor to consider in those structures [Personal communication, Jan Saladeer].

2.4.2 The Netherlands

The Netherlands defines permanent fire load as the combustible materials which contribute to the fire load and are part of the building construction. The definition and calculation processes are prescribed in two guidelines. The general fire load calculation document NEN 6090: Determination of the fire load [47]. The other document, NEN 6060: Fire safety of large fire compartments [48], is utilized when compartments exceed the maximum permitted size in Building Regulations. The basic principles of NEN 6060 pertain to limiting the spread of fire by restricting the total amount of combustible materials and establishing the fire resistance of the compartment. Packages of Measures are prescribed in NEN 6060 to classify protection measures by fire loads. Additionally, these measures require additional fire protection strategies, e.g., Package 1 (low fire load, less protection) to 4 (high fire loads, more stringent requirements). The following illustrates an example between Packages of Measures.

(Initial/final) determination of the fire load

belonging to the compartment with the intended use

↓

	Packages	
	I	II
Maximum permissible total fire load (in kg vh) New construction, industrial function	600 000	1 200 000
Fire alarm system	-	Required
Smoke and heat extraction systems installation	-	Required

Figure 6. Sample measures specified in NEN 6060. The table is not extensive, and the full requirements are shown in NEN 6060.

NEN 6060 specifies that the fire load Q shall be reported in the spruce wood (vurenhout) equivalent. The process of normalizing the fire loads to a wood equivalent provides a standard basis for examining fire loads [3]. This however is called to question since the wood HoC values may vary over several sources and survey methods [8]. The product of the *net* heat of combustion H_{ui} in MJ/kg and the mass of material M_i shall be divided by the spruce wood HoC, 19 MJ/kg vh.

$$Q = \frac{1}{19}\sum H_{ui}\, x\, M_i \quad \textbf{[kg vh, kilogram vurenhout]} \qquad \textit{Equation 7}$$

The guideline proposes the use of calorific values from Table B.2 to B.8 of the guideline. Each material in the tables is assigned a 'Reliability' score, which signifies the level of accuracy of the HoC source. As an example, Polyisocyanurate Foam (PIR) and other pure materials and substances calorific data are taken to be of the highest accuracy. In Table B.2, PIR foams have a table net HoC value of 22.2-26.2 MJ/kg. The guideline strongly suggests that experimental values obtained through NEN EN ISO 1716 [49] shall always be used when available.

In NEN 6060, the main goal is to manage [permanent] fire loads over an identified gross floor area to meet the resistance to fire penetration and fire spread requirements. On the other hand, NEN 6090: Determination of Fire load provides a general approach to calculating [permanent] fire loads. All combustible materials in the area of interest shall be included in the calculation of the fire load Q. Complete combustion of the material is assumed. It should be noted that combustible materials that are shielded or protected may not be included in the calculations. This can be applied when it can be proven in experiments that the shielding material will not collapse in case of fire and that the combustible material is sufficiently protected.

$$Q = \sum H_{ui}\, x\, M_i \textbf{ [MJ]} \qquad \textit{Equation 8}$$

Chapter 5 of NEN 6090 recommends the use of NEN EN ISO 1716 (Bomb Calorimeter) to determine the net calorific value H_{ui} of a material. In place of ISO 1716, Table C.1 of Annex C of the guideline may also be used. The document presents a wide range of calorific values for building materials; however, the guideline maintains that these values are only indicative of complete combustion and do not consider effects like charring. The net calorific values shall only be used as objective measures. Mass M_i of the building element shall be determined in accordance with sec 4.2.2 which states that a calibrated weighing instrument shall be used or by obtaining mass through the volume and density of the material.

2.4.3 Sweden

Determination of permanent fire loads is defined in the guideline Boverket Handbok Brandbelastning (Housing Authority Manual on Fire load) by Boverket (The Swedish National Board of Housing, Building and Planning [44].

In the guideline, permanent fire load is termed permanent *fire energy* and is specified as combustible building elements that exhibit little to no change in their amount over the lifetime of the structure. Building elements include, but are not limited to, load-bearing elements and combustible insulation materials.

Permanent fire loads can be established in two ways: first, as a fixed fire load density of 50MJ/m^2 (per room area). The value was derived from a statistical investigation of different occupancies in the report Fire Engineering Design of Steel Structures [50] and the consequence analysis carried out by Frantzich [51] on the said data. Secondly, permanent fire load Q can be calculated using the mass of material M_i and heat of combustion H_{ui} in Equation 9. The values of the heat of combustion that can be used are listed in Appendix A of the Boverket Handbok Brandbelastning, however the appendix indicates that these HoC values are *effective* heat of combustions from ISO 1716. ISO 1716 does not generate effective heat of combustion values. This was clarified with Frantzich, one of the proponents of the Brandbelastning manual, and was corrected to mean that the guideline pertains to a *net* heat of combustion, considering the efficiency of the combustion process [Personal communication, Håkan Frantzich].

$$Q = \sum H_{ui}\, x\, m_i\, x\, M_i \quad \textbf{[MJ]} \qquad \textit{Equation 9}$$

A combustion factor m_i is also introduced in the equation However, no definite values or references to quantify the combustion factor are given. Estimations of the combustion factor may also not be accurate as this value can be affected by the shape, size, material's position in the combustion area, etc. In addition, the combustion factor is also affected by the fuel properties and position within the combustion area, and ventilation factor of the compartment.

The guideline specifies that any nominal (based on standards and norms) permanent fire energy obtained through calculations should be taken as the characteristic value (cautious estimate) as well. The guideline does not give additional requirements, such as recalculation of the total fire energy, for when the building owner decides to impose structural changes. This is seen when there are modifications brought upon by policy changes to energy efficiency, which the guideline implies that insulation may be added thus increasing the permanent fire load. The guideline requires, however, that in the initial calculation of the permanent fire energy, a conservative estimate should already be made. E.g., A worst-case scenario is assumed that all combustible material is unprotected (protection factor = 1).

2.4.4 United Kingdom

The United Kingdom references EN guideline EN 1991-1-2 as the foundation to determine fire loads and fire load densities. Certain sections of the EN standard were adopted into BS EN 1991-1-2, which then serves as the national guideline. However, an additional document, published document PD 6688-1-2, was released to provide alternative recommendations to some sections of BS EN 1991-1-2. As an

example: Annex E of the BS standard is no longer adopted in fire safety design but is replaced by Annex A (informative) of the PD document. Annex A reports two methods to determine fire load Q: 1) general calculation through Equation 10, 2) application of fire load densities according to occupancy type as listed in Table A.2.

$$Q = \sum H_{ui}\, x\, M_i\, x\, \psi_i \quad \textbf{[MJ]} \qquad \textit{Equation 10}$$

Equation 10 denotes that the characteristic fire load is influenced by a protection factor ψ_i. The value is 0 for protected fire loads that remain unignited even after prolonged fire exposure of their containers. A value of 1 is assigned to the largest fire load. Like the other countries, the UK also utilizes the net calorific value H_{ui} which is derived through BS EN ISO 1716 experiments. Additionally, the PD document lists recommended net HoC values of various materials in Table A.1.

As stated earlier, the UK also adopts another method of classifying first the use of the building and then prescribing fire load densities based on the occupancy type. Table A.2 Fire Load Densities of PD 6688-1-2 is reprinted from another published document, PD 7974-1: Application of fire safety engineering principles to the design of buildings. The study conducted by Hopkin et al. presents their findings on the origin of these adopted fire load densities in the UK [52]. These occupancy fire load characteristics were derived from various literature, namely the CIB W14 Workshop, research by Zalok et. al, and Schleich et al. Industrial buildings base their values upon the work done by Theobald in 1977 wherein he summarized ten fire incidents and five experimental fires as the basis for data. From these incidents and experiments, a range of fuel loads in wood equivalent kg has been reported. Although the data by Theobald includes only building contents and do not indicate whether the building elements have been considered, PD 6688 recommends the determination of fire loads of the building linings and finishings through Equation 10 and then adding these to the occupancy type fire load density. The use of fire load densities based on occupancy is seen to represent perfect combustion. PD 6688-1-2 states that for real-life fires, lower heat of combustion may be expected.

2.4.5 Summary

While each country may vary in methods to obtain data, either through in-situ surveys or prescriptive values based on occupancy type, it is common for all approaches to calculate fire loads through the mass of combustibles and the heat of combustion. It should be noted that for all examined countries, *net* heat of combustion derived from ISO 1716 tests is required for the calculation of the permanent fire

load. A brief visual summary of the similarities and differences among the national guidelines and procedures for Belgium, Sweden, The Netherlands, and The UK is presented in Figure 7.

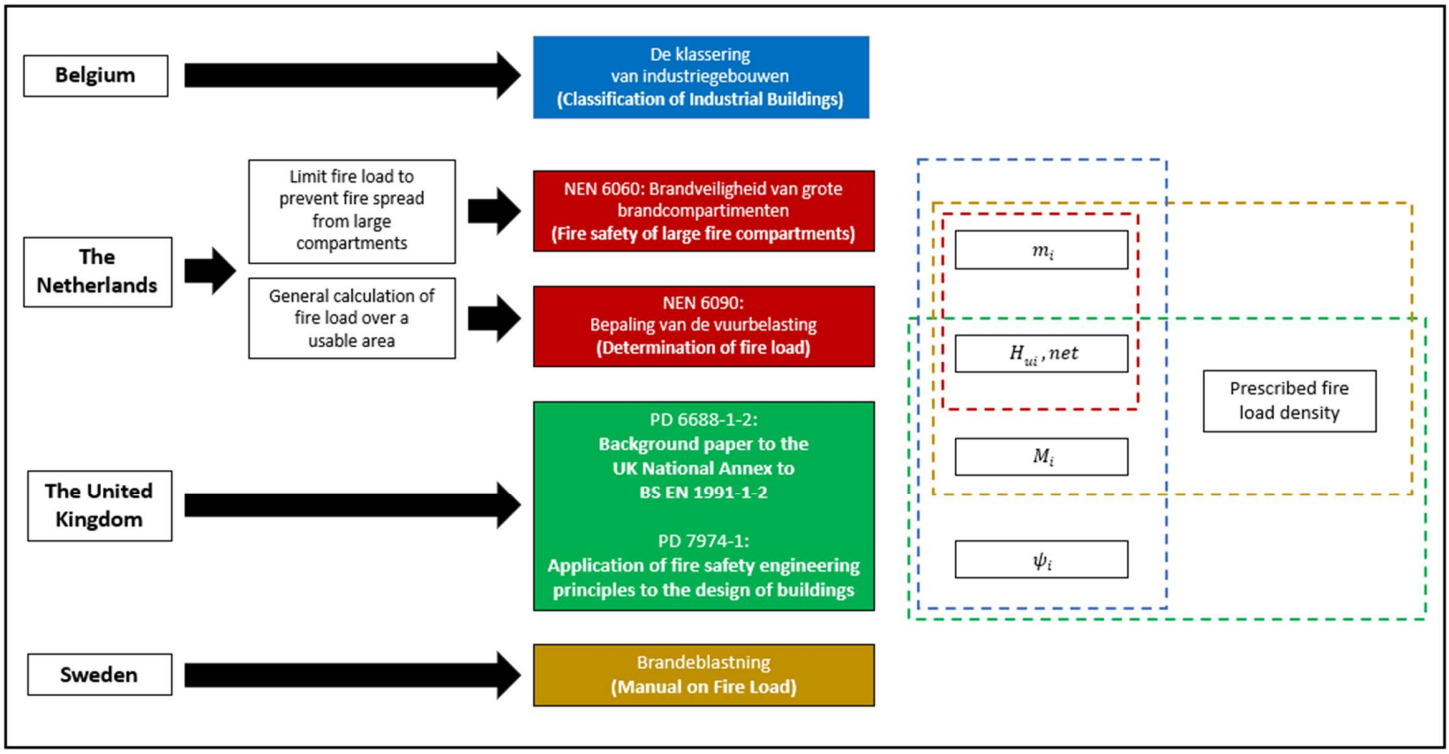

Figure 7. Summary of the national guidelines and the factors to obtain permanent fire loads.

3. Methodology and Materials

This Chapter presents the materials, classified as the *building content (temporary fire load)* or the *building envelope (permanent fire load),* that are used in this project. Details of the experimental configurations and steps taken to conduct the experiments are also reported. Microscale Combustion Calorimeter and Bomb Calorimeter are utilized for finding the *theoretical* Heat of Combustion, while Cone Calorimeter and the 1/3-scaled Room Corner tests are performed to get the *realistic* or *effective* Heat of Combustion.

3.1 Materials

3.1.1 Building Envelope

As stated in national guidelines in Sec 2.4, the building envelope is termed as the permanent fire load and represents structural elements of the enclosure. In reference to the Belgium standard, De klassering van industrie-gebouwen, the building envelope is visualized as the shell of a compartment [45].

A typical sandwich panel system is illustrated in Figure 8 [10,53]. Sandwich panel systems are described as a layer of insulation positioned or 'sandwiched' between two protective layers. In this project, gypsum board and calcium silicate are considered the protective layers while PIR or phenolic insulation is sandwiched in between. A sandwich panel system is mostly utilized as external cladding [54].

The insulation materials were mainly chosen for their common use. Building insulation use is expected to rise in the next years [55]. A survey conducted by the Department of Business, Energy and Industrial Strategy in the UK reveals that *phenolic* and *polyisocyanurate (PIR)* foam materials are two of the four most common insulation materials used for wall retrofit projects. PIR and phenolic are used extensively for internal wall applications. These two types are valued for having high insulating properties while using only relatively less thickness of the materials. Besides the given thermal properties of PIR and phenolic insulation, these two materials are generally less expensive per square meter, thus, are used more compared to high-performing insulation like aerogel [56].

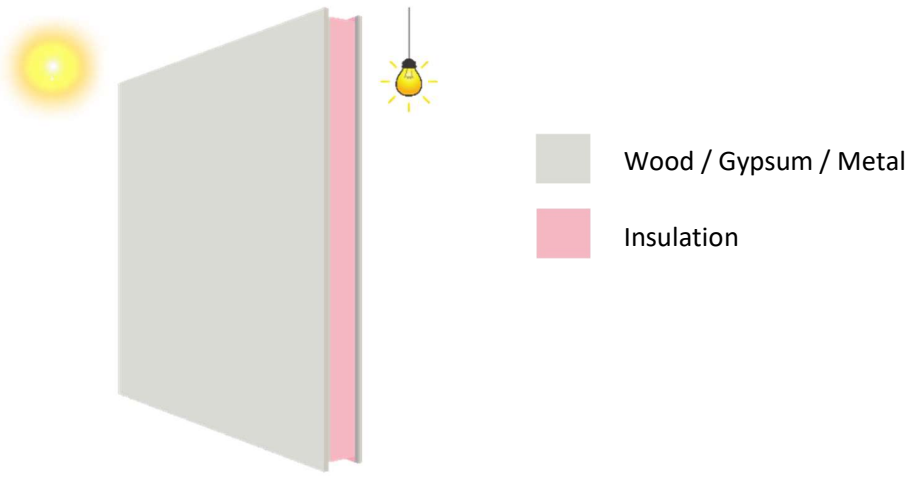

Figure 8. Typical configuration for a sandwich panel system, adopted from [9].

3.1.1.1 PIR Insulation

A slight change to the chemical composition of urethane results in noticeable improvements in the foam properties. PIR (polyisocyanurate) foam is the resulting product when urethane is modified. PIR foams have better dimensional stability, flame resistance, and thermal stability compared to urethane foams [57]. They are used in a wide range of applications, but their defined properties make the material the ideal core for composite panels. Thus, it is used extensively as insulation for the mechanical and industrial sectors.

The PIR utilized in this project is Thermawall TW50. The properties of the PIR insulation include a thermal conductivity of 0.022 W/mK and a material density of 33 kg/m^3 [58].

3.1.1.2 Phenolic Insulation

Phenolic insulation is seen to have a lower thermal conductivity value (0.021 W/mK) than PIR insulation, making phenolic a slightly better insulation material by 10% with a better heat loss reduction. Like PIR, it can also be used in several applications like roofing, wall material, and flooring [59,60].

K15 Kooltherm insulation board represents the phenolic insulation in this project. Additional properties of the material are a material density of 35 kg/m^3 [11] and a Reaction to fire classification of B-s2, d0 (B - Combustible materials – Very Limited contribution to fire, s2 - Emissions with average volume intensity, d0 - No burning droplets) [58].

3.1.1.3 Gypsum board

Gypsum board is the technical name for any board or sheet product that is composed predominantly of sulfate minerals or gypsum [61]. It is deemed fire-resistant because of the presence of non-combustible calcium sulfates (from the plaster and cement that make a gypsum board) in the core. Further, water is added in the production process which adds to the fire resistance because heat is first absorbed by the water molecules. This slows down the disintegration of the entire gypsum board and delays the penetration of heat to the housed insulation. In materials glossaries [62], a gypsum board in its unmodified state is defined as a material with natural fire-resisting properties. Gypsum boards can be modified by any manufacturer to increase their fire resistance capabilities. This results in a wide range of thermal properties that are reported in literature and product specifications. On average, gypsum boards are reported to have a high density of 700 kg/m^3 and a low thermal conductivity value of 0.25 W/mK. Because of this, coupled with a good finishing coat due to the cement, gypsum boards or commonly known as drywall, are ideally used as building materials and partition systems for the industrial sector [40,63].

As insulation is not decidedly placed as the surface layer or the layer directly exposed to the fire, a gypsum board serves as the inner material in the room corner tests.

3.1.1.4 Calcium silicate board

Calcium silicate board is often interchanged with or thought of to be the same as a gypsum board because of the similarities in the surface finish, which is a white and chalky substrate. However, the difference lies in the core minerals [64]. Calcium silicate boards consist of calcium silicate minerals, and other materials like sand, natural or synthetic fibers, or a combination of the two. Hence, these two products are distinct because their applications and properties vary. Compared to gypsum boards, calcium silicate boards retain their integrity when exposed to water [65]. Calcium silicate boards are then better suited for high moisture environments such as marine applications or the internal walls of toilets and bathrooms. The durability tests conducted by Kristanto et al. conclude that since calcium silicate boards show reliable performance in rain tests, they are well-suited as building facades or the outside of a structure. In this project, a calcium silicate board is placed as the outer shell of the room corner test.

3.1.2 Building content

With the addition of the foot bench in this project, the effect of upholstered furniture on the performance of the envelope materials is also studied. A commercial foot bench was chosen for this project because it is ideal for scaled room experiments and is comparable to a sofa or couch in the full dimensions of an ISO room. Upholstered furniture is defined as furniture that is typically composed of padding and fabric cover [18]. The foot bench is the upholstered furniture in this project and represents building content that is normally the 'first item ignited' in enclosure fires. In general, it has been reported that upholstered furniture contributes to some 5,000 house fires that occurred from 2010-2014 [66]. The commercial foot bench was dissected and separated into its respective components as shown in Figure 9.

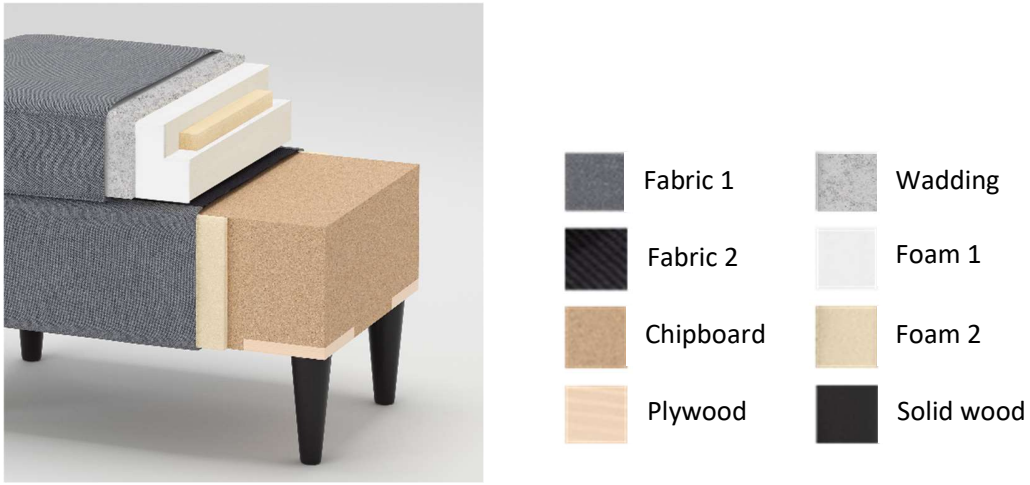

Figure 9. Commercial foot bench cross-section and its components, modified from [65].

3.2 Methods

As it is important to gain a thorough understanding of permanent fire loads, a holistic approach to establishing material behavior is needed. To do this, the project applied an increasing-scale testing approach to examine the Heat of Combustion at each stage by increasing the complexity of testing. The test methods presented herein show a bottom-up approach. The micro-scale tests represent the individual materials in grams of materials tested in idealized conditions. The bench scale tests represent the individual materials as 10-centimeter samples or as layered composites. Finally, the large-scale tests represent the materials in their end-forms in order of meters [18].

3.2.1 Micro-scale tests

Table 1. The materials labeled with "foot bench" as a source are the identified components of the dissected foot bench. The number of test runs for each material is also reported.

Material	Source	MCC (Method A)	MCC (Method B)	Bomb Calorimeter	Sample form in Bomb tests
Fabric 1	Foot bench	2	2	3	Solid
Fabric 2	Foot bench	2	2	3	Solid
Foam 1	Foot bench	2	2	3	Powder
Foam 2	Foot bench	2	2	3	Powder
Wadding	Foot bench	2	2	3	Solid
Chipboard	Foot bench	2	2	3	Solid
PIR Insulation		2	2	3	Powder
Phenolic Insulation		2	2	3	Powder

3.2.1.1 Microscale Combustion Calorimeter / ASTM D7309 [13]

Microscale Combustion Calorimetry (MCC) is one of many thermal analysis techniques that can determine the heat of combustion of solid materials in a constant heat + oxygen-free (Method A) / oxygen-rich (Method B) environment. For Method A, the sample was initially exposed to Nitrogen only in the specimen chamber before it was thermally oxidized in the combustion chamber. Only the Heat of Combustion from the pyrolyzed or volatile gas of the specimen was measured, but not the contribution from any solid residue. In Method B, the sample was initially mixed in 80% Nitrogen / 20% Oxygen before entering the combustion chamber. This is to ensure that the entire sample undergoes complete oxidation. The calorific value of both the specimen pyrolysis gas and the solid residue was determined in Method B. In both Method A and B, *net* heat of combustion was obtained.

Samples from Table 1 were prepared and weighed in order of milligrams (ranging from 2.7 – 5.6 mg). A reiterative process was done in weighing the samples to get an accurate reading in the MCC since oxygen consumption is dependent on the mass of the material.

The specimen cup and sample material were weighed separately, and then together. After weighing, samples were placed in the specimen cup, loaded into the MCC, and then heated to 750°C at a constant heating rate of 1°C/s. Each specimen cup was weighed again after every test run. In the case of Method A, where only the volatile component of the specimen is measured, it is important to weigh the specimen cup after each experiment to obtain the char yield, if any. The char yield is defined as the fraction of unburnt material that is derived by dividing the final mass of the sample by the original mass. Two experimental runs each for Method A and B were done for every material.

The samples were analyzed in the LTH Fire Laboratory in Sweden using a Federal Aviation Administration (FAA) Microscale Combustion Calorimeter and the output heat release rate [Q̇(t)] curve was recorded and further refined in the PCFC Curve Fit Application. The Heat of Combustion was automatically generated from the integral of the area under the Q̇(t) vs time (t) curve divided by the baseline mass of the sample.

Figure 10. A sample of fabric is loaded into the ceramic crucible and tested in both Method A and B.

3.2.1.2 Bomb Calorimeter / ISO 1716 [12]

The Bomb Calorimeter tests were performed in the Kingspan Laboratory in the UK using an IKA C6000 Bomb Calorimeter. The test procedure is following ISO 1716 [12] and determines the gross calorific value of a material when ignited at constant volume and aerobic conditions inside a calorimetric vessel. Three samples (3) were obtained from each specimen listed in Table 1. Before the samples were tested in the Bomb Calorimeter, they were initially ground to powder or reduced to smaller pieces. The samples were then measured to some known grams (ranging from 0.1 – 0.5 g) and placed inside a glass crucible. A combustion aid, depending on the form of the material, was added to the crucible. For solid materials such as wood, wadding, and fabric-based materials, benzoic acid tablets were used. Paraffin oil was added with the foams and insulation materials to ensure that the samples were fully coated with the combustion aid and that complete combustion of the material was achieved. Ignition was done via an electric firing circuit that ignited the cotton thread that was added to the set-up. Oxygen was also introduced within the bomb vessel, which assisted in the combustion of the materials. Temperature differences were noted, and the gross heat of combustion values were determined using Equation 1, $H_{ui,gross} = \frac{E\,(T_m - T_i + c) - b}{M_i}$, for the sample materials. The cotton thread, benzoic acid, and paraffin oil heat of

Combustion values were predetermined, and the machine automatically deducted these values from the final output values.

Figure 11. Bomb calorimeter set-up of chipboard shavings plus benzoic acid tablet (L) and phenolic insulation powder with paraffin oil (R), and cotton thread.

3.2.2 Bench-scale test – Cone Calorimeter / ISO 5660 [33]

Table 2. The specimens in the intermediate test are tested as either: 1. Composite to represent the upper section of foot bench 2. Individual materials to represent the lower section of the foot bench and envelope materials. The number of test runs for each material is also reported.

Material	Source	Cone Calorimeter
Composite 1 • **Foam 1** • **Foam 2** • **Wadding** • **Fabric 1** • **Fabric 2**	Foot bench	3
Foam 1	Foot bench	1[1]
Fabric 1	Foot bench	1[1]
Chipboard	Foot bench	3
Gypsum board		3
PIR Insulation		3
Phenolic Insulation		3

1 One additional test each was carried out for Foam 1 and Fabric 1 because these materials are the dominant components of the foot bench. The additional tests will be used to verify the Heat Release Rate of Foam 1 and Fabric 1.

The Cone Calorimeter test represents the intermediate or bench-scale method to obtain the Heat Release Rate. It is commonly utilized to determine numerous fire-related properties of a material and demonstrate the contribution of these materials in the initial stages of fire development. The FTT Cone Calorimeter was used to estimate full-scale fire performance through representative specimens of the

materials listed in Table 2. Two sample preparation methods were employed for the bench-scale tests, depending on whether the sample is a composite or an individual material.

The composite specimens were prepared according to the steps listed in the CBUF report [67] and ASTM E1474 [68]. To test an accurate representation of the upper section of the foot bench, each component was proportioned according to its dimensions, scaled down, and assembled as a layer of fabrics, foams, and wadding. The resultant composite is a scaled-down version of the main section of the foot bench. Since ASTM E1474 requires that frame elements be not included in the composite construction, the chipboard was tested independently since it is a significant portion of the foot bench.

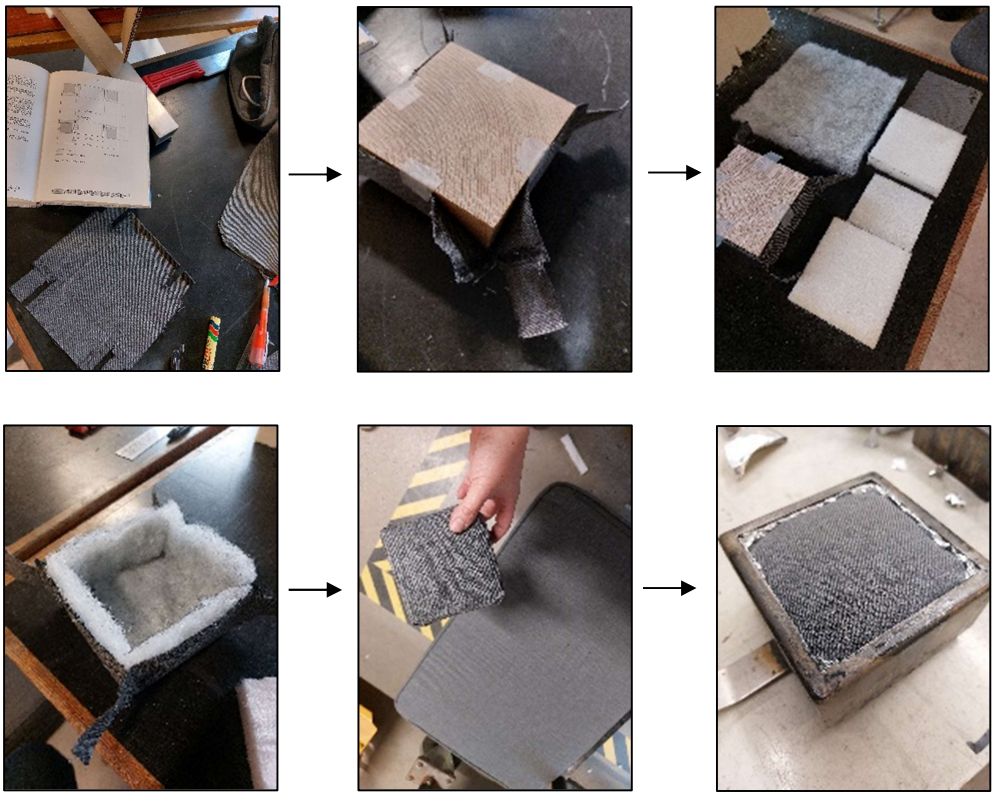

Figure 12. Sample preparation based on the recommended specimen preparation from the CBUF report on fire testing of upholstered furniture.
Top L-R: Fabric was cut and then shaped around a wooden block; internal components of the foot bench were proportioned.
Bottom L-R: Materials were assembled inside the shaped fabric and then tested in the cone calorimeter.

Non-composite materials in Table 2 were measured and cut to a surface dimension of 10 x 10 cm. The materials were weighed, and initial thicknesses and surface area were recorded. The samples were then placed in a sample holder. In the case of the composite, each material was weighed first to determine the ratio of the materials to the overall weight and then weighed together as an assembly. All samples

were ignited through spark ignition and exposed to a heat flux of 35 kW/m^2 in reference to the test procedure [68]. In addition, aluminum foil was placed around the samples to ensure that heating remained constant within the samples. Combustion products traveled through the exhaust hood and the heat release rate was measured by the oxygen consumed during the process. Heat release rate is calculated using the equation from Section 12.3.2 of ISO 5660-1 [33]. From the graphical result of the heat release rate, an effective heat of combustion is derived by integrating the area under the heat release rate curve and dividing it by the total mass loss.

Figure 13. Composite sample is tested in the FTT Cone Calorimeter.

3.2.3 Full-scale test

Table 3. Experimental design for the full-scale tests. The rooms in these cases are also called ISO rooms.

Test number	Materials
1	Calcium silicate board + Foot bench[1]
2	Calcium silicate board + Phenolic insulation + Gypsum board + Foot bench
3	Calcium silicate board + PIR insulation + Gypsum board + Foot bench
4	Calcium silicate board + Gypsum board + Foot bench
5	Open calorimeter test with only the foot bench[2]

1 Test 1 is the base case for the scaled room corner tests.

2 An additional test with only the foot bench is added to compare the differences between an open calorimeter test and the base case where the enclosure can influence the fire dynamics.

3.2.3.1 1/3-Scaled Room Corner Test / ISO 13784-1 [53]

This test was conducted to obtain the Heat Release Rate in a room assembly of building envelope materials. Like the Cone Calorimeter, a room corner test can specify the early fire development (ignition to flashover) of wall and ceiling products when exposed to an ignition source in well-ventilated conditions. The reference guideline ISO 13784-1 [53] states that a room corner test intends to assess the

realistic behavior of sandwich panel systems using their end-use configuration. An ISO room is used as a starting point but is scaled to a third with inner dimensions of 1.2 long x 0.8 wide x 0.8 m high. The ventilation or opening of the room was also scaled down to a third, with dimensions of 0.67 x 0.27 m wide.

Thermocouples were placed around the external walls and inside the core of the sandwich panel system to obtain the temperature changes in the area of the compartment near the ignited foot bench as illustrated in Figure 14.

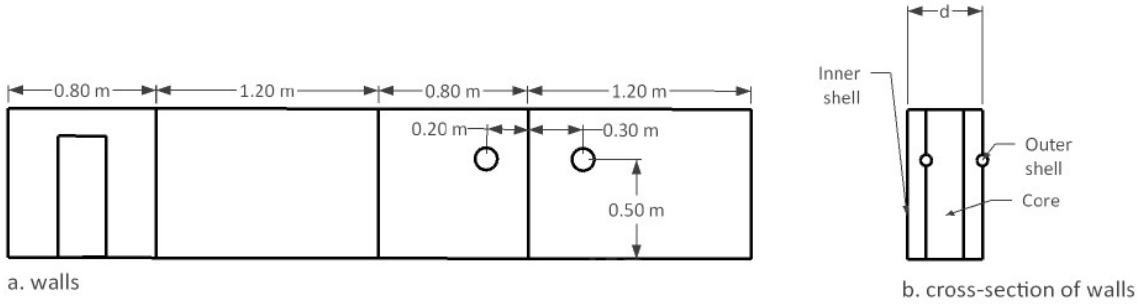

Figure 14. Orthogonal view of the scaled room. Thermocouples were placed in reference to the requirements in ISO 13784-1.

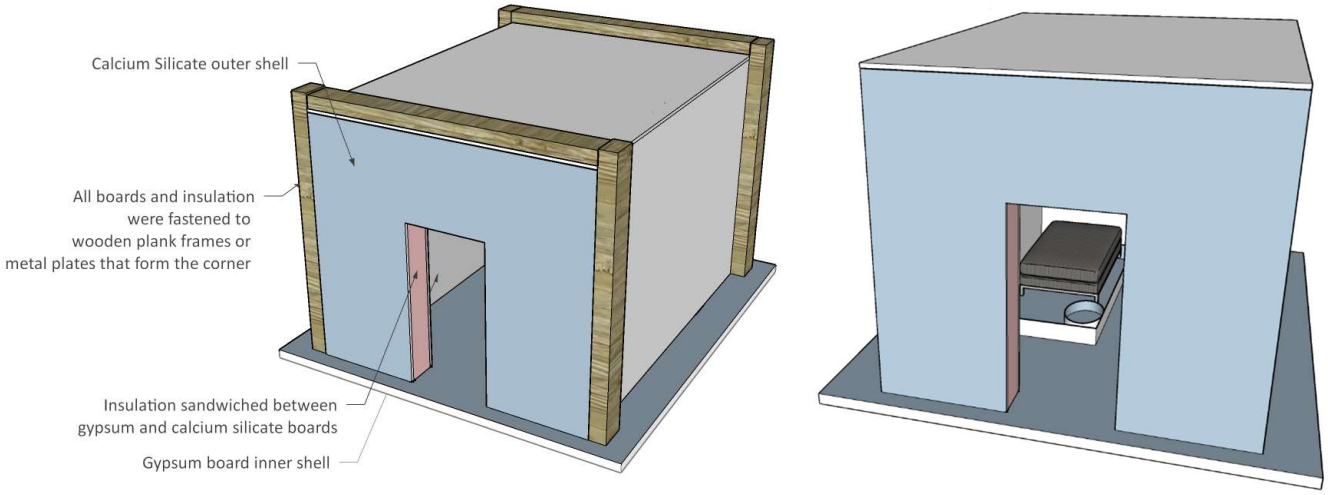

Figure 15. L: Sample configuration for Test 2 and 3 with insulation. R: Test set-up with foot bench inside metal tray. The insulation is housed between the gypsum and calcium silicate board. Door opening shows cut-out to reveal the insulation.

The test was conducted in four (4) cases. In this project, each test was a combination of the components listed in Tests 1-4 in Table 3. The foot bench was placed inside the left corner of the room as shown in Figure 15 to represent the worst-case scenario of an enclosure fire since limited entrainment causes

higher flames and higher temperatures [6]. Based on the Cone Calorimeter tests done, it was observed that the fabric and foam materials melted to form a liquid pool. A metal tray was added at the base of the foot bench to catch the pool drippings.

500mL of Heptane was used as the fuel source in the room corner experiments. A 16cm x 4.5cm high circular pan to hold the Heptane fuel was placed at the corner of the foot bench leg. Water was added until the fuel reaches 3.5cm to ensure that Heptane spreads and burns evenly inside the circular pan.

The Heat Release Rate values per time steps of 3s were recorded and obtained through an oxygen consumption method in an open hood calorimeter. The mass loss of the enclosure was noted through direct weighing of the room corner test during testing.

3.2.3.2 Open Calorimeter Test / ISO 24473 [69]

An additional test (Test 5) was performed on one foot bench in an open calorimeter setup to provide a baseline value of comparison for Cases 1 and 4 in the 1/3-scaled room corner test. The specimen was positioned in the middle of the test area under the hood. Prior to testing, a weighing scale was placed beneath the foot bench and was calibrated to ensure accurate mass loss readings. A gypsum board functioned as a divider between the weighing scale and the specimen to ensure that the scale is protected from the resulting liquid pool from the foam and the fabric materials.

500mL of Heptane was used as the fuel source in the experiment. A 15cm x 5cm high circular pan to hold the Heptane fuel was placed at the corner of the foot bench leg. Water was added until the fuel reaches 4cm to ensure that Heptane spreads and burns evenly inside the circular pan.

The Heat Release Rate values per time steps of 3s were recorded and obtained through an oxygen consumption method in an open hood calorimeter. The mass loss of the enclosure was noted through direct weighing of the foot bench during testing.

Figure 16. Experimental set-up of the open calorimeter test conducted in the LTH Fire Laboratory.

4. Results and Analysis

This Chapter reports the findings from the experimental designs in Chapter 3. The results are presented in four relevant sections to highlight the increased-scale testing approach utilized in this project.

4.1 Microscale Combustion Calorimeter (MCC)

A total of 32 tests were conducted, 16 in Method A and 16 in Method B. The experimental results were plotted in HRR (W/g) vs. Temperature (°C) graphs. Integration of the area under the resulting graph results in the *net* Heat of Combustion for both methods.

Initially, all the foams and wadding within the foot bench were tested once using Method A and Method B to ascertain whether they are made of the same material. It was observed that the inner foam inside the main body of the foot bench and the foam surrounding the lower body of the foot bench behaved similarly. Thus, it was established that these are the same material and conclusively labeled as 'Foam 2'.

While only two replicates were conducted for each material, good repeatability is seen for the tests since the graphs show consistency in the general form of the plots for each material. For experimental results from Method A, nearly Gaussian or bell-shaped graphs are observed since the initiation of material pyrolysis in a purely Nitrogen environment does not decompose the material entirely and the curve represents the pyrolysis gases only. While for Method B, in an air-like environment, subsequent combustion for any solid residue is indicated through a secondary peak in the graphs.

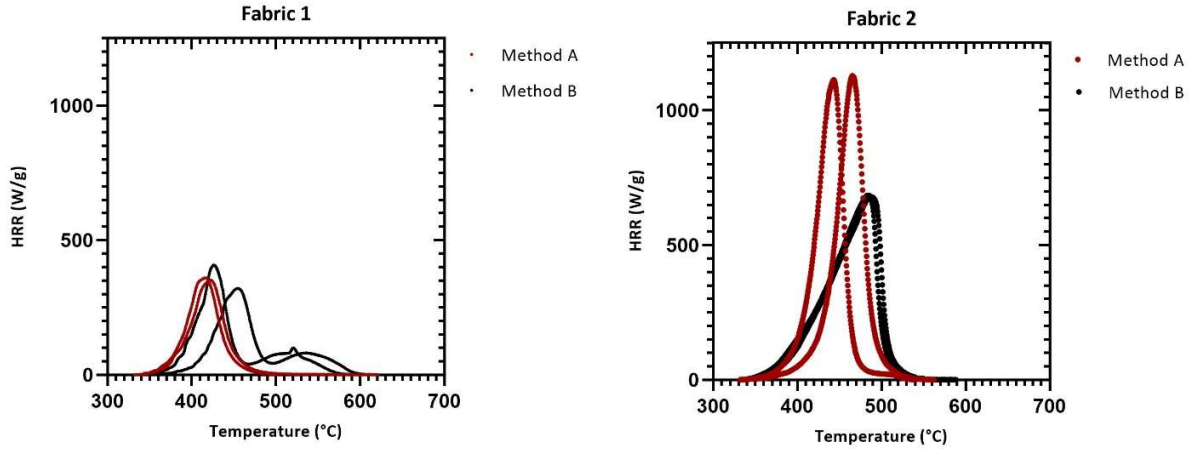

Figure 17. Difference of materials that produce residual material (Fabric 1) vs. materials that easily ignite (Fabric 2).

The numerical values of the net Heat of Combustion as seen in Table 4 are consistent with the above observations. This is better visualized by comparing the experimental results of *Fabric 1* and *Fabric 2*.

Fabric 1 is reported to have an average char yield of 16.34% which was seen as residual material after each experimental run in Method A. In Method B, the remaining residual material is broken down in auxiliary combustion and realized in the second peak. Thermal degradation of Fabric 2 does not result in any residual material and no char yield is reported in either Methods A or B. The resultant plots of Fabric 2 show bell-shaped outlines, an indication that there are no residual materials to burn. Consequently, the Heat of Combustion from the two replicates tested in Method A for Fabric 2 are close in value. The same is also concluded for the two replicates tested in Method B.

Since it has been stated in the previous sections that Method B values are comparable to the obtained Heat of Combustion from the complete combustion in a Bomb Calorimeter, the Method B values are expected to be higher than the ones obtained from Method A [35–37]. By exposing the specimen to an 80% Nitrogen / 20% Oxygen environment for Method B, the material undergoes an oxidation reaction leading to complete combustion. Almost no char yield is anticipated.

The results from testing the individual materials in the Microscale Combustion Calorimeter are summarized as follows. Fabric 2 and Foam 2 materials are considered easily ignitable since no char is observed in both methods.

Table 4. Summary of the Heat of Combustion values derived from Microscale Combustion Calorimeter for test materials. The reported values are averaged for the two replicates per material.

	Method A ***(net HoC for the volatile components only)***		**Method B** ***(net HoC for the volatile components and solid residue)***	
Materials	***Average Heat of Combustion [MJ/kg]***	***Average Char Yield (%)***	***Average Heat of Combustion [MJ/kg]***	***Average Char Yield (%)***
Fabric 1	17.25	16.34	22.30	0
Fabric 2	45.73	0	47.40	0
Foam 1	27.56	1.40	30.41	0
Foam 2	27.66	0	30.95	0
Wadding	16.04	15.37	25.41	0.56
Chipboard	12.63	22.11	19.13	0.40
Phenolic Insulation	8.42	42.97	25.86	2.54
PIR Insulation	14.44	25.92	24.93	1.96

4.2 Bomb Calorimeter

A total of 27 tests were carried out in a Bomb Calorimeter and the experimental results were recorded and plotted as a function of Temperature (°C) vs. Time (minutes) as seen in the figure below. The Bomb Calorimeter automatically generates a *gross* Heat of Combustion after each test.

Due to the volume of the test runs performed, only Test 1 of Phenolic insulation is reported as an example and as seen in Figure 18. It is observed that the figure is representative of the general form and shape of the Temperature-Time curve of all materials.

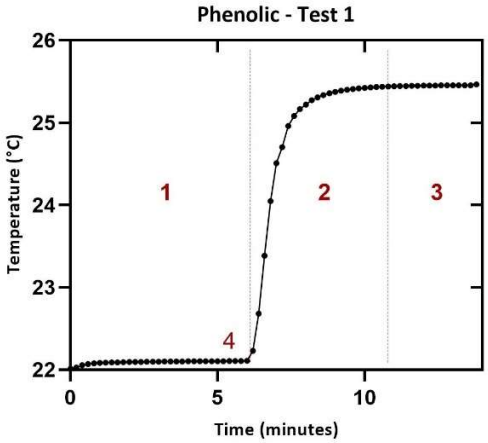

Figure 18. Sample Bomb Calorimeter result showing the Temperature-Time curve for Phenolic insulation.

Section 1 represents the preliminary period wherein the Bomb Calorimeter calibrates and stabilizes to establish the baseline temperature. For all test cases, the recorded baseline temperature is at a room temperature of 22°C. Section 2 is the main [burning] period, with Point 4 showing the initiation of the ignition and transition phase. The increase in temperature in all the experimental runs is indicative that exothermic reactions have occurred, and that heat is released within the test chamber. Lastly, Section 3 shows a plateau or stabilizing of the temperature, which suggests that heat exchange is no longer occurring and that all possible combustible materials have ignited.

It is expected that the resulting Heat of Combustion of the specimen materials are to be exothermic (in Bomb Calorimeter tests, a positive Heat of Combustion value is contrary to the previous discussion that a negative value is assigned for exothermic reactions) since the tested materials are known to be combustible. The Heat of Combustion results for the gypsum board are seen to behave differently. A study conducted by Fangrat [70] for non-combustible building materials reports that gypsum board behaves in two distinct phases: initial dehydration and subsequent endothermic behavior that absorbs heat. Further, the temperature increase observed in the Temperature-Time graph of gypsum-based materials is indicative of the combustion of the paraffin oil only and not of the material. The apparatus automatically deducts the HoC of the paraffin oil from the final HoC, resulting in a negative value since

the gypsum material absorbs heat in the test process. The negative Heat of Combustion obtained in these experiments are similar to the negative values obtained by Fangrat for gypsum façade boards.

To confirm the accuracy of the results obtained from the three experimental trials conducted for each material, the values for Tests 1-3 are evaluated using an acceptability criterion, which requires them to be within 10% of the average of the three results. This is in accordance with the acceptance criteria stated in Table 1 of ISO 1716 *[12]*. The Heat of Combustion values are well within the ±10% of their respective averages, with standard deviations within ± 2*Standard Deviation, as seen in Table 5. The results from the tests are concluded to be highly repeatable.

Table 5. Summary of the Heat of Combustion values derived from Bomb Calorimeter for test materials.

Gross Heat of Combustion [MJ/kg]				
Materials	***Test 1***	***Test 2***	***Test 3***	***Average and σ***
Fabric 1	22.56	22.51	22.40	22.49 ± 0.08
Fabric 2	45.51	45.88	45.75	45.71 ± 0.19
Foam 1	29.11	29.30	28.42	28.94 ± 0.46
Foam 2	28.72	28.07	28.87	28.55 ± 0.42
Wadding	22.22	21.16	21.09	21.49 ± 0.63
Chipboard	18.57	18.57	18.42	18.52 ± 0.09
Phenolic Insulation	25.37	25.72	24.88	25.32 ± 0.42
PIR Insulation	26.17	25.15	25.51	25.61 ± 0.52
Gypsum board	*-1.28*	*-1.04*	*-1.51*	*-0.13* ± 0.24

4.2.1 MCC vs. Bomb Calorimeter HoC values comparison

Ideally, the *net* Heat of Combustion should have been obtained from the Bomb Calorimeter readings to make an exact comparison with the net HoC values from the MCC. ISO 1716 gives the standard method to derive this by subtracting the latent heat of vaporization of the fuel, as a function of the fuel's hydrogen content, from the *gross* Heat of Combustion. However, the process to obtain the fuel's hydrogen content involves separate analysis equipment.

In theory, the Bomb Calorimeter values are presumed to be higher than the MCC values since the Bomb Calorimeter operates in a highly closed system wherein released heat can be recaptured. Previously in Sec. 2.2.1 it has been mentioned that comparative studies have concluded that the results of the MCC Method B and Bomb Calorimeter are comparable [37].

Table 6. Table comparison of the net HoC from MCC Method B and gross HoC from Bomb Calorimeter, assuming that the Bomb Calorimeter HoC values are the true or baseline value.

Materials	**Char Yield in MCC Method B (%)**	***MCC Method B HoC***	***Bomb Calorimeter HoC***	***Absolute Percent Error (%)***
Fabric 1	0	22.30	22.49	0.84
Fabric 2	0	47.40	45.71	3.69
Foam 1	0	30.41	28.94	5.07
Foam 2	0	30.95	28.55	8.40
Wadding	0.56	25.41	21.49	18.26
Chipboard	0.40	19.13	18.52	3.32
Phenolic Insulation	2.54	25.86	25.32	2.12
PIR Insulation	1.96	24.93	25.61	2.62

From the results of the tests, percent errors of the MCC Method B from the baseline HoC values of the Bomb Calorimeter tests are calculated and reported in Table 6. High variations are seen for the foams and wadding materials, while reasonable deviations are seen for the other materials.

The ideal method to confirm the biases would have been to replicate the tests while changing experimental factors such as oxygen volume fraction, heating rate, and temperature. As these factors are not in the scope of the research project, we investigate the findings of similar studies on Microscale Combustion Calorimetry. A study by Guo et al. [39], in collaboration with the FAA, looks into the accuracy of measured values in MCC. The study investigates the factors that can cause biases against the baseline value from the Bomb Calorimeter and recommends correction approaches for the errors. The authors mainly looked into the effect of generated CO_2 from the fuel combustion which affects the mass flow rate of consumed O_2 in the oxygen consumption process. Since some of the oxygen has been replaced by CO_2, the rate at which heat is released is impacted since HRR is a function of the mass flow rate of O_2 into and out of the combustion zone multiplied by the average net heat of complete combustion of O_2 with hydrocarbon fuels. The experimental results showed that some polymers exhibit higher MCC HoC values for Oxygen volume fractions of less than 15%.

4.3 Cone Calorimeter

Fifteen (15) tests were conducted for the specimen materials in the cone calorimeter. The data points are reported in HRR-Time curves. Integration of the area under the curve divided by the main burning period, defined as 10% to 90% of the ultimate mass loss of the material [33], results in an *effective* Heat of Combustion value.

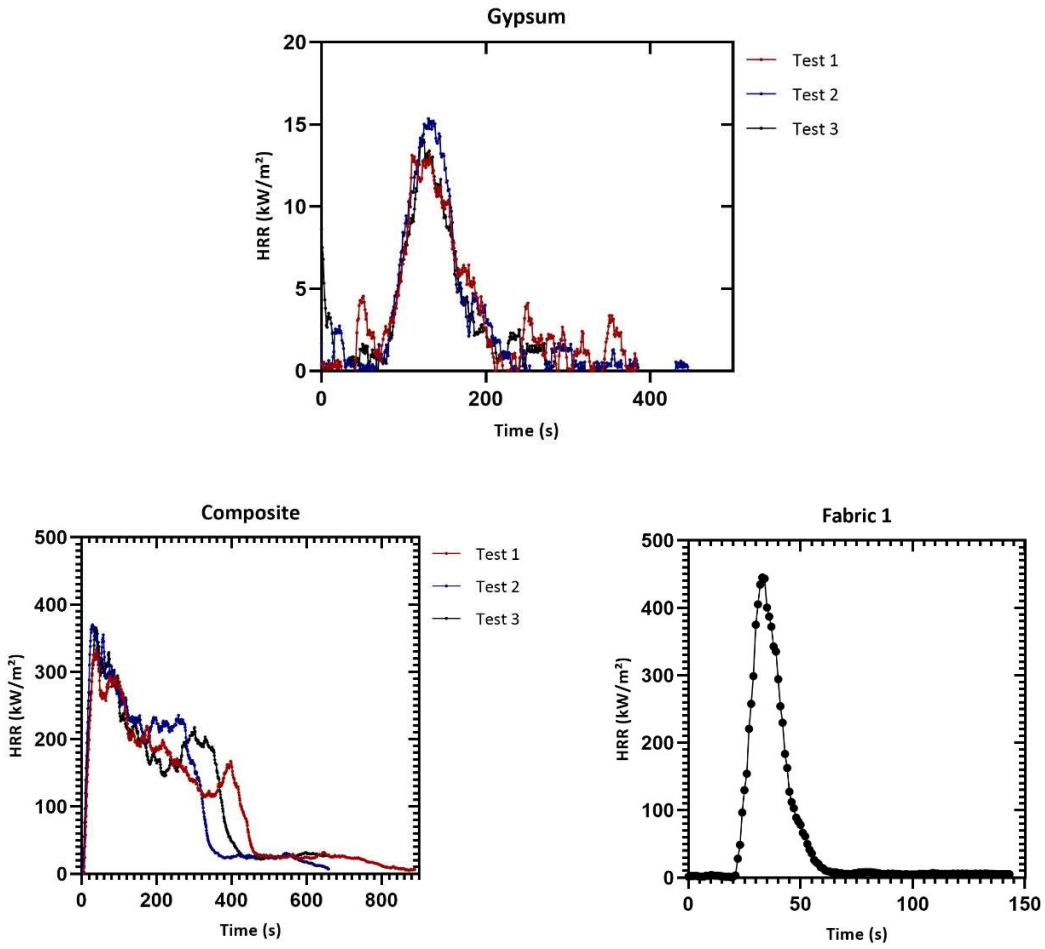

Figure 19. Top: Cone Calorimeter result showing the HRR-Time curve for gypsum board. The main burning periods for all three samples are approximately between 0 – 400s for the paper lining on the gypsum board.
Bottom: Cone Calorimeter results of the Composites. R: Cone Calorimeter result of Fabric 1 only.

An initial assessment of the specimen materials after burning revealed that all materials did not burn completely. In the case of the Composite, the three tests all indicate a sharp rise in the HRR which could be attributed to the initial ignition of Fabric 1 as the outer shell of the composite. Once the fabric ignited and melted, it exposed Foam 1 and the rest of the materials to the heat flux from the radiating cone. The foot bench components eventually lumped in the center of the specimen holder and remained as residual material, exhibiting melting for the fabric and foam materials.

Figure 20. L: PIR and Phenolic insulation samples after burning. R: Remaining composite material after the cone test.

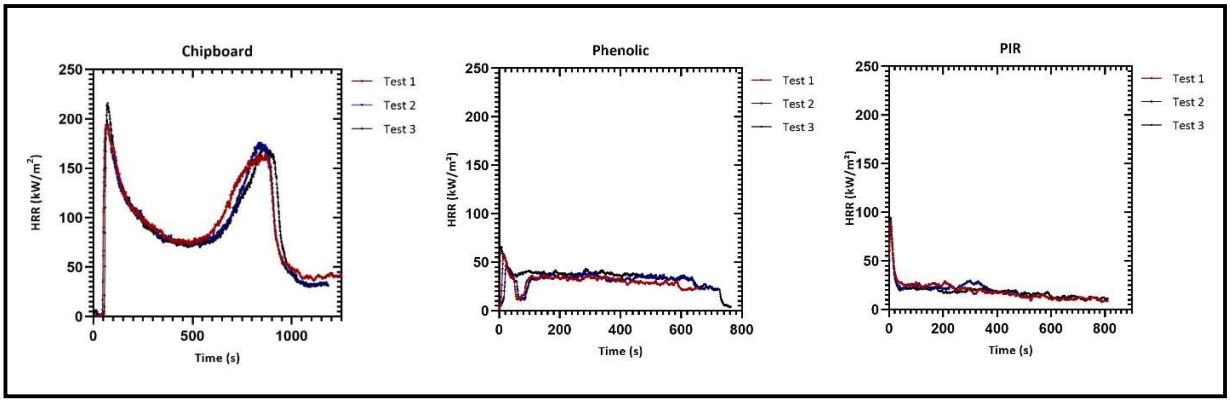

Figure 21. Cone Calorimeter results showing the HRR-Time curve for the insulation materials and chipboard.

The insulation materials and the chipboard all exhibited charring in the decay phases of their respective HRR-Time curves. The plots reach sharp peaks for the HRR, plateau, but never fully reached complete degradation as seen in Figure 21. The figures illustrate the rapid ignition of both insulations and time to peak for the HRR, which have been recorded as igniting as early as 1s for the PIR and peaking at a wider range of 3-30s for both PIR and Phenolic. The PIR insulation shows a slightly higher HRR peak but exhibits a lower HRR in the burning phase, while the Phenolic behaved oppositely, with a lower peak HRR but a higher HRR in the steady burning phase. It is interesting to note that during the duration of testing for the Phenolic insulation, there have been visual and auditory observations of some distinctive behaviors of the insulation. At approximately 200s for the three tests, the material started to crack and make popping noises, possibly indicating chemical degradation. This continued for the next 200s until the test was stopped.

Figure 22. Phenolic insulation after the tests showing cracks.

The Cone Calorimeter results for the chipboard are consistent with experimental studies done on wood-based products [71]. The two peaks demonstrate the charring behavior of wood since the first peak illustrates the surface ignition and burning of the material, then shifts to decay which is seen in the decrease of the HRR curve, but subsequently, the curve starts to increase again. The decline is attributed to the charring phenomenon and the transition to the second peak signifies that the char layer has cracked, allowing for pyrolysis gases from the virgin material sublayer to cause reignition [71].

There are expected variations in the HRR-Time curve of the composites and chipboard due to the strong effect of precision in the sample preparation of the Composites and the chipboard composition with the presence of the different wood particles and glue. However, the graphs show good agreement among the three replicates for all materials and thus it can be concluded from the experiments that good repeatability is achieved when testing upholstered furniture and envelope materials in the Cone Calorimeter. The experimental results are shown to also be within the standard deviations of ± 2*σ in Table 7.

The results from testing the individual materials are summarized as follows:

Table 7. Summary of the Heat of Combustion values derived from Cone Calorimeter for test materials.

Effective Heat of Combustion (MJ/kg)				
Materials	***Test 1***	***Test 2***	***Test 3***	***Average and σ***
Composite	16.54	22.52	21.56	20.21 ± 3.21
Chipboard	13.56	12.30	12.32	12.73 ± 0.72
Phenolic Insulation	19.03	19.02	20.93	19.66 ± 1.10
PIR Insulation	19.88	20.29	17.95	19.37 ± 1.25
Gypsum board	1.00	0.70	1.15	0.95 ± 0.23

4.4 Full-scale tests

4.4.1 Calculation for Effective Heat of Combustion

The *effective* Heat of Combustion values for the room corner tests is obtained by dividing the total energy by the mass pyrolyzed using Equation 4, $H_{ui,eff} = \frac{Q}{M_i}$. However, as the Heptane was allowed to burn completely inside the enclosure, the energy of the fuel Q_{fuel} shall first be deducted from the total energy Q_{total} obtained from the experiments to find the energy from the combustible materials Q_{ui} in the room corner. Q_{total} is derived by integrating the area under the resultant HRR curve from the experiments.

$$Q_{total} = Q_{fuel} + Q_{ui} \quad \textit{Equation 11}$$

$$Q_{total} = M_{fuel}\, x\, H_{fuel} + M_{ui}\, x\, H_{ui} \quad \textit{Equation 12}$$

Table 8. Heptane fuel properties from [6]. These values are used to calculate the Heat Released Q_{fuel} by the fuel.

Density ρ, kg/m³	Volume, mL or m³	Mass = ρ * volume of Heptane, kg	$\dot{M}''_{\infty}$, kg/m2*s	$k\beta$, m⁻¹	$H_{ui,eff}$, MJ/kg	Q_{fuel}, MJ
675	500 or 0.0005	0.3375	0.1010	1.1000	44.6000	15.0525

Once Q_{ui} is calculated, it is divided by the mass pyrolyzed M_{ui}, which is the difference between the final and the initial mass of the rooms from the weighing scale minus the mass of the Heptane. The result of dividing Q_{ui} by M_{ui} is the effective heat of combustion of the combustible materials inside the room.

The test set-ups for the scaled room corner tests are reiterated as follows:

Test case 1: Calcium silicate board + Foot bench
Test case 2: Calcium silicate board + Phenolic insulation + Gypsum board + Foot bench
Test case 3: Calcium silicate board + PIR insulation + Gypsum board + Foot bench
Test case 4: Calcium silicate board + Gypsum board + Foot bench
Test case 5: Open calorimeter test with only the foot bench

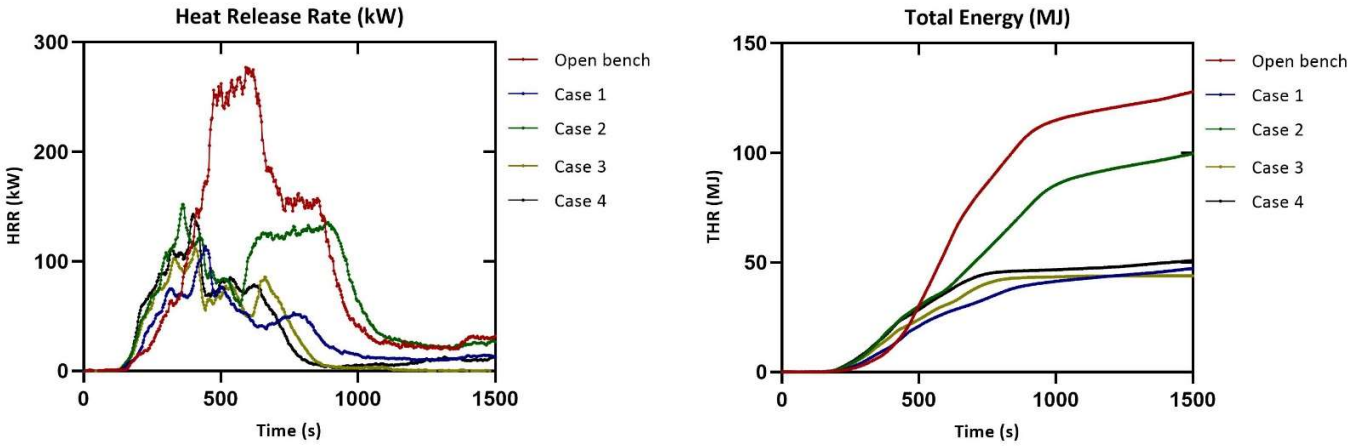

Figure 23. Test cases 1-5 are superimposed in HRR and THR graphs for comparison. L: HRR vs. time; R: THR vs. time.

The graphs in Figure 23 show that for Tests 1-4, the peak HRRs have been reached faster than in the open calorimeter test but the peak HRR is higher in Test 5. This was seen to be fastest for Case 2 – Phenolic insulation at approximately 6 mins. and slowest for the open furniture burn at almost 10 mins.

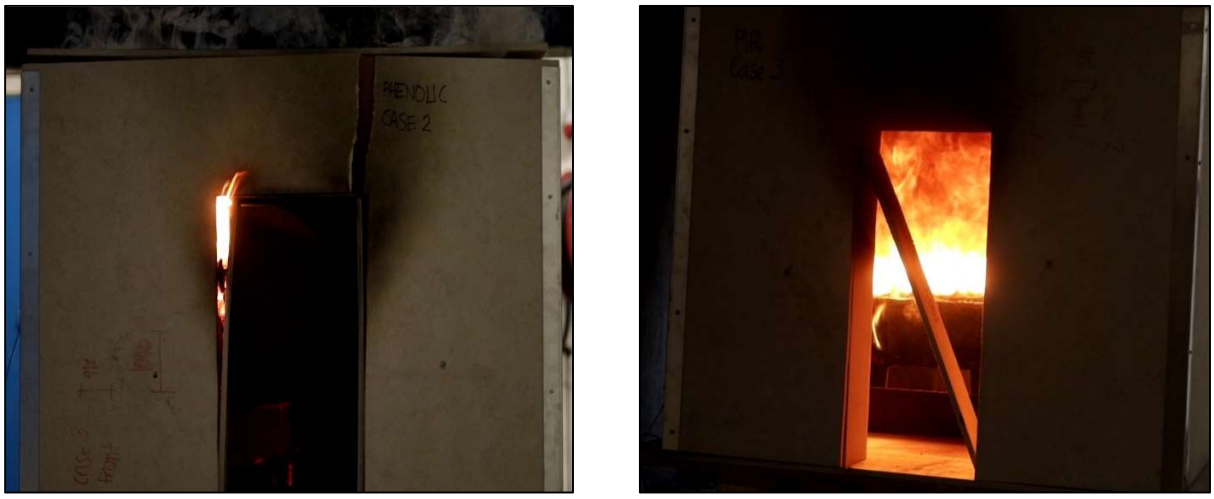

Figure 24. L: Room corner set-up with the phenolic insulation showing collapse at 21 mins, it was seen in the videos that the roof started to collapse at 17 mins. R: Room corner set-up for the PIR insulation showing collapse at 9 mins.

During the testing of Cases 2 (Phenolic) and 3 (PIR), it was observed that the rooms started to collapse within the duration of the testing. Cracking sounds, similar to the ones observed for the cone calorimeter tests, were noted in Case 2 to have started at approximately 3 minutes. At this time, the room for the Phenolic case was not seen to start to collapse. The start of insulation burning was attributed to some cracks in the jointing construction which would have allowed the fire to reach the insulation early. The cracking sound continued until the test was terminated at 25 mins. Like the

Phenolic case, the PIR room also failed during the testing. It was seen in both cases that flames and thick smoke started to escape from the doorway.

While it has been discussed in fire dynamics literature that enclosure and ventilation effects generally would lead to a higher mass loss rate, hence a higher heat release rate [5], the experimental results show otherwise. In addition, the total energy released is higher in the open furniture test. For fires in enclosures, hot gases tend to accumulate in the ceiling and walls and radiate back to the fuel, enhancing the burning rate and time to reach the peak HRR. But another factor to consider for enclosure effects would be the ventilation openings [6]. A limited amount of oxygen from the ventilation opening may cause incomplete combustion and thus, a lesser heat release rate.

Figure 25. Case 2 with the Phenolic insulation showing a visual indication of a ventilation-controlled fire as flames shoot out of the compartment and thick black smoke is also observed.

However, it is not in the scope of the research project to determine the effects of ventilation openings on the total HRR of the enclosure. And thus, an accurate comparison with the obtained HRR in open burn in Test 5 cannot be ascertained. Instead, we look to related literature and studies to support the deviation seen in the full-scale tests. In the CBUF programme [67] that tested the different burning behaviors of upholstered furniture, sample 1:13 which was identified as “Chair”, exhibited similar results to the experimental results of this project. The open calorimeter or free burn done to sample 1:13 resulted in a higher HRR than the room fire tests. One assumption to the high-value HRR recorded for the open furniture burning is that the set-up was well-ventilated, allowing for efficiency in combustion. Whereas, for the room corner test, underventilation might play a factor in the experimental results. It is seen that although the same material mass loss has been recorded for the base case and open furniture

burning, HRR and THR values differ. The material may have been pyrolyzed but as for the efficiency of burning the pyrolyzed gas, the duration of the tests may not have been sufficient for the pyrolysis gases to ignite. The possible effect of the ventilation opening remains inconclusive. It is of interest to study this factor and the effect of limiting the burning duration in future studies.

Table 9. Summary of the numerical data from the graphs in Figure 23.

Test Number	***ΔMass Loss, kg***	***Q_{fuel}, MJ***	***M_{fuel},* kg**	***M_{ui},* kg**	**Assumed *M_{ui}*[2], *kg***	***Total Heat Released (THR) at 15mins, MJ***	***Q_{total} or THR at 25mins, MJ***	***Q_{ui}, MJ***	***Effective Heat of Combustion for 25mins, MJ/kg***	***Recalculated EHC using Assumed M_{ui}[2], MJ/kg***
1	6.00[1]	15.05	0.34	5.66	1.47	39.63	47.25	32.20	**5.69**	**21.90**
2	14.50[1]	15.05	0.34	14.16	9.97	75.29	99.62	84.57	**5.97**	**8.48**
3	7.50[1]	15.05	0.34	7.16	2.97	43.10	43.88	28.83	**4.03**	**9.71**
4	6.50[1]	15.05	0.34	6.16	1.97	46.25	50.88	35.83	**5.82**	**18.19**
5	6.33	15.05	0.34	5.99	-	108.38	127.86	112.81	**18.83**	**-**

1 Mass loss values are taken from the recordings of weighing scales in the experiment. Mass loss was taken to be the difference between the initial **and final recorded mass.**

2 Assumed mass of combustibles represents the fabric and foam only.

An interesting observation from the values in Table 9 is the striking mass loss in Cases 1 and 4. While the mass loss is close in value to that for the open burn in Case 5, the THR and EHC are low in values for those cases. As such, the reported mass loss is assumed to be erroneous since a mass loss of 6.0 and 6.50 kg entails that the entire foot bench must have almost completely combusted as a foot bench weighs only 6.41 kg (See Sec. 4.5 Worked Example). For Cases 1 and 4, it is also assumed that the mass loss should only be from the furniture since the gypsum and calcium silicate boards have no contribution. Images taken after the experiments for the room corner tests are inconsistent with the mass loss recorded since Figure 26 shows the frame elements to be almost intact. A new column labeled *Assumed M_{ui}* is added in Table 9 to represent the mass loss for the foams and fabrics only. The *Assumed M_{ui}* values were calculated as M_{ui} values less the mass of the foot bench chipboard (4.19 kg) from Table 11. With the assumed mass loss for the fabrics and foams deemed as the major combustible material, EHC is also recalculated and shown in the column *Recalculated EHC using Assumed M_{ui}.* Thus, with the recalculation, the EHC obtained is more realistic and is close in value for Cases 1, 4, and 5.

Figure 26. Residual materials after the burning period of 25 mins. The dense components of the foot bench and insulations were not fully consumed but exhibited charring, melting, and delamination.

4.4.2 Flashover

It is of interest to obtain at what Heat Release Rate is flashover expected to occur in the scaled room. Flashover is defined in ISO standards as: "the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure" [6]. To check whether the scaled rooms have reached this stage, a simplified correlation by Thomas [72] based on the opening and room dimensions is used to calculate the HRR for flashover. The scaled room dimensions are 1.2 long × 0.8 wide × 0.8 m high and ventilation is provided by a 0.67 high × 0.27 m wide doorway.

$$\dot{Q}_{FO} = 7.8 * A_T + 378 * A * \sqrt{H} \qquad \textit{Equation 13}$$

Table 10. Summary of the experimental HRR for Flashover vs. calculated HRR for Flashover using Thomas correlation.

Test Number	***Thomas HRR for flashover, kW***	***Peak HRR from experiments, kW***	***Time to Flashover from experiments, mins***
1	94.5	113.67	7.50
2	94.5	151.99	6.05
3	94.5	111.71	6.80
4	94.5	143.09	6.65

Flashover was determined to check that all possible combustible materials in the room have ignited. The peak HRR derived in the experiments includes the HRR for the Heptane fuel since fuel is needed to establish ignition in the rooms.

4.5 Worked Example

A sample calculation using the HoC values from the Microscale Combustion Calorimeter (Method A and B), Bomb Calorimeter, and Cone Calorimeter is performed for the dimensions and material

requirements of the 1/3-scaled room corner test. The purpose of the worked example in this section is to determine the resulting permanent fire loads from the different test methods and perform a comparative analysis of the values.

The components of the theoretical room are as follows:

- Foot bench (w=6.410kg);

  The foot bench is placed inside and flushed against the corner of the room. Before testing, the individual components of the foot bench were weighed separately to get the individual mass of the materials.
- Insulation (t=100mm)

  PIR or Phenolic insulation is sandwiched between the gypsum and calcium silicate board for the theoretical room. The density of the material is derived from technical data sheet values. This density is then multiplied by the volume of material in the theoretical room to obtain the required mass of insulation.

Both the Calcium Silicate and Gypsum boards are not considered in the calculations because of the low values of HoC obtained from the test. It was observed that values obtained for Gypsum boards are negative in the Bomb Calorimeter and less than 1 MJ/kg in the Cone Calorimeter. Calcium Silicate was tested in the Bomb Calorimeter and yielded values less than 1MJ/kg.

In the testing of the Composite in the Cone Calorimeter, the representative samples are deemed to be scaled-down versions of the main component of the foot bench. While there are certain biases from the sample preparation, especially concerning the proportioning of the materials, the used composites in the experiments are deemed suitable. There is also the argument for utilizing a basic approach to testing composites as simple layers of material. However, in foregoing the specialized construction, which was done in this project, the dynamics and interaction of the fabric to the foams may not be considered. With the specialized construction, the behavior of the fabric which surrounds the foam materials, as with upholstered furniture, is well represented [67].

Table 11. Summary of the calculations of fire loads through HoC values from Bomb Calorimeter, MCC, and Cone Calorimeter.

		Temporary Fire Load					
Materials	***Mass (kg)***	***MCC Method A HoC (MJ/kg)***	***Fire Load (MJ)***	***MCC Method B HoC (MJ/kg)***	***Fire Load (MJ)***	***Bomb Calorimeter HoC (MJ/kg)***	***Fire Load (MJ)***
Fabric 1	0.47	17.25	8.09	22.30	10.46	22.49	10.55
Fabric 2	0.04	45.73	1.92	47.40	1.99	45.71	1.92
Foam 1	0.57	27.56	15.63	30.41	17.24	28.94	16.41
Foam 2	0.18	27.66	5.03	30.95	5.63	28.55	5.20
Wadding	0.10	16.04	1.52	25.41	2.41	21.49	2.04
Chipboard	4.19	12.63	52.92	19.13	80.15	18.52	77.58
		Permanent Fire Load					
PIR Insulation	16.26	14.44	234.83	24.93	405.42	25.61	416.45
Phenolic Insulation	17.25	8.42	145.23	25.86	446.04	25.32	436.76

		Temporary Fire Load	
Materials	***Mass (kg)***	***Cone Calorimeter EHC (MJ/kg)***	***Fire Load (MJ)***
Composite	1.36	20.21	27.38
Chipboard	4.19	12.73	53.34
		Permanent Fire Load	
PIR Insulation	16.26	19.37	315.00
Phenolic Insulation	17.25	19.66	339.10

Table 12. Comparison of the fire loads obtained from the four tests.

Fire Load [MJ]			
Tests	**Permanent**		**Temporary**
	Phenolic	**PIR**	
MCC Method A	145.23	234.83	85.12
MCC Method B	446.04	405.42	117.89
Bomb Calorimeter	436.76	416.46	113.69
Cone Calorimeter	339.10	315.00	80.72
1/3-Scaled Room Corner Test	52.37	0	47.25

5. Discussion

This Chapter presents further insights into the results of the experiments and aims to address the stated objectives of this research project using the theoretical review of the guidelines and experimental results.

The objectives are reiterated as follows:

- **Objective 1:** Establish how permanent fire loads are determined in Sweden, Belgium, Netherlands, and the UK through the gathering of design guidelines and presenting a summary of how different countries motivate and calculate permanent fire loads.
- **Objective 2:** Conduct tests on a Microscale Combustion Calorimeter (MCC) and Bomb Calorimeter to obtain theoretical heat of combustion values; Conduct Cone Calorimeter and 1/3-scaled room tests to replicate more realistic fire scenarios and obtain values of the effective heat of combustion in small and medium scale level. From the results of the experiments, a comprehensive analysis shall be carried out.
- **Objective 3:** Calculate and analyze a worked example of the total permanent fire loads based on the heat of combustion values obtained from the MCC, Bomb Calorimeter, Cone Calorimeter, and the 1/3-scaled room corner test.

5.1 Objective #1

To address the Objective 1, a theoretical review was carried out for four countries, Belgium, The Netherlands, Sweden, and the UK, and their respective national guidelines. Although most of the guidelines reference EN 1991-1-2, each country implements its own directives that are applicable to local use. This was also seen in the non-uniformity of how the countries define 'fire load'. In some guidelines, the term 'fire load' was used to describe the fire load density and 'energy' to indicate the fire load.

In most guidelines, table values are readily available for the building content and other occupancy types, except industrial buildings. Furthermore, the guidelines state that when using an occupancy-based approach, permanent fire loads shall be calculated separately and then added to the prescribed fire load densities. Updated and accurate methods to obtain permanent fire loads are needed since there are insufficient prescriptive values for these. In addition, these documents suggest that permanent fire load values are more reliable when derived via in-situ survey, coupled with weighing methods.

An observed similarity in all the guidelines is the recommendation for the use of the net heat of combustion derived from the Bomb Calorimeter. Referencing the Bomb Calorimeter experiments in this project, obtaining the net heat of combustion is not straightforward as it requires a separate hydrogen content analysis of the tested specimen. To quote an apparatus manual: *Because of the difficulty in*

accurately determining the hydrogen content of the sample, and the fact that the hydrogen content of most fuels is fairly low, the gross heat of combustion is usually reported in preference to the net value in most applications [73]. It is seen that further research is needed to unify national guidelines and the limitations of Bomb Calorimeter instrumentation. Marlair et al. [74] investigated predictive models, i.e., Boie, Dulong, and Vonracek, to obtain as accurate net HoC values from gross HoC as precisely as possible. The study concludes that materials with known chemical formulas can be predicted but still show scatter in the data. More experimental measures are needed to close the gap for non-homogenous materials. In this project, this challenge is highlighted since insulation foams and novel wood product compositions are lesser known and remain trade secrets. An argument could be made that the heat of combustion for these materials must either be derived from direct testing or from manufacturer technical sheets. In reference to the experimental results in the Bomb Calorimeter for a single material, i.e., Fabric 1, standard deviations are still expected even with three replicates for a relatively known material (Fabric 1 was seen to be Polyester). We can only assume the potential uncertainties for HoC values to magnify in complex materials.

In the theoretical review carried out in Section 2.4, guidelines for Belgium and Netherlands report a dependency of the fire protection strategies and usable areas on the calculated [total] fire load. This presents a compelling case for obtaining accurate values for the permanent fire loads since a higher obtained fire load results in a higher classification of the building. In some cases, an overdesign may ensue once the analysis conducted involves a higher volume of materials and not just the dimensions from the 1/3-scaled room corner test.

5.2 Objective #2

To study the fire behavior of envelope materials with respect to the effect of increasing scale testing and complexity of sample types, a total of 78 tests were conducted and broken down as follows: MCC (32 tests), Bomb Calorimeter (27 tests), Cone Calorimeter (15 tests), and 1/3-scaled room corner (4 tests). The primary focus of this objective is to investigate the fire behavior of building envelope materials, mainly insulation foams, in the context of the Heat of Combustion. Objective #2 then prompted an examination of the viability of using micro samples to quantify the energy released in materials and predict accurate potential severities of fire in a compartment. In performance-based design, often the concept of the “worst-case” scenario is predicated on past fires, which may or may not be similar to an examined compartment. While utilizing micro samples is seen to yield conservative HoC values, it drives the question: does it correctly represent the worst-case fire scenario or system performances on larger

scales? Realistically, materials in compartments, whether in the building envelope or building content, cannot be treated as isolated systems but rather synergistic performances must be taken into account. Thus, the need to perform increasing scale testing was established in this thesis project. In the micro-scale tests, nearly complete combustion in the perfect testing conditions of Method B MCC and the Bomb Calorimeter was observed for all materials. The next level of testing in Method A MCC examined the effect of changing the pyrolyzing conditions through inert N_2. Similarly, the effect of increasing the sample size from milligrams of powder to 10x10cm 3D samples and composite construction was investigated in the Cone Calorimeter. The results showed significant variances from the ideal testing conditions when testing in Method A MCC and the Cone Calorimeter. With the lower recorded values of the heat of combustions in Method A MCC and Cone Calorimeter, one can readily conclude that material interactions and sample sizes impact the burning behavior of materials. The final stage of testing looked into utilizing the end form of the materials in a 1/3-scaled room corner test. In the room corner configurations, the insulation foams were treated as a portion of a sandwich panel system and the foot bench as the identified first-burning furniture in compartment fires. Although heat transfer effects were not accounted for, the results show that numerous factors are important to impact the Heat of Combustion and permanent fire load calculations in large-scale experimentation.

First is material-to-material interaction. In comparison to testing of the materials in purely ideal conditions and as individual materials in the MCC and Bomb Calorimeter, testing in the Cone Calorimeter and full-scale tests show behavior such as melting, charring, and delamination as expressed in the previous sections. This was seen in the HRR vs. Time curves of the Cone Calorimeter and full-scale tests that despite extending the tests to as long as 25 minutes, the materials did not completely ignite.

The second factor to impact HoC is the importance of well-constructed compartments. The negligible calorific values from the gypsum and calcium silicate boards are to be expected since non-combustible materials like gypsum and calcium silicate boards are supported by national guidelines and the experimental results of this project to have no significant contribution. However, it was seen in the full-scale tests that the long-term performance of these materials has a significant effect on the propagation of the fire to the insulation materials, which were housed between the gypsum and calcium silicate boards. In Cases 2 and 3 of the 1/3-scaled room corner tests, the subsequent collapse of the boards led to the exposure of the insulation and eventual pyrolysis and ignition of the insulation. This prompts the reinvestigation of national guidelines such as that of The Netherlands which claim that fire loads of combustible materials can be neglected once the outer casing, e.g., the roofing, or wall envelopes, are

proven to protect inner combustible materials during the required fire resistance. Since the national guidelines do not specify a specific period in which the outer casing should remain intact, long-duration burning could significantly lead to collapse and expose the combustible materials.

Third, ventilation conditions and burning duration. As mentioned in the *Results and Analysis* section, the low values for the heat of combustion from the scaled room corner tests may be attributed to underventilation and early extinction of the flame. A case then could be argued that similar high heats of combustion may be expected if the testing duration was allowed to extend for the materials to completely ignite.

5.3 Objective #3

Table 12 reports the summary of the permanent and temporary fire loads resulting from the HoC values obtained through Methods A and B in the MCC, Bomb Calorimeter, Cone Calorimeter, and Full-scale tests.

To determine the overall fire loads, Equation 5 expressed as $Q = \Sigma M_i \, x \, H_{ui}$ was utilized, which makes it straightforward to determine fire loads because of the additive nature of the equation. The method entails obtaining the individual materials' Heat of Combustion from the various tests and multiplying it with the mass of the material. In the case of the micro- and bench-scale tests, the HoC is multiplied by the entire mass of the foot bench and envelope materials in the worked example. While for the full-scale tests, the fire load is obtained directly from the experiments.

Further analysis of the calculated fire loads shows that the full-scale tests exhibit the lowest value. This is supported by the experimental results in Table 9 which show that the underventilated conditions in the scaled room corner test did not allow for full thermal degradation of the materials. The fire loads obtained from Method A of the MCC show also low total heat release values for both permanent and temporary since only the energy released from the pyrolyzed gases is recorded but not from the solid residue. Additionally, the next reported fire loads are the ones from the Cone Calorimeter testing. The Cone Calorimeter exhibited charring in the materials because of the additional material thickness and material-to-material interaction in the composites.

An interesting result from the experimental programs is the obtained permanent fire loads for the building envelope. The permanent fire loads of the Phenolic and PIR in the 1/3-scaled rooms were derived by subtracting Case 1 temporary fire load value from the experimental results of Cases 2 and 3. For the ideal testing conditions in Bomb Calorimeter and Method B MCC, the permanent fire load values would be the maximum with complete combustion. Comparing this to the values obtained in realistic

combustion tests, Bomb and Method B MCC results show values of more than 8x than the room corner and Method A MCC. These are distinct for the insulation materials, but the conclusion is not similar for the foot bench or the building content. In the room corner tests, the foot bench was directly exposed to the fire and thus was consumed first and was the major source of the energy released versus the insulation materials which were housed behind the gypsum boards. It was seen that the presence of the other envelope materials, gypsum and calcium silicate boards, provided means to shield the insulation. As such, the resulting fire loads in Cases 2 and 3 could indicate that the resulting fire load is mainly from the foot bench with the higher value in the Phenolic case due to the subsequent burning of the insulation. The rooms were dismantled after the tests, and it was seen in Case 3 (PIR) that the insulation showed minimal charring as seen in Figure 26. The resulting permanent fire load for PIR is almost the same in value when compared to the base cases (Cases 1 and 4) and indicates that in Case 3, only the furniture contributed to the energy released. However, the discussion remains in the context of the experimental set-up and extrapolation to other applications should be done with caution. It is still important to repeat the test set-up since PIR has the potential to release significant energy.

It could be seen that the effect of the building content was negligible to the ignition of the building envelope to a certain extent. As the insulation was not directly exposed to the fire, non-combustible materials provided means to delay insulation ignition.

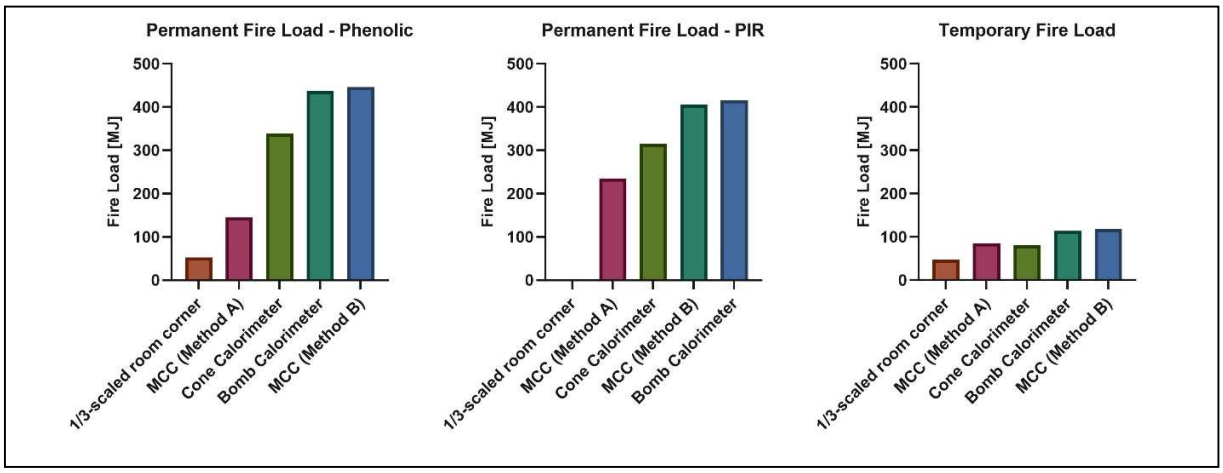

Figure 27. Summary of the fire loads derived from the experiments.

6. Conclusions

The overarching goal of the project is to understand the performance and fire behavior of building envelope materials which was successfully done through an increasing-scale experimental program. To arrive at the fire load calculations, the Heat of Combustion values of reference materials were first derived from the Microscale Combustion Calorimeter, Bomb Calorimeter, Cone Calorimeter, and Room Corner tests.

From the Results and Analysis and Discussion Chapters, the following conclusions are reached:

- Due to the experimental set-up and test conditions, it was concluded that to obtain a gross HoC, the Bomb Calorimeter and Method B of the MCC are optimal methods to characterize the maximum released energy. The net heat of combustion is best characterized by Method A of the MCC. Lastly, the Cone Calorimeter and scaled room corner tests were deemed appropriate to obtain the effective heat of combustion. It was seen from the Bomb Calorimeter and MCC Method B that the values of the HoC are highest because of the ideal burning conditions of the apparatus. The net HoC is ideal to be derived from MCC Method A since it closely relates to the pyrolyzing phenomena on the surface of the burning item. Lastly, the Cone Calorimeter and room corner tests resembles more realistic burning conditions and thus generates the effective heat of combustion.
- Testing the materials in their end-form, as composites, or in thicker samples results in lower Heat of Combustions, which supports the case that materials perform differently under influencing factors.
- Material behavior is not a linear concept. From the experimental results, no two replicates yield the same result. As such, materials with relatively unknown compositions are best quantified through experimentation rather than using literature values.
- The experimental results of the thesis project support the case for obtaining fire load calculations, even quantifying other fire properties, as a systemic performance rather than treating materials in isolation.
- The experimental results in the scaled tests show the benefits of understanding material layering and the positives of good construction to minimize energy released from combustible materials.

The Heat of Combustion is fundamental in defining the total fire load or energy within a compartment. In a design fire, the fire load is the anticipated energy released in fire incidents and is often linked to the temperature growth in the room. Defining fire loads is a strong starting point to quantify fire severity and can even give insights to relevant fire design information such as burning duration. However, its application is better coupled with understanding other factors such as the rate at which the energy is released and ventilation factors. This thesis project concludes that in understanding the fire behavior of building envelope materials in Performance-based design, bench-scale tests serve as an attractive starting point to better quantify fire loads since from this method, composite testing and larger samples can be examined vs. testing in micro-scale. Compared to larger-scale testing, bench-scale tests are less costly and time-consuming to execute.

The research opens the possibilities of additional studies like the consideration of ventilation conditions to fire development and material ignition. A potential future study is to vary the ventilation openings and examine the effect of such to the final permanent fire load values of the scaled room corner tests. Although the results of the project offer additional insights into the burning behavior of varied materials in scaling effects, the conclusions are not to be taken at face value. Some techniques would result in overestimation of the fire load and some in underestimation and as such, would impact fire protection strategies. It is at the discretion of the fire engineer to assess the applicability of the experimental results and understand the context of the experimental design that was used in this thesis project.

It has been seen in the experiments that additional replicates for the room corner tests are needed to further strengthen the experimental results. Additionally, the potential uncertainties, which are encompassed in the limitations and delimitations of the project, must be addressed through a sensitivity analysis. It was also seen that certain uncertainties and biases rose from the Composite sample preparation in the Cone Calorimeter, and the load cell used to measure the mass in the room corner tests.

In closing, the thesis project demonstrated successfully that several techniques can be used to quantify fire loads. It is not the intention of the project to give a prescriptive option and argue that one technique is better than the other. Rather, it intends to provide a valuable perspective on material behavior in different experimental programs in increasing-scale testing.

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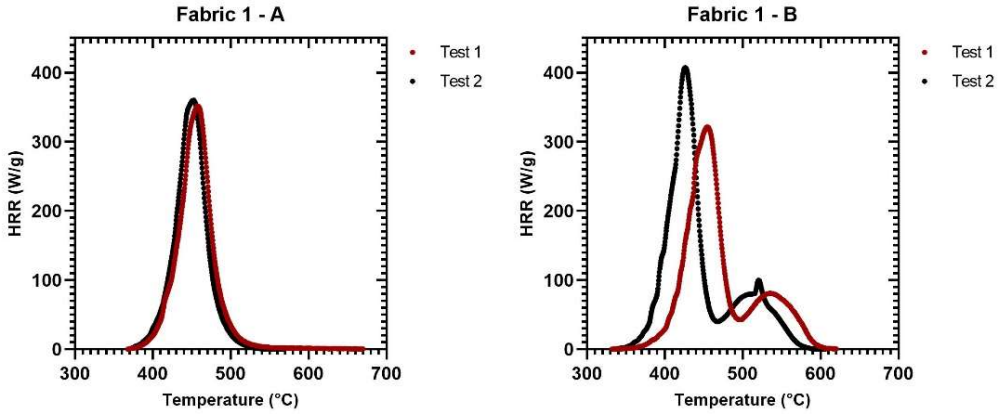
Annex

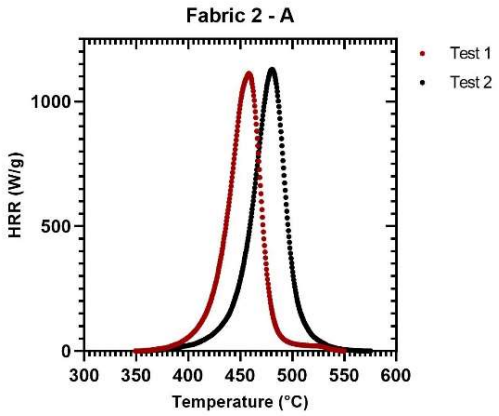
This section contains the raw data from the experiments and additional graphs not included in the main body of the manuscript.

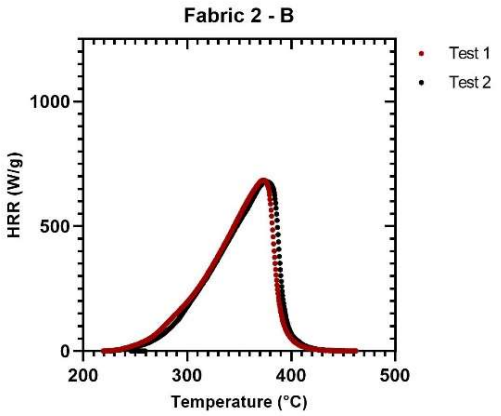
A.1 Microscale Combustion Calorimeter

Fabric 1						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1657	0.1705	0.0048	0.1665	16.67	17.44
Test 2	0.1651	0.1701	0.0050	0.1659	16.00	17.05
Method B						
Test 1	0.1670	0.1700	0.0030	0.1670	0.00	21.77
Test 2	0.1665	0.1718	0.0053	0.1665	0.00	22.82

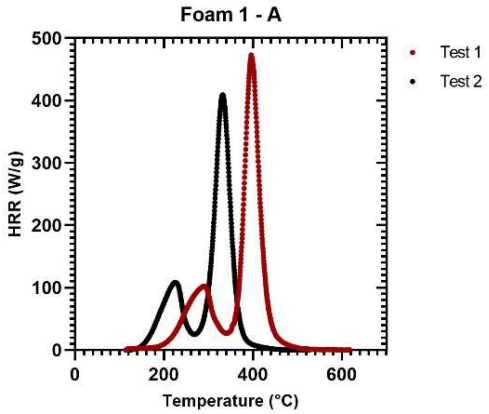


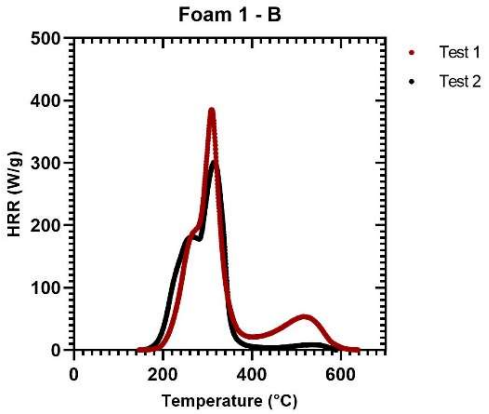
Fabric 2						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1665	0.1717	0.0052	0.1665	0.00	44.93
Test 2	0.1657	0.1689	0.0032	0.1657	0.00	46.52
Method B						
Test 1	0.1651	0.16778	0.0027	0.1651	0.00	46.98
Test 2	0.1669	0.1702	0.0033	0.1669	0.00	47.81



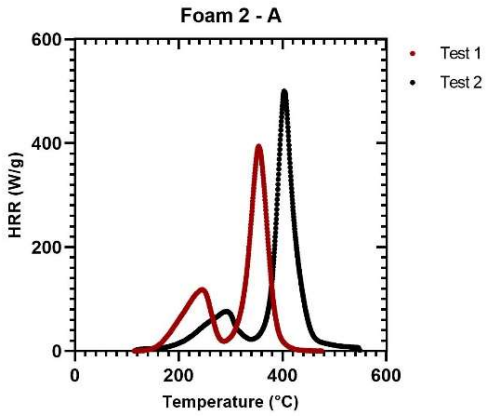


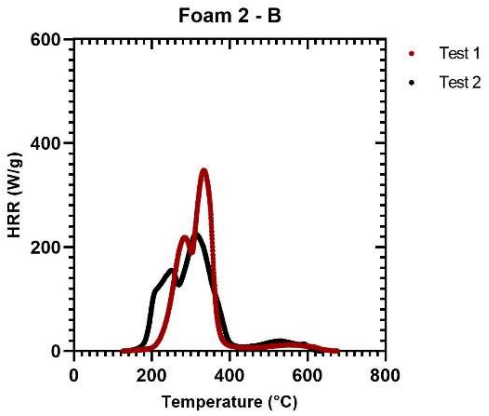
Foam 1						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1664	0.1716	0.0052	0.1664	0.00	29.34
Test 2	0.1662	0.1716	0.0054	0.1664	2.79	25.77
Method B						
Test 1	0.1657	0.1710	0.0053	0.1657	0.00	32.98
Test 2	0.1669	0.1716	0.0048	0.1669	0.00	27.83



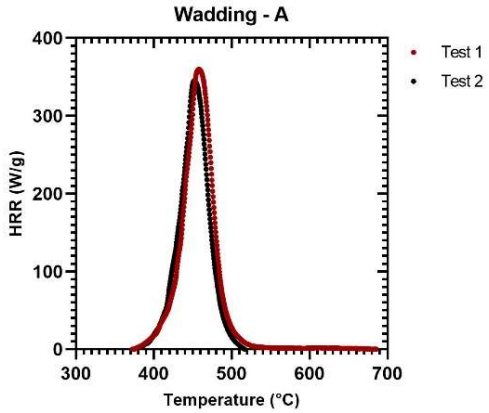


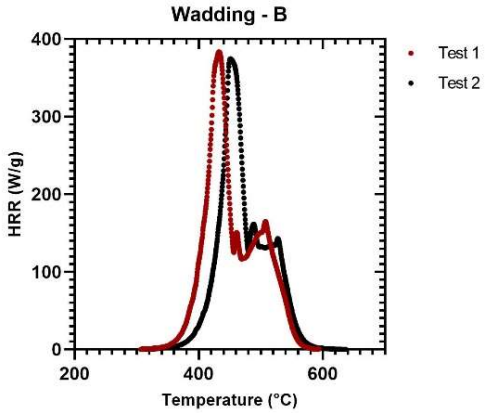
Foam 2						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1651	0.1701	0.005	0.1651	0.00	26.00
Test 2	0.1657	0.1709	0.0052	0.1657	0.00	29.32
Method B						
Test 1	0.1670	0.1722	0.0052	0.1670	0.00	30.57
Test 2	0.1666	0.1718	0.0052	0.1666	0.00	31.33



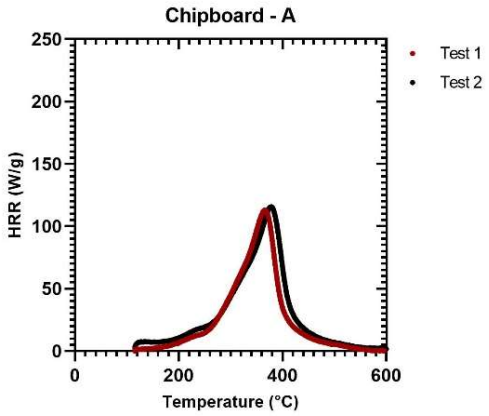


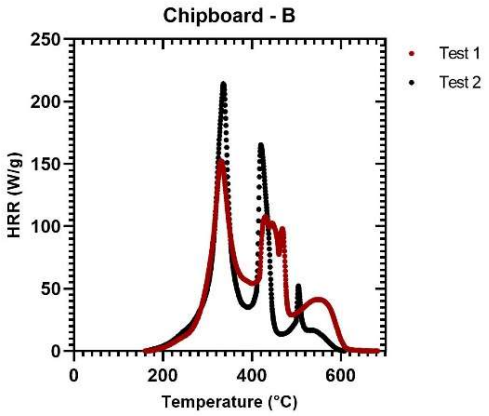
Wadding						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1671	0.1716	0.0045	0.1678	15.56	16.76
Test 2	0.1679	0.1727	0.0048	0.1686	15.18	15.31
Method B						
Test 1	0.1659	0.1710	0.0051	0.1659	0.00	26.32
Test 2	0.1656	0.1701	0.0045	0.1657	1.12	24.50



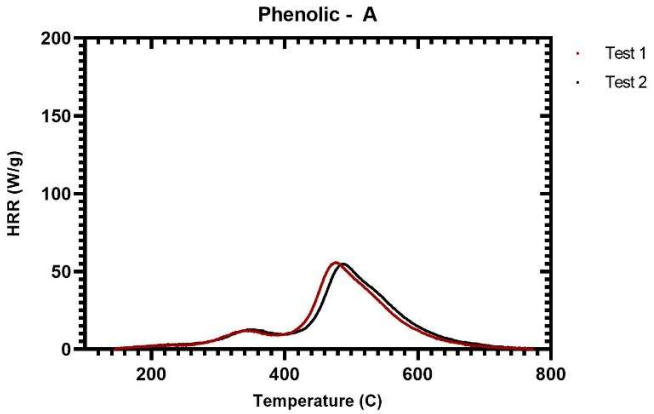


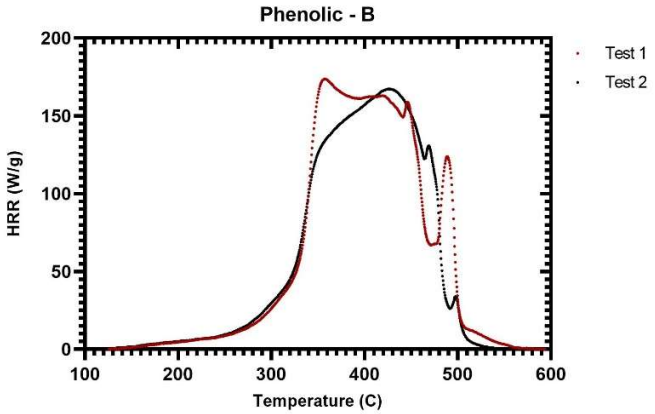
Chipboard						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	0.1662	0.1717	0.0054	0.1674	20.44	11.56
Test 2	0.1656	0.1703	0.0047	0.1667	23.78	13.69
Method B						
Test 1	0.1681	0.1736	0.0056	0.1681	0.00	21.02
Test 2	0.1675	0.1724	0.0050	0.1675	0.80	17.23



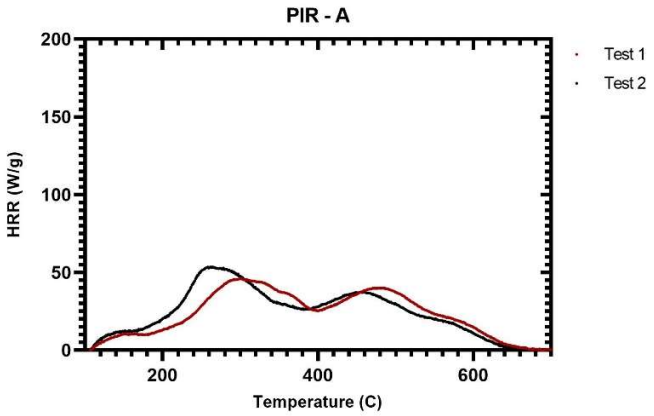


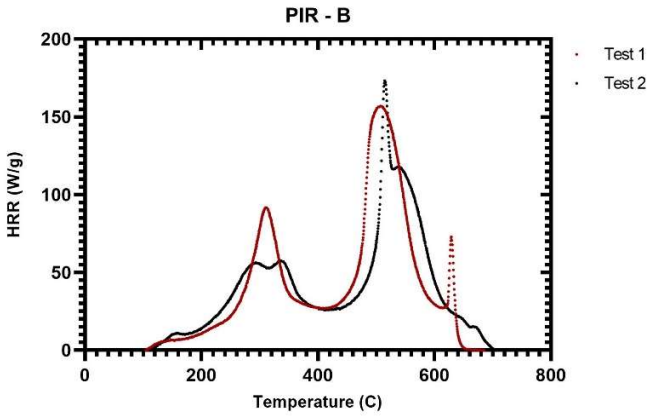
Phenolic Insulation						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	-	-	0.0049	-	42.86	8.32
Test 2	-	-	0.0065	-	43.07	8.51
Method B						
Test 1	-	-	0.0056	-	1.79	26.19
Test 2	-	-	0.0061	-	3.28	25.53





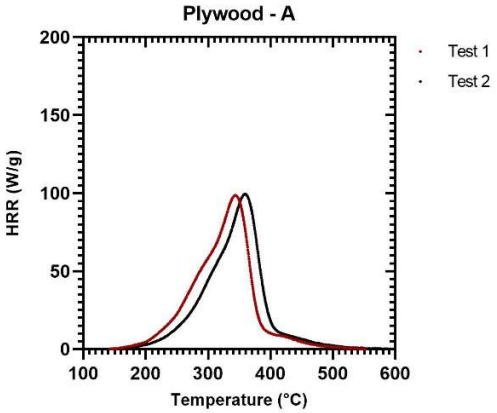
PIR Insulation						
	Total mass (g)				*% Char yield*	*Net H_{ui} (MJ/kg)*
	Cup	*Sample + Cup*	*Sample*	*Cup (after test)*		
Method A						
Test 1	-	-	0.0041	-	26.83	14.21
Test 2	-	-	0.0036	-	25.00	14.66
Method B						
Test 1	-	-	0.0052	-	1.92	25.21
Test 2	-	-	0.0050	-	2.00	24.65

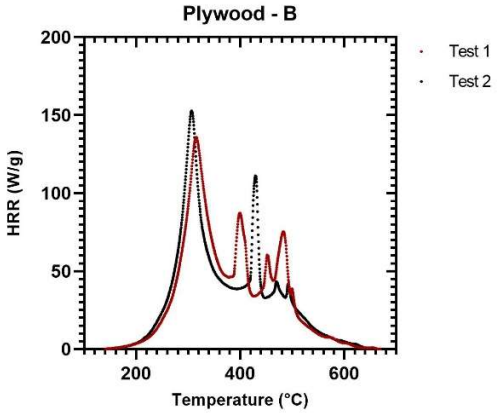




Additional tested materials

Plywood						
	Total mass (g)				% Char yield	Net H_{ui} (MJ/kg)
	Cup	Sample + Cup	Sample	Cup (after test)		
Method A						
Test 1	-	-	0.0069	-	18.84	9.45
Test 2	-	-	0.0074	-	20.27	9.33
Method B						
Test 1	-	-	0.0079	-	2.53	16.96
Test 2	-	-	0.0075	-	2.67	16.67





A.2 Bomb Calorimeter

Fabric 1			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	22.558	22.511	22.397
Specimen mass (g)	0.2051	0.2022	0.2036
Combustion Aid	Benzoic acid tablets (2 pieces)		
Aid mass (g)	0.9948	0.9943	1.0081

Fabric 2			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	45.513	45.877	45.754
Specimen mass (g)	0.1076	0.1066	0.2035
Combustion Aid	Benzoic acid tablets (1.5 pieces)		
Aid mass (g)	0.8114	0.6725	0.7860

Foam 1			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	29.106	29.299	28.421
Specimen mass (g)	0.1073	0.1046	0.1022
Combustion Aid	Paraffin oil		
Aid mass (g)	0.5613	0.5484	0.5149

Foam 2			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	28.724	28.069	28.865
Specimen mass (g)	0.1015	0.1023	0.1050
Combustion Aid	Paraffin oil		
Aid mass (g)	0.5312	0.5487	0.5082

Wadding			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	22.218	21.158	21.085
Specimen mass (g)	0.1076	0.1226	0.1092
Combustion Aid	Benzoic acid tablet (1 piece)		
Aid mass (g)	0.5427	0.5685	0.5055

Chipboard			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	18.565	18.565	18.415
Specimen mass (g)	0.5097	0.5153	0.5064
Combustion Aid	Benzoic acid tablet (1 piece)		
Aid mass (g)	0.4855	0.5030	0.4865

Phenolic Insulation			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	25.366	25.720	24.880
Specimen mass (g)	0.1005	0.1009	0.1079
Combustion Aid	Paraffin oil		
Aid mass (g)	0.5307	0.5384	0.5420

PIR Insulation			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	26.170	25.150	25.505
Specimen mass (g)	0.1000	0.0992	0.1052

Combustion Aid	Paraffin oil		
Aid mass (g)	0.5304	0.5415	0.5287

Additional tested materials

Gypsum Board			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	-1.280	-1.037	-1.512
Specimen mass (g)	0.2012	0.2034	0.2202
Combustion Aid	Paraffin oil		
Aid mass (g)	0.6002	0.6176	0.6095

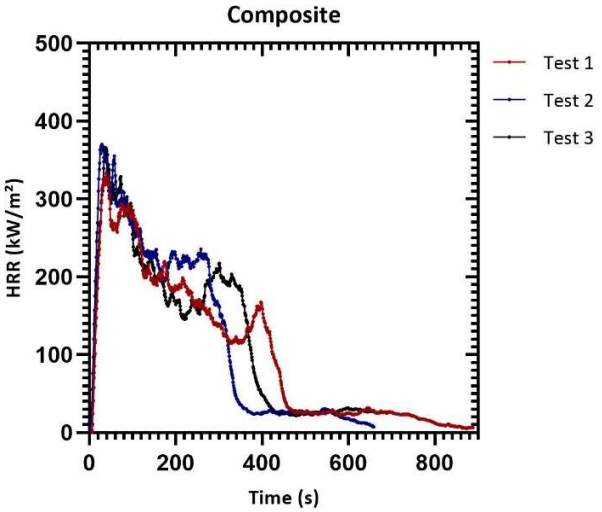
Plywood			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	18.613	18.603	18.643
Specimen mass (g)	0.5034	0.5007	0.5041
Combustion Aid	Benzoic acid tablet		
Aid mass (g)	0.5045	0.5029	0.4963

Solid Wood			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	18.641	18.594	18.456
Specimen mass (g)	0.5091	0.5025	0.5009
Combustion Aid	Benzoic acid tablet		
Aid mass (g)	0.5001	0.5083	0.4800

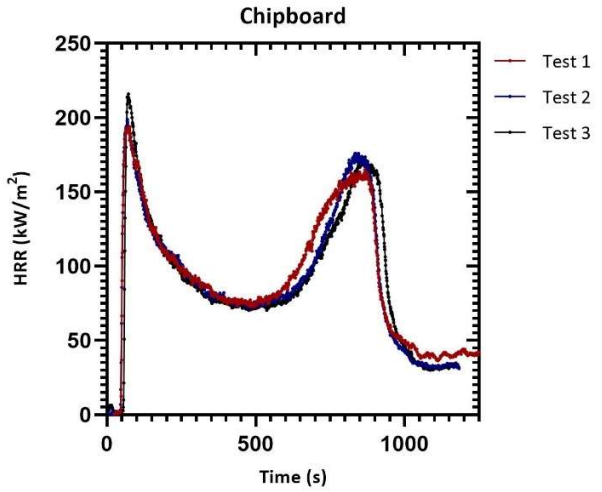
Calcium Silicate Board			
	Test 1	***Test 2***	***Test 3***
Gross H_{ui} (MJ/kg)	0.312	0.560	0.548
Specimen mass (g)	0.2029	0.2011	0.2082
Combustion Aid	Paraffin oil (Test 1 and 2), Benzoic acid tablet (Test 3)		
Aid mass (g)	0.6148	0.4733	1.0817

A.3 Cone Calorimeter

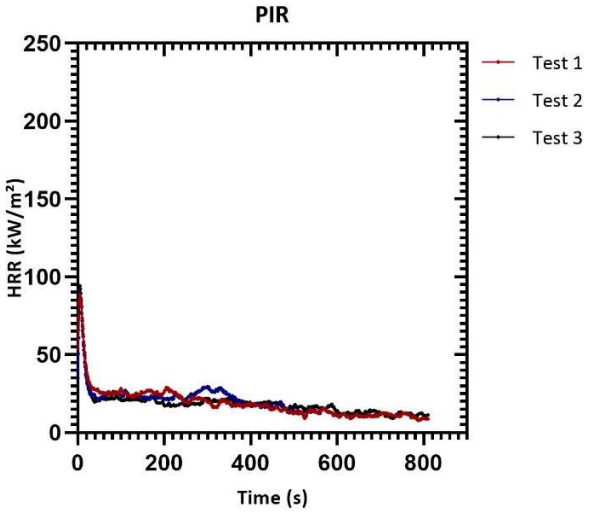
Composite					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m^2)***	***Time to Peak HRR (s)***
Test 1	34.5	57	16.54	332.76	39
Test 2	33.3	53	22.52	370.10	29
Test 3	34.2	54	21.56	366.07	37



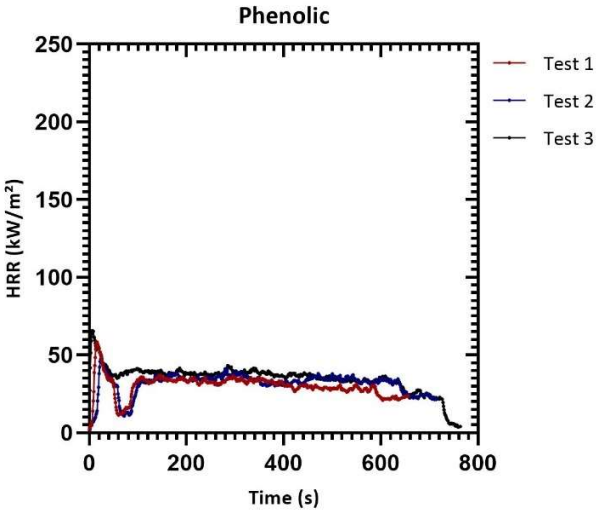
Chipboard							
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***1st Peak HRR (kW/m²)***	***Time to Peak HRR (s)***	***2nd Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	98.4	15	13.56	193.83	77	164.94	867
Test 2	99.5	15	12.30	198.74	69	176.02	839
Test 3	100.6	15	12.32	215.91	72	173.87	856



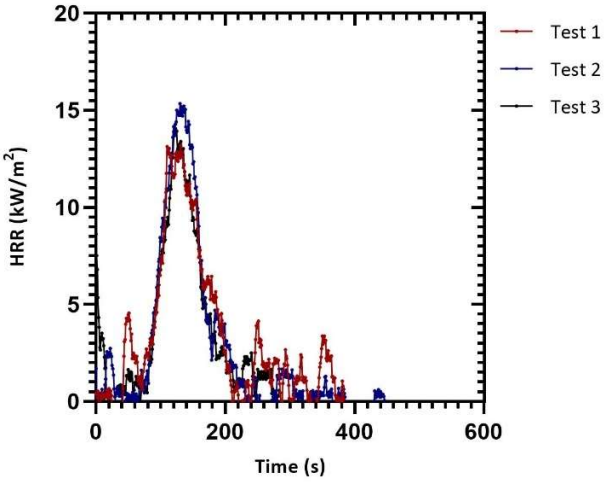
PIR					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	13.9	51	19.88	88.45	5
Test 2	12.9	50	20.29	89.47	7
Test 3	14.2	51	17.95	94.18	5



Phenolic					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	17.3	50.5	19.03	58.34	16
Test 2	16.6	50	19.02	49.09	25
Test 3	17.4	51	20.93	65.74	6

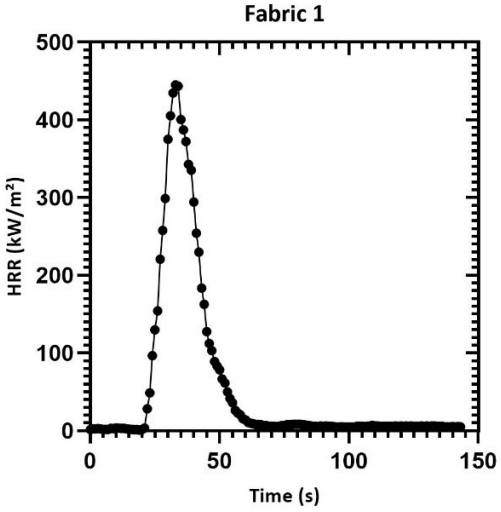


Gypsum					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	91.9	12	1.00	13.18	131
Test 2	92.0	12	0.70	15.35	130
Test 3	91.5	12	1.15	14.06	124

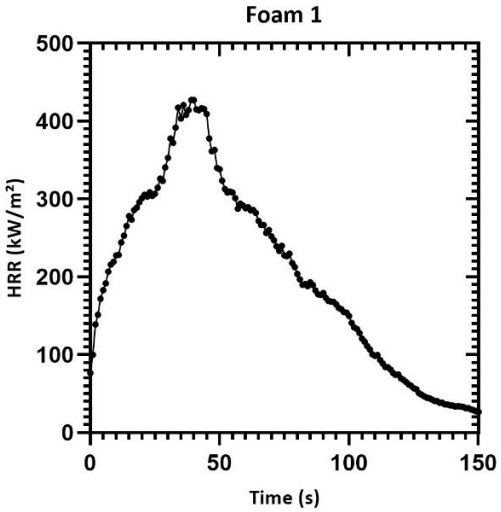


Additional tested materials

Fabric 1					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	4.2	1	16.70	445.23	33

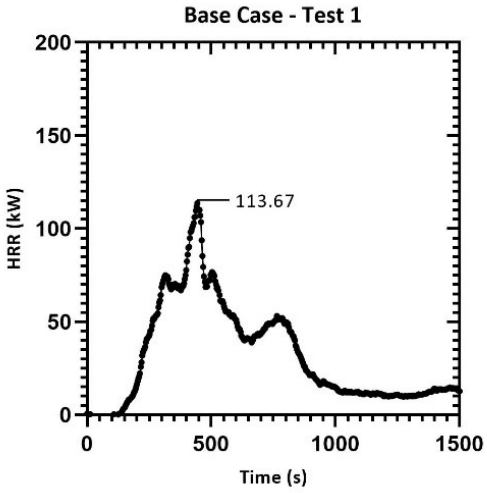


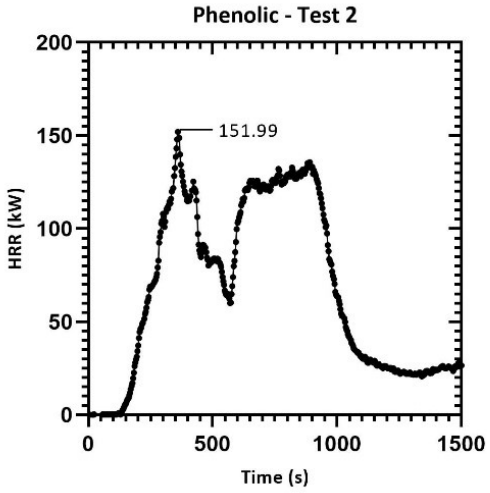
Foam 1					
	Total mass (g)	***Total Thickness (mm)***	***Effective H_{ui} (MJ/kg)***	***Peak HRR (kW/m²)***	***Time to Peak HRR (s)***
Test 1	10.9	38	24.60	427.34	39

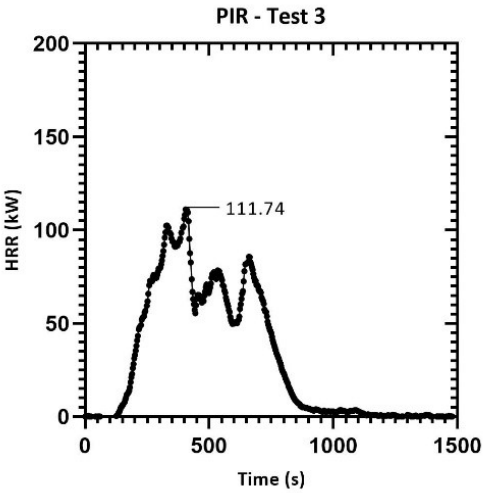


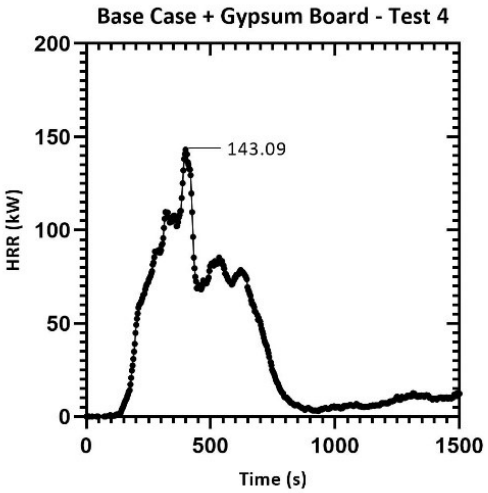
A.4 Full-scale tests

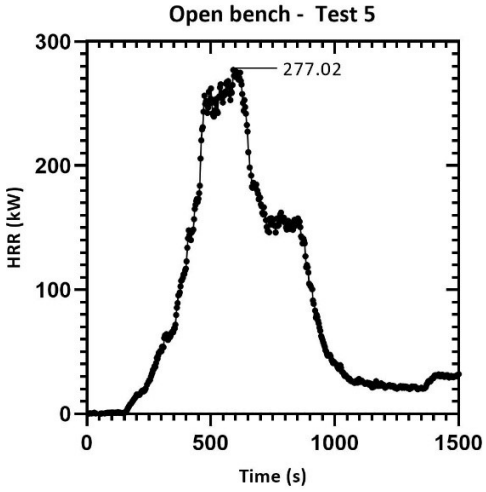
Test Number	*ΔMass Loss (kg)*	*Peak HRR (kW)*	*Time to Peak HRR (mins)*	*Q_{total} at 15mins (MJ)*	*Q_{total} at 25mins (MJ)*
1	6.00	113.67	7.50	39.63	47.25
2	14.50	151.99	6.05	75.29	99.62
3	7.50	111.71	6.80	43.10	43.88
4	6.50	143.09	6.65	46.25	50.88
5	6.33	277.02	9.85	108.38	127.86



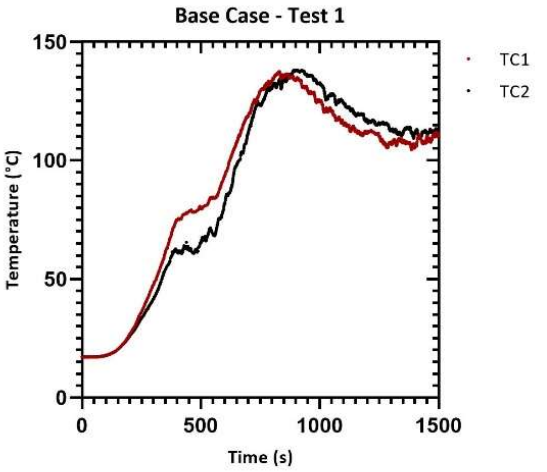


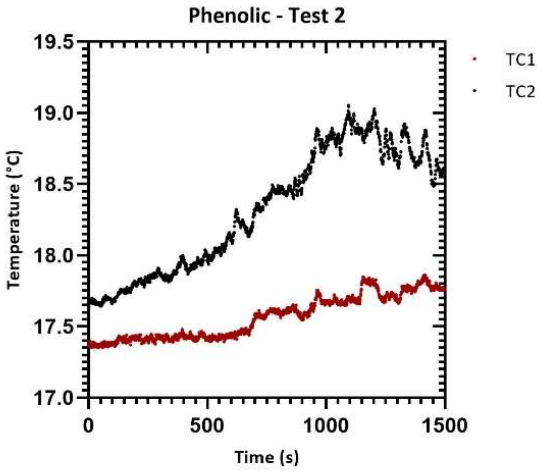


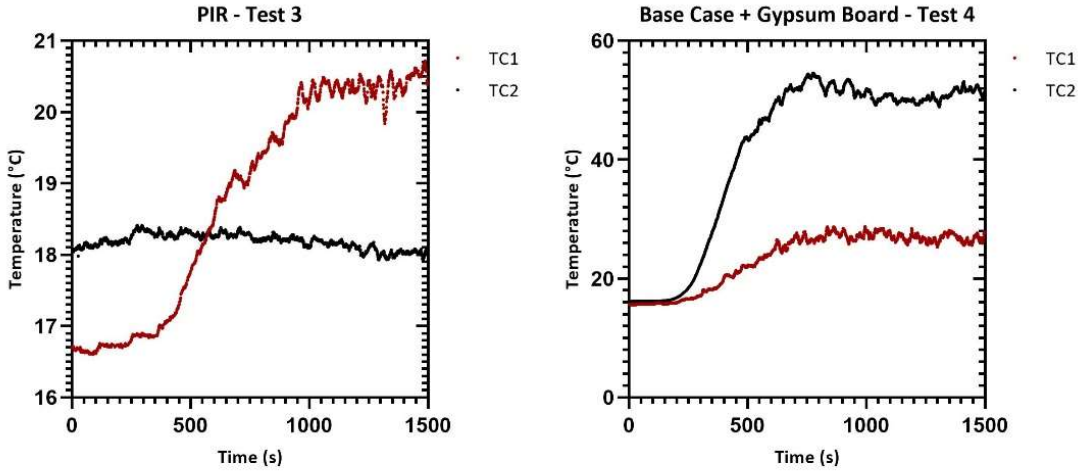




A.5 Thermocouple graphs from Tests 1-4







A.6 Calculation for Flashover

$\dot{Q}_{FO} = 7.8 * A_T + 378 * A * \sqrt{H}$

Inner dimensions: 1.2 long x 0.8 wide x 0.8 height m

Opening dimensions: 0.67 height x 0.27 wide m = 0.1809 m^2

$A * \sqrt{H} = 0.67\ x\ 0.27\ x\ \sqrt{0.67} = 0.1481$

$A_T = \big((2 * 1.2 * 0.8) + (2 * 0.8 * 0.8) + (2 * 1.2 * 0.8)\big) - 0.1809 = 4.9391\ m^2$

$\dot{Q}_{FO} = 7.8 * 4.9391 + 378 * 0.1481 = 94.5\ kW$

A.7 Calculation for Mass and Volume of material from 1/3-scaled room corner test

Inner dimensions: 1.2 long x 0.8 wide x 0.8 height m

Opening dimensions: 0.67 height x 0.27 wide m

	Mass from Cone Calorimeter (kg)	***Volume from Cone Calorimeter (m^3)***	***Density (kg/m^3)***
Gypsum	0.0918	0.00012	765
Phenolic Insulation	-	-	35
PIR Insulation	-	-	33

Gypsum mass

	length	*height*	*thickness*	*volume*	*qty*	*total volume*	
wall	1.20	0.80	0.01	0.01	2.00	0.02	
back	0.82	0.80	0.01	0.01	1.00	0.01	
front	0.82	0.80	0.01	0.01	1.00	0.01	
ceiling	0.82	1.22	0.01	0.01	1.00	0.01	
					total	0.05	
					mass	37.33	kg

PIR Insulation mass

	length	*height*	*thickness*	*volume*	*qty*	*total volume*	
wall	1.22	0.91	0.10	0.11	2.00	0.22	
back	1.02	0.91	0.10	0.09	1.00	0.09	
front	1.02	0.91	0.10	0.08	1.00	0.08	
ceiling	1.22	0.82	0.10	0.10	1.00	0.10	
					total	0.49	
					mass	16.26	kg

Phenolic Insulation mass

	length	*height*	*thickness*	*volume*	*qty*	*total volume*	
wall	1.22	0.91	0.10	0.11	2.00	0.22	
back	1.02	0.91	0.10	0.09	1.00	0.09	
front	1.02	0.91	0.10	0.08	1.00	0.08	
ceiling	1.22	0.82	0.10	0.10	1.00	0.10	
					total	0.49	
					mass	17.25	kg