

# Does timber burn?

A field study of naturally weathered  
fire-retardant-impregnated timber façade

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**Thesis**  
**Division of Fire Safety Engineering**

**Does timber burn?**  
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**Lund 2025**

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**Abstract:**

This study investigates how natural weathering affects the fire performance of fire-retardant-impregnated timber façade. Results from a Cone Calorimeter testing showed significant differences in fire properties between different parts of the façade slats, with more weather-exposed surfaces exhibiting slower ignition but higher peak heat release rate per unit areas. Timber color was found to correlate with fire performance, suggesting that color could serve as a visual indicator of the façade's condition. The research highlights challenges in fire-retardant documentation, maintenance guidelines and long-term performance assessment. It also raises concerns about the potential uneven distribution of fire retardants within the timber, where the middle section of the slats performed similarly to untreated pine. Key findings underscore the need for greater transparency from manufacturers, clearer maintenance protocols, a better understanding of how fire retardants adhere to and distribute within wood, and more accurate methods for assessing the long-term durability of fire-retardant-treated timber under real-world conditions. Collaborative research between the construction industry, fire-retardant manufacturers and research institutions is encouraged/essential to develop sustainable and fire-safe timber façade solutions.

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## Förord

Texten är ett examensarbete om 22,5 högskolepoäng vid Lunds Tekniska Högskola, LTH, och kan betraktas som grundforskning av hållbarheten hos brandimpregnering av naturligt åldrade träfasad. I dagens samhälle är trä ett eftertraktat material till allt ifrån smörknivar som till fasadbeklädnader. Men hur fungerar det egentligen med trä som fasadmaterial på byggnader med stora skyddsbehov? Kunskap om brandimpregnerad träfasads beständighet efter naturlig åldring efterfrågas av såväl fastighetsförvaltare, försäkringsbolag, byggprojektörer, brandkonsulter med flera, och är anledningen till att examensarbetet skulle kunna betraktas som behovsmotiverad grundforskning.

Arbetet begränsas till fallstudien av en byggnad i södra Skåne. På grund av tidsramen på 22 veckor ges det ej förslag på praktiska lösningar utöver att belysa fördelen med behovsmotiverad samverkansforskning. Till exempel mellan byggbranschen, brandimpregneringsföretagen och forskningsinstitut för att på ett målinriktat sätt komma fram till brandsäkra och hållbara lösningar av hur trä ska kunna användas som beklädnader i vårt samhälle.

Tack vare kloka handledare har det funnits möjlighet att bolla tankar fram och tillbaka för att till slut landa i detta examensarbete. Därför vill jag tacka Konrad Wilkens på avdelningen för brandteknik LTH för hans expertis och australienska sätt som alltid har fått mig att fördjupa min förståelse av brand och trä i denna snåriga bransch. Dessutom vill jag tacka min externa handledare Carl Pettersson hos RED Fire Engineers, som har granskat examensarbetet och hjälpt till att ge perspektiv utifrån på vad som bör förtydligas och förbättra förståelsen av arbetet för er läsare.

Utan tillgång till den naturligt åldrade fasaden hade examensarbetet inte gått att genomföra. Därför vill jag tacka Region Skåne, dess brandingenjör i skrivande stund och byggnadens fastighetsförvaltare som var till stor hjälp i att tillhandahålla delar av deras fasad till studien. Utöver det praktiska bidraget är det imponerande att se en ansvarstagande fastighetsägare och involverade samhällsaktörer hjälpa till med det de kan.

Min engelsktalande själsvän Maya Levine som varit en guldklimp för granskning av språket och inte minst programmeringshjälten Kaspian Jakobsson, min klippa för alla ettor och nollor: tack så mycket för all er hjälp!

Till sist en stor eloge till mina nära och kära som är en fantastisk källa av avkoppling i form av middagar, konserter, skidresor och annat skoj 😊

Trevlig läsning!

## Summary

This thesis investigates the impact of natural weathering on the reaction to fire performance of fire-retardant-impregnated timber façades through small-scale fire testing. The study examined samples from different positions (front, mid and back) of façade slats exposed to natural weathering for approximately two years in the south of Sweden (2022 to 2024). Cone Calorimeter testing was used to evaluate various fire performance parameters, including time to ignition, heat release rate and flame spread characteristics.

Results indicate significant differences between more and less-weathered surfaces. More exposed surfaces exhibited delayed ignition times but higher peak heat release rate per unit areas, whereas less exposed surfaces showed the opposite trend. The study also identified a correlation between the color differences of the timber slat surfaces and fire performance, suggesting that color differences could serve as a visual indicator of façade condition. Additionally, the findings revealed potential inconsistencies in fire-retardant distribution within the timber. It also highlights systematic challenges in documentation, maintenance guidelines and long-term performance assessment.

The thesis contributes to the understanding of fire-retardant durability in exterior applications and underscores the need for improved maintenance guidelines and clear regulatory frameworks to ensure long-term fire protection in timber façades. While limited by the amount of sample and the testing scale, this study provides valuable insights for future research on the effects of natural weathering on fire-retardant timber facades.

Moving forward, interdisciplinary collaboration between the construction industry, fire-retardant manufacturers and research institutions is wished for to create fire-safe and sustainable solutions for the use of wood claddings in our society.

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## 1 Introduction

Chapter 1 introduces the common thread of the thesis work, beginning with introducing what a fire-retardant is. The core of the thesis is presented under “issues to be addressed” and can be spontaneously revisited throughout the reading as a reminder of what all the information circles back to. The purpose and aim can likewise be revisited sporadically. An overview of the methodology is also presented and to close the first chapter off, the thesis’ boundaries are outlined.

### 1.1 What a fire-retardant is

Fire-retardants are a type of chemical that can be applied to different materials to alter the materials’ fire properties, see more in Chapter 2.3. Fire retardants for timber are used to maintain the natural aesthetics of wood while adding the necessary fire protection according to the relevant building code [1]. To be noted is that a fire-retardant treatment cannot make timber non-combustible.

### 1.2 Motivation for fire-retardant treatment of timber façades

The main strategy for ensuring fire safety in tall and large buildings typically revolves around preventing fire spread beyond its designated compartment and confining it to the area of origin [3] p.20. However, the building’s façade presents a potential pathway for fire propagation across different compartments. Fire-retardant treatment of timber façades is designed to mitigate this risk by enhancing the material’s resistance to ignition, reducing heat release rates and slowing the spread of flames. Further elaboration on these mechanisms is provided in Chapter 2.3.

The aim of fire-impregnation is to allow timber to be exposed and still meet the required fire classification. Clear coatings are also found on the market for exterior use for which the underlying substrate degradation caused by UV light is its main concern [2]. This thesis only addresses fire-retardant impregnation.

However, exposure to weather and wind, so-called natural weathering, has been shown to significantly reduce the durability of the fire-retardants within as short as a few weeks [4] to a few years [5]. The main research about naturally weathered timber façade was made nine years ago by Birgit Östman and Lazaros Tsantaridis [5] and since then the fire impregnation compounds has developed, but the research of testing naturally weathered samples has barely been conducted. Therefore, this thesis was produced.

### 1.3 Field study in Malmö

A tall building with sections of timber façade provided the material for this thesis. The timber slats had been weather exposed between one to two years, 2022 to 2024 and the closest weather station is “Malmö SMHI:s mätstation”. The slats are taken from façade elements close to the ground where the top of the slats had been undercover from windowsills and the lower parts of the slats had been five to ten centimeters from stone paving. Detailed information about the slats is found in Chapter 1.

## 1.4 Issues to be addressed

This study investigate how fire-retardant-impregnated timber from a 1-2-year-old façade from a building in southern Sweden reacts to fire. The following are issues that will be addressed throughout the thesis.

1. Is there a difference between the reaction to fire properties between different parts of the timber slats? Three main factors that are studied:
  - Least versus most weather-exposed parts of the timber slats.
  - East versus north side of the façade.
  - Fire-retardant timber versus non-treated and non-weathered pine timber.
2. Does the color of the timber slat indicate its reaction to fire properties?
3. What issues can be identified with researching naturally weathered fire-retardant-impregnated timber?

## 1.5 Purpose

The purpose of the thesis is to investigate if there is a difference in expected fire performance between more and less weather-exposed parts of the façade in Malmö.

## 1.6 Aim

The work aims to gain data on fire retardant performance from a naturally weathered façade on a real building. Then based on the data be able to quantify and correlate the performance based on other published data. In addition, the thesis aims to raise awareness and discussion among professionals on how existing timber façades may contribute to a fire spread in the event of a fire.

## 1.7 Overview of Methodology

The research methodology of the thesis involved three main parts, beginning with a literature review, followed by experimental tests in the Cone Calorimeter and finishing with an analysis of the results. The analysis was done with the help of MatLab and Excel to understand the data and create figures and tables to present the results pedagogically. Detailed information about each step is presented later on in the thesis.

## 1.8 Delimitations

This study was conducted as a thesis project and is therefore constrained by a time frame of 22 weeks. Due to limited time and available resources, the number of samples and with that repeats of test were restricted. As a result, the following aspects are excluded from the scope of the study:

- No evaluation or assessment of the fire retardant product, the impregnation process, the façade modules, or the building as a whole.
- No analysis of smoke production or composition.
- No chemical analysis of the fire-retardant agent.
- No measurement of fire-retardant concentration within the timber slats.
- No recommendations or proposed solutions regarding shortcomings within the field of fire-retardant treatments.

## 1.9 Guide for the reader

Chapters 1 to 1 presents background information about the field of fire and safety engineering as well as the history of fire retardants. Chapter 1 presents the methodology of the thesis work and Chapter 1 presents the material properties of the timber slats used in this study. The results of the study are shown in Chapter 5 and the analysis of the results is presented in Chapter 1. The thesis is wrapped up with a discussion in Chapter 1 followed by a broader conclusion in Chapter 1. After the reference list in Chapter 1, there are 12 appendixes with extended information.

## 1.10 Definition of commonly used terms in this research area:

The following are explanations of words and usages of words in this thesis.

### *Timber or wood*

In the fire and safety context, these words are generally used interchangeably. In this thesis, *timber* is dominant when in context as a building material and *wood* is used more when discussing the general material properties of wood and how it responds to fire.

### *Aged or weathered*

This thesis will mainly use the word *weathered*. Both words are used in the literature interchangeably, similar to wood and timber. Since this thesis is about an external façade, the impact of different weathering plays a crucial role in the aging of the timber; therefore, the term *weathered* is used in this thesis. *Aging* can imply just the passing of time where the material undergoes a natural change simply as a result of time, whether or not the material is exposed to external environmental factors.



## 2 Background

Chapter 2 gives a brief background on fire, timber, the field of fire safety and why it is a part of the sustainability development of a society. The chapter also highlights a few striking tall buildings with timber façades.

### 2.1.1 History

Fire has played a crucial role in human development, offering warmth, light, and the means to cook food [6]. Despite these benefits, fire also presents significant risks and can lead to devastating disasters.

Involuntary fires have, and will continue to, occur. The fire safety field exists to prevent these fires and minimize their impact on societies. Well-designed fire safety systems are crucial in preventing, detecting, mitigating, suppressing and even controlling fires. While fires will continue to arise and cause disasters, fire safety engineering aims to reduce their severity.

In the context of cities, fire safety engineering grew into a field of study because of extended fires roaming through societies, starting with the earliest documentation of a devastating fire in Rome in 64 AD [7]. Conflagrations, extensive fires that destroy a great deal of properties [8], throughout history are still talked about today. Three remarkable city fires are:

Year 64 AD - the Great Fire of Rome, 70% of the city burned to the ground [9].

Year 1666 – The Great London Fire, 85% of the city destroyed [10].

Year 1888 – more known in Sweden; Sundsvall and Umeå fires where >70% of the cities burned to the ground [11,12]. These events mark a turning point for Swedish insurance companies, making them take fire risks into account [59].

Already after the Great Fire of Rome, fire safety engineering actions were implemented into society. Regulations on claddings for the restoration of the city were drawn up: no combustible materials allowed on the exterior walls [7]. That was the end of timber as exterior claddings in Rome. Later on, during the Industrial Revolution, conflagrations continued around the world, but less often than before. The decrease of conflagrations was a result of the industrialization and usage of noncombustible materials, such as concrete and steel [ibid].

Today there are several building codes all over the world. In Sweden, the regulations regarding fire and safety engineering are written in the “Boverkets byggregler, BBR 30 chapter 5 [13]. These building codes are designed to create social, environmental, and economic sustainability by ensuring the construction of safe buildings, where fire safety is a small but crucial aspect of the process.

#### 2.1.1.1 Sustainability

Fire protection is a part of a society's sustainability in at least three areas: social, environmental and economical [14]. Through fire and safety engineering, modern cities and societies can be spared from conflagration and with that let communities thrive.

Protecting the people from fires contributes to social sustainability within a community. Secondly, fires release carbon dioxide that contributes to global warming as well as toxins that contaminate nature [14]. With prevention, mitigation, early warning, suppression and controlling functions: fire and safety engineering can reduce the environmental effects of fires and with that add environmental sustainability to the world.

Lastly, time and money spent on thorough fire and safety engineering when planning and constructing buildings will likely be less expensive than rebuilding cities. Careful and well-thought-through building projects are, therefore, also good for the economic sustainability of communities, companies and families.

### 2.1.2 Brief Background about timber as a building material

Wood is one of the oldest natural materials and has been successfully used for constructing buildings and various building elements throughout the history of time [1,7,15]. The main advantages of wood are that it regulates temperature, moisture and light effectively and that it here in Sweden grows close to where the buildings are built [16,17]. Untreated wood exposure, no paint, waxing, or coating, has also shown to have an enhancing effect on emotional well-being by lowering the heart rate, thus having a calming effect on people [18]. Despite the positive properties of wood, it has other inherent properties to consider.

A natural material, such as wood, means that it is a part of nature's cycle. Wood will eventually deteriorate into mulch and soil, to then be turned back into new living plants, unless it is treated in one or another way [19]. To hinder wood from deterioration and microbial attacks, it can be treated in many different ways to gain protection against different types of climate impacts [1,19].

However, there is more to consider than sun, wind and water in our increasingly densely populated society, where buildings are growing taller and becoming more complex: **wood burns**.

### 2.1.3 Examples of wood in tall or large buildings

This subchapter presents examples of where timber is one of the main building materials. The examples are of tall or large building since that is when the regulations about fire protecting wood is applied in Sweden. In contrast, smaller houses are typically not required to have fire protection measures on their facades or structure.

#### **Sweden's Tallest Wooden Building: Sarah Kulturhus [20]:**

- **Type:** Public building and hotel
- **Location:** Skellefteå, a city in northern Sweden.
- **Height:** 20 stories
- **Details:** The building uses wood sourced from the surrounding area, to help reduce the carbon footprint as well as supporting local industries. The structure incorporates massive timber and Cross-Laminated Timber (CLT) elements. CLT is a sustainable construction material known for being strong, lightweight and environmentally friendly.

#### **Stockholm Wood City [21]:**

- **Type:** Neighborhood
- **Location:** Stockholm, Sweden
- **Height:** Varies
- **Details:** An ongoing project that aims to make Stockholm a global leader in sustainable wood construction. The focus is on sustainable architecture, aiming for lower carbon emissions.

**Qville Apartment Block [22]:**

- **Type:** Apartment building
- **Location:** Gothenburg, Sweden
- **Height:** 5 stories
- **Details:** Heat-treated and fireproofed timber façade and decking

**Kv. Taklampan [23]:**

- **Type:** Apartment building
- **Location:** Hammarbyhöjden, Stockholm, Sweden
- **Height:** 5 stories
- **Details:** Fireproofed façade

**79&Park Gärdet [24]:**

- **Type:** Apartment building
- **Location:** Gärdet, Stockholm, Sweden
- **Height:** 10 stories
- **Details:** Fireproofed façade

**Uludağ Ski Resort [25]:**

- **Type:** Hotel
- **Location:** Turkey
- **Height:** 6 stories
- **Details:** On January 29th, 2025, a building with a wooden façade recently burned down. Although the façade was reported to have fire impregnation, there are also claims that regular, non-fire-impregnated timber was used in its construction. This building is included in the thesis as it occurred during the time when the thesis was written and it also works as a reminder that fires can occur during the winter.

## 2.2 Properties of wood and timber with fire

This subchapter presents information about wood, its basic structure as well as the main causes of deterioration of exterior timber.

### 2.2.1 What is wood?

Wood is a material that is produced by nature where heavy large molecules, called polymers, are mixed to create what is known as wood. The main polymers in wood are cellulose c. 50%, hemicellulose c. 25% and lignin c. 25%. The proportions between the molecules can vary depending on the type of wood [26] p.263. The configurations of the cellulose molecules allow the molecules to align themselves into microfibrils which creates the stability and structure of the cell wall [27] p.210. The microfibrils are then bound to each other by hemicellulose and lignin during the growing process of the tree [27] p.210, lignin is known as the “glue” of wood.

Wood is a hygroscopic material which normally contains absorbed moisture from the surrounding air [19] p.52. If the surrounding moisture content and temperature change, the moisture content in the wood will change as well. Parts of the water are bound by weak hydrogen bonds to hydroxyl (OH) groups of the cellulose [27] p.210. If the relative humidity in the surrounding air is high enough, there will also be free water in voids within the wood which is held by capillary forces [ibid]. The free water will be released first, either when the relative humidity lowers or when the wood is heated towards 100°C.

#### 2.2.1.1 Burning of wood

The burning of wood can be divided into the following: heating and moisture evaporation, pyrolysis, flaming combustion, solid phase oxidation (char/glowing combustion) and ash formation. The moisture evaporation begins at around 100°C and the temperature for pyrolysis depends on several factors of the wood, such as density, thickness, surface roughness and potential surface treatments. Generally wood starts to burn with a pilot flame at a surface temperature of 300-400°C and spontaneous ignition happens at around 500-600°C [28], resulting in flaming and or char combustion. Ash is the solid residual after complete combustion and usually contains calcium among other non-combustible trace elements from wood [29].

The grain structure of wood varies depending on the direction of its grains and with that how flames and fire behave around wood. The thermal conductivity parallel to the grain is about twice of perpendicular to the grain [27] p.215. Along the grain, volatiles can then travel more easily than perpendicular to the grain, which can be an explanation of why volatiles and flames can appear as jets from knots and ends of burning sticks [ibid].

Different burning behavior from knots are noted in the results from this Cone Calorimeter tests, see Chapter 5.

#### 2.2.1.2 Deterioration of wood

Outdoor climate causes deterioration of timber façades through three dominating factors: sunrays, rain and wind [19] p.54.

Sunrays cause damage mainly through UV light and the hot temperature direct sunshine can cause. UV light degrades the lignin, causing the characteristic browning of the wood on sun-faced façades that are covered from rain. It is noted that UV light makes lignin more mobile and can move around in the structure, but the phenomenon is not well understood [2]. If the damaged lignin is at a rain-exposed part of a façade the lignin is washed out with the rain, causing the smooth grey appearance [19] p.56.

Rain can damage wood and timber making it more prone to infestation as well as leaching eventually treatments the timber has in it. Wind in combination with rain, *driving or slashing rain*, can also cause mechanical damage on the surface of a façade [19] p.56. The north facing façade in this thesis is exposed to slashing rain, rain that bounces back up from the ground onto the surface, damaging the surface with small stones, see Chapter 1 material properties of the timber samples.

Wind, together with particles in the air and insects such as wasps, polish the surfaces of timber façades [2,30]. This type of weathering is hard to predict and replicate in a lab environment and is an important factor to consider when choosing a weather protection for the façade.

### 2.2.2 Fire spreading theory

This subchapter is advised to be read slowly and carefully to digest its meaning. Drysdale D explains in his book “Introduction to fire dynamics” [27] that fire spread depends on the thickness of materials and how easily they catch fire and that fire growth speeds up over time after ignition. Which factor matters more between peak heat or ignition resistance (remember this for subchapter 2.5.1), thus depends on the fire scenario and if the material is thermally thick or thin.

The timber in this study is thermally thick for the time up to ignition.

For thick materials, the time to ignition depends on the square of the ignition temperature – if the material needs a higher temperature to catch fire, it will take longer to ignite. For thin materials, the time to ignition depends directly on the ignition temperature. After ignition, the rate of fire spread over a surface, is proportional to the time after the material ignites, squared. That means the fire grows faster as time passes. Therefore, the key factors for controlling a fire will depend on the particular fire situation, even if one would like it to be simpler than that [49]. See more in chapter 2.5.5.1.

## 2.3 Fire-retardants

Chapter 4 presents information about fire retardants, mostly in the context of façade usage.

### 2.3.1 History of fire-retardants

Already during the Egyptian time, a solution of alum was added to timber to enhance the timber's fire properties [31] p. 229. The main drive for innovation of fire retardants began with the growth of the plastic industry and the widespread use of polymers. With the extended usage of plastic, firefighters reported more severe fires and denser smoke. It got more difficult to fight fires during the 1960s and 1970s than before [31].

As a result of the severe fire problem, empirical tests for flammability, such as the Cone Calorimeter, were developed to enable to test different materials fire properties. In the SFPE Handbook, Society of Fire Protection Engineering [31] p. 229, presents the main drivers behind the development of fire retardants, as summarized in Table 1. The toxicity of fire retardants was a widespread problem during the 2000s and is supposedly resolved in today's fire retardants.

Table 1: SFPE table with the drivers in fire-retardant development. FR = fire-retardant.

<i>Decade</i>	<i>Event</i>	<i>Demand</i>
1960s	Widespread availability of cheap polymer products – more serious fires	Reduced ignitability
1970s	Smoke much worse	Reduced smoke
1980-1990s	Development of the Cone Calorimeter (and emphasis on peak heat release rate per unit area, rather than ignitability)	Reduced Peak Heat Release
	Increase in deaths from smoke inhalation	Reduced Fire Toxicity
2000s	Halogen FRs found across ecosystem	Halogen-free FRs
2010s	Climate change and other environmental concerns become mainstream	Sustainable FRs

### 2.3.2 Properties of fire-retardants

Fire retardants for wood are developed to improve the reaction to fire performance of the product it is applied to. The highest fire classification in the European classification system for combustible products may even be reached with additives of fire retardants [32] p.710. For external walls, such as façades, there are no European harmonized solutions, where some countries have further requirements than others [32] p.35. In Östmans and Buchunas book “Fire Safe Wood in Buildings” [33] the differences between countries' approach to timber façades are summarized for the interested reader.

Because of the vast range of different fire retardants on the market it is helpful to find a way of categorizing them. How they are supposed to be categorized is not an easy choice. One way is to categorize them in how they slow down a fire growth: physically or with chemically:

- | Physically                         | Chemically                    |
|------------------------------------|-------------------------------|
| ○ By cooling                       | ○ Reaction in the gas phase   |
| ○ By formation of protective layer | ○ Reaction in the solid phase |
| ○ By dilution                      |                               |

SFPE has chosen another way to categories fire retardants according to their “phase” following: gas phase or condensed phase. Figure 1 on the next page shows the classifications presented in SFPE p. 230 figure 7.47 [31]. More thorough reading about fire retardants can be done in [27] p. 211-215 and [31] p. 229-254.

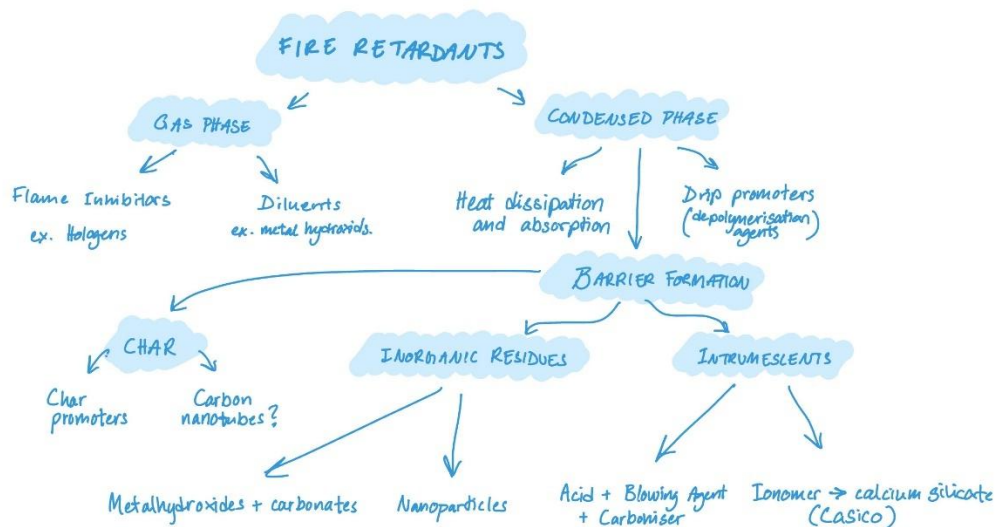


Figure 1: Classifications of fire-retardants according to SFPE.

Char promoters are usually activated by the presence of an ignition source [34]. Therefore, a shorter time to ignition is wanted for fire retardants of this sort, as it allows them to activate more quickly and inhibit flame spread [58]. This is why it can be observed that fire retardant timber has a faster ignition time than plain timber.

### 2.3.3 Fire-retardants adhesion in timber

Fire retardants can either be incorporated into the timber during the manufacturing process or applied later on by surface treatment [31] p. 231, [32] p.170. In the manufacturing process, the fire-retardant is usually incorporated through vacuum impregnation and that is the method used for the timber slats in this study.

Apart from how the fire-retardant is applied to the timber product, as described in the above subchapter, fire-retardants can also be divided into additive or reactive fire-retardants [2] p.9053 [31] p. 231:

#### Additive retardants:

- Applied by dipping, spraying, vacuuming, or brushing.
- Do not chemically bond to the wood which leads to it being more likely to migrate out of the timber. Usually, salt based and water soluble.

#### Reactive retardants:

- Chemically functionality to react to the timber → Less likely to migrate out of the timber.
- More expensive than additive retardants.

The quantity of fire-retardant chemicals included in the final timber product plays a crucial role in determining how well the product resists and reacts to fire [32] p.170. A lower concentration of fire-retardant equals less fire protection. Therefore, additive retardants have resin (or external pain) to keep the fire retardant trapped in the timber. It is well established in the field of fire retardants that migration and leaching of fire-retardants causes significant challenges to the long-term durability of exterior applications, such as timber façades.

According to an employee at the impregnation company, the fire retardant used in the timber slats in this study is said to react with the wood cells, binding to the cellulose and hemicellulose. Based on this description, the treatment is considered a reactive fire retardant. However, no detailed information about its mechanism of action is available on the company's website or in the publicly accessible product documentation provided to purchasers.

#### 2.3.4 Leaching of fire-retardants

Leaching of fire-retardants is a well-known problem with wood impregnations such as fire-retardants in timber. Leaching of fire-retardants is highlighted in for example Östmans and Tsantaridis "Durability of the reaction to fire performances of fire-retardant-treated wood products in exterior applications – a 10-years report" [5] and Hill, Kylmäläinen and Rautkaris "Review of the use of solid wood as an external cladding material in the build environment" [2] as well as by fire impregnator companies [35]. Therefore, research in developing lech-resistant fire-retardant is an important topic, see for example [36], [37] and [38].

#### 2.3.5 Accelerated aging and natural weathering

Both methods are complementary to each other – accelerated aging exists for rapid testing of materials and natural weathering gives a more thorough understanding of a material's long-term performance in a given environment.

Despite the increasing outdoor use of fire-retardant-treated timber, methods for predicting its service life remain poorly established [39]. The following is a quick reminder of what the two types of tests entitle.

##### **Accelerated aging method**

Accelerated aging aims to simulate long-term environmental exposure in a shorter time by using artificial conditions such as extreme temperatures, humidity, UV light and cycles of wetting and drying. These tests aim to replicate years of natural weathering in a matter of weeks or months, providing a quick and cost-effective way to predict the long-term durability of a product.

These tests help manufacturers assess the weathering resistance of timber coating, fire-retardants and other finishes in a controlled and reproducible environment. The test-method is a valuable tool to estimate a product's approximate behavior in outdoor climates and a necessity in the innovation of new fire retardants. However, be aware that it mimics only certain aspects of real-world weathering and is not a reliable source of information for a fire-retardant timber products life span.

There is ongoing research on how to improve the artificial-weathering tests for fire-retardant-treated timber which can be read more about in the article "Artificial-weathering test requirements for fire-retardant-treated wood to reproduce optimal chemical retention and moisture conditions" [39].

**Natural weathering method**

Natural weathering tests expose the timber to an actual outdoor environment over time. The timber samples are exposed to sunlight, rain, wind and temperature fluctuations as well as insects, birds, other animals and fungi – a true weathering process.

Natural weathering tests are lacking in the fire-retardant industry. “It takes too long time” is the answer given by fire-retardant /impregnator companies when asked about natural weathering tests. Even though they emphasize that real-world data is the only way to really know how a material is behaving after weathering. However, as this thesis is written, there are initiatives to build test centers in Sweden and hopefully at other places as well, with the aim to fill the natural-weathering-information-gap in the field of fire retardants.

## 2.4 How fire safety in timber buildings is regulated

Chapter 2.4 presents a brief background on how fire safety in timber buildings is regulated in Sweden. The regulations can be seen as a source of inspiration for fire-retardant developers, since their products have to meet the requirements that the regulations set. Without the regulations, there would be no need to innovate or improve fire-retardants, at least when looking at the fire-retardant business from an economic point of view. In the end of the day, it all comes down to economics.

### 2.4.1 Regulations of timber façades

For external walls, such as façades, there are no European harmonized solution, where some countries have further requirements and others have less [3]. In the book “Fire Safe Use of Wood in Buildings” [33] the differences between countries approaches to timber façades are summarized and well-illustrated for the interested reader. The following presents how the fire regulations are built in Sweden.

#### 2.4.1.1 The planning and building act, PBL

The planning and building act, PBL, is a Swedish law that governs land use, urban planning and construction to ensure sustainable and safe development [40]. It sets rules ensuring that buildings and infrastructure meet safety, accessibility and environmental standards to create a good living environment [40]. PBL also says that when a building is built, the building must be kept in good condition and maintained so that its design and technical properties are essentially preserved. The following citation is translated from Swedish to English with the help of Generative AI:

*“A building must be kept in good condition and maintained so that its design and the technical properties referred to in 4§ are essentially preserved. The maintenance should be adapted to the character of the surroundings and the building's value from a historical, cultural-historical, environmental and artistic perspective.”* [40] Chapter 8, 14 §.

#### 2.4.1.2 Boverket's building regulations, BBR

PBL is the overarching law issued by the Swedish Parliament, where BBR provides detailed technical requirements issued by Boverket.

Today in Sweden, buildings taller than three stories, building class Br 1, must be built so that the following requirements are met for the façade [13]:

1. The separating function is maintained between fire compartments,
2. The spread of fire inside the wall is limited,
3. The risk of fire spreading along the façade surface is limited,
4. The risk of personal injury due to falling parts of the exterior wall is limited.

Usually the requirements are met by building with non-combustible materials (A2-s1,d0). Points 2, 3 and 4 are considered to be met if a façade element has passed the SP FIRE 105 full scale test. It is also possible to demonstrate with an analytical performance-based design that the façade element meets the above requirements. Analytical design is required for all buildings with a very high need for protection, Br 0 [13].

#### 2.4.1.3 *Lagen om skydd mot olyckor, LSO*

According to Swedish law (LSO 2003:778), building owners and operators are legally responsible for fire protection. They must maintain equipment for fire extinguishing and take necessary measures to prevent and limit fire damage. Systematic fire protection work involves organizing and documenting fire protection measures to ensure maintenance and implementation of reasonable actions, both technical and organizational.

The estate manager has expressed concerns about the lack of maintenance guidelines for preserving the fire protection of the façade, including approved cleaning methods. Neither the fire impregnation company nor the distributor was able to provide guidance on how the façade should be maintained when asked.

As of January 1, 2021, the requirement for building owners to submit a written fire protection report to the municipality has been removed, but owners and operators still need to ensure adequate fire protection and systematic fire protection work [57].

#### 2.4.1.4 *SS EN 16755:2017 and DRF-class*

Standards are established to help the industry determine whether a process or product meets the expected requirements and performance criteria. SS EN 16755:2017 is a Swedish standard, also known as DRF-class: Durability of Reaction to Fire performance. Fire-retardant treated wood products can be EN 16755 classified for interior and exterior use [41]. The standard is based of the old Swedish Nordtests [42].

The test evaluates the fire properties before and after accelerated aging. The Single Burning Item test method SBI-method EN 13823, is the preferred test method for the standard but there has been an alternative test method with the Cone Calorimeter ISO 5660-1 [43]. Which means that a product can get a DRF classification, either from a small-, or a little larger test.

The Swedish Institute of Research, RISE and Danish Institute of Fire and Security Technology, DBI, has paused their classifications with EN 16755 using the Cone Calorimeter as a test method until further notice. This is due to uncertainties regarding the level of safety achieved when using a Cone Calorimeter for validating the aging resistance of products intended for external use according to EN 16755:2017 [43].

The samples in this study have an SS EN 16755 certification for exterior use after accelerated aging, see Appendix 9 - Documentation EN 16755.

## 2.5 Fire testing

Chapter 2.5 presents an overview of principles and problems with fire testing of materials, specifically timber. It is a recap for the advanced reader and as information for the novice in the fire and safety engineering field. Richard T. Hull has dedicated chapter 11 of the book “Advances in Fire-retardant Materials” [44] to explain fire testing. The subchapters headings in this thesis are hand-picked from Hulls book.

### 2.5.1 Principles and problems with fire testing

To be able to compare fire behaviors there is a need to quantify and numerically measure the fire performance. To make the testing as close to a real-world fires as possible, big tests are preferred, but they are very expensive and therefore less reproducible than small-scale tests [44]. Testing materials are usually also only available in small quantities: hence, small-scale tests are the most common way of conducting fire tests [44]. However, Hull R.T [ibid] explains that many small-scale tests have built-in weaknesses or limitations that fail to recreate or show how intense the heat created from a large-scale fire can be. The results from a small-scale test can therefore be misleading, if applied out of context: for example a real-world fire will likely have a **much stronger** heat release rate than shown from the small-scale test [44].

Further, Hull R.T informs that there are two schools of thought when it comes to fire science and preventing fire growth: minimizing the peak heat release rate per unit area and extending the ignition resistance. It appears that the peak heat release rate per unit area controls the initial flame spread from the first object to other objects: why minimizing the peak heat release rate per unit area is a key factor in preventing fire growth. The other school emphasizes the resistance of the next object to even starting burning: higher piloted ignition temperature or longer delay time before ignition to be the key factor in preventing fire growth [44].

Both *minimizing the peak heat release rate per unit area* and *resistance to catch fire* are factors that fire-retardant formulators probably have in mind. The fire-retardants are supposed to make the timber have a longer ignition time and lower heat release rate than non-treated timber.

The Cone Calorimeter is an adequate testing method to measure these two factors and that is why the Cone Calorimeter will be used for this study.

### 2.5.2 Reaction-to-fire tests

Reaction-to-fire tests, test how a material reacts when exposed to a given heat source (e.g. fire). There are multiple different standardized test methods and all products with specified fire performance must have passed some sort of testing to be allowed on the market [44]. Fire-retardant formulators and developers need simple ways of measuring how the retardant behave in a fire. To do this, they use a few smaller tests to track progress in the making of fire-retardants.

According to Hull R.T, the most common material fire tests are the limiting oxygen index (LOI) and the Underwriters’ Laboratory UL 94 test (both measures how easily it is to extinction the fire) and the Cone Calorimeter, which measures time to ignition and rate of heat release. More thorough information about these tests can be read in the book [44]. **The Cone Calorimeter test will be explained more thoroughly in subchapter 2.5.5 and is the method used for in this study.**

### 2.5.3 SP-FIRE 105

SP-FIRE 105 is an example of a full-scale fire testing method for façades. The test method is developed by the former “Statens Provningsanstalt”, today known as Research Institutes of Sweden – RISE. The test aims to simulate a full-scale fire impact from an apartment fire and measures the façade fire properties such as: fire spread, falling building parts, temperature by the eaves and radiation to the next floor’s façade [46].

Test methods in a lab environment always have their limitations when comparing the results to a real-world fire scenario. Further readings on the limits of SP-fire 105 test method and big scale testing in general, can be found in the books “Fire Safety in Timber Buildings” [3] and in “Fire safety of façades” [47]. To be noted is that passing a test does not mean that the fire cannot spread via the façade system.

*“The requirements [authors addition: of SP FIRE 105] accepts the spread of fire in the façade and on the façade surface up to two floors above the fire room to the level of lower edge of the window.” [47]*

Since the fire is allowed to spread to the adjacent apartment, that is the next fire compartment, a passed SP-FIRE 105 test only ensures compliance with points 2, 3, and 4 of the regulations. Point 1, “The separating function is maintained between fire compartments,” remains unaddressed. See the points in subchapter 2.4.1.2

### 2.5.4 Ignitability

Ignition, when a material catches fire, is a complex phenomenon that can be read more thoroughly about in the “SFPE handbook of fire protection engineering” [31]. Basically, ignition happens when the pyrolysis gases released from the material mix with the surrounding air in the right condition and then give enough heat back to the material, to self-sustain the pyrolysis process [44]. For this to occur, the heat released when the material burns, must be greater than the heat needed to turn the material into gas: a phenomenon closely linked to the material’s mass loss rate at ignition [ibid].

### 2.5.5 The Cone Calorimeter

Comparative evaluations of materials is what the Cone Calorimeter is mainly used for [31]. It is the most widely used testing method to study fire behavior of materials and it is standardized in International Organization for Standardization (ISO 5660) and the American Society for Testing and Materials (ASTM E1354) [31,48]. The essential principle of the method is to measure the decreasing oxygen concentration in the combustion gases of the sample subjected to a given heat flux [48]. It is a small-scale test method that provides rich information, with relatively little sample material [48]. The test provides various flammability parameters such as:

- HRR – heat release rate
- THR – total heat release rate
- **PHRRPUA – peak of heat release rate**
- **TTI – time to ignition**
- MLR – mass loss rate
- TSR – total smoke release
- EHC – effective heat of combustion
- Etc.

The focus in this study is on PHRRPUA and

It is of value to note that ignition does not directly or necessarily correspond to “flammability” measured by LOI or UL 94 since the latter are extinction tests and the Cone Calorimeter is an ignition test. Further explanation of the Cone Calorimeter can be read in [31], [49] and [50]. The worldwide acceptance makes it important to highlight its limitations of the method when results are presented.

### 2.5.5.1 Why the Cone Calorimeter can be used to describe a materials ignitability

The Cone Calorimeter test can describe the ignitability of a material, something that is of interest when formulating fire-retardants. A materials ignition temperature (TTI or  $T_{ig}$ ) can be seen as an inherent property of the material; in this thesis the material is fire-retardant timber and untreated timber. Ignition temperature ( $T_{ig}$ ) is assumed to be independent of the applied heat flux, therefore the ignition temperature will not change even if it is exposed to more or less energy. The time to ignition ( $t_{ig}$ ) is the time required for the surface of the material to reach ignition temperature ( $T_{ig}$ ) [49]. For thermally thick materials, for example a timber slat, it is shown that:

$$t_{ig} = \frac{\pi}{4} kpc \left[ \frac{T_{ig} - T_0}{q_{ext} - CHF} \right]^2 \quad \text{Equation 1}$$

In the Cone Calorimeter, the critical heat flux (CHF) is characterized for each material which is connected to the ignition temperature. *Equation 1* above shows a linear relationship between applied heat flux  $q_{ext}$  and time to ignition  $t_{ig}^{-0.5}$ , showing that the material properties: thermal inertia ( $kpc$ ), time to ignition ( $t_{ig}$ ), the ignition temperature ( $T_{ig}$ ) and the critical heat flux (CHF) can be used to describe the ignitability of a material [49]. Note that these are not truly inherent properties because their values change significantly depending on the Cone Calorimeter set up such as the distance between the sample holder and heater or the use of a spark ignitor or flame [31,48,49].

Time to ignition (TTI) is a key in fire-retardants because it indicates how long a material resists ignition. Some fire-retardants want a fast ignition so that the retardants can be activated and lower the heat release, while others prevent the timber to ignite.

### 2.5.5.2 Limits with the Cone Calorimeter

The Cone Calorimeter, as all fire testing methods, has limitations which should be considered. Some of these are outlined below as a reminder of its constraints:

- **Scale of testing:** It simulates a small-scale fire scenario, and it is not perfectly representing a real-world, large scale, fire behavior.
- **Heat source limitation:** It can create a constant radiant heat flux between 0-100 kW/m<sup>2</sup>. A real fire-scenario usually has turbulence and with a variation of radiant heat flux over time.
- **No external ventilation control:** It does not take account for varying oxygen levels with ventilation changes during the test period, which greatly can impact the results.
- **Difficult to handle:** The machine needs a lot of preparation and does not alert the user if a step is missed. Human errors are therefore a prominent factor in the usage of the machine.
- **Material types:** It is developed for solid, non-porous materials and may not be suitable for smaller samples than tested in this study.

## 2.6 Theory of data analysis

Chapter 6 describes why Thermally Response Parameter, TRP and Fire Propagation Index, FPI are used as a comparison method in this thesis. Both theories are also explained.

The TRP and FPI value are useful to evaluate and compare the FRONT, MID and BACK results.

Higher TRP = slower time to ignition

Higher FPI = faster flame spread

### 2.6.1 Thermally Response Parameter – TRP

TRP is a combination of thermal inertia and ignition temperature and is used to describe how quick a material reacts to heat in a fire scenario. It quantifies a materials thermal response when exposed to high temperatures. The TRP value can then be used to assess the fire behavior of building materials, structures or components. For this thesis it will be used to compare FRONT, MID and BACK samples to each other.

The following equations are based on the assumption that the material is thermally thick and behaves as a semi-infinite solid up to the point of ignition. The samples used in this study are considered thermally thick until time-to-ignition, as demonstrated by showing that  $L > 4\sqrt{\alpha t}$  [27] p. 47, see *Appendix 3 - Extended calculations*.

The TRP can be calculated with the data given from the test results from the Cone Calorimeter test. Two main points of information is needed from the tests: time-to-ignition,  $t_{ig}$  and the radiant heat flux,  $\dot{q}_e''$ , that radiated onto the sample [27] p. 258. *Equation 2* is used to calculate the TRP value [51]:

$$\frac{1}{\sqrt{t_{ig}}} = \sqrt{\frac{4}{\pi}} \frac{\dot{q}_e''}{TRP} \quad \text{Equation 2}$$

Where	$t_{ig}$	is the ignition time at the radiant heat flux (s)
	$\dot{q}_e''$	is the radiant heat flux onto the sample (kW/m <sup>2</sup> )
	TRP	is Thermal Response Parameter (kW s <sup>1/2</sup> )

The TRP values were calculated by plotting  $\frac{1}{\sqrt{t_{ig}}}$  on the y-axis and the radiant heat flux  $\dot{q}_e''$  on the x-axis. The slope of the graph is then used to calculate the TRP value for FRONT, MID and BACK.

A higher TRP means either increase in thermal inertia or increase in ignition temperature → slower time to ignition, which can delay the spread of fire. Low TRP values indicates low thermal inertias, meaning the material heats up quickly, potentially accelerating fire development.

### 2.6.2 Fire Propagation Index – FPI

The Fire Propagation Index, FPI, is developed to be able to use small-scale tests to compare flame spread velocities of materials [51]. Here it was used to compare FRONT, MID and BACK samples to each other.

High FPI values means that there is a higher likelihood of flame spread. In Engströms and Psajds thesis [4], their samples which are of the same or very similar type of wood and fire-impregnation as the samples in this study, had FPI values of:

Un-weathered: 10,6 -17,2

Weathered: 19,7 – 23,4.

FPI for this thesis were calculated with the equation for horizontal orientation of testing in the Cone Calorimeter, since that is the orientation of the test, according to *Equation 3* [51]:

$$FPI = k_1 \frac{(0.42\dot{Q}'')^{1/3}}{TRP} \quad \text{Equation 3}$$

Where	FPI	is the peak Flame Propagation Index
	$k_1$	scaling factor for horizontal cone test (1200)
	$\dot{Q}''$	is the peak heat release rate per unit area per unit area from the samples tested at radiant heat flux at 50 kW/m <sup>2</sup>
	TRP	is Thermal Response Parameter (kW <sup>s</sup> <sup>1/2</sup> )

### 2.6.3 T-test

The t-test is a way to see if there is a real difference between two averages (means) or if the difference is just random chance. It aims to answer the question “Are these two groups actually different, or does it just look that way?”. There are three main types:

- **One-sample t-test:** Compares a sample mean to a known value.
- **Independent t-test, two sample:** Compares means of two unrelated groups.
- **Paired t-test:** Compares means of the same group before and after a change.

Key assumptions: data is normally distributed, uses interval/ratio scales and groups (if independent) have similar variances [52]. It tests a null hypothesis, that there's no difference between means. If the calculated t-value exceeds the critical value from a t-distribution table, the null hypothesis is rejected.

The data in this study is considered to be independent and a double sample, independent t-test is therefore conducted, see Subchapter 3.3.3.

### 2.6.3.1 Limitations of t-test

When performing a t-test with unequal sample sizes there are several potential issues and sources of errors that should be considered. The main limitations of the field study are that the number of samples are restricted as well as human errors in the process. The following are to be considered with small sample sizes:

- **Reduced statistical power:** A small sample size, for example 4 compared to 17 tests, can reduce the power of the test, meaning there is a chance of not detecting a true effect, if one exists. This is due to larger variability in the estimates of means, which makes it harder to detect real differences.
- **Unequal variance:** The t-test assumes that the variance of both groups is equal, an equal spread in the data. With small sample size the groups mean may not be similar. In this case the HRR and TTI have equal spread and therefore this is not a problem in this study.
- **Increased standard error:** the standard error of the means will be larger with smaller sample sizes. Larger standard error may lead to a less accurate estimate of the difference between groups.
- **Violation of normality assumption:** T-test assumes that the data are approximately normally distributed, especially in small sample sizes. If the data is not normally distributed the t-tests results will not represent the reality. The samples in this study are assumed to be normally distributed, even the sample size of 4.
- **Risk of overfitting:** The tests of a smaller sample size can be overly influenced by outliers or extreme values from just a few data points, which might not reflect the true population of tests. This is not an issue in this study because the HRR and TTI values do not contain any extremes or outliers.

## 2.7 Overview of previous research

This subchapter presents examples of already conducted studies of natural weathering of fire-retardant-impregnated timber façades. The report Fire Safety in timber Buildings [3] has recently (year 2023) summarized studies about fire-retardant treatments and surface coatings. The main results from Östmans and Tsantaridis 10 year report [5] and the results from Engström and Psajds thesis [4] will be presented. Three studies from 2024 on the subject will also be mentioned.

### **Durability of the reaction to fire performance of fire-retardant-treated wood products in exterior applications: a 10-year report [5]**

This paper was published in 2017 and presents several long-term studies on the fire performance of fire-retardant-treated (FRT) wood over time. They are based on European, Nordic and North American systems and include both accelerated aging and natural weathering over up to ten years. The main findings were:

- The *hygroscopic properties* of most FRT wood products remain unchanged compared to untreated wood.
- FRT wood products can maintain their fire performance after aging if the fire-retardant retention levels are sufficiently high.
- However, many FRT products lose most of their fire-resistant properties during weathering.
- Paint systems are crucial for maintaining fire performance, especially for exterior applications after exposure to weathering.

### **Beständigheten hos brandimpregnerat trä [4]**

This report was conducted and published in 2023 at Lund University. It examined the properties of fire-retardant-impregnated wood, with a focus on its durability and the effectiveness of accelerated aging methods in predicting long-term performance, compared to natural aging. The study combined a literature review, interviews, and practical experiments. Samples exposed to natural weather conditions for several weeks were tested using the ISO 5660-1 Cone Calorimeter, the same method as in this study. The main findings were:

- A significant difference in ignition time and total heat release rate was observed between weather-exposed and non-exposed samples.
- Infrared spectroscopy showed a reduction in fire-retardant levels in the weather exposed material.
- These findings indicate that the material's properties change after just a few weeks of exposure.

Next page presents studies from year 2024:

**Artificial-weathering test requirements for fire-retardant-treated wood to reproduce optimal chemical retention and moisture conditions [39]**

This study investigates methods for predicting the service life of fire-retardant-treated wood exposed to outdoor conditions, particularly humid atmospheres and rain. The researchers aimed to establish a method for predicting chemical loss from fire-retardant-treated wood using artificial weathering tests, based on the EN927-6 standard. The study found that fire-retardant-treated wood:

- Absorbs more moisture than untreated wood, with moisture content varying from 11% to 50% throughout the year.
- Two sets of specimens with different initial moisture contents (0% and 25%) were subjected to artificial weathering tests for 2520 hours. The results showed acceleration coefficients (indicating how quickly chemical retention matches outdoor conditions) ranging from 4.1 to 11.3 for 0% moisture and 5.1 to 11.4 for 25% moisture content.
- Specimens with higher initial moisture content exhibited more consistent acceleration coefficients.
- Additionally, specimens with penetrating or semi-film-forming coatings had larger acceleration coefficients. The study discusses how moisture absorption impacts the uniformity of these coefficients.

**Enhancing water resistance and flame retardancy of wood through phytic acid catalyzed in-situ polyesterification [38]**

This study explores a novel method for enhancing wood properties through in-situ polyesterification. It involves a chemical process where citric acid and D-sorbitol are used to create polyester directly on the wood (called in-situ polyesterification). Phytic acid is used as a catalyst to speed up or improve this process. The method improves wood's dimensional stability, biological durability, water resistance and flame retardancy. Phytic acid lowers the curing temperature and activation energy of the reaction, enhancing esterification and thermal stability of the polyester. Treated wood showed a 44% reduction in polyester leaching, a 33.8% water repellency efficiency and a 46.2% anti-swelling efficiency. It was also exhibited flame retardancy, with a 33.1% oxygen index and a 47.5% reduction in total heat release, due to phytic acid's dual action in both solid and gas phases.

Before this material can be used for outdoor decoration or architectural purposes, its mechanical strength, resistance to decay and durability over time must be studied in more detail.

**Fire performance of Pinus taeda wood treated with zinc borate before and after leaching [53]**

This study examines the fire performance of Pinus taeda (loblolly pine) wood from northeastern Uruguay treated with zinc borate, a fire-retardant synthesized in the lab. The researchers tested how leaching affects the fire-retardant properties of the treated wood. Various thermal degradation parameters were analyzed, including flame spread, carbonized area, carbonization index and mass loss, with the wood exposed to flames for 30, 60 and 80 seconds in a Vandersall tunnel.

Micromorphological analysis of the wood's surfaces was conducted using scanning electron microscopy to assess fiber damage, zinc borate distribution and the impact of leaching. The results showed:

- significant improvements in fire resistance for the zinc borate-treated wood across all exposure times.
- Additionally, leaching did not compromise the fire-retardant properties, suggesting that the treated wood is suitable for outdoor use in harsh conditions.



### 3 Methodology

Chapter 3 is divided into three main subchapters where the first explains how the literature review was done, the second explains how the experiments were conducted and the last walks through how the data analysis was done.

#### 3.1 Literature review

The thesis topic emerged from informal discussion and observations in the fire and safety engineering field and to the transition into a more conscious and sustainable building material. Wood and timber have been widely discussed as sustainable building materials, leading to increased interest in how they behave under fire exposure. The call for further research of naturally weathered fire-retardants in Engström and Psajd thesis [4] is why this thesis exist today.

#### **Covidence**

Later on an *overview of previous research* was conducted to see if there was a need for further research with this topic as well as finding relevant information within the field. To help structure and follow the literature review the application Covidence was used. It makes the literature review process transparent for those interested in following the process [54], see more *in*

*Appendix 1 – Prisma Covidence* method. A so called “extraction” was not made because the tool was only used to keep track of the literature review.

### 3.2 Experimental methodology

The main source of information for the thesis is through experiments. Each step on the way from demounting of the timber façade, testing in the Cone Calorimeter, to how the results were handled, is explained in text and with photographs.

#### 3.2.1 Timber façade to sample sizes

The timber slats were prepared for the Cone Calorimeter through three main steps: demounting from the façade, sawing to right sizes, followed by acclimation in a weather chamber. The steps are explained with accompanying pictures below.

The timber slats were demounted from the façade Friday the 27<sup>th</sup> of September 2024 by a professional from the façade distribution company, see Figure 2. The timber slats from each weather line North and East were marked to keep them distinguished from each-other. They were then stored indoors in the building it was demounted from, until they were picked up and moved to the fire lab at LTH.

The slats had dust and stones stuck onto them, already when they sat up on the façade. The north facing façade had more stones and dust on them than the east, see Figure 3. Each rib got carefully brushed with a toothbrush to remove dust and small stones were removed by a tweezer, so that the sawing tools would not get damaged by the stones, see Figure 4. The slats then got marked according to the sample size for the Cone Calorimeter before they got sawed into the right dimensions.



Figure 2: Placement of slats on the west facing façade.



Figure 3: Slat with stone.



Figure 4: Hole in slat after removal of stone.

Since the size of the slats are approximately 4.5 x 4.5 cm, the sample size for the Cone Calorimeter was 9,0 x 9,0 cm to get as closed to the standard 10 x 10 cm sample size for the Cone Calorimeter, see [50]. Each rib was first marked and then sawn into the right size, see Figure 5 to Figure 10. There were three nails in each rib that had to be sawed around, leaving six eligible test pieces per rib. The slats were also split in half, see Figure 9, to shorten down the test time later in the Cone Calorimeter test and to distinguish between front (weathered) and BACK (less exposed), leaving each rib contributing with 12 test pieces. The samples were then placed in the climate chamber to get the set temperature of 23°C and moisture content 50% according to the Cone Calorimeter standard ISO 5660:1.



Figure 5: Slats before sawing. Left four slats belong to the west facing façade and the rest to the north.

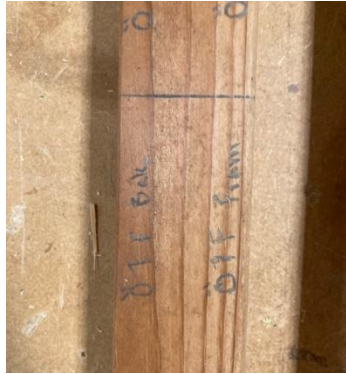


Figure 6: Marking of slats.



Figure 7: Slats sawed into pieces.



Figure 8: All test pieces after sawing.



Figure 9: Closeup on test pieces after sawing.



Figure 10: Transportation of test pieces to the lab.

### 3.2.2 Climate chamber settings

The climate chamber was used to acclimate the samples to the same moisture and temperature prior the test in the Cone Calorimeter were made. Acclimating the samples allows the testing method to be more imitable, leading to more comparable results. The chamber was set on 23 °C with a constant humidity of 50 % according to the standard ISO 5660-1 [60]. The timber samples were placed in the climate chamber with a small space between each piece to ensure full coverage of the acclimation, see Figure 11. All samples were stored in the climate chamber from Monday the 7<sup>th</sup> of October 2024 until testing day for each sample, resulting in at least 2 weeks of acclimatization. The samples were collected from the climate chamber in pairs of three, so three tests per collecting.



Figure 11: Test pieces in the climate chamber.

### 3.2.3 Cone Calorimeter calibration and settings

The Cone Calorimeter must be calibrated according to the Lund University's Manual, see *Appendix 4 - Cone Calorimeter set up*, every morning before the tests start. The calibration was done together with a supervisor that works at the division of fire and safety engineering at LTH.

### 3.2.4 ConeCalc on the computer

ConeCalc is the program that is connected to the Cone Calorimeter test. It logs all the results of the test and calculates the heat release rates, HRR, of each test.

### 3.2.5 Documentation and sample preparation of the test pieces

Each test piece was thoroughly documented with a pencil, photos and notes in excel. One sample contains two test pieces, and each sample went through the following steps:

#### Documentation

1. Collection from the climate chamber (in groups of three samples).
2. Weighing each sample (one sample = two test pieces together), Figure 12.
3. Attributes documentation in the excel spread sheet (such as knots and holes).
4. Photographing with camera and phone camera, Figure 13.



Figure 12: Scale with a sample on.



Figure 13: Photo of sample.

Step 5-9 were done one sample at a time.

5. One sample (two test pieces) placed in the sample holder, surrounded by aluminum foil and ceramic wool, **Fel! Hittar inte referenskölla.** Figure 14 Figure 16. The aluminum foil and ceramic wool were reused between samples until it looked too rough, see Figure 17.



Figure 14: Preparation table and sample holders ready for sample fitting.



Figure 15: How it looked MID-day testing.

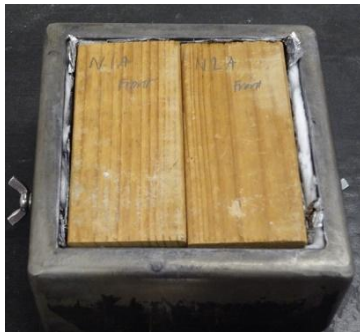


Figure 16: How a sample with sample holder looked after fitting.

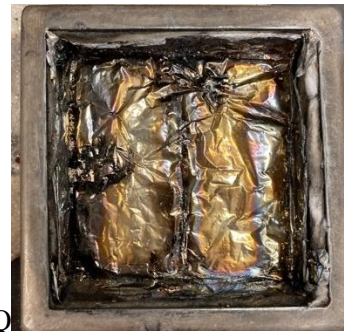


Figure 17: How aluminum foil looked like when it was time to change it.

- a. Then the sample was taken out of the sample holder.
  - b. The sample holder with ceramic wool and aluminum was placed on the holder.
    - i. The scale on the Cone Calc was tared.
    - ii. The sample holder was removed from the scale.
  - c. The sample was put back in the sample holder.
6. All parameters (weight, thickness etc) were plugged into the Cone Calc.
  7. Sample ready to be tested, see steps in the following subchapter.
  8. Results were run through ConeCalc, see the following subchapter.
  9. Results were saved onto the computer.

#### Last step was done at the end of each day

10. All result files for the day were copied and moved to a USB-stick for double storage (on the computer and on the USB-stick).

### 3.2.6 Procedure of the Cone Calorimeter test

The samples were tested with a radiant heat flux of 30, 50 and 70 kW/m<sup>2</sup>. A radiant heat flux of 50 kW/m<sup>2</sup> is a common number in the literature and therefore was chosen to be the most frequent tested radiant heat flux. This is to be able to use the results from this study to compare to results from other studies.

A heat flux of 30 kW/m<sup>2</sup> was chosen for testing, as it reflects the early stages of a material catching fire, when the heat exposure is generally lower. This is particularly interesting when considering fire spread along a façade, where the radiant heat flux decreases with distance from the fire source. Understanding how the material reacts to lower levels of radiant heat flux can provide insight to the ignition behavior of timber slats located further from the fire, compared to those exposed to higher heat flux levels, such as 50 and 70 kW/m<sup>2</sup>, closer to the ignition point.

A heat flux of 70 kW/m<sup>2</sup> was chosen for testing, as it represents more severe fire conditions that may occur when flames are in closer proximity to the façade. This level of exposure is relevant for understanding how timber behaves when subjected to intense radiant heat, such as in areas directly adjacent to or above an active fire. By examining the material's response under these conditions, insights can be gained into its ignition behavior and contribution to fire spread in the most exposed parts of the façade.

A heat flux of 70 kW/m<sup>2</sup> was chosen to observe the material's response under more intense conditions. The same step size used to reach 30 kW/m<sup>2</sup> from 50 kW/m<sup>2</sup> was applied upward, landing on 70 kW/m<sup>2</sup> to provide a structure in the choosing of radiant heat fluxes.

Each test, after the sample preparation, followed these steps:

1. Cone Calc calibrated.
2. Press start on Cone Calc on the computer.
3. Sample holder, with sample in, was placed under the cone.
4. The spark igniter was placed over the sample.
5. Cover was removed and “start test” button was pressed simultaneously.
6. Full attention on the sample to catch when ignition happens.
  - a. When ignition happened the button “ignition” was pressed on the computer.
7. Monitoring of the testing.
8. End test on Cone Calc on the computer.
  - a. Either when steady state arrived or until flameout, depending on if there was enough time to wait until cool down or not.
9. Sample holder was removed from test position up to the cool down shelf.



Figure 18: MID test in the Cone Calorimeter.

### 3.2.7 Management of the results

The data and results of the tests went through data analysis to make graphs and tables to be able to understand and illustrate the results more easily. Cone Calc calculated the PHRRPUA of each test. MatLab was used to plot graphs and to do the color analysis of each sample's colors. The color graphs were then compared to the PHRRPUA curves. Lastly the results of the data-analysis were studied and discussed, forming the discussion and conclusion of the thesis.

### 3.3 Data analysis

This subchapter explains how the data analysis was conducted.

#### 3.3.1 MatLab, what to plot against what

The results from the tests were processed with MatLab to facilitate plotting of graphs. What to show in the results and how to present the result was discussed between the author and the supervisors. The results were clustered into different groups to be able to study and highlight differences in the results.

The thesis aims to show the differences in the reaction to fire properties of different parts of the slats. The samples from Malmö were also compared to non-weathered and non-treated pine timber and the non-weathered Thermowood.

#### 3.3.2 TRP and FBI calculations

TRP and FBI calculations were made in Excel, see *Appendix 3 - Extended calculations*.

#### 3.3.3 T-test

Independent t-tests are used to assess if there is a difference between groups of samples [52]. The aim in this study is to assess if there is a real difference, or just chance, between the groups FRONT, MID, BACK, non-treated and TW, see results in Subchapter 6.3.

A double sample independent t-test was conducted on the peak heat release rate per unit area *PHRRPUA*, average heat release rate *average HRR* and time to ignition *TTI* values. The samples are independent since the backside is so little weather-exposed that it is considered to be non-weather-exposed, while the FRONT is weather-exposed and the middle samples are assumed to have less fire-retardant than the outside (front, back and sides) of the slats.

The assumption that there is less fire-retardant in the MID of the slats than on the surface, is derived from information from the fire-retardant company. This was also observed during the Cone Calorimeter tests in this study, where the MID samples showed similar burning behavior and patterns of char and ash formation to those of the non-treated, non-weathered samples. Therefore, it was decided to consider the MID samples as independent from the BACK and FRONT samples, even though all three groups are from the same timber slats.

The t-test was conducted in MatLab using the *PHRRPUA*, *average HRR* and *TTI* given from the Cone Calorimeter tests. The *average HRR* is calculated over the first 180 seconds, as this time frame captures the majority of changes in heat release rate, see all graphs of the results in Chapter 5.



## 4 Material properties of the timber samples

Chapter 1 presents the material properties of the timber slats before the Cone Calorimeter testing. It is unclear if the documentations, where some of the information below is taken from, are linked to this product. The uncertainty lies in the lack of written connection confirming that the tested product is the same type as the one delivered to the customer. To be noted is that the documentations are said to belong to this same type of product by the distributor company and the impregnation company.

Table 2 contains measured information from before the tests were made. See all information in *Appendix 5 - Detailed information about the samples*.

Table 2: Information about the samples.

Sample	<i>Malmö façade</i>	<i>Regular pine</i>	<i>Thermowood</i>
Weathered	About 1-2 years	No	No
Mass (g)	60-102	90-102	97-104
Thickness (mm)	18-21	20-21	21
Exposed Area (cm <sup>2</sup> )	76-80	84.6	88.4

**Information about the fire impregnation handed by the distribution company, see**

*Appendix 8 - Declaration of performance and Appendix 9 - Documentation EN 16755:*

<b>Material:</b>	89 % Thermowood pine, Siberian
	11 % Water resistant fire impregnation
<b>Surface layer class :</b>	B-s2,d0
<b>Before accelerated aging:</b>	EXT according to EN 16755:2017
<b>After accelerated aging:</b>	EXT according to EN 16755:2017, “Durable over time”

**Extra:**

**Type of impregnation:** Reactive, according to the fire impregnation company.

**SP FIRE 105 test:** Not SP FIRE 105 tested according to the distributor company:  
“It was never a question to get it SP FIRE tested.”



## 5 Results Cone Calorimeter tests

Chapter 5 presents the results of the Cone Calorimeter tests. It is always compelling to show as much as possible of the results in the results chapter. However, one does not want to lose the reader because of the vast number of graphs. To the eager reader, skim through this chapter and see if there is a pattern among the graphs.

The graphs are made from the data measured by the Cone Calorimeter for each test. To emphasize and highlight significant results, photos and drawings do also appear in this chapter. Further elaboration and comments on the results and the thesis as a whole, is found in Chapter 1 and 1.

Each graph show a typical heat release to time curve for thermally thick materials that char, with a peak followed by a steady state and then a second peak, see comparison on page 336 in [49].

### 5.1 Structure of the results

The result for each heat flux is plotted in one figure, leaving three main figures in total. Graphs in the main figures have then been dimmed to highlight graphs of interest, creating new graphs to make it more comprehensive. The main figures are found in *Appendix 7 – Extended results*.

Each heat flux (30, 50 and 70 kW/m<sup>2</sup>) has its own subchapter with the following structure to create consistency and transparency in what is shown in the results chapter.

#### Radiant heat flux

- East side
- North side
- East vs North side
  - FRONT
  - MID
  - BACK

Be attentive to the colors of the graphs and the names of the sample. One sample does not have a consistent color throughout all the graphs, this is because the colors are changed between the figures with the intention to make it easier to distinguish the different samples in each graphs depending on what the figure is intended to show. One color-consistency is that **East** is usually represented with **yellow/orange/red** and **North** with **blue** colors.

The test time was set to about 700 seconds to ensure that there was time to test all the samples, therefore the second peak or burnout was generally not reached. The time to ignition cannot properly be read from the graphs in this chapter and is therefore presented in Appendix 3 - Extended calculations and together with the color analysis in Chapter 1.

### 5.2 Deviations

All tests that were conducted during Friday the 25th of November are not presented in the PHRRPUA to Time graphs. That is because *the analyzer switch* on the Cone Calorimeter was forgotten on "CO/CO<sub>2</sub>", instead on switched over to "sample gas". That means that the gas from the samples burning was not measured and registered correctly and therefore there are no valid values for the CO/CO<sub>2</sub> measurements from these tests.

Most of the invalid sample-gas test from Friday the 25th were made at radiant heat flux 50 kW/m<sup>2</sup>. For future testing it is wise to spread out the different types of tests, to different days, so that there is less vulnerability in the large test pool for human errors such as this one. Further analysis of errors in the test-procedure et cetera is presented in Chapter 1.

### 5.3 30 kW/m<sup>2</sup>

To be viewed in this chapter are results from tests made with radiant heat flux 30 kW/m<sup>2</sup>.

#### 5.3.1 East side 30 kW/m<sup>2</sup>

Results of the east side at radiant heat flux 30 kW/m<sup>2</sup>. Darker color of the graph represents the BACK of the slats, and lighter color the front. The peak heat release rate per unit area, PHRRPUA, is approximately 150 kW/m<sup>2</sup>, see Figure 19. The FRONT samples have a higher PHRRPUA than the BACK samples, see Figure 20.

Thermowood has lower PHRRPUA, followed by FRONT, and the non-treated samples have the highest PHRRPUA, see figure 22. The MID sample has a similar burning behavior as the non-treated samples, see figure 23.

The least weather-exposed sample “E back sl 3 4 pos A” has a lower PHRRPUA than the most exposed sample “E front sl 3 4 pos F”, see Figure 23. The least exposed position A, front vs BACK, is shown in Figure 24. The most exposed position F is shown in Figure 25. The PHRRPUA for position F is higher than position A.

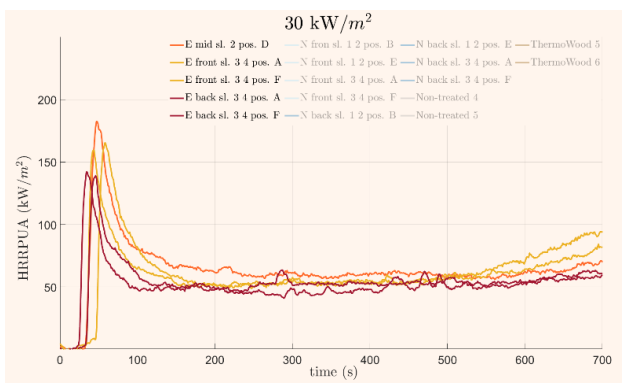


Figure 19: East slats all graphs.

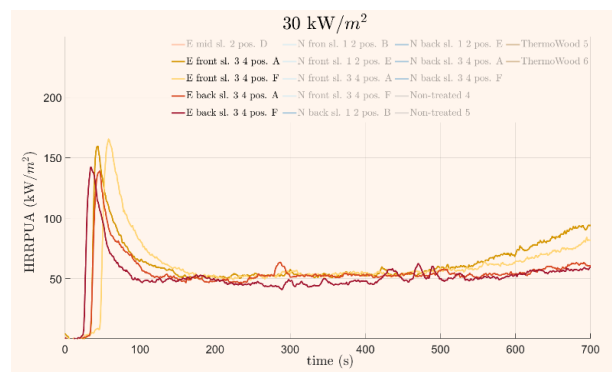


Figure 20: East FRONT vs BACK.

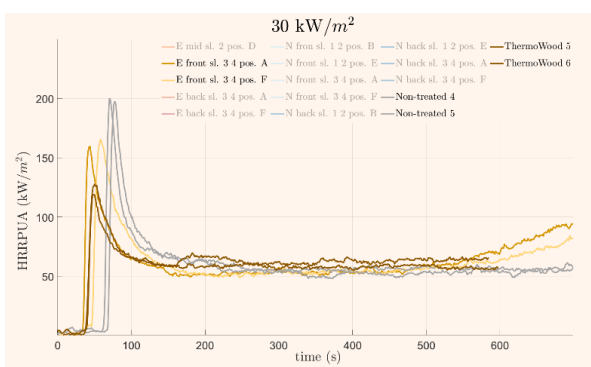


Figure 21: East FRONT vs Thermowood vs NON-treated.

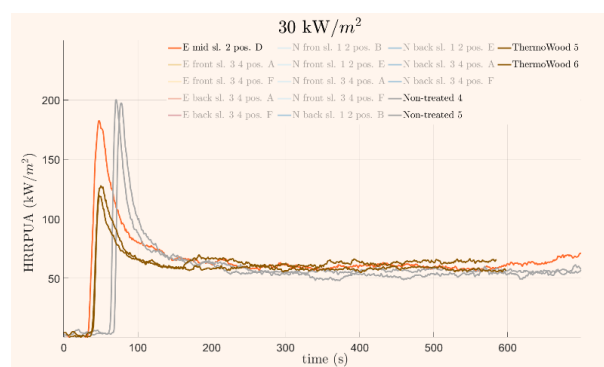


Figure 22: East MID vs Thermowood vs NON-treated.

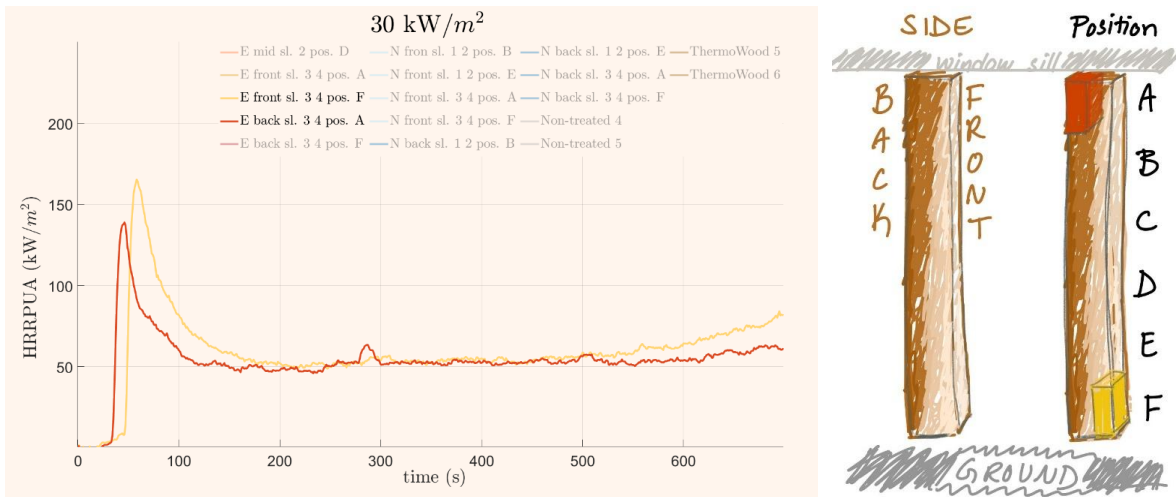


Figure 23: East most vs least weather-exposed.

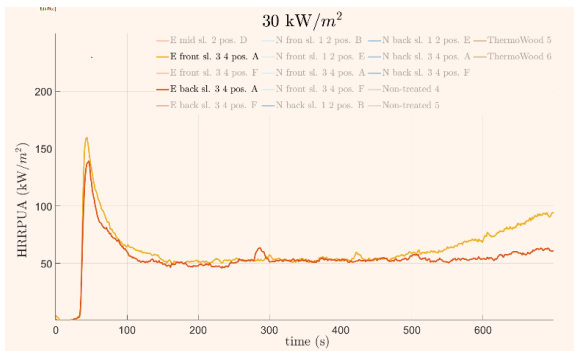


Figure 24: East position A front vs BACK.

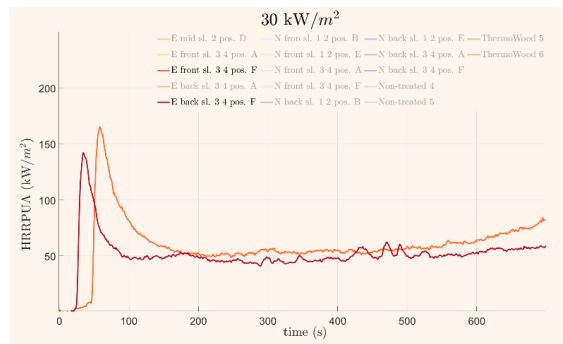


Figure 25: East position F front vs BACK.

### 5.3.2 North side 30 kW/m<sup>2</sup>

Results of the north side at radiant heat flux 30 kW/m<sup>2</sup>. Darker color of the graph represents the BACK of the slats, and lighter color the FRONT.

The peak heat release rate per unit area, PHRRPUA, is approximately 110 - 180 kW/m<sup>2</sup>, see Figure 26. The FRONT samples have a higher PHRRPUA than the BACK samples, see figure 27, and compare Figure 28 to Figure 29. Thermowood have lower PHRRPUA, followed by FRONT, and the non-treated samples has the highest PHRRPUA, see Figure 27.

The most exposed position F has the highest PHRRPUA of the fire-retardant-impregnated timber among the FRONT samples, see Figure 28. The BACK samples all have a similar burning behavior compared to each other, except for sample “N back sl. 1 2 pos. B”, see Figure 29.

The difference between the least, and most weather exposed samples are shown in Figure 30 where the most exposed sample “N front sl. 1 2 pos. E” have a higher PHRRPUA. Second to least, and most weather exposed samples are shown in Figure 31 where the same tendency is shown as in Figure 30.

The difference between FRONT and BACK at the same position are shown in Figure 32 and Figure 33, and it shows that the FRONT has a higher PHRRPUA than the BACK.

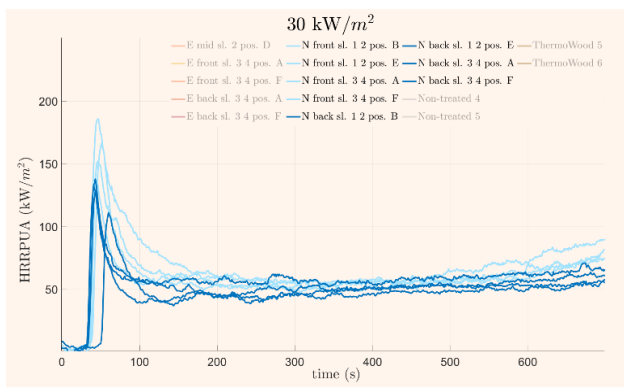


Figure 26: North FRONT vs BACK.

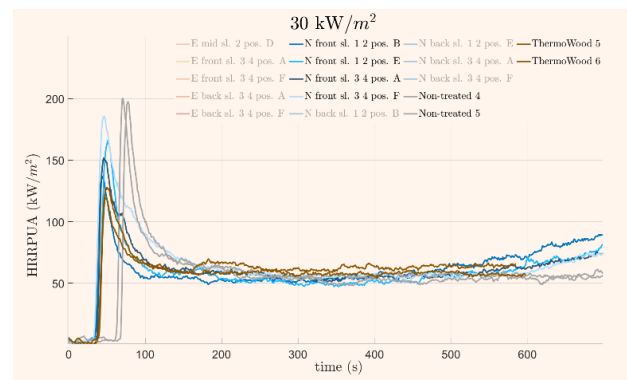


Figure 27: North FRONT vs Thermowood vs NON-treated.

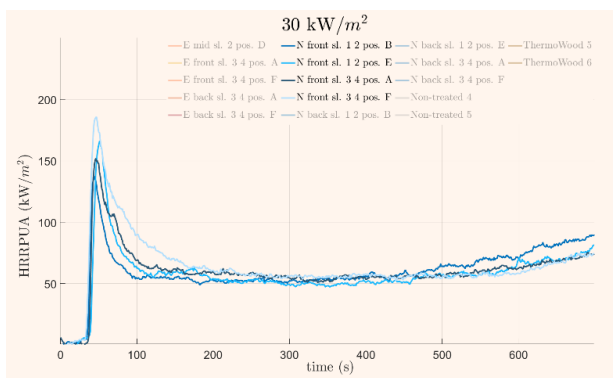


Figure 28: North FRONT.

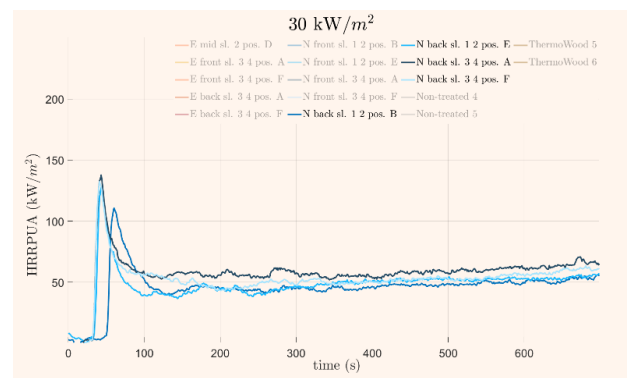


Figure 29: North BACK.

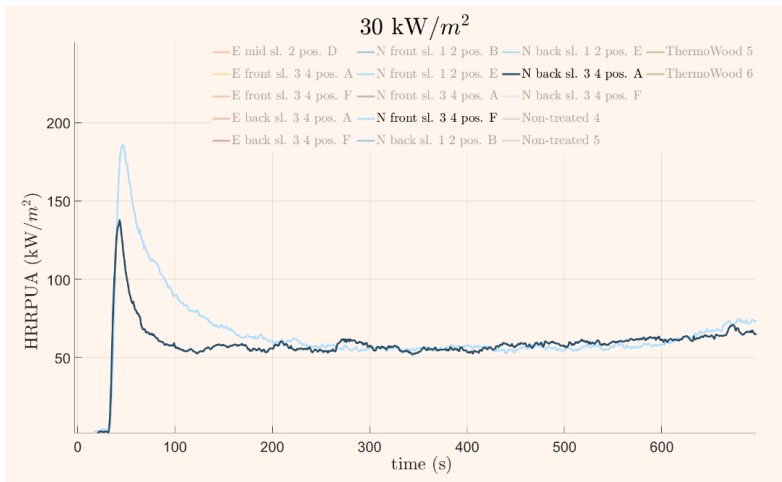


Figure 30: North most vs least weather-exposed.

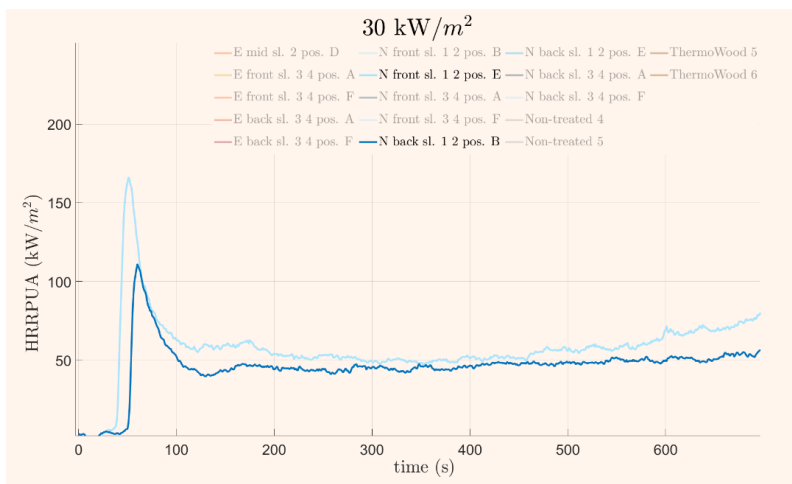
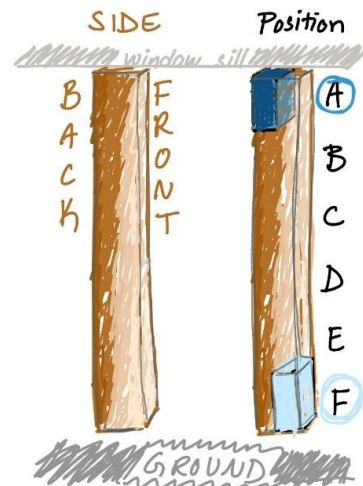


Figure 31: North second to least vs most weather-exposed.

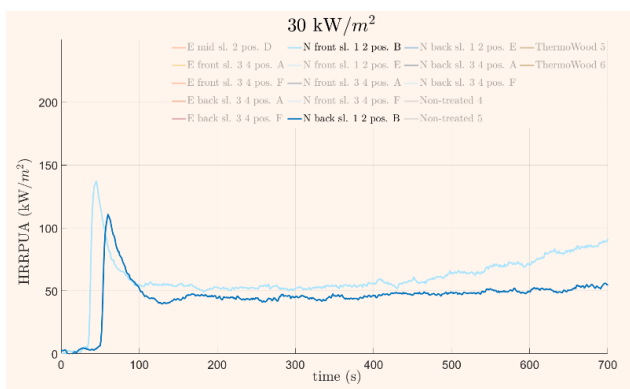
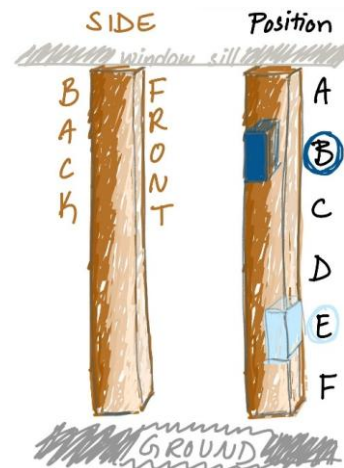


Figure 32: North position B, FRONT vs BACK.

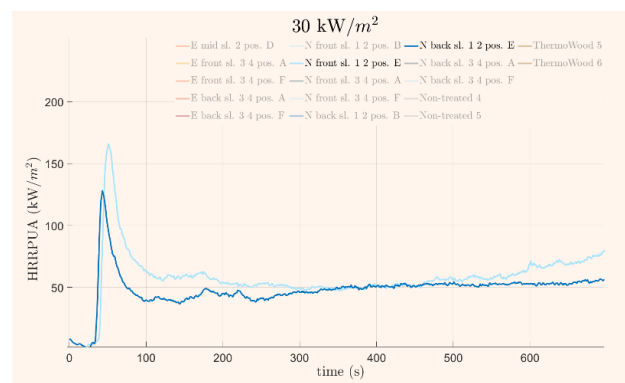


Figure 33: North position E, FRONT vs BACK.

### 5.3.3 East VS North side 30 kW/m<sup>2</sup>

The following figures show east, and north samples tested at radiant heat flux 30 kW/m<sup>2</sup>.

#### 5.3.3.1 FRONT

The FRONT samples have a similar burning behavior and PHRRPUA independent on the weather line, see Figure 34. The FRONT samples have a slightly lower PHRRPUA than the non-treated samples, and a higher PHRRPUA than Thermowood, see

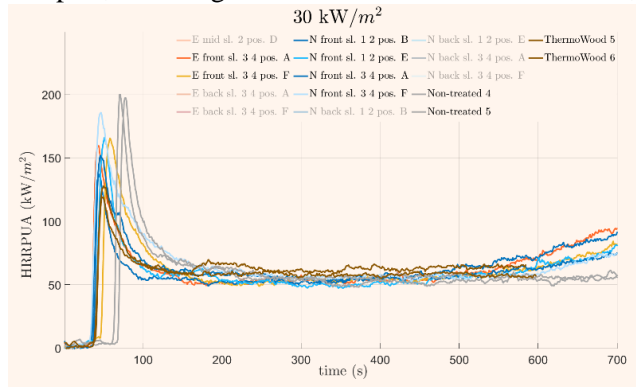


Figure 35.

The position, further from the ground and closer to the window sill is A, of the sample seems to be of more relevance than the weather line, see Figure 36, and

Figure 37.

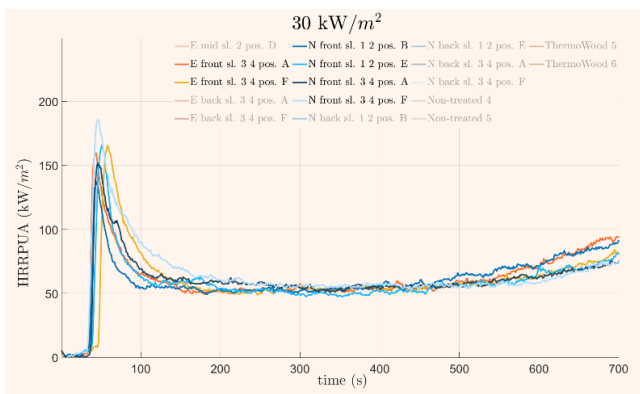


Figure 34: East vs North, FRONT

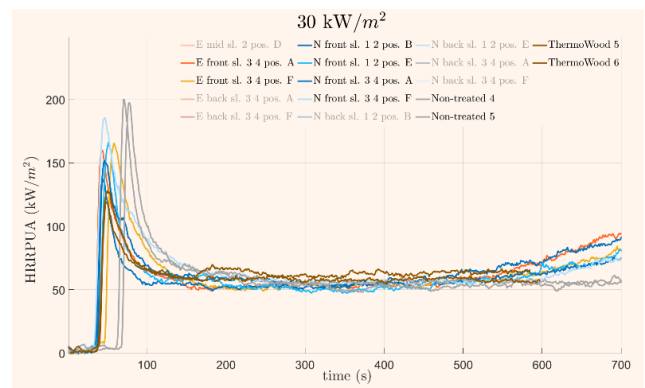


Figure 35: East vs North vs Thermowood vs Non-treated, FRONT

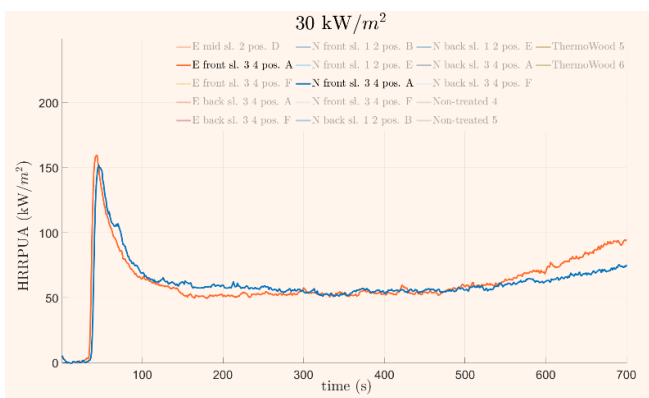


Figure 36: East vs North, position A.

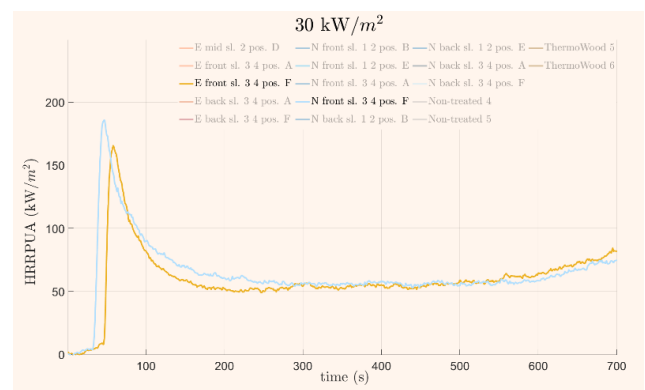


Figure 37: East vs North, position E.



5.3.3.2 MID

There is only one sample at radiant heat flux 30 kW/m<sup>2</sup> from the MID, see Figure 38. This is because other radiant heat fluxes, and positions were prioritized out of the limited amounts of samples. It was for example argued that multiple MID tests at 50 kW/m<sup>2</sup> were of more interest than multiple MID tests at 30 kW/m<sup>2</sup> because the radiant heat flux 50 kW/m<sup>2</sup> appears more often in the literature.

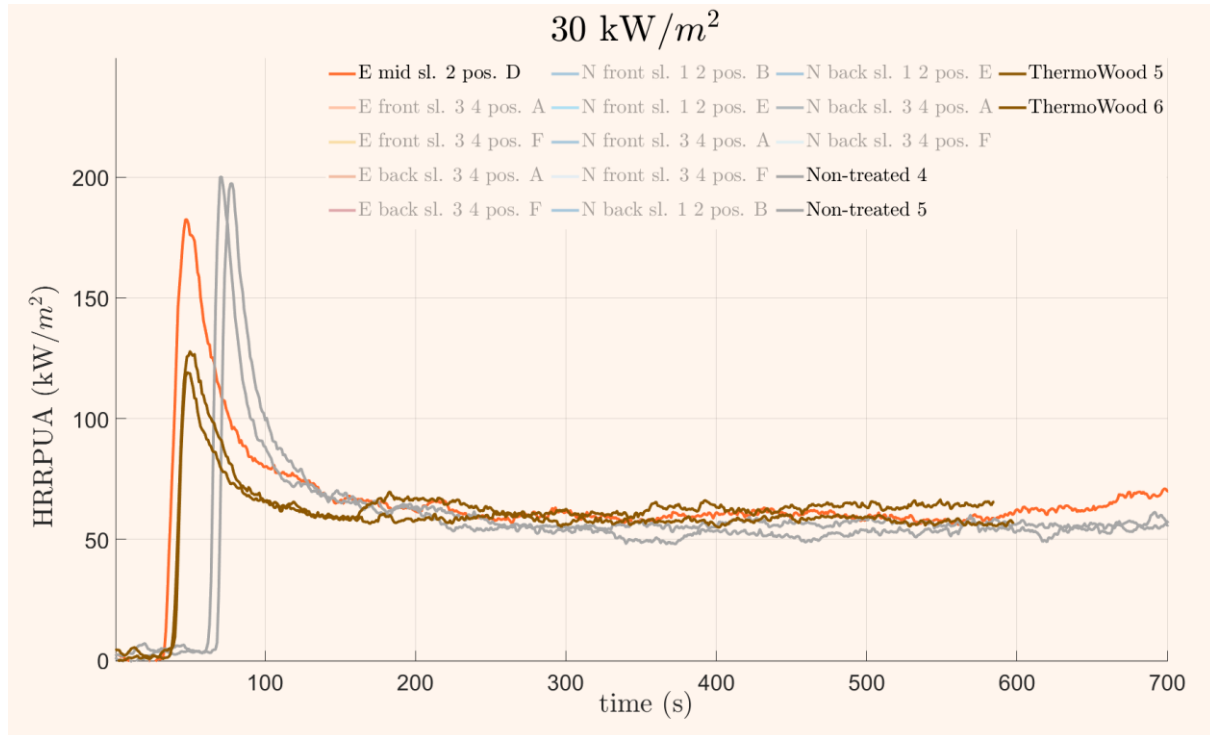


Figure 38: East MID vs Thermowood vs NON-treated.

5.3.3.3 BACK

The BACK samples have a similar burning behavior independent of the weather line, see Figure 39. All BACK samples have a lower PHRRPUA than the non-treated samples, and a slightly higher PHRRPUA than Thermowood, see Figure 40.

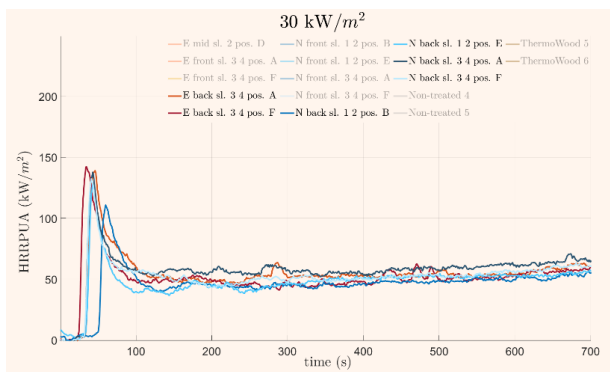


Figure 39: North vs East BACK.

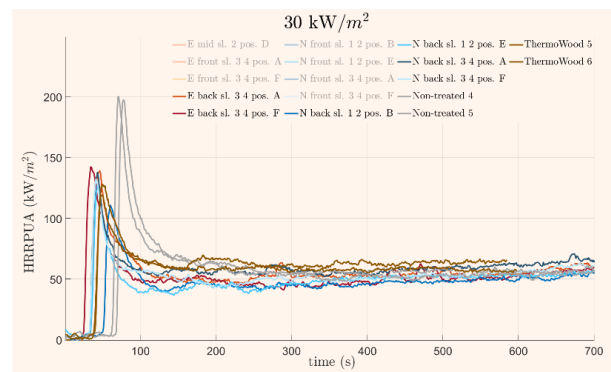


Figure 40: North vs East vs Thermowood vs Non-treated, BACK.

## 5.4 50 kW/m<sup>2</sup>

To be viewed in this chapter are results from tests with radiant heat flux 50 kW/m<sup>2</sup>.

### 5.4.1 East side 50 kW/m<sup>2</sup>

The PHRRPUA change between approximately 150 – 210 kW/m<sup>2</sup> for the fire-retardant-impregnated timber samples, see Figure 41. The heat release rate HRR between FRONT and BACK differ with 50 kW/m<sup>2</sup>, see Figure 42.

The FRONT samples reach their second peak earlier than the BACK, non-treated or Thermowood samples, see Figure 43. The MID samples have a similar PHRRPUA as the non-treated samples, see Figure 44. Visual observations during the tests noted that the MID samples exhibited burning behavior similar to that of the non-treated samples. Both the flaming characteristics and char formation of the MID samples closely resembled those of the untreated timber, and differed noticeably from the char formation observed of the fire-retardant-impregnated timber samples. The residue from the MID and non-treated samples were similar and distinguished from the fire-retardant-impregnated timber samples.

All samples extracted from two slats on the east-facing side were tested at a heat flux of 50 kW/m<sup>2</sup> across all positions. The results are presented in Figure 45. Least vs most weather-exposed samples are shown in Figure 46.

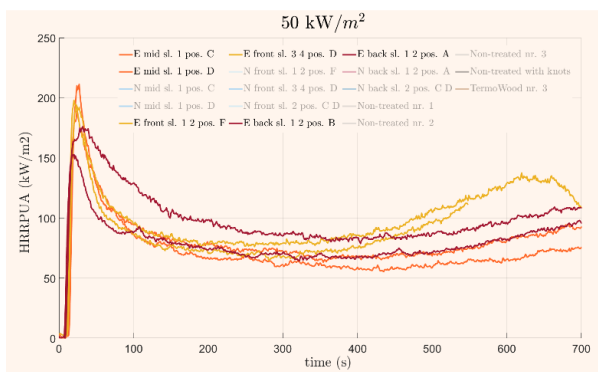


Figure 41: East all values at 50 kW/m<sup>2</sup>.

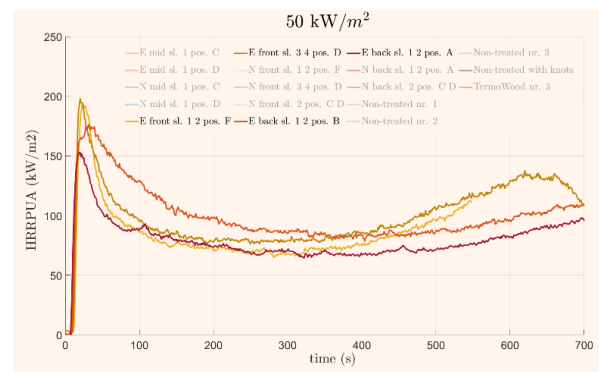


Figure 42: East FRONT vs BACK.

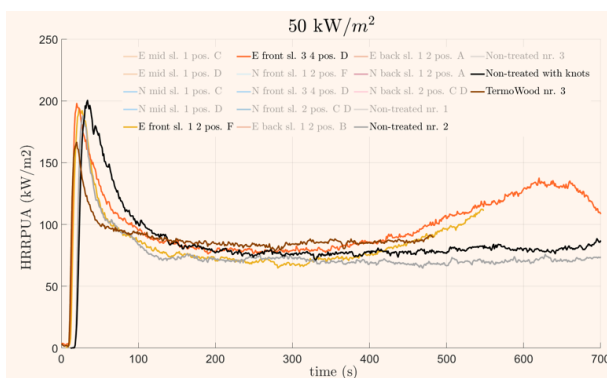


Figure 43: East FRONT vs Thermowood vs NON-treated.

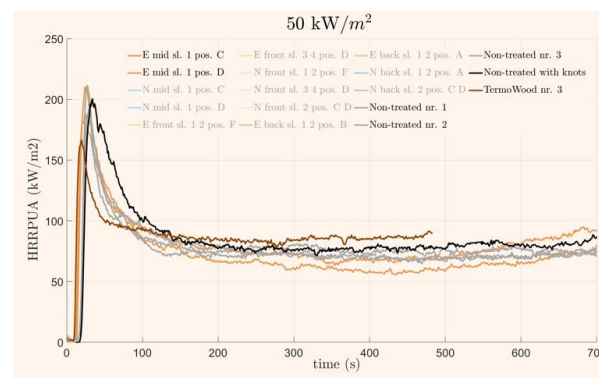


Figure 44: East MID vs Thermowood vs NON-treated.

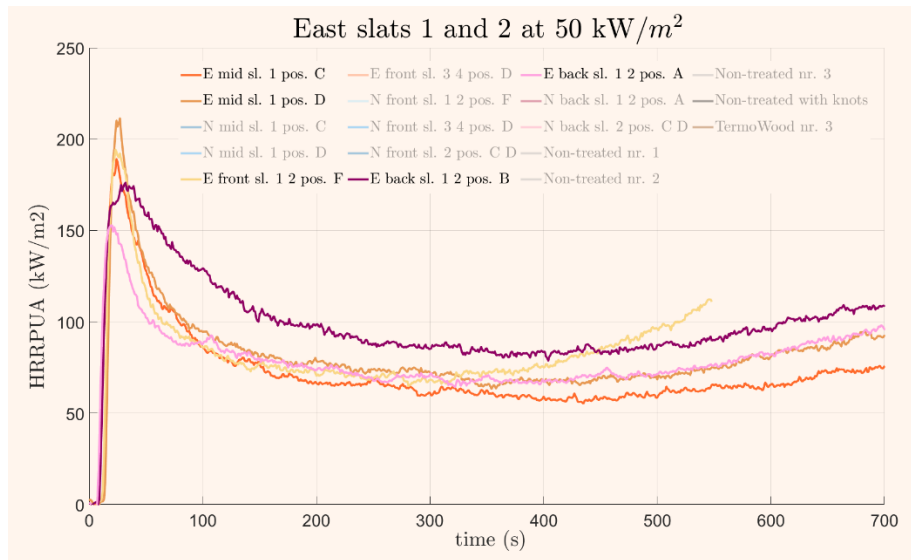


Figure 45: East slats 1 2.

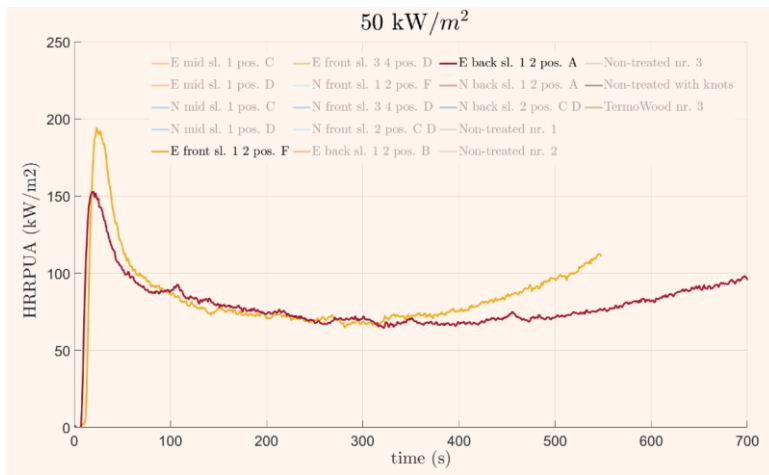


Figure 46: East most vs least weather exposed samples.

### 5.4.2 North side 50 kW/m<sup>2</sup>

All north-facing samples tested at 50 kW/m<sup>2</sup> are shown in Figure 47 where it can be read that the FRONT and MID samples have a higher PHRRPUA than the BACK samples. The PHRRPUAs have a span between 140 to 230 kW/m<sup>2</sup>. The FRONT samples have a higher PHRRPUA and meets their second peak quicker than the BACK samples, see Figure 48 and Figure 51.

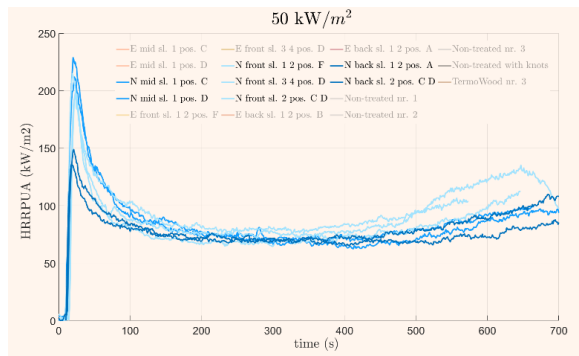


Figure 47: North all values at 50 kW/m<sup>2</sup>.

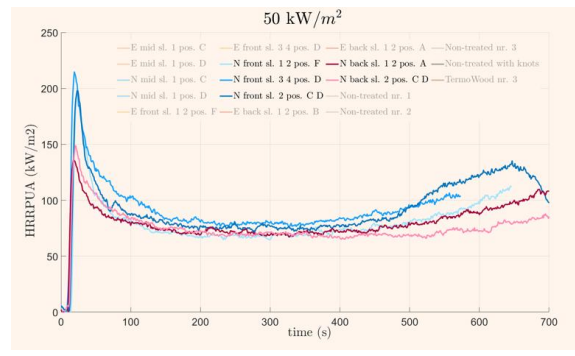


Figure 48: North FRONT vs BACK.

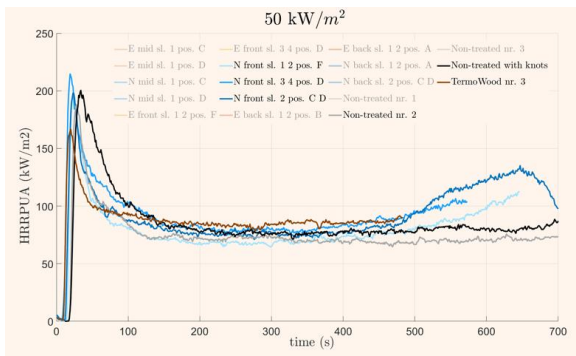


Figure 49: North FRONT vs Thermowood vs NON-treated.

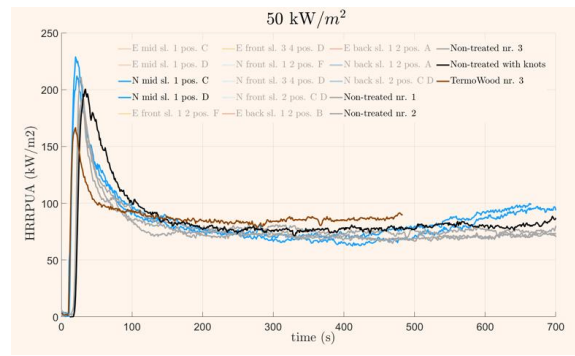


Figure 50: North MID vs Thermowood vs NON-treated.

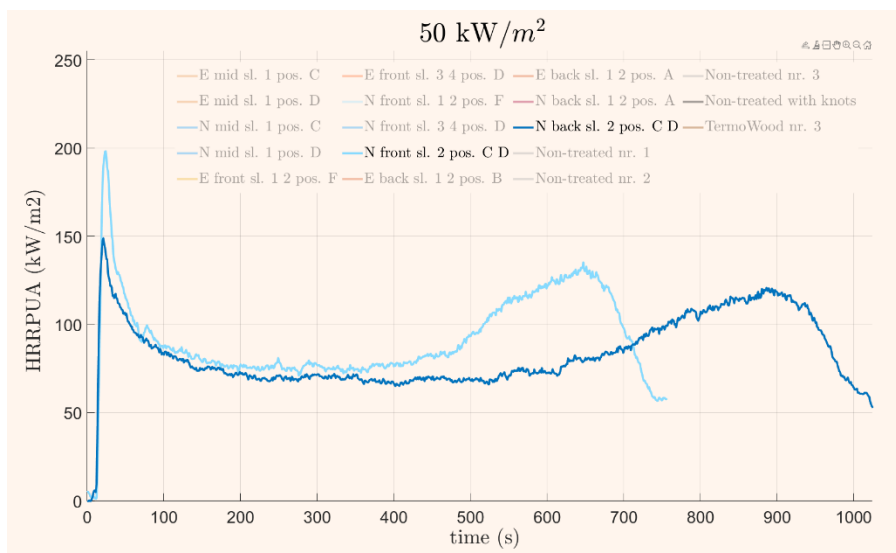


Figure 51: North slat 2 position C D, FRONT vs BACK.

### 5.4.3 East VS North sides 50 kW/m<sup>2</sup>

East vs north side at radiant heat flux 50 kW/m<sup>2</sup> is shown in the figures below. The PHRRPUA is about the same for east and north, around 200 kW/m<sup>2</sup>.

#### 5.4.3.1 FRONT

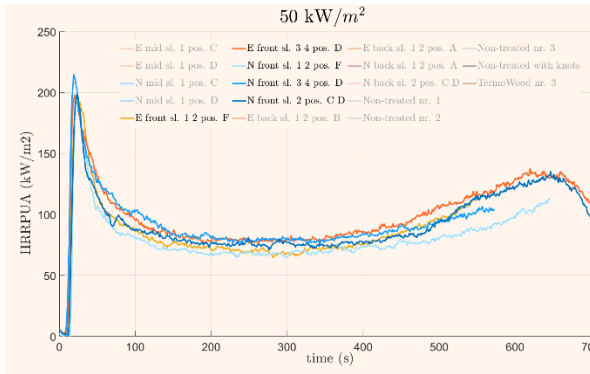


Figure 52: East vs North, FRONT.

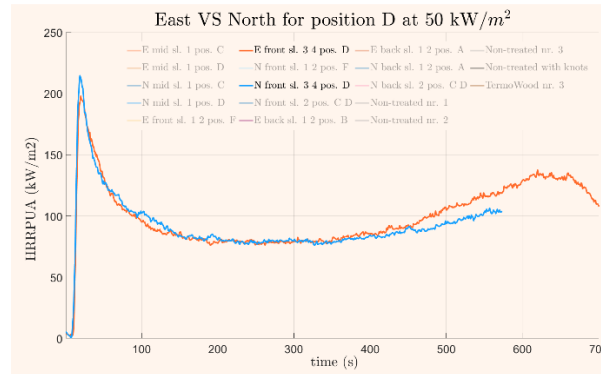


Figure 53: East vs North, position D.

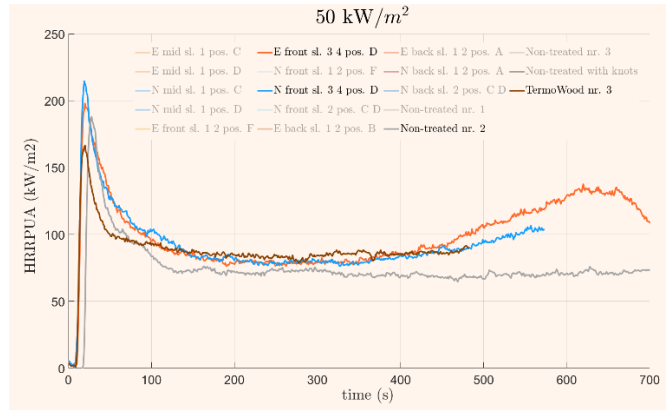


Figure 54: East vs North vs Thermowood vs Non-treated, FRONT.

#### 5.4.3.2 MID

The differences between the MID samples of slat one, position C and D, for north and east side is shown below in Figure 55. Continuing to show east and north MID compared to non-weathered: non-treated pine timber and Thermowood in Figure 56.

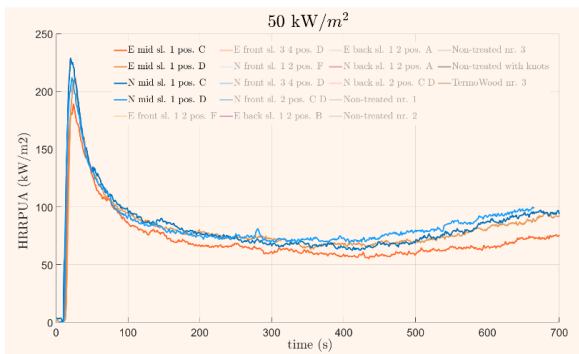


Figure 55: East vs North MID.

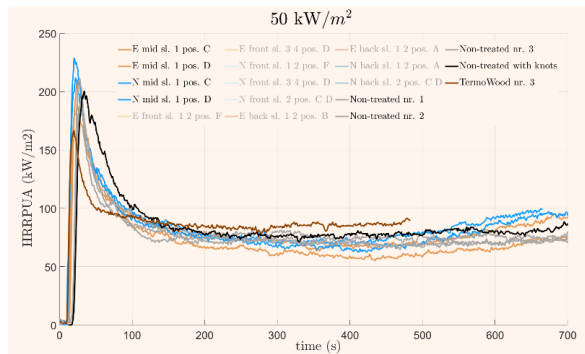


Figure 56: East vs North vs Thermowood vs Non-treated, MID.

### 5.4.3.3 BACK

The BACK of the timber slats, being the least exposed to weather, appear to retain the highest amount of fire-retardant content. This observation is supported both by the experimental findings and discussions with the fire-retardant manufacturers, who have noted that the fire-retardant is often concentrated within the outermost millimeters of the timber and may gradually leach out due to rain and weathering. Therefore, it is of interest to compare the BACK of east to north as shown in Figure 57 and compare those to the non-weathered or fire-impregnated Thermowood and pine, see Figure 58. They illustrate what the difference can look like.

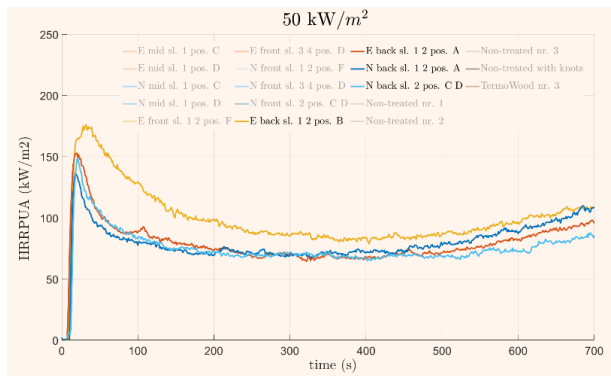


Figure 57: East vs North, BACK.

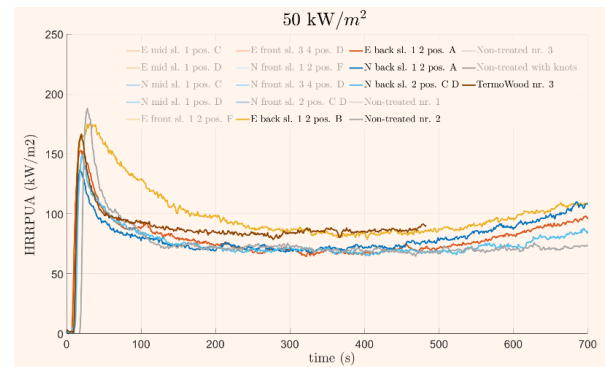


Figure 58: East vs North vs Thermowood vs Non-treated.

The yellow graph “E BACK sl. 1 2 pos. B” does not follow the other graphs pattern. When only looking at the sample names “E BACK sl. 1 2 pos. A” vs yellow “E BACK sl. 1 2 pos. B”, two test that have almost the same origin from east slats 1 and 2 with the neighboring positions A and B at the same radiant heat flux, it could be thought that they should have pretty much identical graphs, which they do not. This could be because of the sample to the yellow graph contains a larger knot, see Figure 60, which the rest of the samples do not, see Figure 59, Figure 61 and Figure 62.



Figure 59:  
Orange graph, sample  
“E BACK sl. 1 2 pos. A”.



Figure 60:  
Yellow graph, sample  
“E BACK sl. 1 2 pos. B”.



Figure 61:  
Dark blue graph, sample  
“N BACK sl. 1 2 pos. A”.



Figure 62:  
Light blue graph, sample  
“N BACK sl. 2 pos. C D”.

## 5.5 70 kW/m<sup>2</sup>

To be viewed in this chapter are results from the radiant heat flux 70 kW/m<sup>2</sup>.

### 5.5.1 East side 70 kW/m<sup>2</sup>

The BACK sample has the lowest PHRRPUA, followed by FRONT and then the MID sample has the highest, see Figure 63. In the figure it can also be read that the FRONT samples reach their second peak faster than the BACK and MID samples.

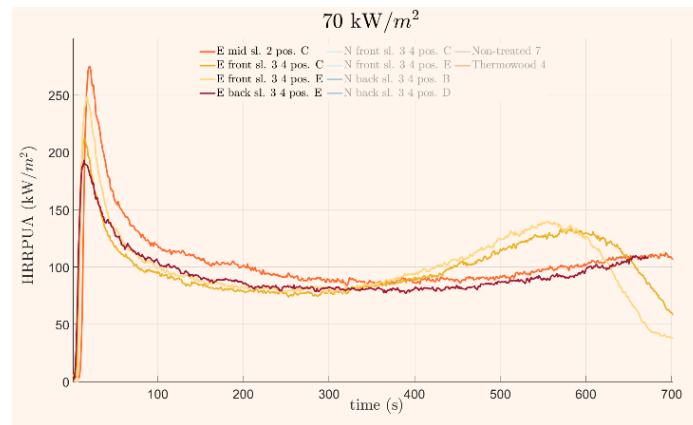


Figure 63: East results.

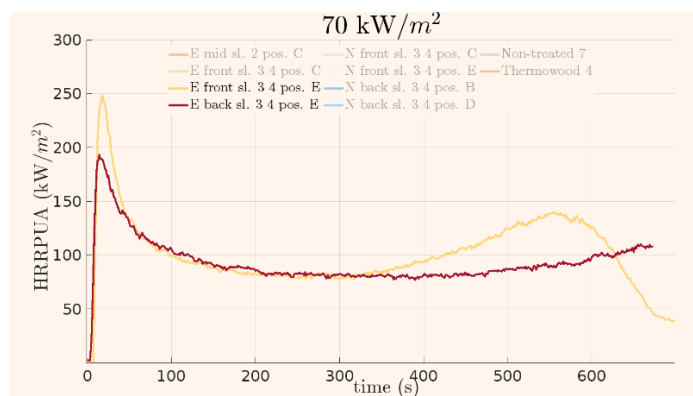


Figure 64: Same position, FRONT vs BACK

### 5.5.2 North side 70 kW/m<sup>2</sup>

Peak heat release rate per unit area is between 200 to 250 kW/m<sup>2</sup> for the north side, see

Figure 65. The FRONT samples are represented by light blue, and the BACK are represented with dark blue color.

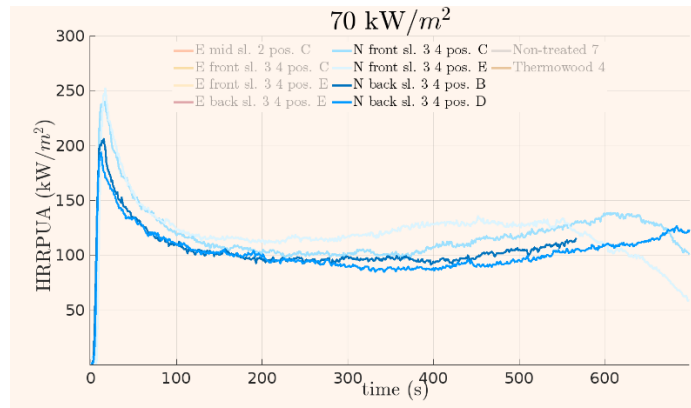


Figure 65: North BACK vs FRONT at 70 kW/m<sup>2</sup>

5.5.3 East VS North side 70 kW/m<sup>2</sup>

East vs north side at radiant heat flux 70 kW/m<sup>2</sup> is shown in the figures below. The PHRRPUA is approximately the same for the samples from east and north side, around 200-250 kW/m<sup>2</sup>. East is represented by yellow/orange/red colors and north with blue colors.

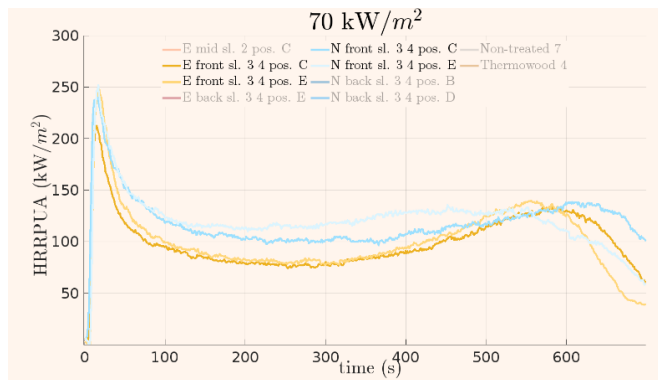


Figure 66: FRONT

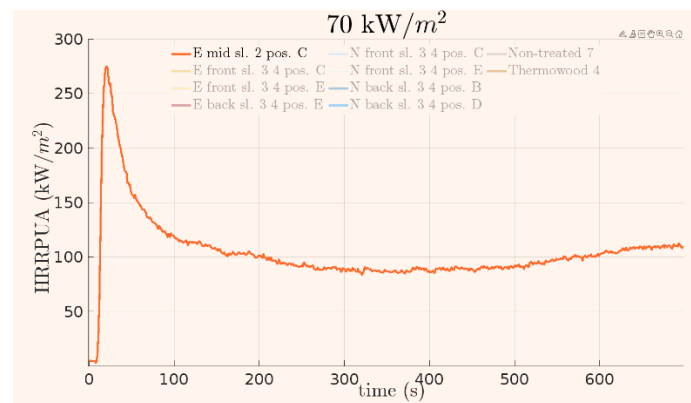


Figure 67: MID

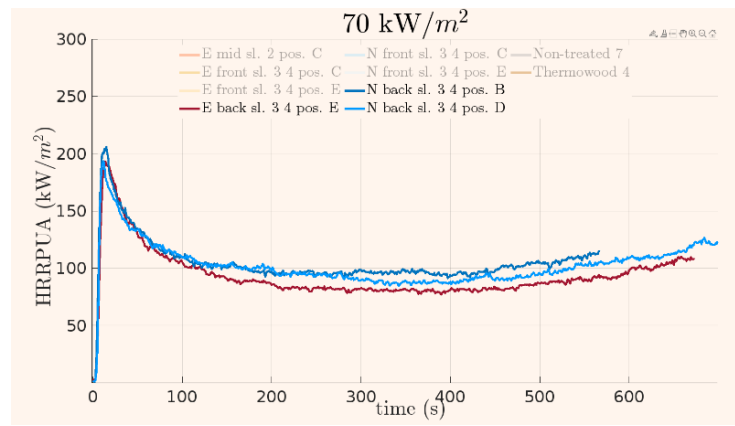


Figure 68: BACK

## 5.6 Observation of burning behavior, char and ash formation

The following figures show the difference before and after the Cone Calorimeter test. Unfortunately, no photographs were taken of the charred MID or Thermowood samples, as their documentation was not initially thought interesting during the experimental phase and only became relevant during the thesis writing process.

Figure 69 show the typical appearance of a BACK sample before and after the Cone test. Figure 70 show the appearance of a burned knot from a BACK sample. The BACK samples have a shinier char surface than the non-treated samples, compare to Figure 71 which show a typical char formation of a non-treated and non-weathered sample.

Figure 72 show a MID sample before and after the Cone Calorimeter test. The post-test image shows the side that faced downward in the sample holder, as this surface displayed an unusual texture that drew immediate interest. Consequently, a photograph of the upward-facing side was not taken. The texture reminds of shaving cream, when the bottle is not well shaken, and of white lichen.

Figure 73 shows sample “N front. sl. 1 2 pos. B” before and after the Cone Calorimeter test. Slat 2 position B had a stone hole in it, which also is noticeable in the char formation after the test. The stone hole has a whiter ash formation, similar to the appearance of the non-treated samples in Figure 71. Why it looks like the hole is further down on the ash picture could be because of the angle of the photograph or that it has a knot on the BACK in the upper left corner, resulting in a more aggressive burning and char building compared to the rest of the sample, pushing onto the rest of the timber.

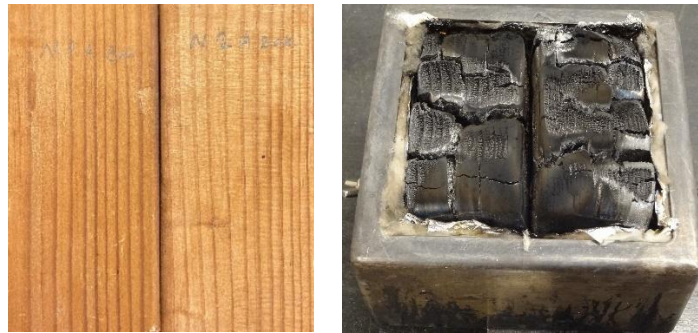


Figure 69: Typical appearance of a BACKside sample before and after Cone testing.



Figure 70: Sample E\_1B2B\_BAK with knot. The right photo is the appearance of the knot charring of sample E\_1B\_BAK.

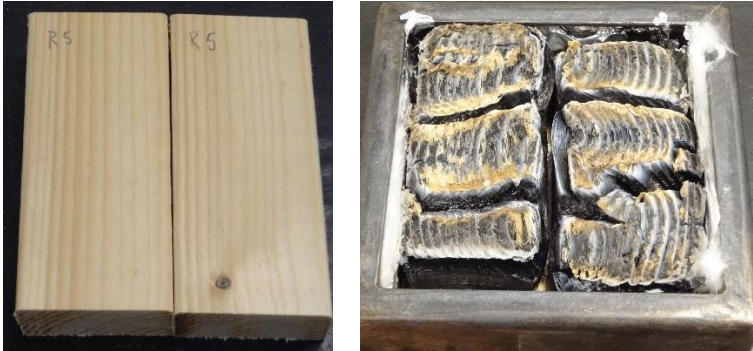


Figure 71: Non-treated and non-weathered sample before and after the Cone test.



Figure 72: Sample E\_2\_D\_MID. The right photo is from the "BACKside" of this sample, the part facing down into the sample holder, after burning.



Figure 73: Sample N\_1B2B\_FRONT before and after Cone testing



## 6 Analysis of the results

Chapter 6 presents the analysis of results from the Cone Calorimeter. A photo-analysis, TRP and FPI values are presented.

### 6.1 Photo analysis

The following text explains the graphs on the next page. Triangles, circles, and squares represent samples from the FRONT, MID, and BACK positions, respectively. The left y-axis is shown in blue, while the right y-axis is in orange. Blue shapes correspond to values plotted on the left y-axis, and orange shapes correspond to values on the right y-axis. The x-axis is shown in black but is not color-coded in the shapes. Each x-value has one blue and one orange shape, representing a single sample.

Left y-axis:   Blue                   Heat release rate per unit area (kW/m<sup>2</sup>)

X-axis:        Black                Average RGB Intensity

Right y-axis: Orange               Time to ignition (s)

△ :           FRONT           Sample from front side of slat

○ :           MID                Sample from MID of slat

□ :           BACK               Sample from BACK side of slat

It is observed that the BACK samples tendency is to the down left corner of the graph and the MID and FRONT are to the upper right side of the graphs, see Figure 74, Figure 75, Figure 76. This correspond to the TRP values where front and MID values are higher than the BACK value, see subchapter 6.2 below.

#### Sample without HRRPUA values

The test from Friday the 25<sup>th</sup> of October 2024 are lacking their heat release rate per unit area because the sample gas was left on CO/CO<sub>2</sub> on the Cone Calorimeter. The following graphs only show time to ignition against mean RGB values.

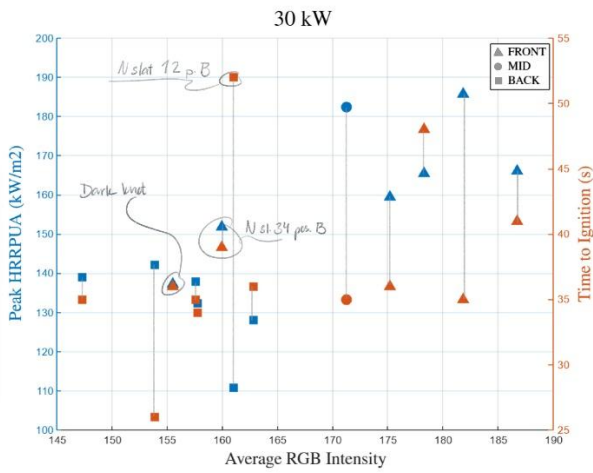


Figure 74: Radiant heat flux 30 kW/m<sup>2</sup>

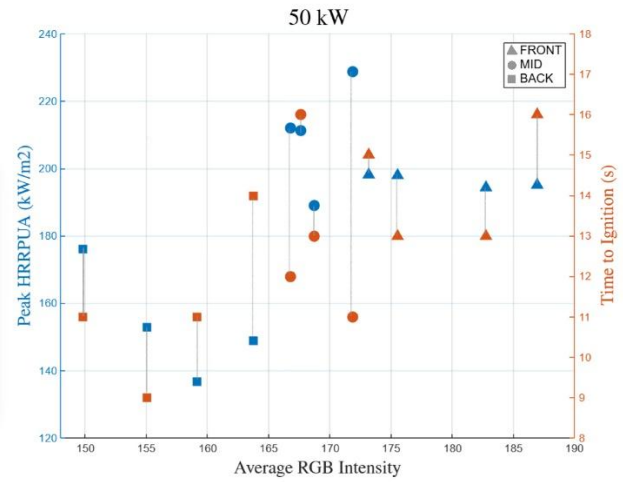


Figure 75: Radiant heat flux 50 kW/m<sup>2</sup>

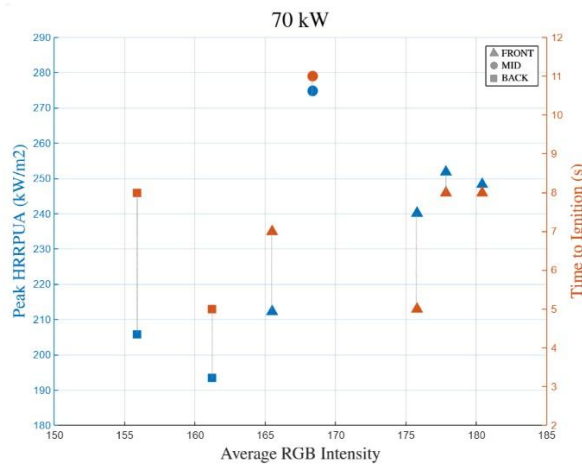


Figure 76: Radiant heat flux 70 kW/m<sup>2</sup>

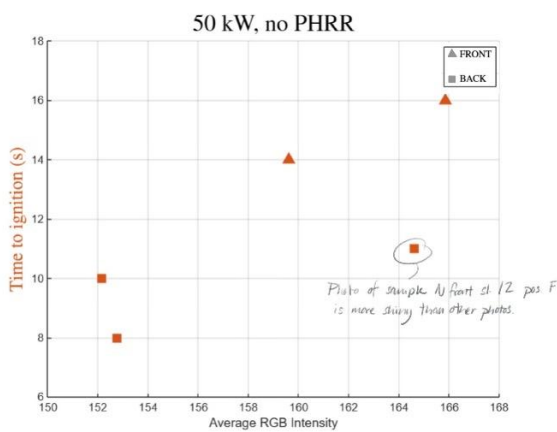


Figure 77: Samples missing PHRRPUA but have valid TTI for a photo analysis

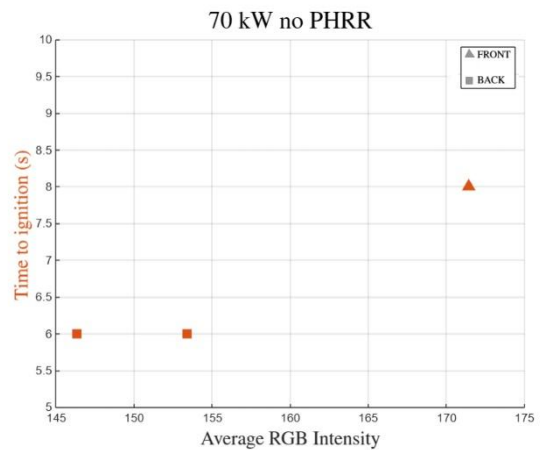


Figure 78: Samples missing PHRRPUA but valid TTI for a photo analysis

## 6.2 TRP and FPI values

The following are the TRP values for FRONT, MID and BACK of the samples.

A higher TRP means either an increase in thermal inertia or increase in ignition temperature → slower time to ignition, which can delay the spread of fire. Low TRP values indicates low thermal inertias, meaning the material heats up quickly, potentially accelerating fire development.

Higher FPI values means that there is a greater flame spread.

Table 3: TRP and FPI values

Sample	TRP	FPI
FRONT	213	24,5
MID	217	24,6
BACK	191	25,2

## 6.3 Statistical significance of the results

The t-tests are made on all valid data for PHRRPUA, average HRR and TTI. There was no t-test done on the data from the Friday 25<sup>th</sup> of October with the invalid pump settings, as well for other samples that lack HRR information.

Smaller sample sizes in general make it harder to detect a true difference, if one exists. In other words, it can wrongly be concluded that there is no significant difference when there is one or find a significant difference that does not exist, see subchapter 2.6.3.1.

For this section of the results all radiant heat release rates are clustered together and the factors compared to each other are FRONT, MID, BACK, TW (Thermowood) and non-treated. The different radiant heat fluxes (30, 50 and 70 kW/m<sup>2</sup>) are clustered together to increase the sample size. All the front samples for all heat fluxes are together and then a t-test was performed. The same procedure for BACK, MID, TW and non-treated pine. When clustering all heat fluxes together it disregards the influence of radiant heat flux and evaluates only if there is an overall difference between the compared factors.

Table 4 presents the number of tests done per factor. Table 5 presents an overview of the t-test results. A t-test is statistically significant if the p-value is over 0.05, see Appendix 7 – Extended results: T-test results.

Table 4: Number of tests per FRONT, MID, BACK, TW and non-treated.

Factor	Number of tests
<b>FRONT</b>	17
<b>MID</b>	6
<b>BACK</b>	18
<b>TW</b>	4
<b>Non-treated</b>	6

Table 5: Overview of t-test results

Comparison	Peak HRRPUA Statistically significant different	Average HRRPUA Statistically significant different	TTI Statistically significant different	Sample size
<b>FRONT to BACK</b>	Yes	No	No	28
<b>FRONT to MID</b>	No	No	No	21
<b>BACK to MID</b>	Yes	No	No	19
<b>Non-treated to MID</b>	No	No	No	12
<b>TW to MID</b>	Yes	No	No	10
<b>TW to non-treated</b>	Yes	No	No	10
<b>TW to FRONT</b>	Yes	No	No	19
<b>TW to BACK</b>	No	No	No	17
<b>Non-treated to BACK</b>	Yes	No	No	19



## 7 Discussion

Chapter 1 addresses the issues stated at the beginning of the thesis. The results from the Cone Calorimeter testing show that there are differences in the reaction to fire properties between different parts of the timber slats. The color change over time of the timber slats can be an indicator of the timber's reaction to fire properties. Although considerable information is available on fire retardants and weathering of timber, it is difficult to interpret, making it challenging to gain a clear understanding of how fire-retardant-treated timber works and how it reacts to weathering. To provide a foundational overview of the results, general trends will be the first point of discussion.

### 7.1 FRONT vs BACK

In this small-scale experimental thesis from a field study in Malmö, the results show that natural weather exposure affects the reaction to fire properties of the samples. The least weather-exposed samples (BACK) have a faster time to ignition and greater flame spread, but lower peak heat release rate per unit area than the most weather-exposed samples (FRONT). The FRONT samples have a slower time to ignition, lesser flame spread and higher peak heat release rate per unit area than the BACK samples. The least weather-exposed samples have lower peak heat release rate per unit area than the most weather-exposed samples. This is shown in Figure 23, Figure 30, Figure 31 and Figure 46. FRONT samples, which are more weather-exposed than the BACK samples, do in general also have a higher peak heat release rate per unit area than the BACK samples, which can be read from the graphs in the results, Chapter 5.

The slower time to ignition and higher peak heat release rate per unit area suggests that there is less fire retardant in the FRONT samples than the BACK. This observation is only true if the fire retardant is a char promoter whereas a char promoter needs ignition to be activated. Though it is unclear what type of fire retardant it is, the burning behavior and the results point towards that it is a char promoter. The longer time to ignition and higher peak heat release rate per unit area observed in the FRONT samples is contrary to the expected behavior of a char-promoting fire retardant. This supports the observation that there is likely less fire retardant remaining in the FRONT samples compared to the BACK. See the theory behind this in subchapter 2.3.2.

The FRONT versus BACK results are also statistically significant for both the peak heat release rate per unit area and average heat release rate per unit area according to the t-test analysis in subchapter 6.3. FRONT versus BACK is not statistically significant for the time to ignition.

The thermal response index TRP indicates that the FRONT and MID samples have a slower time to ignition than the BACK samples and the fire propagation index FPI indicates that the BACK samples have a greater flame spread than the FRONT and MID samples. See results for TRP and FPI in subchapter 6.2.

### 7.2 East vs North and other points of the compass

The reaction to fire performance is similar between east and north and it can be concluded that the weather line is not the main factor to investigate further. The conclusion is founded on the results in subchapters "East VS Northside" in Chapter 5. Therefore, it seems like weather exposure is the relevant factor in this study, such as BACK and FRONT of the slats. A t-test on the weather directions result would have been good to have but was not thought of until this sentence was written and will not be conducted.

In addition to this observation the position on the façade could be a relevant factor for the results, which will remain unknown until further research. The slats in this study were positioned close to the ground on both east and north direction of the facade. Slats from south and higher up on the façade

were supposed to be a part of the study as well, but the person helping with demounting the façade was not allowed to work on a latter and therefore there are none of these characters in this thesis. This building did not have reachable timber façade, on the west side either.

Despite the slats were positioned close to the ground they were not much damaged from traffic. There are no regular car, bike or scooter traffic by the façade. There are buildings around this building, which affects the wind and sun exposure as well. Also snow maintenance and gardening could play a role in the slats performance; however, there has barley been any snow in Skåne during the past two years and there are no plants to garden where the slats were positioned.

For future studies it would be of interest to investigate the difference between different positions on the façade as well as comparing north vs south direction since those are thought to be the least and most sun exposed parts of the building.

### 7.3 What about the MID samples?

There were in total six MID tests conducted, four at 50 kW/m<sup>2</sup> and the remaining two at 30 respectively 70 kW/m<sup>2</sup>. The materials for the samples were limited and the MID samples were not prioritized because a fire is not likely to start in the MID of the slats. On the other hand, it is of interest to see and evaluate the reaction to fire properties of the MID samples, since “all of the wood is supposed to have equivalent concentrations of fire-retardants in them after the impregnation” according to what the fire impregnation company vocally informed.

If the concentration of fire-retardants were consistent, then FRONT, MID and BACK would all perform the same in the Cone Calorimeter test, which is not the case. The MID samples burning behavior were similar to the burning of the non-treated and non-weathered pine samples. Specifically, the char and ash formation looked similar between the MID samples and the non-treated non-weathered pine samples; unfortunately, there are no photographs of this. On the other hand, there are photos of the down-facing side of a burned MID sample in subchapter 5.6, Figure 72. The fluffy, white lichen feeling of the down-facing side of the MID sample might be fire-retardant doing its thing for the outer layer of the slat.

### 7.4 Peak heat release rate per unit area, time and char promotion

The samples release the highest amount of energy within the first 100 seconds of the test. This is because the samples have the most amount of easily accessible combustible material within the first 100 seconds of the test. When char starts to form, the heat release rate decreases until a steady burning state is reached. The reason for that is because char acts as a physical and thermal barrier which stops a bit of the heat exposure [58].

Physically, the char hinders volatiles from being released from the timber underneath the char. Thermally, the char isolates the underlying timber from radiant external heat exposure. The isolation from the radiant heat exposure slows down the production of volatiles. The physical barrier hinders the volatiles from being released, leading to less heat release rate per unit area than before the char was formed. Therefore, there is a decrease in heat release when char starts to form, as seen in the graphs in Chapter 5. The steady burning state is reached when equilibrium is reached between the release of volatiles from the samples and the heat transfer into the samples [58].

The main takeaway of this is that char acts as a protective layer, regardless of whether the samples have been impregnated with fire retardants or not.

## 7.5 Color

The color analysis suggests that the appearance of timber slats may serve as an indicator of their reaction-to-fire-properties, see subchapter 6.1. Lighter-colored areas ignited more slowly but exhibited a higher peak heat release rate per unit area. Darker-colored areas ignited more quickly but had a lower peak heat release rate per unit area.

However, it is important to acknowledge that this study did not include measurements of fire-retardant content within the timber slats, due to limitations in time and available resources. As such, it cannot be said whether the observed color differences are a direct result of fire-retardant degradation or simply natural weathering effects common to both treated and untreated timber. Nonetheless, the results show a possible relationship between fire-retardant presence and surface color variation, something that would be interesting to see more research of.

## 7.6 Small-scale tests are not big-scale tests

The results from this study are from a small-scale test which has its limitations, see more in subchapter 2.5.5.2. **The result, discussion and conclusions from this thesis are therefore not to be held to any higher standard than the limitations of the test.** Still, these small-scale test results can be an indicator of larger scale or in real world performance. Therefore, small-scale tests are still necessary and relevant in the field of fire-retardant timber.

The Cone Calorimeter is an adequate testing method to measure peak heat release and time to ignition, the two central factors studied in this thesis. This, together with the amount of façade available for testing and the repeat setting that can be obtained with the Cone Calorimeter, is why this small-scale testing method is suitable and was used for this study, see more in subchapter 2.5.1.

### 7.6.1 SP-FIRE 105 vs Cone Calorimeter

Comparing the SP-Fire 105 test method to Cone Calorimeter results are, at first sight, a bit like comparing apples to pears. Both tests assess fire behavior. But when understanding the tests more, they are more like chocolate to strawberries, complementing each other. The Cone Calorimeter is used to evaluate a material's fire property at the lab scale, leaving results that indicate what a full-scale SP-Fire 105 test could show. The SP-Fire 105 test could then be used to see how these materials behave in a largescale fire scenario when integrated into a building element, such as the façade. Therefore, these two tests should neither be directly compared nor pitted against each other.

Brief summary of different aspects measured by the two testing methods:

*Table 6: Differences between SP-Fire 105 test and Cone Calorimeter test.*

Aspect	SP-Fire 105 [46]	Cone Calorimeter [49, 50]
Fire spread	Yes	No
Smoke development	Yes	Yes
Heat release	Yes (total heat release)	Yes (heat release rate)
Structural integrity	Yes	No
Fire resistance	Yes	No
Time to ignition	No	Yes
Peak heat release rate per unit area	No	Yes
Total heat release rate	No	Yes
CO and CO <sub>2</sub> emissions	No	Yes
Effective heat of combustion	No	Yes

## 7.7 Human errors

To minimize human errors, safety measures such as being well-rested and taking photo documentation were implemented.

Human errors result in holes in the data from the study where the heat release rate of these tests cannot be used. As already mentioned throughout the thesis the testing's done Friday the 25<sup>th</sup> of October have invalid information about heat release rate due to a faulty setting resulting in less number of tests at 50 kW/m<sup>2</sup>. With larger sample sizes the t-test could have been more accurate resulting in an even more significant result, or less significant result. This error could have been compensated for by conducting more tests of the same type, which unfortunately was not possible due to lack of time and samples.

The tests from Friday the 25<sup>th</sup> of October are not valid heat release rate data since the sample gas was forgotten on CO/CO<sub>2</sub> from the calibration. Some of these were compensated with the “compliment” tests shown in Appendix 5 - Detailed information about the samples. In future testing, it might be worthwhile to spread out the type of tests conducted during a day to spread the risk of potentially losing data. All the tests from Friday were tested with a radiant heat flux of 50 kW/m<sup>2</sup>.

## 7.8 Additional observations

This subchapter presents observations made throughout the thesis process which are not necessarily connected to the results of the tests in the Cone Calorimeter, but equivalently important findings about fire-impregnated-timber façades.

### 7.8.1 Why is it so hard to retrieve, read and understand the documentation of a product?

Throughout the writing process, there have been challenges in retrieving and understanding the documentation for the fire-retardant-impregnated timber product used on the building. Given that the building was completed less than three years ago, it should be straightforward to gain documentation of the façade. After several emails and phone calls, the documents regarding the façade were finally obtained.

The documents were said to belong to the same product: the timber slats. However, there is no reassurance or linkage between the documents and the product. Therefore, it is unclear if the documentation is for these timber slats.

Despite the modern Swedish language and expertise among the readers (students, supervisors, maintenance team etc), there were still question marks regarding what the information stated. Therefore, generative AI was also consulted to understand and explain the text, see more in Appendix 11 – Generative AI to understand documentations.

The façade system from where the timber slats originate does not have an SP-FIRE 105 test. This type of building requires that the façade has passed the SP-FIRE 105 test or its equivalent. The fire and safety engineering report (see Appendix 10 – Extraction from the fire engineering report) has made a performance-based design and argues that a SBI test result is equivalent to a SP-Fire 105 test, which is not true. This points to lack of industry consensus and knowledge of how to safely use timber for building facades.

A definitive answer to the question posed in this subchapter's title remains unclear. However, documentations of a product should be accessible, easy to read, and comprehensible to a broad audience: including researchers, professionals in fire and safety engineering, maintenance persons as well as students.

#### 7.8.1.1 SP-Fire 105 test ok ≠ safety

This thesis does not aim to assess fire testing methods, but it is worth mentioning that passing a SP-FIRE 105 test is not equivalent to a safe façade. A passed test shows that the façade meets some requirements for an exterior façade system, but does not give information about long-term robustness against fire.

#### 7.8.2 Samples direct from the fire impregnation factory

Even though the BACK samples are less exposed to weathering, they are still affected by the climate. The BACK samples serve as this study's "best" samples, with the thought that they have the most fire impregnation in them.

It would have been interesting to have samples of fire-impregnated timber direct out of the factory to be able to compare FRONT, MID, BACK and non-weathered fire-impregnated timber samples to each other. Since there are no samples direct from the factory, it is important to note that samples straight out from the fire impregnation factory might have different reactions to fire properties than the BACK samples in this study.

Patchiness of fire retardants could influence the results of the BACK samples in this study. Engström and Psajd [4] noted that there were large variances in the fire performance between the samples direct out of the factory, even though they were from the same batch. They found that some of their samples had high peak heat release rate per unit area while others did not even catch fire. It would have been interesting to see if there is a similar problem with patchiness from the production of this facade.

Eight slats were tested in this study and since there are no slats straight from the factory, it is unknown if these slats had a lot or little fire retardants in them compared to new slats from the factory. This could be of interest to investigate further in future research.

#### 7.8.3 Fire-retardants distribution

This is not an issue to be addressed for the thesis, but it is noted that fire-retardants are more present in the surface of the slats relative to the rest of the slats. This is something that the fire-retardant companies themselves have flagged for.

The MID samples' burning behavior, together with the appearance of the ash formation of the holes in the front samples, suggests that fire-retardants are more present in the surface of the timber, relative to the rest of the slat. This is based on the burning behavior, the char and ash formation is distinguishable from the appearance of the unharmed surface samples.

#### 7.8.4 The number of samples is limiting

Small number of samples are a limiting factor since it limits the number of repeat tests. More repeats lead to more accurate trends, which then lead to more accurate conclusions. The small number of samples, for example, can affect the t-test analysis so that it looks like there is a statistical significance where there is none, or vice versa. Therefore, the t-test analysis of Thermowood (TW), MID and non-treated are to be read with this information in mind.

#### 7.8.5 Accelerated aging = natural weathering?

The timber samples in this study are tested with accelerated aging, see Appendix 9 - Documentation EN 16755 and are said to have a life span *durable over time*. The results of this thesis imply otherwise, despite the small-scale testing. The same result is shown by Engström and Psajd [4]. The shortcomings in the accelerated aging estimations are also noted by Östman and Tsantaridis [55]. The results of this study also suggest that accelerated aging methods need to be improved to be used as an estimation of real-world natural weathering for fire-impregnated timber façades.

### 7.8.6 Why is it so hard to understand fire retardants?

Still, after weeks of reading about fire retardants and talking to people in the field, it is hard to understand how fire retardants work together with timber. It is unclear how fire-retardants interact with the wood, if it reacts with the wood cells and if so, how that reaction works. Since understanding the chemistry and physics of the fire-retardant-impregnation is not the focus of this thesis, it is neither resolved nor explained properly.

However, the confusion around how fire-retardant timber works is not only a problem when writing this thesis, but also a larger issue for fire and safety engineers. They must answer questions about both existing timber facades and take a stand on building new ones. **If a full-time thesis writer struggles to find answers, how are professional fire and safety engineers going to have time to find the answers?**

### 7.9 Who's responsible for the fire protection now and what about maintenance?

This question was asked early in the process, while it is not a main issue addressed by the thesis, it has become another question without an answer.

As explained in Subchapter 2.4.1.1, PBL says that a building is supposed to keep the essential properties of the design of the building. The façades can be an essential part of the buildings fire safety, and it therefore falls under PBL to be maintained throughout the building's life expectancy. For example, it is standard that sprinkler systems are monitored and tested according to specifications from the manufacturer. For the façade system there should be a maintenance guide on how to maintain the fire protection in the timber slats. It would also be of relevance to include an easy way of measuring the amount of fire protection there is left in the timber slats, without damaging the façade.

The fact that there today are no maintenance guides or tools for the building manager of measuring the amount of fire protection in the timber slats is concerning.

Is the façade supposed to be exchanged after a year or two? Or maybe painted with fire-retardant coating? How come the fire-retardant impregnation companies cannot answer questions about maintenance and how the adhesion to the timber works? Are fire-retardant impregnated timber façades environmentally and economically justified? These type of questions are also highlighted by Engström and Psajd [4].



## 8 Conclusion

This study has demonstrated that natural weathering significantly influences the fire performance of fire-retardant-impregnated timber. Tests of 1–2-year-old naturally weathered fire-retardant-impregnated timber slats from a field study in Malmö, Sweden, has been conducted using the Cone Calorimeter. The key findings include:

The degree of weather exposure creates distinct differences in fire performance. More weather-exposed surfaces (FRONT) showed slower time to ignition, but higher peak heat release rate per unit area, while less exposed surfaces (BACK) exhibited the opposite trend. These differences were statistically significant for heat release rates but not for ignition times.

North VS east direction did not seem to have an impact in this study. For future research it would be interesting to investigate south VS north to see if increased UV light influences the samples fire behaviors.

The color of timber slats may serve as an initial indicator of fire performance. When initially mounted on the building their colors were darker. With time and weathering, they change color. Lighter-colored areas generally exhibited slower ignition times but higher peak heat release rate per unit area, while darker areas had faster ignition times with lower peak heat release rate per unit area. This observation suggests a potential visual assessment tool for evaluating timber façade conditions.

The burning behavior of MID samples raised questions about the fire-retardant distribution within timber slats. Their results similarities to untreated pine suggests that fire retardants may be concentrated primarily in surface layers rather than uniformly distributed throughout the material.

The study also highlights challenges in the field of fire-retardant timber, including:

1. The lack of clear documentation and understanding of fire-retardant mechanisms.
2. Insufficient maintenance guidelines for maintaining long-term fire protection.
3. The gap between passing a fire test and real-world performance.
4. Inconsistencies between accelerated aging and natural weathering of timber façades.

Addressing these challenges could be done via:

- Improved documentation and transparency from fire-retardant manufacturers/impregnators.
- Development of clear maintenance protocols for fire-retardant timber façades as well as a tool to measure fire-retardant presence.
- Clearer regulatory frameworks for maintaining fire protection over time.
- Further research into the long-term durability of fire-retardant treatments of timber.

Moving forward, interdisciplinary collaborations between the construction industry, fire-retardant manufacturers / impregnators and research institutions will be essential in developing fire-safe and sustainable solutions for wood claddings in our society, which, admittedly, is no small task.



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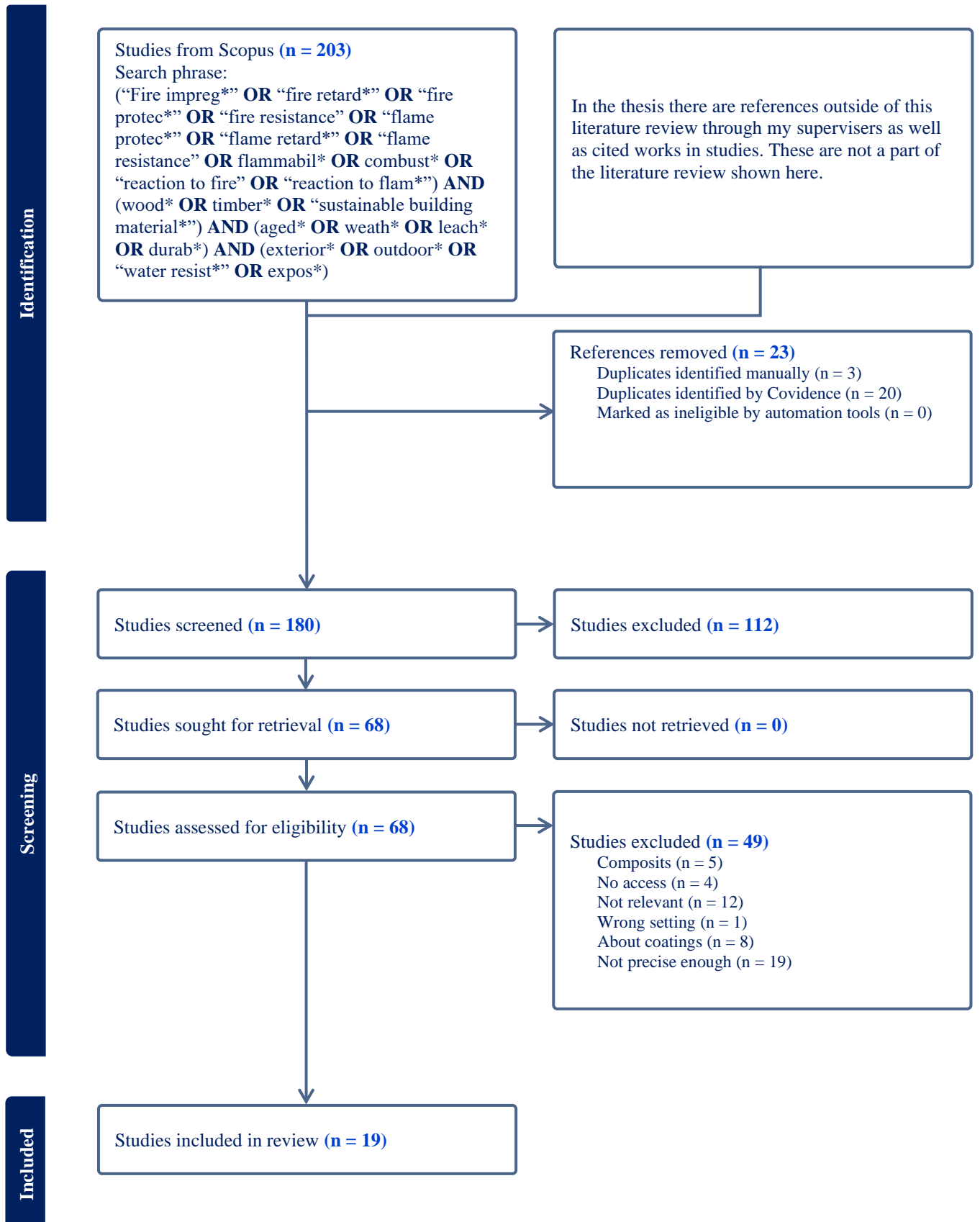
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Appendix 1 – Prisma Covidence method



Included studies ongoing (**n = 0**)  
 Studies awaiting classification (**n = 0**)

## Appendix 2 - Photos of the façade

The following are small glimps on where the slats are taken from. The North facing façade was dirtier than the east facing façade, see Figure 79 and Figure 80.



Figure 79: North position of the slats on the façade.



Figure 80: East side position of the slats on the façade.

## Appendix 3 - Extended calculations

### Thermally thickness calculation

The samples for this thesis are considered to be thermally thick until time-to-ignition which is shown by assuring that  $L > 4\sqrt{\alpha t}$ .

This was confirmed by calculating  $4\sqrt{\alpha t}$  and comparing it to the thinnest sample  $L = 0,0018$  m. The  $\alpha$ -value was assumed to  $2,10 \times 10^{-7}$ , Douglas fir, from [56]. Douglas fir is a type of pine and was there for chosen to represent this thesis pine specimens.

$$\begin{aligned} L &= 0,0018 \text{ m} \\ \alpha &= 2,10 \times 10^{-7} \\ t &= 1 \text{ to } 400 \text{ s} \end{aligned}$$

$L = 0,0018 > 4\sqrt{\alpha t}$  was confirmed for all 400 seconds concluding that the samples can be considered to be thermally thick until time to ignition (a lot under 400 s) for all samples.

### TRP and FPI calculations

Calculations for TRP and FPI followed chapter “Data analysis” on page 30 – 34 in [51] and Chapter 2.6 Theory of data analysis. The following values in figure 66-68 were used in the calculations for FRONT, MID and BACK.

Sample = name on sample

$\text{kW/m}^2$  = Radian heat flux onto samples

tig = time to ignition

#### FRONT

Table 7: Values for FRONT

$\text{kW/m}^2$	Sample	tig	$1/\sqrt{\text{tig}}$
30	'E_3A4A_FRONT'	36	0,16666667
30	'E_3F4F_FRONT'	48	0,14433757
30	'N_1B2B_FRONT'	36	0,16666667
30	'N_1E2E_FRONT'	41	0,15617376
30	'N_3A4A_FRONT'	39	0,16012815
30	'N_3F4F_FRONT'	35	0,16903085
50	'E_1F2F_FRONT'	13	0,2773501
50	'E_3D4D_FRONT'	13	0,2773501
50	'N_1F2F_FRONT'	16	0,25
50	'N_2CD_FRONT'	15	0,25819889
50	'E_1B2B_FRONT'	16	0,25
50	'N_1A2A_FRONT'	14	0,26726124
70	'E_3C4C_FRONT'	7	0,37796447
70	'E_3E4E_FRONT'	8	0,35355339
70	'N_3C4C_FRONT'	5	0,4472136
70	'N_3E4E_FRONT'	8	0,35355339
70	'E_3B4B_FRONT'	8	0,35355339

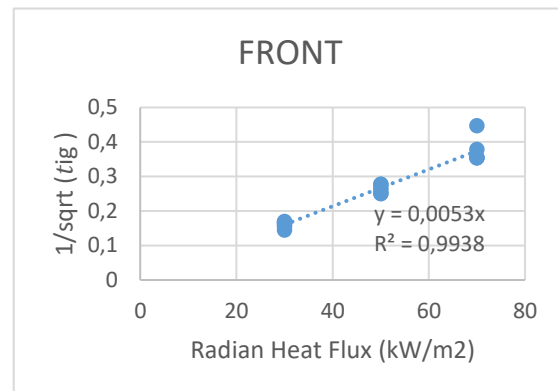


Figure 81: Curve for TRP calculation

MID

Table 8: Values for MID

kW/m <sup>2</sup>	Sample	tig	1/sqrt(tig)
30	'E_2D_MID'	35	0,16903085
50	'E_1C_MID'	13	0,2773501
50	'E_1D_MID'	16	0,25
50	'N_1C_MID'	11	0,30151134
50	'N_1D_MID'	12	0,28867513
70	'E_2C_MID'	11	0,30151134

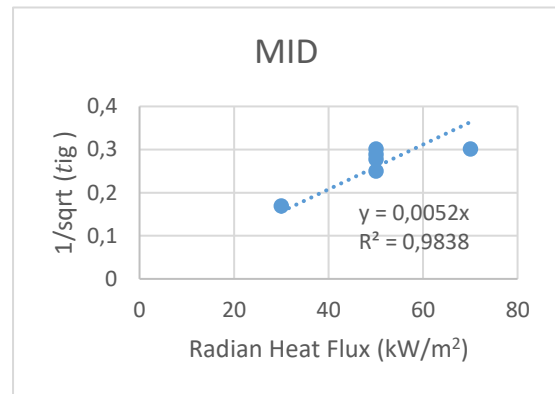


Figure 82: Curve for TRP calculation

BACK

Table 9: Values for BACK

kW/m <sup>2</sup>	Sample	tig	1/sqrt(tig)
30	'E_3A4A_BAK'	35	0,16903085
30	'E_3F4F_BAK'	26	0,19611614
30	'N_1B2B_BAK'	52	0,13867505
30	'N_1E2E_BAK'	36	0,16666667
30	'N_3A4A_BAK'	35	0,16903085
30	'N_3F4F_BAK'	34	0,17149859
50	'E_1A2A_BAK'	9	0,33333333
50	'E_1B2B_BAK'	11	0,30151134
50	'N_1A2A_BAK'	11	0,30151134
50	'N_2CD_BAK'	14	0,26726124
50	'E_1E2E_BAK'	8	0,35355339
50	'E_1F2F_BAK'	10	0,31622777
50	'N_1F2F_BAK'	11	0,30151134
70	'E_3B4B_BAK'	6	0,40824829
70	'N_3B4B_BAK'	8	0,35355339
70	'N_3D4D_BAK'	5	0,4472136
70	'E_3E4E_BAK'	6	0,40824829
70	'N_3E4E_BAK'	6	0,40824829

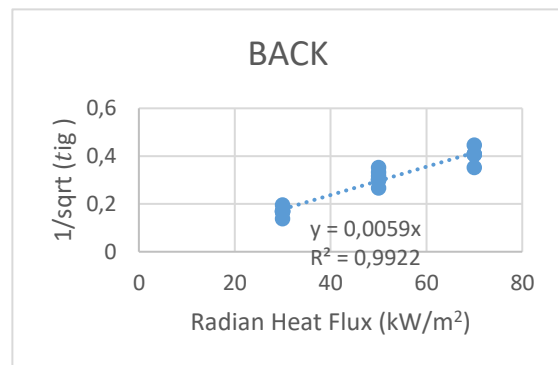
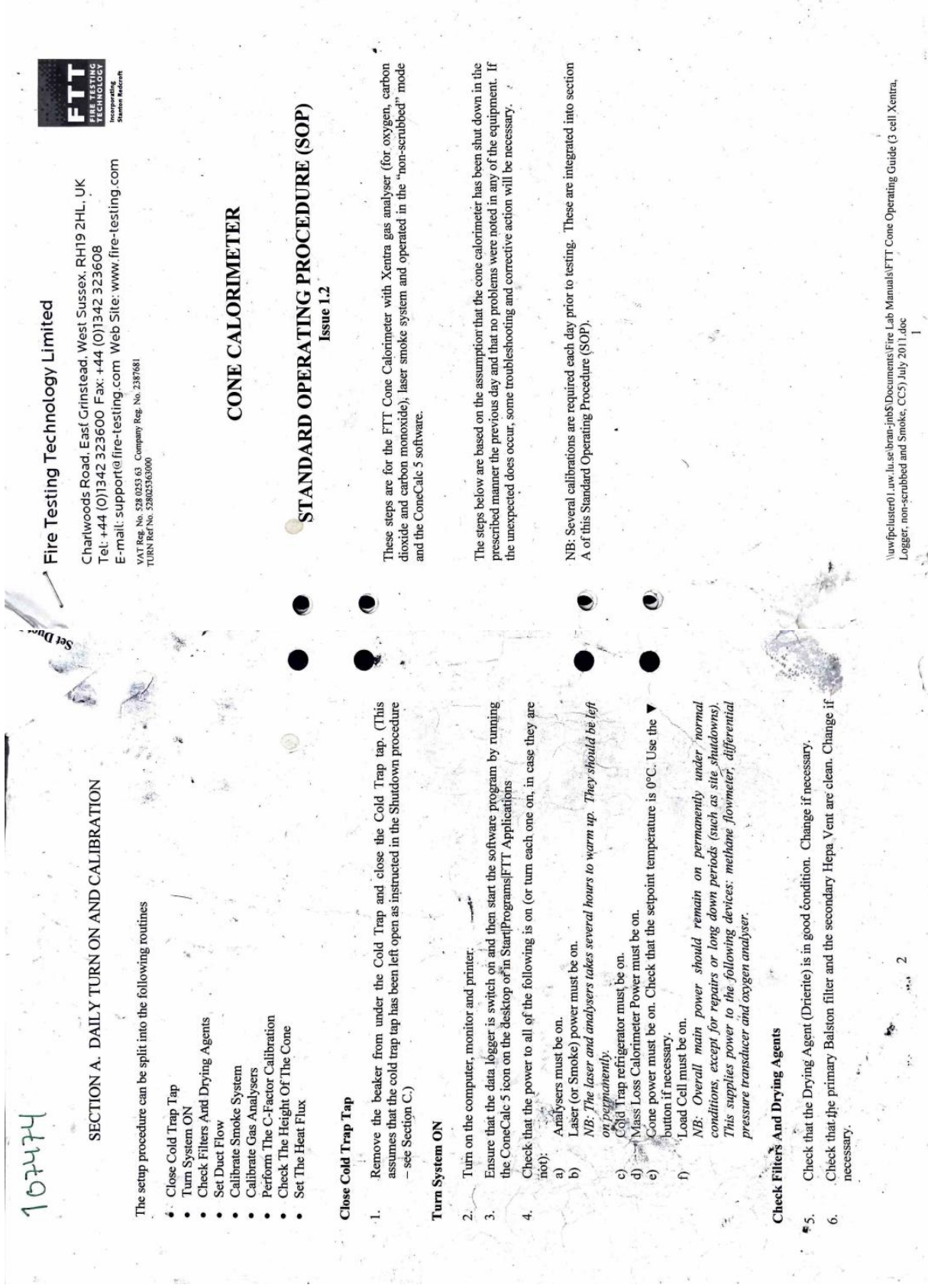


Figure 83: Curve for TRP calculation

## Appendix 4 - Cone Calorimeter set up

The following are photos of the description of how the Cone Calorimeter was set up and taken care of during the experiment weeks.



110 = 0,04068  
 Men 0,04072

### Set Duct Flow

7. Check that the duct Fan, sample Pump and room extraction are switched off.
8. In the software, select Calibrations\DPT & Flow. Ensure that the Exhaust Control is switched off (this closes the ports on the differential pressure transducer) and then press the **Zero** button. Then press **OK** to record the zero point of the DPT calibration.
9. Switch the duct Exhaust Control on and switch the room extraction on. Enter 24 l/s as the required flow rate and press **OK**. Adjust the speed control to set the Volume Flow Rate to the required level (24 l/s). When 15 consecutive readings within 2 l/s of the required flow have been measured then the software will tell you that the flow is correctly set. Then press **OK** to return to the Calibrations panel.

### Calibrate Smoke System

10. Calibrate the Smoke System:
  - a) Place the "smoke zero blank" between the laser and the compensating photodiode (next to the laser).
  - b) Select the software routine: Calibrations\Smoke and then press the **Zero** button. (Check that the Calibrated Main and Compensating signals [PDM(-) and PDC(-)] are 0.000.)
  - c) Remove the smoke zero blank and ensure that the blank slot and filter slot is covered.
  - d) Press the **Balance** button to adjust the input values of each of the photodiodes to give a normalised ratio of 1.000 (this is in the PDC(-) and PDM(-) displays). If not then press the **Balance** button again.
  - e) Then press the **OK** button.
 

[Additionally you may perform a secondary smoke system calibration as follows

    - e1) Then press the **Filter Calibration** button.
    - e2) Place the ND 0.3 filter in the main slot (at the front of the Cone, above the control panel) and ensure that this filter is selected using the radio buttons. Also check that the correct value of the filter is entered in the text box.
    - e3) Then press **Start**. Wait 60 s for the data to be collected.
    - e4) Check that the Optical Density Correction Factor is between 0.95 and 1.05. Then press **OK**. If not within these limits, then check that the filter is in position correctly and that the correct filter is selected in the software and that the same filter value is on the computer screen and repeat the routine again.
    - e5) Remove the filter and turn the filter cover to stop any light hitting the photodiode.]

### Calibrate Gas Analysers

11. Turn on the sample Pump and check for leaks or blockages. Ensure that the pressure to the analyser is 5 psi on the gauge inside the rack (the flow to the oxygen analyser should be 3 - 3.5 l/min and the flow to the CO/CO2 analyser should be 3 - 3.5 l/min). If leaks are present, locate the source of such leaks and correct the problem.

12. We then calibrate the Oxygen and CO/CO<sub>2</sub> Analysers. This will involve checking the zero, using nitrogen, and then setting the value at that for dry ambient air, namely 20.950% for the oxygen analyser, and the Span Gas values for the CO and CO<sub>2</sub> analyser.
  - a) With the lab extraction, fan and pump on, check that the volume flow rate is 24 l/s (use Status).
  - b) Make a note of the flow into the oxygen cell and the CO/CO<sub>2</sub> cell still with the pump on by moving the flags on the flowmeters to the position of the float.
  - c) Turn off the pump.
  - d) Select the software routine Calibrations\Gas Analysers.
  - e) Turn on the nitrogen cylinder.
  - f) Turn the valve below the oxygen flowmeter to the Nitrogen position AND the CO/CO<sub>2</sub> valve (below the CO/CO<sub>2</sub> flowmeter) to the Nitrogen position.
  - g) Adjust the nitrogen flow from the regulator on the bottle to obtain the same flow as that value noted in 12 b. **THIS IS VERY IMPORTANT.**
  - h) Wait until the oxygen, CO and CO<sub>2</sub> readings stabilise at approximately 0.00%.
  - i) Zero the CO on the analyser, using the menu system (Menu\Calibrate\Password 4000\Manual Call\▲CO\Low Cal\0.0000%\Yes) When the CO reading has stabilised at 0.000% then press Quit twice.
  - j) Then press ▼ and ▲ to select the CO<sub>2</sub> channel. Select Low Cal and ensure the display says 0.000% and select Yes to perform the calibration. Then press Quit twice.
  - k) Then press ▼ and ▲ to select the Oxygen channel. Select Low Cal and ensure the display says 0.000% and select Yes to perform the calibration. Then press Measure.
  - l) In the Gas Analysers Transducer Calibration panel press the **Zero** button in the Oxygen Cell section. After the routine has finished (the progress bar has reached the top) check that the Oxygen reads 0.000% on the computer screen.
  - m) Then press the **Zero** buttons in the CO<sub>2</sub> cell and CO cell sections. Check that the CO<sub>2</sub> and CO both read 0.000% on the computer screen. Do NOT press the **OK** button.
  - n) Turn off the nitrogen cylinder.
  - o) Turn the Oxygen Analyser valve to Air or Sample Gas.
  - p) Turn the CO/CO<sub>2</sub> analyser valve to CO/CO<sub>2</sub> Span Gas.
  - q) Turn on the calibration gas cylinder.
  - r) Set the CO/CO<sub>2</sub> flow rate to the value noted in 12 b by adjusting the gas cylinder valve.
  - s) On the analyser menu system select Menu\Calibrate\Password 4000\Manual Call\CO\High Cal then ensure that the value is that stated on the calibration gas bottle certificate. Then select Yes to perform the calibration of the CO cell. When the reading has stabilised press Quit twice.

- select Yes to perform the calibration. When the reading has stabilised press Measure.
- Then press the **Span** button in the Oxygen Cell section on the computer screen.
- Then press **OK** then **Main**.
- If the CO is not within -0.002% to 0.002% then set the zero ONLY ON THE ANALYSER. [Select Menu|Calibrate|Password 4000|Manual Cal|CO|Low Call then ensure that the value is 0.000%. Then select Yes to perform the calibration. When the reading has stabilised press Measure.]
- Place the burner in position under the cone, ensure the spark igniter is in the idle position and push the Ignition button on.
- Turn the methane cylinder on.
- Select the software option: **C-factor**, then **Routine**.
- Enter the required information, including the atmospheric conditions (temperature, relative humidity and pressure). Then press **OK**.
- Open the shutters under the Cone heater (if not already open).
- Ensure that the methane valve is OFF and then select **Yes** to perform the pre-run calibrations.
- Ensure that the methane is off and press **Start** to collect the baseline data.
- When instructed to turn the methane on, place the igniter over the methane burner.
- Turn the methane ball valve on half way.
- When the methane ignites then turn the methane valve fully on. Then remove the igniter.
- Adjust the methane flow to obtain approximately 5 kW (bottom left graph and display).
- Allow the data collection part of the routine to complete and turn the methane off when instructed. (Do NOT adjust the methane flow valve or the pressure regulator on the bottle during the data collection phase (last 3 minutes of the routine).
- The routine lasts for 6 minutes of burning – turn the gas off using the Methane On/Off valve when instructed and collect the after-test baseline data.
- Then press the **Stop** button to finish the routine when instructed.
- Turn the Pump off.
- Press **Save** to save the C-factor (and select which C-factor you wish to save). Make a note of the calibration factor and compare with previous values. The acceptable range for the instrument is 0.040 - 0.046. Measurements on two successive test days shall not differ by more than 0.002. Such differences indicate malfunctions which require rectification before testing is continued. (Typically a high C-factor results because of leaks or blockages, a very high C-factor means that the cold trap is still open, a low C-factor may be due to a leak in the methane line or a faulty mass flow meter.)
- Press the **Exit** button to return to the Main panel.
- t) Then press **▼** and **▲** to select the CO<sub>2</sub> channel. Select High Cal and ensure the display shows the value is that stated on the calibration gas bottle certificate and select **Yes** to perform the calibration of the CO<sub>2</sub> cell. Then press **Measure**.
- u) Check that the CO and CO<sub>2</sub> Span Values on the computer screen match those on the calibration gas bottle certificate (if not then edit the values). Then press the **Span** buttons for the CO<sub>2</sub> and CO cells. Check that the CO and CO<sub>2</sub> values are adjusted to the correct span concentrations.
- v) Turn off the calibration gas supply at the gas cylinder.
- w) Turn the CO/CO<sub>2</sub> analyser valve to Sample Gas.
- x) Turn on the sample Pump.
- y) Let the oxygen concentration stabilise for at least 5 minutes.
- z) On the analyser menu system select Menu|Calibrate|Password 4000|Manual Cal|Oxygen|High Call then ensure that the value is 20.95%. Then select **Yes** to perform the calibration. When the reading has stabilised press **Measure**.
- aa) Then press the **Span** button in the Oxygen section on the computer screen. Check that the Oxygen value on the computer screen is 20.950%.
- bb) Leave the sample pump on.
- cc) Then press the **OK** button to accept all the gas analyser calibrations. Then press **Main** to return to the Main panel.
- ### Perform The C-Factor Calibration
13. Perform a heat release system calibration with methane to determine the "C-factor".
- a) In the software, select **Status**.
- b) Ensure that the sample Pump is on and has been running for at least five minutes.
- c) Check that the following values are displayed:
- Oxygen reads 20.950 %
  - CO<sub>2</sub> reads -0.04 %
  - CO reads 0.00 %
  - Volume flow at orifice reads 24 l/s.
- d) Press **OK**.
- e) Ensure that the methane bottle is turned off and that the Methane ball valve (on the Cone Calorimeter) is off. Then select Calibrations|Zero MEMs and press **Zero** in the Methane Mass Flow Meter section to zero the methane flow meter. (If a soot mass flow meter is also installed then you must also press **Zero** in the Soot Mass section). Check that the Methane (slpm) is 0.00.
- f) Then press **OK**.
- g) Select **Calibrations|Gas Analysers**.
- h) On the analyser check the oxygen concentration is 20.95%. If it is not 20.95% then reset the span by using the menu system: select Menu|Calibrate|Password 4000|Manual Cal|Oxygen|High Call then ensure that the value is 20.95%. Then

**SECTION B. SAMPLE PREPARATION AND TESTING**

1. Before testing a set of materials check that the scale of the load cell output is appropriate for the masses of the specimens that will be tested.

To set up the load cell output, firstly determine the maximum mass,  $m_{max}$ , of the samples you will be testing. Choose a range slightly higher than this largest mass. For example, if your samples weigh about 80g, select 100g as a full scale load. This value has to be entered into the Newport controller and into ConeCalc.

To enter the value into the Newport controller (full details are in the Cone Calorimeter Users' Guide).

PUSH	DISPLAY	COMMENTS
MENU×17	OT.SC.OF	
MIN	READ 1	
MAX/MIN	00000.0	READ 1 must be 00000.0
MENU	OUTPT1	
MAX/MIN	00.0000	OUTPT1 must be 00.0000
MENU	READ 2	
MAX/MIN	$m_{max}$	Enter maximum mass here (e.g. 00100.0)
MENU	OUTPT2	
MAX/MIN	10.0000	OUTPT2 must be 10.0000
MENU	STORED→RESET	

To enter the value into ConeCalc select **Configure** and then edit the Load cell transducer calibrations so that the four numbers match those entered into the Newport controller (i.e.  $0 - 10 V = 0 - m_{max} g$ ). Then press **Accept**. Then select **Status**. Take the mass on the load cell and check that the Newport and computer screen both show zero. Then place a mass of the load cell and check that the mass displayed in the dialogue box is the same as that on the Newport (providing the Newport is indicating a mass below that entered above).

*Note that it is very important that the mass does not exceed the Mass span value ( $m_{max}$ ) because the Newport controller will display the correct mass but the signal sent to the computer will "top out" (the signal will be greater than 10 V) and hence yield an incorrect mass. In such a case, all parameters involving mass calculations would be invalid.*

2. Collect the sample, from the controlled temperature/relative humidity cabinet, measure, and record the sample mass, thickness and the area of the top surface.
3. Prepare the sample.
  - a) Wrap the sample in one layer of heavy-duty aluminium foil, shiny side towards the sample, covering the sides and bottom and leaving the testing surface exposed  
*NB: The fibre blanket must be dried by heating to 150°C for at least 3 hours and then placed in a desiccator containing silica gel to remove any water.*
  - b) Place sample in a clean horizontal specimen holder, which contains a fibre blanket.

- cc) Turn the Ignition off.
- dd) Remove the methane burner.

**Check The Height Of The Cone**

14. Ensure that the cone height is 25 mm above the sample surface.  
*Use a 23 mm spacer with the edge frame on the sample holder to ensure that the height is correct for remove the edge frame and place a dummy specimen in place so that the surface is level with the inside of the edge frame, then use a 25 mm spacer.*

**Set The Heat Flux**

15. To set the Heat Flux.
  - a) Ensure that the cooling water to the heat flux meter is flowing.
  - b) Open the shutters under the Cone heater.
  - c) Place a non-combustible ceramic cover on the load cell platform.
  - d) Remove the red cap from the heat flux meter.  
**NEVER TOUCH THE BLACK SURFACE.**
  - e) Place the heat flux meter under the Cone heater and ensure that it is 25 mm from the base of the cone heater. Use a 25 mm spacer to check this distance – take care to NOT touch the black surface. Remember that the Cone may be HOT!!
  - f) Select **Heat Flux**.
  - g) Select the required heat flux from the drop down list and then set the temperature controller to give approximately the required heat flux. This is done by pressing the ▼ and ▲ buttons on the temperature controller.
  - h) When the temperature has stabilised then look at the heat flux meter reading (Irradiance).
  - i) Wait until the heat flux stabilises before taking a reading. Adjust the temperature using the ▼ and ▲ buttons until the irradiance is at the required level (the Irradiance display will be green).
  - j) When stable press the **Save & Exit** button.
  - k) Remove the flux meter and ensure that a backing block is placed on the load cell platform to protect the load cell from heat damage.
  - l) Check that the copper end of the heat flux meter is cold.
  - m) Place the red cap on the flux meter and put it in the clips behind the Fire Model.

8. Testing:
- Ensure that the shutters are open and do NOT put the specimen on the load cell.
  - Press **Start Baseline** and collect at least 60 s of data.
  - When instructed to insert the specimen, close the shutters.
  - Place the sample, held in the specimen holder (with the appropriate mounting method) on the load cell and allow the mass to stabilise.
  - Pull down the protection screens.
  - Move the spark igniter into position and ensure that the Igniter button is on.
  - Open the shutters under the Cone heater carefully and press button S on the handset.
  - Record the time at which sustained ignition occurs by pressing button I on the handset **and remove the spark igniter**.
  - Press button E on the handset to mark an event time. This time will be displayed in the Comments dialogue box after the end of the test where comments about the event can be entered.
  - When the specimen stops flaming then press button F on the handset (this records the flameout time).
  - Collect data for a further 2 minutes.
  - Press the S key on the handset to stop the test or press the **Stop** button.
  - If the specimen does not ignite within 10 minutes, terminate the test and discard the sample, unless the specimen is showing signs of heat evolution or unless specific alternative instructions have been received from test sponsor.
  - Remove the specimen and place the ceramic cover on top of the load cell.
  - To perform the next test go to step 2.
  - Turn off the pump if you are not going to conduct any further tests for the next 10 minutes.
- If needed, use the optional retainer frame and/or wire grid. If a different mounting procedure is to be used, as specified by the test sponsor, take the appropriate steps. Make a note of the mounting procedure used.
  - Remove the specimen from the sample holder. Remove the cover on the load cell platform and place the empty holder (including edge frame if used) on the load cell. Allow the mass to stabilise and then press the Tare button on the Mass Loss Calorimeter Control Unit.
  - Remove the sample holder from the load cell and replace the cover on the load cell platform. **DO NOT PRESS THE TARE BUTTON AGAIN.**
  - Put the specimen in the holder and secure the edge frame to the specimen pan.
4. Check the system one more time, as follows:
- Ensure that there is sufficient drying agent in the column.
  - Check that the soot filters are clean.
  - Check that the laser system slots are covered.
  - Turn the sample Pump on.
  - Check that the flow rates to the oxygen and CO/CO<sub>2</sub> analysers are the same as they were following the calibration of the analyser.
  - Check that the volume flow rate through the duct is 24 l/s.
  - Check that the heater temperature is the same as the temperature noted at the time of the heat flux setting.
  - Check the distance between the cone heater and the sample surface to confirm that it is set at 25 mm, using an identical empty specimen holder as a guide.
  - Ensure that the pump has been running for at least 5 minutes. Then reset the span of the oxygen analyser by using Calibrations/Gas Analysers and then press **Span** in the Oxygen Cell section to set the oxygen concentration to 20.950%. *Note that you may have to also adjust the span in the analyser software.*
  - Ensure the spark electrode is in the idle position and then turn the spark Igniter on.
5. Select **Start Test** and then enter the specimen information. Remember that your tests are performed "Non-scrubbed" and you must enter the correct laboratory conditions (temperature, RH and atmospheric pressure).
6. Then press **OK**.
7. Then perform the pre-run calibrations by pressing the **Yes** button.

## SECTION C: SHUT-DOWN PROCEDURE

1. Adjust the Cone temperature to 0°C.
  2. Wait until the Cone heater temperature is below 250°C
  3. Turn the duct Fan off.
  4. Turn the room extraction off.
  5. Turn the following buttons OFF:
    - a) Pump
    - b) Cold Trap
    - c) Load Cell
    - d) Ignition
    - e) Cone
    - f) Power
- Leave the Analysers and Smoke buttons On all the time.**
6. Shut down the ConeCalc application and turn the computer off. Then turn the data logger off.
  7. Ensure that the gas bottles are off.
  8. Ensure that the cooling water is off.
  9. Place a beaker under the Cold Trap and open the Cold Trap tap to collect the water. Leave the tap open until the next time the instrument is used.



	2024-10-24	N_3F4F_FRONT	30	70,1	19	76,5
	2024-10-24	N_1E2E_FRONT	30	61,7	19	76,5
	2024-10-24	E_3A4D_FRONT	30	63,1	19	76,5
	2024-10-24	N_1B2B_FRONT	30	64,9	19	76,5
	2024-10-24	N_3A4A_FRONT	30	71,2	19	76,5
	2024-10-24	E_3F4F_BAK	30	73,7	21	76,5
	2024-10-24	N_3F4F_BAK	30	77	20	79,9
	2024-10-24	N_1E2E_BAK	30	77	22	76,5
	2024-10-24	E_3E4E_FRONT	70	64,9	18	79,9
	2024-10-24	N_3E4E_FRONT	70	68,6	18	76,5
Friday	2024-10-25	E_1A2A_FRONT	50	69,3	20	76,5
	2024-10-25	E_1B2B_FRONT	50	79,5	20	76,5
	2024-10-25	E_1E2E_FRONT	50	74	19	79,9
	2024-10-25	N_1A2A_FRONT	50	58,1	18	76,5
	2024-10-25	E_1E2E_BAK	50	71	20	76,5
	2024-10-25	E_1F2F_BAK	50	73,6	21	76,5
	2024-10-25	N_1F2F_BAK	50	75,1	21	77,4
	2024-10-25	TW_1	50	104	21	88,4
	2024-10-25	TW_2	50	97,7	21	88,4
	2024-10-25	E_3B4B_FRONT	70	68,1	17	76,5
	2024-10-25	N_3B4B_FRONT	70	77,2	19	76,5
	2024-10-25	E_3E4E_BAK	70	77,7	21	79,1
	2024-10-25	N_3E4E_BAK	70	74,9	23	74
Tuesday_2	2024-10-29	E_1C_MID	50	74,3	19	80,8
	2024-10-29	E_1D_MID	50	70,6	20	76,5
	2024-10-29	N_1C_MID	50	69,4	17-22 (20)	76,5
	2024-10-29	N_1D_MID	50	69,9	17-22 (20)	76,5
	2024-10-29	R8	70	72,9	21	84,6
	2024-10-29	E_2C_MID	70	83	17-21 (19)	76,5
Wednesday_2	2024-10-30	N_3D4D_BAK	70	77,7	21	76,5
compliment	2024-10-30	N_3C4C_FRONT	70	73,2	18	76,5
compliment	2024-10-30	E_3C4C_FRONT	70	66,2	18	80,8
compliment	2024-10-30	N_3D4D_FRONT	50	70,5	19	76,5
compliment	2024-10-30	E_3D4D_FRONT	50	68,1	19	76,5
compliment	2024-10-30	E_2D_MID	30	70,3	20	76,5
compliment	2024-10-30	N_3C4C_BAK	20	78	21	76,5
	2024-10-30	E_3C4C_BAK	20	82	21	76,5
	2024-10-30	E_3D4D_BAK	70	80,1	21	76,5
	2024-10-30	N_2CD_FRONT	50	59,2	18	76,5
	2024-10-30	N_2CD_BACK	50	68	18	76,5
	2024-10-30	TW_3	50	99,8	21	88,4
	2024-10-30	TW_4	70	98,9	21	88,4
	2024-10-30	TW_5	30	102,1	21	88,4
	2024-10-30	TW_6	30	98,4	21	88,4

## Appendix 6 – Position and photos of samples

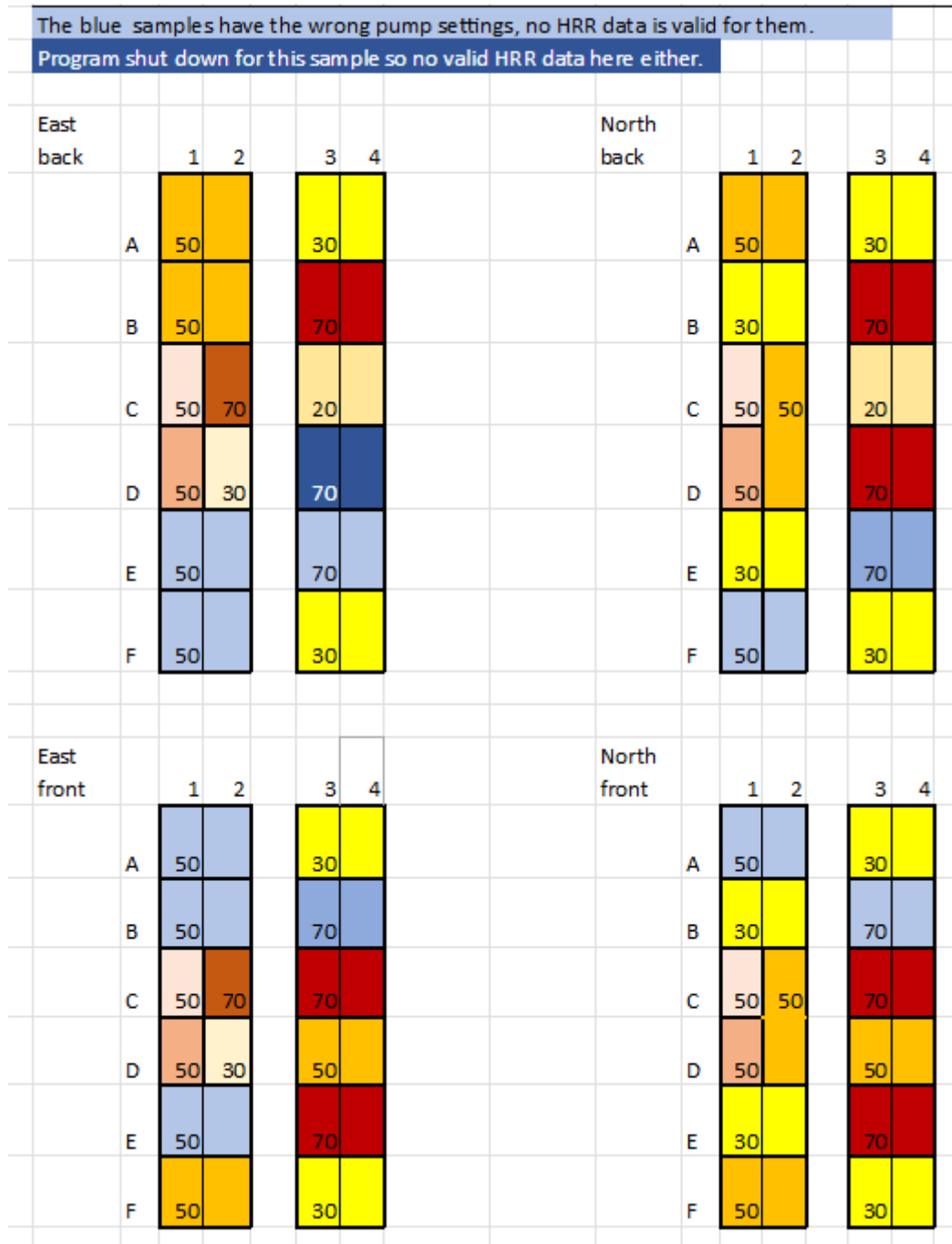
### Sample positions

E MID sl. 1 2 pos. C is the dark brown sample at radian heat flux 70 kW/m<sup>2</sup>

E MID sl. 1 2 pos. C is the brown sample at radian heat flux 50 kW/m<sup>2</sup>

E MID sl. 1 2 pos. D is the lighter brown sample at radian heat flux 50 kW/m<sup>2</sup>

E MID sl. 1 2 pos. C is the light brown sample at radian heat flux 30 kW/m<sup>2</sup>



Photos of samples

30 kW/m<sup>2</sup>



Figure 84:  
E\_2D\_MID



Figure 85:  
E\_3A4A\_BAK



Figure 86:  
E\_3A4A\_FRONT



Figure 87:  
E\_3F4F\_BAK



Figure 88:  
E\_3F4F\_FRONT



Figure 89:  
N\_1B2B\_BAK



Figure 90:  
N\_1B2B\_FRONT



Figure 91:  
N\_1E2E\_BAK



Figure 92:  
N\_1E2E\_FRONT



Figure 93:  
N\_3A4A\_BAK



Figure 94:  
N\_3A4A\_FRONT



Figure 95:  
N\_3F4F\_BAK



Figure 96:  
N\_3F4F\_FRONT



Figure 97:  
TW\_5



Figure 98:  
TW\_6

50 kW/m<sup>2</sup>

Figure 99:  
E\_1A2A\_BAK



Figure 100:  
E\_1B2B\_BAK



Figure 101:  
E\_1C\_MID



Figure 102:  
E\_1D\_MID

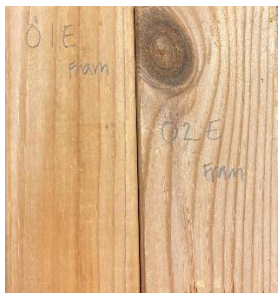


Figure 103:  
E\_1E2E\_FRONT



Figure 104:  
E\_1F2F\_FRONT



Figure 105:  
E\_3D4D\_FRONT



Figure 106:  
N\_1A2A\_BAK



Figure 107:  
N\_1C\_MID



Figure 108:  
N\_1D\_MID



Figure 109:  
N\_1F2F\_FRONT



Figure 110:  
N\_2CD\_BAK



Figure 111:  
N\_2CD\_FRONT

50 kW/m<sup>2</sup> from Friday tastings, with no HRR data



Figure 112:  
E\_1B2B\_FRONT



Figure 113:  
E\_1E2E\_BAK



Figure 114:  
E\_1F2F\_BAK



Figure 115:  
N\_1A2A\_FRONT



Figure 116:  
N\_1F2F\_BAK

70 kW/m<sup>2</sup> from Friday tastings, with no HRR data



Figure 117:  
E\_1A2A\_FRONT



Figure 118:  
E\_3B4B\_FRONT



Figure 119:  
E\_3E4E\_BAK



Figure 120:  
N\_3E4E\_BAK

70 kW/m<sup>2</sup>



Figure 121:  
E\_2C\_MID



Figure 122:  
E\_3B4B\_BAK



Figure 123:  
E\_3C4C\_FRONT



Figure 124:  
E\_3D4D\_BAK



Figure 125:  
E\_3E4E\_FRONT



Figure 126:  
N\_3B4B\_BAK



Figure 127:  
N\_3B4B\_FRONT



Figure 128:  
N\_3C4C\_FRONT



Figure 129:  
N\_3D4D\_BAK



Figure 130:  
N\_3E4E\_FRONT

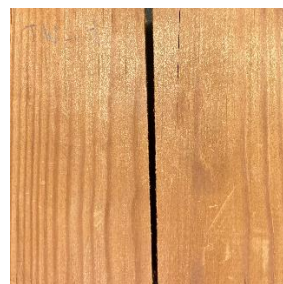


Figure 131:  
TW\_4

## Appendix 7 – Extended results

### Main graphs

The following figures represents all values with radiant heat flux 30, 50 and 70 kW/m<sup>2</sup>.

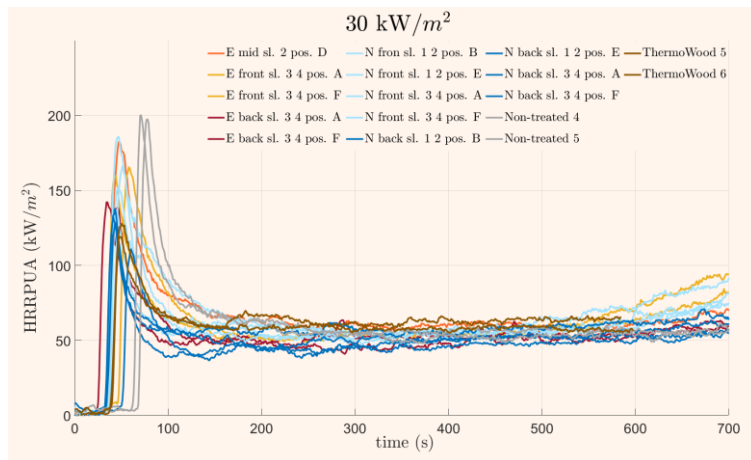


Figure 132: All graphs at radiant heat flux 30 kW/m<sup>2</sup>.

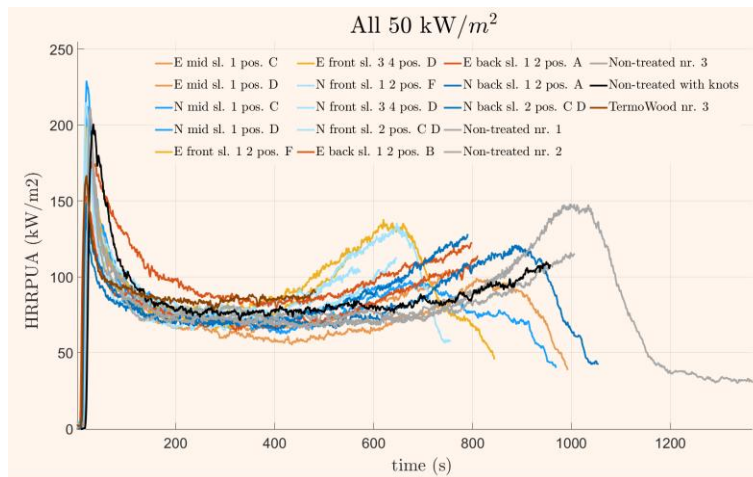


Figure 133: All graphs at radiant heat flux 50 kW/m<sup>2</sup>.

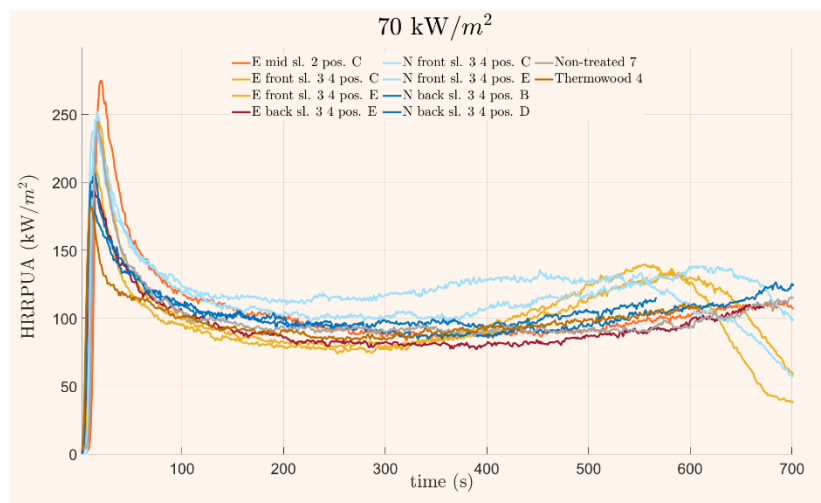


Figure 134: All graphs at radiant heat flux 70 kW/m<sup>2</sup>.

## T-test result

### Explanation of t-test terms for the following tables:

When a double-sample double sample t-test is run in MATLAB (ttest2 function), the outputs are the results of the hypothesis test and each term has a specific meaning:

- i. **h**: This is the **hypothesis test result**. It is a binary value (0 or 1). If  $h = 0$ , it means that there is not enough evidence to reject the null hypothesis at the chosen significance level (i.e., the means are not significantly different). If  $h = 1$ , it means that there is enough evidence to reject the null hypothesis (i.e., the means are significantly different).
- ii. **p**: This is the **p-value**. It represents the probability of observing the data assuming that the null hypothesis is true. A small p-value (less than 0.05) suggests that the null hypothesis can be rejected.
- iii. **ci**: This is the **confidence interval** for the difference between the two sample means. It gives a range of values within which the true mean difference lies, based on the data.
- iv. **tstat**: This is the **t-statistic** value, which is the test statistic used to determine whether the difference between the two sample means is statistically significant. It is calculated by dividing the difference between the sample means by the standard error of the difference.
- v. **df**: This stands for **degrees of freedom**. It is related to the sample size and is used to determine the critical value for the t-distribution. For a two-sample t-test, degrees of freedom are calculated as the total number of observations in both samples minus 2.
- vi. **sd**: This stands for **standard deviation**. In the context of the t-test, it might refer to the standard deviation of each sample or the standard deviation of the difference in means.

There are three tables showing the main results of the t-tests. Table 11 show the t-test results for peak heat release rate per unit area per unit area, PHHRPUA. Table 12 show the t-test results for average heat release rate per unit area, Average HRRPUA. Table 13 show the t-test results for time to ignition, TTI.

Table 11: T-test results of PHHRPUA

<p>Comparing PeakHRR front to back:</p> <p>h = 1</p> <p>p = 0.0026</p> <p>ci = 15.6905 66.1465</p> <p>stats = <a href="#">struct</a> with fields: tstat: 3.3340 df: 26 sd: 32.3890</p>	<p>Comparing PeakHRR front to mid:</p> <p>h = 0</p> <p>p = 0.2051</p> <p>ci = -56.7066 13.0012</p> <p>stats = <a href="#">struct</a> with fields: tstat: -1.3123 df: 19 sd: 34.4738</p>	<p>Comparing PeakHRR bak to mid:</p> <p>h = 1</p> <p>p = 6.2505e-04</p> <p>ci = -94.4369 -31.1055</p> <p>stats = <a href="#">struct</a> with fields: tstat: -4.1823 df: 17 sd: 30.4099</p>
<p>Comparing PeakHRR non-treated to mid:</p> <p>h = 0</p> <p>p = 0.5055</p> <p>ci = -46.6910 24.5938</p> <p>stats = <a href="#">struct</a> with fields: tstat: -0.6907 df: 10 sd: 27.7067</p>	<p>Comparing PeakHRR TW to mid:</p> <p>h = 1</p> <p>p = 0.0117</p> <p>ci = -115.3617 -19.5914</p> <p>stats = <a href="#">struct</a> with fields: tstat: -3.2495 df: 8 sd: 32.1696</p>	<p>Comparing PeakHRR TW to non-treated:</p> <p>h = 1</p> <p>p = 0.0078</p> <p>ci = -93.3780 -19.4778</p> <p>stats = <a href="#">struct</a> with fields: tstat: -3.5216 df: 8 sd: 24.8234</p>
<p>Comparing PeakHRR TW to front:</p> <p>h = 1</p> <p>p = 0.0297</p> <p>ci = -86.1765 -5.0712</p> <p>stats = <a href="#">struct</a> with fields: tstat: -2.3737 df: 17 sd: 34.1565</p>	<p>Comparing PeakHRR TW to back:</p> <p>h = 0</p> <p>p = 0.7834</p> <p>ci = -40.5471 31.1364</p> <p>stats = <a href="#">struct</a> with fields: tstat: -0.2798 df: 15 sd: 29.4097</p>	<p>Comparing PeakHRR non-treated to back:</p> <p>h = 1</p> <p>p = 0.0012</p> <p>ci = 23.6320 79.8132</p> <p>stats = <a href="#">struct</a> with fields: tstat: 3.8848 df: 17 sd: 26.9766</p>

Table 12: T-test results for average HRRPUA

<p>Comparing AvrageHRR front to back:</p> <p>h = 0</p> <p>p = 0.2489</p> <p>ci = -8.5843 31.7037</p> <p>stats = <a href="#">struct</a> with fields: tstat: 1.1796 df: 26 sd: 25.8619</p>	<p>Comparing AvrageHRR front to mid:</p> <p>h = 0</p> <p>p = 0.3124</p> <p>ci = -33.2457 11.2048</p> <p>stats = <a href="#">struct</a> with fields: tstat: -1.0378 df: 19 sd: 21.9829</p>	<p>Comparing AvrageHRR bak to mid:</p> <p>h = 0</p> <p>p = 0.0906</p> <p>ci = -49.1326 3.9722</p> <p>stats = <a href="#">struct</a> with fields: tstat: -1.7942 df: 17 sd: 25.4994</p>
<p>Comparing AvrageHRR non-treated to mid:</p> <p>h = 0</p> <p>p = 0.2114</p> <p>ci = -33.4597 8.3838</p> <p>stats = <a href="#">struct</a> with fields: tstat: -1.3353 df: 10 sd: 16.2636</p>	<p>Comparing AvrageHRR TW to mid:</p> <p>h = 0</p> <p>p = 0.1043</p> <p>ci = -48.1674 5.5162</p> <p>stats = <a href="#">struct</a> with fields: tstat: -1.8321 df: 8 sd: 18.0325</p>	<p>Comparing AvrageHRR TW to non-treated:</p> <p>h = 0</p> <p>p = 0.4546</p> <p>ci = -34.5738 16.9986</p> <p>stats = <a href="#">struct</a> with fields: tstat: -0.7859 df: 8 sd: 17.3234</p>
<p>Comparing AvrageHRR TW to front:</p> <p>h = 0</p> <p>p = 0.4355</p> <p>ci = -37.5275 16.9174</p> <p>stats = <a href="#">struct</a> with fields: tstat: -0.7987 df: 17 sd: 22.9288</p>	<p>Comparing AvrageHRR TW to back:</p> <p>h = 0</p> <p>p = 0.9359</p> <p>ci = -31.4610 33.9702</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.0817 df: 15 sd: 26.8446</p>	<p>Comparing AvrageHRR non-treated to back:</p> <p>h = 0</p> <p>p = 0.4318</p> <p>ci = -16.2682 36.3527</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.8053 df: 17 sd: 25.2670</p>

Table 13: T-test results for TTI

<p>Comparing TTI front to back:</p> <p>h = 0</p> <p>p = 0.9578</p> <p>ci = -11.5176 12.1330</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.0535 df: 26 sd: 15.1819</p>	<p>Comparing TTI front to mid:</p> <p>h = 0</p> <p>p = 0.4059</p> <p>ci = -8.2874 19.6207</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.8500 df: 19 sd: 13.8019</p>	<p>Comparing TTI bak to mid:</p> <p>h = 0</p> <p>p = 0.4427</p> <p>ci = -9.0256 19.7435</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.7860 df: 17 sd: 13.8141</p>
<p>Comparing TTI non-trated to mid:</p> <p>h = 0</p> <p>p = 0.1438</p> <p>ci = -7.2177 42.8843</p> <p>stats = <a href="#">struct</a> with fields: tstat: 1.5862 df: 10 sd: 19.4735</p>	<p>Comparing TTI TW to front:</p> <p>h = 0</p> <p>p = 0.8023</p> <p>ci = -16.4176 20.9176</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.2543 df: 17 sd: 15.7232</p>	<p>Comparing TTI TW to back:</p> <p>h = 0</p> <p>p = 0.7833</p> <p>ci = -16.9098 22.0252</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.2800 df: 15 sd: 15.9740</p>
<p>Comparing TTI TW to mid:</p> <p>h = 0</p> <p>p = 0.3896</p> <p>ci = -12.1513 27.9847</p> <p>stats = <a href="#">struct</a> with fields: tstat: 0.9097 df: 8 sd: 13.4819</p>	<p>Comparing TTI TW to non-treated:</p> <p>h = 0</p> <p>p = 0.5297</p> <p>ci = -44.7285 24.8952</p> <p>stats = <a href="#">struct</a> with fields: tstat: -0.6569 df: 8 sd: 23.3869</p>	<p>Comparing TTI non-treated to back:</p> <p>h = 0</p> <p>p = 0.2020</p> <p>ci = -7.3563 32.3050</p> <p>stats = <a href="#">struct</a> with fields: tstat: 1.3272 df: 17 sd: 19.0442</p>

## Appendix 8 - Declaration of performance

From "Byggvarudeklaration 2015", dated 2019-10-08:

### Vara och/eller delkomponenter

Fas	Leverans				
Komponent	Barrträ		Vikt% av produkt		
<b>Kommentar</b>					
Material	Ämne	Koncentrationsintervall (%)	EG/CAS/Alternativ beteckning	Kandidatlistan	Utfasningsämne
Thermowood furu, Sibirisk		>89		<input type="checkbox"/>	<input type="checkbox"/>

Komponent	Impregnering		Vikt% av produkt		
<b>Kommentar</b>					
Material	Ämne	Koncentrationsintervall (%)	EG/CAS/Alternativ beteckning	Kandidatlistan	Utfasningsämne
Vattenfast brandimpregner		=11		<input type="checkbox"/>	<input type="checkbox"/>
Vattenfast brandimpregner	Dicyandiamidformaldehydcopi<4		26591-12-8	<input type="checkbox"/>	<input type="checkbox"/>
Vattenfast brandimpregner	Fomaldehyd	<0.03	50-00-0	<input type="checkbox"/>	<input checked="" type="checkbox"/>
Vattenfast brandimpregner	Forsforsyra	<6	7664-38-2	<input type="checkbox"/>	<input type="checkbox"/>
Vattenfast brandimpregner	Melamin-formaldehydcopolym<0.7		9003-08-1	<input type="checkbox"/>	<input type="checkbox"/>

From declaration of performance, dated 2022-08-11:

### 7. Angiven prestanda

Väsentliga egenskaper	Deklarerade värden		
Reaktion vid brandpåverkan	<b>Brandklass</b>		
	<b>Träslag</b>	<b>Tjocklek</b>	<b>Ytskiktssklass</b> i enlighet med EN 13501-1
	ThermoWood	19-48 mm	B-s2,d0
	ThermoWood	>48 mm	B-s3,d0
	ThermoAsk	20 mm	B-s2,d0
	ThermoAsk	>20 mm	B-s3,d0
	<b>Bakomliggande material</b>		
	<b>Montering</b>	<b>Minimum densitet [kg/m<sup>3</sup>]</b>	
	Med eller utan luftspalt	≥525 (med en tjocklek på ≥12 mm)	A1 eller A2
	Med eller utan luftspalt	≥37,5 (med en tjocklek på ≥20 mm)	A1
Användningsområde	E – utomhus (CEN TS 15912)		
Typ av panel	Brandskyddsbehandlad ytterpanel		
Träslag	PNSY (furu) eller FXEX (Ask)		
Naturlig beständighetsklass	2 - ThermoWood (enligt SS EN 350) 1 - Thermoask (enligt SS EN 350)		
Densitet	420 kg/m <sup>3</sup> (minsta medeldensitet)		
Infästning	Rostfri syrafast A4		

## Appendix 9 - Documentation EN 16755

<b>RI SE</b>	<b>ASSESSMENT</b>		
	Contact person RISE [REDACTED]	Date 2020-02-25	Reference [REDACTED]
			Page 1 (1)

**Assessment for [REDACTED] according to EN 16755**

This assessment is written on behalf of [REDACTED]  
classification report according to EN 16755:2017.

The results for Scots pine (*Pinus sylvestris*) sapwood according to hygroscopicity test is 22,9 % moisture content.

The results for fire retardant treated Western Red Cedar with treatment Exterior Fire-X according to fire test is for  $HRR_{30s\ ave}$  54 kW/m<sup>2</sup> and for  $THR_{600s}$  increase is not possible to calculate (no ignition before accelerated weathering).

The requirements according to EN 16755:2017 are:

- Moisture content < 28%
- $HRR_{30s\ ave} \leq 150$  kW/m<sup>2</sup>
- $THR_{600s}$  increase < 20% compared to fire testing before the weather exposure

This gives that the product [REDACTED] fulfils the requirements for DRF Class INT1, INT2 and EXT in EN 16755:2017 for all wood species.

**RISE Research Institutes of Sweden AB**  
**Building Technology - Wood Building Technology**

Performed by [REDACTED]	Examined by [REDACTED]
----------------------------	---------------------------

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## Appendix 10 – Extraction from the fire engineering report

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### Ytterväggar

#### Ytterväggar

Fasadytor ska vara utförda av obrännbart material. I begränsade delar på plan 10-11 kan dock fasadbeklädnad av material typgodkänt för ytterväggskonstruktion enligt SP Fire 105 användas. Begränsade delar av fasaden på plan 10 utförs i brandskyddsimpregnerat trä som håller brandteknisk klass B-s1,d0. Denna klassificering är avsedd för innerväggar men är högre än fasadklassificering enligt SP 105. Det brandimpregnerade träet ska vara utformat för utomhusbruk (EXT).

Ytterväggskonstruktioner ska utformas så att

- den avskiljande funktionen upprätthålls mellan brandceller,
- brandspridning inuti väggen begränsas,
- risken för brandspridning längs med fasadytan begränsas,
- risken för personskador till följd av nedfallande delar av ytterväggen begränsas.

Ovanstående krav uppfylls genom följande:

Ytterväggskonstruktioner som vid provning enligt SS-EN 13501-2 med brandpåverkan enligt standardbrandkurvan uppfyller tillämpliga delar av kraven i BBR avsnitt 5:531 på avskiljande funktion uppfyller krav i punkt 1.

Ytterväggar som enbart innehåller material av lägst klass A2-s1,d0 eller som avskiljs på ett sådant sätt att en brand inuti väggen hindras från att sprida sig förbi avskiljande konstruktion, uppfyller krav i punkt 2 på skydd mot brandspridning inuti väggen.

Ytterväggar uppfyller krav i punkt 3 om de utförs i lägst klass A2-s1,d0.

Ytterväggar ska utformas så att kravet i punkt 4 uppfylls så att risken för nedfallande byggnadsdelar, såsom glassplitter, mindre putsbitar och liknande begränsas.

Växtlighet på fasad betraktas ej som del av fasadmaterial. Växter skall ej torka ut om de är heltäckande och täcker flera våningsplan.

## Appendix 11 – Generative AI to understand documentations

Generative AI was asked to clarify the documentation. Names of companies have been replaced by X, Y and Z to keep their anonymity.

### About the fire engineering report

**Question:** Hi, can you help me choose façade for the stories 10 and 11 for my building. Here is the fire engineering report for the building.

**Answer:** Based on the fire protection documentation provided, I notice there are some specific requirements and exceptions for the façade on floors 10-11. Let me help analyze the requirements:

According to section 5.3.1 of the document:

1. The general requirement is that façade surfaces should be made of non-combustible material
2. However, there is a specific exception allowed for floors 10-11:

"In limited parts on floors 10-11, façade cladding of material type-approved for exterior wall construction according to SP Fire 105 can be used."

Additionally, it mentions that "Limited parts of the façade on floor 10 can be executed in fire-retardant impregnated wood that meets fire class B-s1,d0. This classification is intended for interior walls but is higher than façade classification according to SP 105."

Based on these requirements, you have a few options for floors 10-11:

1. Main option: Use any façade material that is type-approved according to SP Fire 105 testing standard for exterior walls
2. Limited areas could use fire-retardant impregnated wood that meets B-s1,d0 class (but only on floor 10)
3. Default option: Use non-combustible materials for the rest of the façade areas

### About the documentation of the material

**Question:** These are supposedly documentations about the same material, however I have trouble with seeing the connection between them, do you find one?

**Answer:** I understand your confusion. Looking at these documents more carefully for any connections:

There doesn't seem to be a clear direct connection between these documents. While they appear to be for fire-retardant timber, there are some discrepancies:

1. The first document is from XXX
2. The second document is from XXX
3. The RISE assessment is issued to YYY

However, there is an interesting detail in the RISE assessment that might provide a link:

"YYY has permission from ZZZ to use 2P00490-B classification report according to EN 16755:2017."

This suggests there might be some relationship between these companies, but from these documents alone, we can't definitively establish that these are describing the exact same product.

To properly establish if these are indeed for the same material, we would need:

1. Clear product identification numbers linking the documents
2. Cross-references between the documentation
3. Explanation of the relationship between XXX, YYY and ZZZ.

## Appendix 12 - Usage of generative AI

The following table presents how the author has used generative AI as a tool for the thesis.

<b>Usage of Generative AI tools</b>	<b>Yes or No</b>
1) I used in my report a Generative AI tool (e.g. ChatGPT or similar)	Yes
2) I used a GAI tool as language editor (i.e. to correct grammar mistakes, etc.)	Yes
3) I used GAI to retrieve information	No
4) I used GAI to get help in writing code	Yes
5) I used GAI for translations	Yes
6) I used GAI to generate graphs/images	No
7) I used GAI to help structuring my content	No
It was used to: <ul style="list-style-type: none"> <li>- Generate base scripts for MatLab</li> <li>- Translate words from Swedish to English and vice versa</li> <li>- Help with reformulating paragraphs of text</li> <li>- Check grammar</li> </ul>	