Design Fire for Building Content in Arson Scenarios

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Abstract
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In this thesis the possibility of predicting components behaviour when accelerants are added is investigated by use of small-scale experiments. The specimens were ignited with a smaller ignition source and the heat release rate was measured using oxygen calorimetry. Data was analysed using factorial analysis and functional analysis. It was showed that both methanol and heptane affected parameters such as the time to peak, peak heat release rate and growth rate in a way that made the foam and fabrics behave worse.
With superposition was it possible to predict the total heat released with a 12% error on average for standard non flame retarded foam.

The increase in growth rates is found to be of such magnitude that accelerant as part of the ignition source should be accounted for in the design phase if an arson scenario is deemed likely.

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Disclaimer

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June 1, 2014

Read & approved

Abstrakt (Danish)

Omkostningerne af brande forårsaget af brandstiftelse tegner sig for mellem 0.1 og 0.4 % af et lands BNP globalt, er det skønnet. Hvis brandstifteren benytter sig af flydende brandbar væsker er potientalet og risikoen for tab af liv forøget. Det er ønskværdigt at reducere dette ved at medregne brandbare væskers effekt i design fasen.
I dette speciale er muligheden for at forudsige individuelle komponenters opførsel og effekt undersøgt når der tilføjes brandbare væsker ved brug af ned-skaleret eksperimenter. Prøverne blev antændt med anvendelse af en mindre antændingskilde og brand effekten blev målt ved iltforbruget. Data blev analyseret ved brug af faktoriel og funktionel analyse.
Det blev vist, at både metanol og heptan forværrede vigtige parametre såsom tid til maksimum effekt, maksimum effekt og effektudviklingen. Dette forværrede skummet og stoffets opførsel. Den samlede brandbelastning var mulig at forudsige med superposition med 12% afgivelse med standard skummet.
Forøgelsen i effektudvikling er fundet af sådanne størrelse at brandbare væsker som en del af antændelseskilden anbefales inkluderet i design fasen hvis brandstiftelse er vurderet som et sandsynligt scenarie.

Abstract

The cost of fires caused by arson on a global-scale is estimated between 0.1 and 0.4% of a country's GDP. If arsonist uses liquid accelerants is the potential for growth much greater and the risk for loss of live is increased. It is desirable to reduce this risk by anticipating the accelerant in the design phase.
In this thesis the possibility of predicting components behaviour when accelerants are added is investigated by use of small-scale experiments. The specimens were ignited with a smaller ignition source and the heat release rate was measured using oxygen calorimetry. Data was analysed using factorial analysis and functional analysis. It was showed that both methanol and heptane affected parameters such as the time to peak, peak heat release rate and growth rate in a way that made the foam and fabrics behave worse.
With superposition was it possible to predict the total heat released with a 12% error on average for standard non flame retarded foam.
The increase in growth rates is found to be of such magnitude that accelerant as part of the ignition source should be accounted for in the design phase if an arson scenario is deemed likely.

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Contents

List of Symbols

Symbol		Unit
A	Area	$[m^2]$
E	Energy per kg O_2 Consumed	$[kJ/kg_{O_2}]$
E_i	Step i of Data Set E	
f(Re)	Function of Reynolds Number	$\left[\frac{\sqrt{\frac{2\Delta p}{\rho}}}{V}\right]$
HRR	Heat Release Rate	$[kW]$
k_c	Exhaust Duct Shape Factor	
M_a	Molar mass of Incoming Air	$[g/s]$
m_i	Step i of Data Set m	
M_{O_2}	Molar Mass of Oxygen	
$\dot{m}_e$	Mass Flow Rate	
p_0	Ambient Pressure	$[Pa]$
p_s	Saturation Pressure	$[Pa]$
$\dot{Q}$	Heat Release Rate	$[kW/m^2]$
$\dot{Q}_{peak}$	Peak Heat Release Rate	$[kW/m^2]$
RH	Ambient Relative Humidity Fraction	
s	Data Step	
t	Chapter 1 - Time	$[s]$
t	Chapter 3 - Time step	$[s]$
T_0	Ambient Temperature	$[K]$
THR	Total Heat Released	$[MJ]$
TTP	Time To Peak	$[s]$
ΔH_{eff}	Effective Heat of Combustion	$[MJ/kg]$
$PHRR$	Peak Heat Release Rate	$[kW/m^2]$
X_{O_2}	Measured Oxygen Fraction	
$X^0_{O_2}$	Ambient Oxygen Fraction	
X_{CO_2}	Measured Carbon Monoxide Fraction	
$X^0_{CO_2}$	Ambient Carbon Monoxide Fraction	
X_{H_2O}	Measured Water Fraction	
α	Chapter 1 - Growth Factor	$[kW/s^2]$
α	Chapter 2 - Expansion Factor	
ϕ	Oxygen Depletion Factor	
ρ_e	Density of Exhaust Gases	$[kg/m^3]$

Abbreviation		Unit
$ASET$	Available Safe Egress Time	$[s]$
C	Cotton Fabric	
EPC	Euclidean Projection Coefficient	
ERD	Euclidean Relative Difference	
FSE	Fire Safety Engineering	
FR	Flame Retarded	
H	Heptane	
M	Methanol	
NFR	Non-Flame Retarded	
PBD	Performance-Based (Fire) Design	
P	Polyester Fabric	
PC	Polyester-Cotton Fabric blend	
$RSET$	Required Safe Egress Time	$[s]$
SC	Secant Cosine	

Variations with respect to SI decimals relationships such as kilo and mega may occur.

List of Tables

List of Figures

Chapter 1

Introduction

The engineering discipline of fire safety engineering (FSE) has within the last 40 years captured the attention of the scientific world. It was fuelled by a societal pressure to reduce the number of fatalities and expenses as result of fires. Older sciences, relative to FSE, such as mathematics and physics both play a key role in the everyday work of the fire safety engineer, where derivations and physical models are continuously used in modern societies to predict the fires development, spread and impact. Models are often based on empirical correlations originating from experiments e.g. ceiling jet by Alpert [1], plume theories by Zukoski [2], Heskestad [3] and McCaffrey [4].

Tests often play a large role in assessing fire safety properties for various materials. Correlations and extrapolations of these are used to tell something about how said material impacts a design, is it contributing, neutral or maybe reducing the development of a fire.
The first recorded attempt to make a standardised test was as early as 1902 in the U.S, but failed. It was not until 1936 that the first standardised test was approved. It was for textile flammability and was approved in England. Two years later did the NFPA 701 Bunsen-burner test, in the U.S, get approved [5]. Since then, have the field of fire science bloomed and especially in the 70's and 80's where a lot of important research took place. Noticeable and important research with respect to this thesis, is the oxygen consumption method [6, 7], the realization and acknowledgement of the importance of the Heat Release Rate (HRR) with respect to determining the size of the fire [5], and testing of various upholstered furniture to determine their contribution to room fires with respect to the measured heat release rate [8, 9].

1.1 Statistical Research

In the U.S, during a five year period spanning from 1973 and 1982 were 26.2% of civilian fatalities caused by significant influence of upholstered furniture fires [10]. In the years between 1980 to 1984 is it estimated that 1220 civilian fatalities were caused every year on average by upholstered furniture, in which it is meant that the

furniture significantly contributed to the development of the fatal fire [11]. During the five year period from 2007 to 2011 were the number of fatalities roughly got reduced by two thirds to approximately 450 in average per year. Even though the home structure fires, with first large item to ignite being an upholstered furniture, only count for merely 2%, the number of fatalities is greatly disproportional and cause 20% of all civilian fatalities by fires on an annually basis.

In Europe, was the upholstered furniture also a significant contributor in terms of civilian fatalities and property damage. In the late 80's and early 90s was it shown that the majority of European civilian fatalities were because of fire in upholstered furniture [12].

In England, similar trends to the U.S was shown. The origin remained unspecified except for a dwelling occupancies, the cause of civilian deaths between 1982 to 1986 was on average 538 per year, and lowered to 260 between the years 2006 to 2010 [13]. Fatalities caused by furniture and furnishings as first large item to ignite was on average estimated to be 163 from 1986 to 1990 and lowered to approximately 70 from 2001 to 2006 [14]. The main contributor to these fatal fires were due to smoking materials e.g. cigarettes [15]. The number of fatalities in fires were reduced over these years, but the percentage of which resulted from upholstered furniture fires remained roughly the same from 48% to 43%. This indicates a general trend towards better fire safety, but no change with respect to furniture fires.

In Sweden home fires account for the majority of civil fatalities, close to 75%. The numbers of fatalities due to fires has been almost constant during a 20 year period, spanning from 1988 to 2008, where 100 to 150 fatalities occurred every year [16].

The decreasing fatalities in the U.S, and the United Kingdom in general, arose from the passing and implementation of the California Technical Bulletin (TB 117 and TB 133 [17] (or State equivalent)) and the Furniture and Furnishing Fire Safety Regulations [18], respectively [13] [10]. These standards required a certain level of fire resistance in upholstered furniture and mattresses. The implementation led to a reduction in ignitability and flammability of upholstered furniture in following years. This significantly improved the survival chances for occupants during a fire. This is especially true for public buildings where the TB 133 is required by law, whereas dwellings are not under the same strict requirements.

1.2 Upholstered Furniture Research

After the implementation of the aforementioned fire tests, were manufactures forced to provide proof of compliance by spending large sums of money on numerous fire tests. This lead to a demand from manufactures side to reduce the costs by means of alternative and cheaper furniture behaviour predictions of their products. Researchers worked on correlations between bench-scale and full-scale tests to save the industry some money on the countless of tests needed on all their products [9, 19].

By finding a correlations between bench-scale and full-scale tests, researchers hoped to predict the furnitures contribution to its Heat Release Rate(HRR) and general contribution to fire [20]. The single item-item tests did not show how a product would behave in reality [21], and the small-scale tests could not predict the full-scale behaviour to a satisfactory degree [10]. Besides focusing on the materials in modern upholstered furniture, was the location of the ignition source researched in great detail [22, 23]. The focus has been on the influences of various upholstered furniture contributions in terms e.g. smoke production, heat release rate, peak heat release rate and mass loss rate during a fire.

Babrauskas [8] state that the interaction between covers and foams are impossible to predict based on single material burnings. Gallagher[24] comes to same conclusion by stating; single item tests such as covers can be resistant enough to withstand a fire test, and the foam likewise, but when placed on top of each other they could fail. These experiments were conducted with various fabrics and foams, but no accelerants were included in the research.

Most furniture tests, such as the TB133 [17], BS-EN 1021-1&2:2006 [25] [26] uses a smouldering ignition source, a match equivalent and paper, respectively, as ignition sources. Furniture tests are not designed to predict or limit fire behaviour in case of arson and certainly not the use of an liquid accelerants as a part of the ignition source, also pointed out in literature [17, 25, 26].

1.3 Intentional Fire Statistics

Statistics from England and Wales both from 2009 and 2010 show that more than 32,000 intentional fires were reported by the police [27], in 2004 that number was 28,000 of which 16,100 occurred in other buildings than domestic buildings [28]. In 2008 Sweden had 11,000 reported fires in buildings, of these, $10-15\%$ were reported as arson fires [29] of which 2950 were in public buildings and 400-500 in school buildings alone [16]. In the years between 1996 and 2004 it was assessed by Swedish fire officers that 11% of all fires were caused by arson [21].

In New Zealand, the number of intentional fires in 2004/05 was 1013 [30] equivalent to 15.6% of all reported fires. In the U.S 306,300 intentional fires were reported in average every year over a five year period from 2005 to 2009 of which 18% (55134) were in structures and 33080 in residential properties [31]. In the years from 2007 to 2011, 28,900 fires were annually reported as intentional home structure fires [11].

These data show how widely spread the problem of intentional fires are on an international scale. The cost of fire was estimated to range between 0.1% and 0.4% of a country's GDP in the years between 2005 and 2007 [32], which is a substantial amount of money for any country and is very desirable to reduce. It is furthermore estimated that arson contributes to between 15% and 50% of total fire related cost

in developed industrial countries [33].

The national data is freely available and the extent of which intentional set fires are a legit threat on a global scale with respect to frequency, fatalities and financially expenditure. It is troubling that manufactures are required to test their product with a ignition source not equivalent to a large ignition source, comparable or equivalent to a liquid accelerant. The ignition source plays a key role in the developing phase of a fire, and if underestimated could lead to under-predicted growth rates with catastrophic consequences.
National and International fire tests are designed to grade and classify products, but does not cover all possible scenarios encountered once sold and the most probable case might not be what it is tested for.

The tests are not questioned or deemed irrelevant at all, but it necessarily is not a representation of how a product behaves in the 'real world', especially if an arson scenario is relevant for the design.

1.4 Design Fires

It is customary when doing a design fire to look through literature for HRR for furnishings representing the chosen area of design the e.g. building, room, atrium, warehouse. When doing so for a arson scenario, the literature is scarce and this thesis aims to provide and enlighten certain areas of interest with respect to usage of accelerants in the design phase.
Extensive research have been done in order to provide fire safety engineers with knowledge about the growth rate, α, the Peak Heat Release Rate(PHRR), $\dot{Q}_{max}$, mass loss rate, $\dot{m}''$ and fraction of species, Y_i, in order to estimate the fire required for design purposes.
The growth rate of the fire, is normally known as the *fire growth factor*, α and given in kW/s^2 and plays a central role in the initial phase of any fire. The fire growth rate is a part of the t-squared fire curve, seen in Equation 1.1, commonly used in determining the beginning of fire scenario in Performance-Based (Fire) Designs known as *PBD*.

$$\dot{Q} = \alpha \cdot t^2 \tag{1.1}$$

$\dot{Q}$ is the heat release rate is given in kilowatts (kW), α is the growth factor given in kilowatts per second squared (kW/s^2) and time, t, is in seconds (s).

The recognition of problems requiring performance-based fire protection solutions has been increasing in line with ever so changing engineering limitations and desire to challenge said limits. Performance-Based Designs are the result of these engineering developments and it is becoming more and more accepted as a valid solution in fire safety legislations worldwide. Worldwide is the prescriptive solution still the most frequently used solution to fulfil fire safety requirements which got its own

advantages. The prescriptive solution does provide advantages over performance solutions, but it is also very rigid and at times more expensive and got its shortcomings when e.g. a complex geometry is at hand. These limitations and inadequacies have been recognised by several countries worldwide. To mention some countries which have implemented PBD (year of implementation in brackets) are: Sweden(1994) [34], New Zealand(1994) [34], Australia(1995) [34], United States(1995) [34], Norway(1997) [35], Denmark(2004) [36].

Common to all the aforementioned national legislation, the requirement is to protect life safety of the occupants and provide structural stability of the building. These two requirements are focusing on different phases during a fire. Life safety is a concern in the beginning of a fire also referred to as, the *growth phase*, whereas the structural stability is mainly concerning the steady phase of the fire. The fully developed fire after flashover has occurred is where the structural members are being stressed the most.

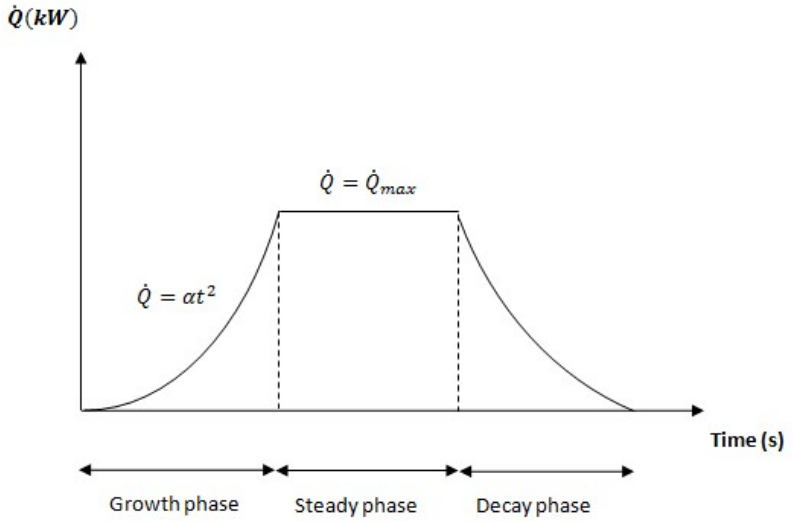

Figure 1.1: A simple fire design curve.(*Initial ignition or smondering phase is omitted here*) inspired by Steffansson [37]

The time frame for the growth rate is usually considered in minutes and for most cases less than $30min$ [38]. The steady phase on the other hand can be anywhere from $30min$ to days if the fuel load is large enough, but will usually be in the range of a few hours due to fire brigade intervention, limited fuel and hopefully good fire safety design [38], the time frame is simplistically illustrated in Figure 1.1.

In prescriptive designs requirements, limitations and certain procedures are followed to the letter, which then is deemed an acceptable solution by legislation. The performance-based codes are often using qualitative phrases such as "*safe guard people from injury*" and terms such as "*reasonable*","*acceptable*" and "*adequate*" when determining the level of safety. It is essential in performance-based fire protection to compare stated performance criteria with one or several trial designs. These per-

formance criteria fall under the goals and objectives, such as: life safety, property protection, continuity of operations or something fourth close to the owners heart. Before being able to analyse, it is necessary to develop one or several design fire scenarios. These are used to test one or several trial designs. The evaluation whether the performance criteria are met or not is critical in order to select the optimal solution [39]. It is customary to develop several representative design fires and combine them into a few design fire scenarios. It is much harder for the fire engineer and the authority having jurisdiction to evaluate and requires more knowledge to apply and approve [39] and is therefore important for the engineer to have validated input values for their designs.

One of the early steps in the process is to identify possible fire scenarios and what affects them e.g ignition source, first item to ignite, geometry of compartment and fuel in the room. In this process, it is useful to review statistical and historical data from comparable facilities as a starting point and move to other analytical techniques if data is inadequate. Various analytical techniques, such as a *What if?* analysis, *Event Tree Analysis* or *Fault Tree Analysis* could be used.
During the early stage of a fire, where the growth phase is important, occupant life safety is a concern. It is common to use the terms ASET and RSET as a pass/fail marker when considering life safety in PBD. The time frame where occupants are evacuating determining the Required Safe Egress Time (RSET). The time before critical conditions (tenability limit) are met is the Available Safe Egress Time (ASET). These two times are compared and determines whether enough time for safe egress is available (ASET>RSET) or not.

The growth phase is paramount in terms of life safety. If the growth rate is underestimated, the design will over-predict the ASET, thus possibly endangering occupants trying to evacuate in untenable conditions. Nilsson *et al* [40] showed how the α value increased by up to 70 %, if arson was present compared to without, in the studied cases.

Another important parameter is the Time To Peak (Heat Release Rate implied) which affects the Available Safe Egress Time (ASET) that is compared to the Required Safe Egress Time (RSET) in the design phase. These two parameters are included in all performance-based fire designs and is a key parameter for occupant safety and in most cases dictate if a design is considered safe or not.

It is in the best interest of users and occupants to have a margin as large as possible between between ASET and RSET, also know as the safety factor [39]. From a owners point of view it is unwanted with a 'too safe' design from a financial perspective. This cause some conflict of interests, and it is the engineers task to satisfy both parties and valid data makes this task easier.

This translates into a low time To Peak (TTP) is generally a bad thing for the design of a building since it does not allow a lot of time for evacuation. Although a low

TTP is not necessarily a bad thing if the PHRR of the material is not sufficiently high to cause spread or even sustain flaming by its own such as shown in Figure 3.2 on page 21 for Flame Retarded foam (FR).

1.5 Research of Accelerant Impact

Throughout literature, and presented in previous sections, it has been pointed out that; fires in public buildings have a greater potential for loss of life compared to residential buildings [10, 21, 41], that upholstered furniture contribute immensely to the HRR [12, 11, 14] and that arson is a problem that cannot be ignored in the design phase if it is anticipated to be at risk for arson attacks [27, 28].

Public buildings are frequently subjected to arson attacks, and it is critical that considerations to this are made as early as the design phase as possible, especially if a performance-based fire safety solution is being implemented. PBD allows for this to be considered and accounted for. Unfortunately there is not a lot of data available when the fire engineer tries to take it into account.

Some researchers have tried to determine the effects of accelerants with respect to the HRR and the impact in the Time To Peak (TTP). Richards [30] showed the effect of a Molotov cocktail with respect to the HRR and PHRR and identified the general use of accelerants as a "*critical fire scenario that would benefit in terms of life safety if considerations were made in the design process*". Janssens [23] investigated the impact of a liquid accelerant, gasoline, poured onto foam in different locations of upholstered mock-ups, e.g. seat, armrest, back. In terms of time to ignition were there no difference between the large burner and the the accelerant, whereas the small ignition source had a significant increase of ignition delay.

Unfortunately, like mentioned, most furniture tests are done with small or minor ignition sources which makes the job for the fire safety engineer challenging in terms of assessing if the data is applicable to the problem or if extrapolation can be made, and to what extend.

A limited amount of research has been done on the effects of accelerants within the field of fire safety engineering, but, as stated it is evident that it will impact the fire growth, and is important to account for, thus, justifying the work done in this thesis.

If arson is considered in the fire safety design, it is possible to predict the HRR by use of single item testing.
A factorial scalar analysis and a functional vector analysis were chosen as method of analysis in order to use quantitative methods to perform statistical comparisons in contrast to a qualitative comparison. A priori analysis using the superposition principle was performed on the raw data of HRR and Total Heat Released (THR).

Chapter 2

Experimental Description

The aim of this chapter is to describe; the materials used, the methodology, the experimental set-up and the chosen methods of analysis. All tests were conducted at the Department of Fire Safety at Lunds University's own fire laboratory. The goal of the experiments were to clarify if, and if so, to what extend liquid accelerants impacted the Heat Release Rate(HRR) curve with respect to time, when designing for arson scenarios.The conducted experiments were done under the assumption that it was the 'first large item' to ignite and therefore is the behaviour under a radiative source not enlightened in this thesis.
In order to test this, an experimental method was chosen. The samples were small-scale of 19.9 by 19.9cm.

2.1 Choice of Materials

Two unique kinds of foam were tested, a $25kg/m^3$ standard polyether based polyurethane foam without flame retardant and a $37kg/m^3$ flame retarded polyether based polyurethane coldfoam. Besides the two types of foam, three fabrics were tested: a 100% cotton, 75% cotton 25% polyester blend and finally a 100% polyester fabric. The used accelerants were heptane and methanol.
The two different kinds of foam were chosen to see the how flame retarded foam would perform compared to a non flame retarded foam. The foams were selected based on the possibility to have as many parameters comparable as possible such as thickness, density and main chemical components.
The fabrics were chosen based on a online study on *ikea.dk* and *stof2000.dk*(fabric2000) of fabrics used for numerous upholstered furniture and cotton and polyester were among the most used fabrics. A combination of the polyester and cotton was chosen to see what effect a blend product would have.
The acceelerants were chosen partly because of convenience and availability, but also because data with respect to arson investigations are scarce and literature references to limited data from 1982 and 2001, both provided by Babrauskas[42].

2.1.1 Foams

Two kinds of foam were chosen with different properties, this was done in order to gain knowledge of various foams and look for general trends.

Both foams were a polyether based flexible polyurethane. The flame retardants is a composite of phosphorous, chlorine and bromine produced by the Carpenter [43]. The foams were cut and labelled numerically according to its given experimental number, as well as weighed and measured to control the mass and partly to control the density provided by the distributor. To make sure each specimen and its two duplicates were given optimal conditions to perform consistently their mass was made sure to be within 5% of the mean value, like done in the CBUF project [12].

The average mass of the 36 Flame Retarded(FR) foam samples were $49.2g$ with a standard deviation of $1.0g$ and maximum $\pm 2.3g$ of difference from mean. An average size of $19.9cm$ along both sides and $4cm$ of thickness was measured. The average density was determined as $31kg/m^3$ using Equation 2.1.

$$\rho_{FR} = \frac{49.2g}{19.9cm \cdot 19.9cm \cdot 4cm} \approx 31\frac{kg}{m^3} \tag{2.1}$$

Whereas the distributor labelled it as $37kg/m^3$.

The 36 Non Flame Retarded(NFR) foam samples were also measured and weighed and found to have an average mass of $43.4g$ with a standard deviation of $0.5g$ and maximum $\pm 1.0g$ of difference from the mean. An average size of 19.9cm along the sides and $5cm$ of thickness was measured. The resulting density was $22kg/m^3$ calculated by using Equation 2.2.

$$\rho_{NFR} = \frac{43.4g}{19.9cm \cdot 19.9cm \cdot 5cm} \approx 22\frac{kg}{m^3} \tag{2.2}$$

Where as the distributor labelled it as being $25kg/m^3$.

The $2.3g$ and $1.1g$ of differences fall within the set $\pm 5\%$ limit - as done in CBUF [12] - these limits corresponds to $2.5g$ and $2.2g$ for FR and NFR, respectively.

The difference in densities are not critical to the experimental set-up, but calculated and presented for ease of comparing results to other references and external experiments.

2.1.2 Fabrics

Three kinds of fabrics were chosen, this was done in order to show results and trends from more than a single products and have an indication of the general impact of various fabrics.

The three kinds of fabric were, a 100% Cotton (C), 100% Polyester(P) and a 25% Polyester-75% Cotton blend(PC) were used to test the influence of various fabric coverings impact on the HRR.

The densities measured per squared meter were determined by weighing and measuring numerous samples of each fabric and taking an average of it. The densities of the different fabrics are presented in table 2.1 and given in mass per area.

Fabric	Density $[kg/m^2]$
Cotton	0.160
Polyester	0.400
Cotton and Polyester	0.183

Table 2.1: Density of fabrics.

2.2 Accelerants

Heptane (H)[C_7H_{16}] and methanol (M)[CH_4O] were used as accelerants. An initial study was done early in the process with the purpose to identify the amount of accelerants needed to make a significant(noticeable) change in the HRR. As described by Richards [30] does the amount of accelerant impact the burning of the specimens. If too much is chosen the effect of the accelerant dominates the data. If too little is chosen the effect of accelerant will be negligible. The study is described in *Appendix B Initial Accelerant Study*. The findings determined that $9ml$ was sufficient to notice a difference in the HRR, and still corresponding to a realistic quantity of accelerants used in a possible arson scenario as explained in the *Appendix B Initial Accelerant Study*.
Firstly, two accelerants were chosen because the research from arson crime scenes are scarce. Heptane and methanol contain very different energy content, $44.6MJ/kg$, $20.0MJ/kg$, respectively [38] and therefore provide different results. Secondly, two were chosen to show a generally trend and not represent just a single accelerant.

2.3 Ignition Source

Normally, a larger ignition source is used in tests [17, 18], but those are for full scale experiments and the contribution of five double sheets of newsprint equivalent of $90g$ was assumed be too great and could disguise the material behaviour and contribution of interest. It was desired to have an ignition source which did not impact the behaviour of the materials in a negative or positive manner, thus as neutral as possible. A strong, but not too strong, ignition source was required to consistently ignite the samples. A 2 by $2cm$ piece of cardboard dipped in methanol

and removed of any excess methanol was chosen. It was consistently placed in the centre of the samples prior to imminent ignition by a common safety-match. The random cut piece of cardboard was measured and weighed on a load cell in order to determine its density by use of Equation 2.3.

$$\rho_{cardboard} = \frac{27.49g}{16.1cm \cdot 21.0cm \cdot 0.6cm} \approx 136kg/m^3 \tag{2.3}$$

and found to be approximately $136kg/m^3$. The amount of additionally transferred methanol prior to ignition of the test specimens was not measurable and regarded as negligible towards the overall HRR. The reason not to simply use a safety-match was due to risk of insufficient burning time before self-extinguishing. Except for a few fabric tests were the overall contribution of the ignition source unnoticeable with respect to the measured HRR.

2.4 Experimental Set-up

The experiments were conducted under a large hood where the specimens were located directly below. The HRR was measured by use of the oxygen depletion method by Huggett [6, 7]. It was calculated in accordance with ISO 5660-1:2002 [44] and the cone calorimeter's user Guide [45]. The calculation procedure followed were by Jannssens [46], and is fully explained in the *Appendix C Calculation Procedures*. The energy released by the specimen is calculated by equation 2.4 in kilowatts. The main part of the calculation procedure is briefly explained below.

The oxygen depletion method is, as the name suggest, a method using the measurement of depleting oxygen in the incoming gas measured in the exhaust duct. This depletion is transformed into energy released by the specimen by use of several measured parameters including the heat released per unit mass of oxygen consumed $[MJ/kg_{O_2}]$. It is widely accepted that this value is fairly constant around $13.1MJ/kg_{O_2}$ $\pm 5\%$ [46, 44, 7] for organic fuels. This value was used for the burning of all specimens because the exact heat of combustion was unknown.

$$\dot{Q}(t) = E\frac{\phi}{1+\phi\,(\alpha-1)}\dot{m}_e\frac{M_{O_2}}{M_a}\left(1 - X^0_{H_2O} - X^0_{CO_2}\right)X^A_{O_2} \tag{2.4}$$

Where the E is the energy per kg of oxygen consumed($13100[kJ/kg_{O_2}]$), α is the expansion factor[-], ϕ is the oxygen depletion factor [-], $\dot{m}_e$ is the mass flow rate in the duct[kg/s], $X^A_{O_2}$ is the measured oxygen mole fraction in the duct[-], $X^0_{CO_2}$ is the ambient carbon dioxide mole fraction[-], $X^0_{H_2O}$ is the mole fraction of water in the incoming air[-], M_{O_2} is the the molecular mass of oxygen in [kg/mol], M_a is the molecular weight of the incoming air in [kg/mol].

The experiments were conducted by testing foam, fabric and accelerant, both combined and separately. A Yates order was set up for a factorial design system which

was used to determine and analyse if differences arose. The fractional factorial design set-up can be found in *Appendix F Factorial Design Set-up.*
The fractional factorial design used was a two-way design, which means that maximum two factors contribute to the outcome, e.g. the cover and accelerants impact on a certain type of foam. This was done to investigate impacts of the different components used in the experiment. The factorial design matrix was based on two factors with 2 levels and a three factor with also two levels result in $2^2 \cdot 3^2 = 36$ tests of which one is without foam, without cover and without accelerant, resulting in 35 test groups. The factorial design set-up can be found in the *Appendix F Factorial Design Set-up* with gray cell colouring for experiments of higher interactions, or none at all.

The 35 tests groups were repeated 3 times to show satisfactory repeatability and add certainty to the results and conclusions. This results in 105 unique tests. The repeatability was quantified using functional analysis [47, 48] following three parameters, namely the relative difference, the inner product and the projection coefficient. These parameters are explained in *Section 2.5 Analysis Methodology.*
A rough rule of thumb taken from the factorial analysis says; that main effects tend to be higher than two-way interaction and even higher than third-way interactions and so forth[49].

All foam samples were cut, measured, as previously mentioned, and weighed to keep track of their mass and their mass lost during the experiments. All foams as well as fabrics were inspected to ensure no inconsistencies in terms of e.g. creases, holes or dirt were present. An explicit experimental procedure can be found in *Appendix A Experimental Procedure.*

The naming of the materials was strived to be as simple and transparent as possible, thus: 'H' for Heptane, M for Methanol, 'FR' for flame retarded coldfoam, 'NFR' for non flame retarded standard foam, 'C' for cotton fabric, 'PC' for polyester-cotton fabric bland, 'P' for polyester fabric and finally '- 1,-2 OR -3' for the repetition indication. A experimental abbreviation could look like: NFRCH-1 for the first test of heptane accelerant poured over the coldfoam covered with cotton padding(ignited with a methanol covered piece of cardboard). Or H-3 for the third test of heptane alone. All abbreviations are summarized in Table 2.2 below.

Material	Abbreviation
Flame Retarded foam	FR
Non Flame Retarded foam	NFR
Cotton	C
Polyester-Cottton	PC
Polyester	P
Heptane	H
Methanol	M
Number in series	1, 2 or 3

Table 2.2: Abbreviations of materials, used for naming purpose.

In order to limit the contribution of uncertainties and errors in terms of noise and drifting in measuring and analysing equipment. A randomisation of experiments were done to prevent cotton fabric by default yielded different values compared to polyester just because the equipment was drifting ever so slightly during several days of experiments despite continuous daily calibration.

The randomization scheme was done by assigning all tests a random value between 0 and 100 by use of Excel and arranged after increasing value. The scheme is found in *Appendix G Ranked Order of Experiments* and was used to dictate the order in which the experiments were conducted.

2.5 Analysis Methodology

2.5.1 Factorial design

The full factorial design was done following the procedures described in *Experiment! planning, implementing and interpreting*[49] and a reduced explanation is given below.
A 2 by 2 by 3 cube is illustrated in Figure 2.1, with foams, accelerants and fabrics as axis. Every intersection represents an experiment to be conducted, where $(-;-;-)$ represents the previous mentioned 36^{th} and omitted experiment.

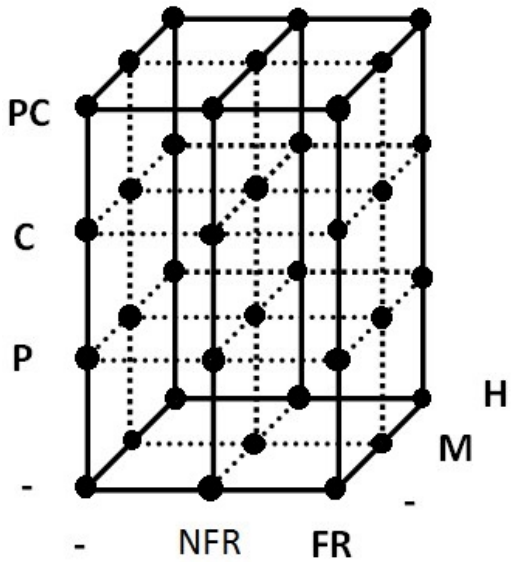

Figure 2.1: Full factorial design presented as a 3-dimensional rectangle.

For the explanatory simplicity, a limited example is presented in Table 2.3 for a single foam type, fabric and accelerant. The *Response* column is the chosen value of the analyses e.g PHRR, TTP or Heat Released (HR). Materials are indicated with -1 and (+)1 as not-present and present, respectively. The column with interactions

between *Fabric* and *Accelerant* is sorted out by multiplying the values in the previous columns on the same level. The effect of the combine experiment is determined as half the relation between tests without any of the two, and including both, with the response from the first separately and the second separately. This says something about the combined effect of the two and up against how they are separately. This also means that it is impossible to say if the fabric's effect is stronger with/without accelerant or if the accelerants effect is stronger with/without the fabric seen as it is a multiplication between -1 and (+)1 in the set-up e.g. $\frac{X+V}{2} - \frac{Y+Z}{2} = \frac{V+X}{2} - \frac{Z+Y}{2}$.

	Fabric	Accelerant	Cover+Accelerant	Response
Foam	-1	-1	(-1) (-1) =1	X
Foam+Fabric	1	-1	(1)(-1)=-1	Y
Foam+Accelerant	-1	1	(-1)(1)=-1	Z
Foam+Fabric+ Accelerant	1	1	(1)(1)=1	V
Effect:	$\frac{Y+V}{2} - \frac{X+Z}{2}$	$\frac{Z+V}{2} - \frac{X+Y}{2}$	$\frac{X+V}{2} - \frac{Y+Z}{2}$	

Table 2.3: Full factorial design, inspired by Experiment! [49]

As previously mentioned in Section 2.4 - are the main effects strongest and also the easiest to interpret seen as a positive effect means a higher response with the column analysed and negative is opposite, thus a lower response with the column being analysed. This is further explained and demonstrated later in *Chapter 3 Results*.

2.5.2 Functional analysis

Where the factorial design analysis gives a quick indication of important factors with respect to key scalar(point value) parameters does the functional analysis offer a way of comparing two curves with each other. The functional analysis lies its roots in linear algebra, analysis and geometry [47]. It is based on vector notation which makes it possible to get a quantitative analysis able of comparing data sets containing several measurements, e.g HRR with respect to time, over the entire duration, and not just a scalar as the factorial analysis does.

This was used for two separate comparisons - firstly to show repeatability for the experiments, fully attached in *Appendix E Repeatability analysis*. Secondly, to show how well combinations of curves correspond to another one by using superposition e.g. NFR+PC+H compared with NFRPCH or PC+H with PCH.

The functional analysis is based on the norm, the inner product and the angle between the curves. The norm used here is the Euclidean Relative Difference (ERD) which is a measurement of the relative distance between the two curves. A value of

0 means they are identical and 0.2 suggest a difference between the two curves of 20% on average, the ERD is calculated in equation 2.5.

The Euclidean Projection Coefficient (EPC) is a measure of distance between the two curves, it finds a factor which multiplied with data set m_i minimizes the difference to data set E_i, meaning the two curves on average. A EPC of 1 suggest the two curves are as close to being on top of each other as possible. The EPC is calculated in equation 2.6 and a value of 0.8 means that E is 80% of m, and 1.2 means it is 20% higher in average over the whole duration.

The third value is the inner product, also called the Secant Cosine (SC). It compares the shape of the two curves. A time and data step, t, s, respectively, was required and should be chosen with care. If the time step was too large the trend of the curves would not be detected, and if too small the random experimental noise would dictate the result. A suggested ratio of 0.05 between time step,s, and number of measurement points, n, is proposed by Galea *et al* [48]. A SC of 1 means the curves have same shape. If two identical curves are off-set from each other the SC would be 1, since the shape of the two curves remained the same. The Secant Cosine is calculated in equation 2.7.

$$\frac{\|E-m\|}{\|E\|} = \frac{\sqrt{\sum_{i=1}^{n}(E_i-m_i)^2}}{\sqrt{\sum_{i=1}^{n}E_i^2}} \tag{2.5}$$

where E is the first data set, and m is the second data set.

$$\frac{\langle E,m\rangle}{\|m\|^2} = \frac{\sum_{i=1}^{n}E_i\cdot m_i}{\sum_{i=1}^{n}m_i^2} \tag{2.6}$$

where E is the first data set, and m is the second data set.

$$\frac{\langle E,m\rangle}{\|E\|\|m\|} = \frac{\sum_{i=s+1}^{n}\frac{(E_i-E_{i-s})(m_i-m_{i-s})}{s^2(t_i-t_{i-s})}}{\sqrt{\sum_{i=1+s}^{n}\frac{(E_i-E_{i-s})^2}{s^2(t_i-t_{i-1})}\sum_{i=1+s}^{n}\frac{(m_i-m_{i-s})^2}{s^2(t_i-t_{i-1})}}} \tag{2.7}$$

where E is the first data set, and m is the second data set.
The size of the time step, t, was varied. t ranged from $2sec$ with the accelerants alone since they peaked very quickly and had a duration of roughly $40-50sec$, up to $10sec$ for some experiments and finally, a maximum of $20sec$ for experiments lasting over $400sec$. Galea *et al* [48] estimates the success criteria for the parameters based on his work, these are displayed in Table 2.4 and were adopted as success criteria for this work as well.

ERD	< 0.4	
0.6	$<$ EPC $<$	1.4
0.6	$<$ SC	

Table 2.4: Functional analysis limits.

It is important that all three functional parameters are within these limits, in order for the curves to be considered similar to a satisfactory degree.

In order to determine which combination predicted the curve the best was a *Score* calculated as the sum of numerical deviations from the optimal value of the functional analysis parameters. The score is an average deviation and determined using equation 2.8, a value of zero suggests perfect match. The results for all the combinations are found in *Appendix H Functional Comparison Analysis*.

$$\text{Score} = \frac{|ERD| + |1 - EPC| + |1 - SC|}{3} \tag{2.8}$$

Chapter 3

Results

As mentioned, the focus of this work is the design fire in case of arson scenarios - therefore the O_2, CO_2 and mass loss parameters are not presented and the sole focus is the calculated HRR(which depends on CO_2 and O_2) and TTP. The raw data contain all values.
The functional analysis was used to compare the HRR between two - or more - test over their full durations.

The data obtained from the 105 experiments were sorted and a representative curve from each test group e.g. FR-1, H-3, NFRPM-2, was chosen for further analysis. The analysis is divided into several smaller sections, also looking into the accuracy of the superposition by use of functional analysis.

All data were gathered by a datalogger and rounded to nearest 1 second interval. All the data were analysed by use of Excel and all raw files and processed data are available in the attached URL link provided in the back of the Appendix.

3.1 Analyses Methods

As mentioned in *Chapter 2 Experimental Description*, a Yates order was used to set up the full factorial design. The design was randomized to prevent undesirable - yet possible - drifting affecting the results. Two main methods of analysing the data was done by using: a full factorial design analysis and functional analysis based on superposition. The Yates order displayed in *Appendix Factorial Design Set-up* was split into several smaller categories namely: NFRPCM, FRPCM, NFRPCH, FRPCH and additionally for Cotton (C) and Polyester (P). A total of 12 different designs based on the initial planned experiments. Values analysed were: Time To Peak(TTP), Peak Heat Release Rate(PHRR) and Total Heat Released (THR).

Illustrated in Figure 3.1 is the HRR results for two experiments, one with with

Non-Flame Retarded foam with Polyester-Cotton blend(NFRPC), the other one is Non-Flame Retarded foam with Polyester-Cotton blend and Methanol(NFRPCM) both measured in Heat Release Rate Per Unit Area (HRRPUA), with respect to time. A factorial analysis on the peak values would be insufficient to describe the relations between the two curves as they grow and decay differently despite their peak being some-what similar. The factorial design analysis for these two experiments displayed in Figure 3.1 - if including the NFR data - and shows that the effect of PC is $22kW/m^2$ and M is $60kW/m^2$. This indicates that the PHRR is higher with the fabric, and even higher with the accelerant included.

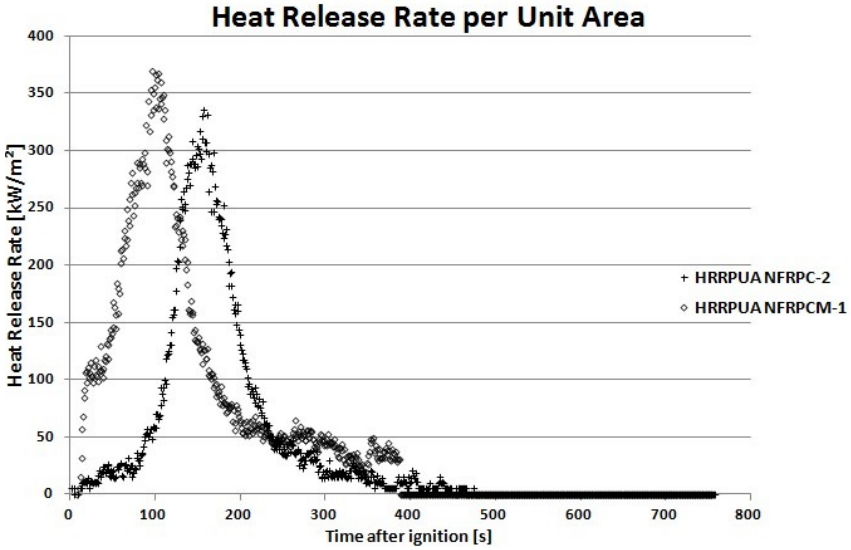

Figure 3.1: HRRPUA comparison of NFRPC and NFRPCM.

The functional analysis would say something about the resemblance between the two curves, and thus provide a way of determining if they were the same to a certain satisfactory degree, if so, is the impact of added methanol not significant.

3.2 Repeatability

The complete repeatability analysis using functional analysis is found in *Appendix Repeatability analysis*, here is it just summarized. Some of the experiments were only conducted once due to limited igniteability, these were FR, FRC and FRP. This means that the 32 remaining combinations were repeated three times and analysed with the three aforementioned parameters ERD, EPC and SC giving a total of 288 values to be analysed.

A summary of all tests shows 211 out of 288, equivalent of 75% were within previously mentioned limits in Table 2.4. Out of the 35 test groups did 9 not show satisfactory repeatability, these groups were, the three fabrics, C, P, PC. The flame

retarded foam alone and with fabrics, FR, FRC, FRP, FRPC. Surprisingly did the standard foam with cotton not show repeatability, NFRC, same as flame retarded foam with methanol, FRM.

The fabrics were producing very limited HRR, and their curves, as illustrated in Figure 3.2, where relative large oscillations were measured and therefore also not within the limits. One could argue, based on Figure 3.2, that they yield $0.5kW$ in average and is in that sense constantly low.

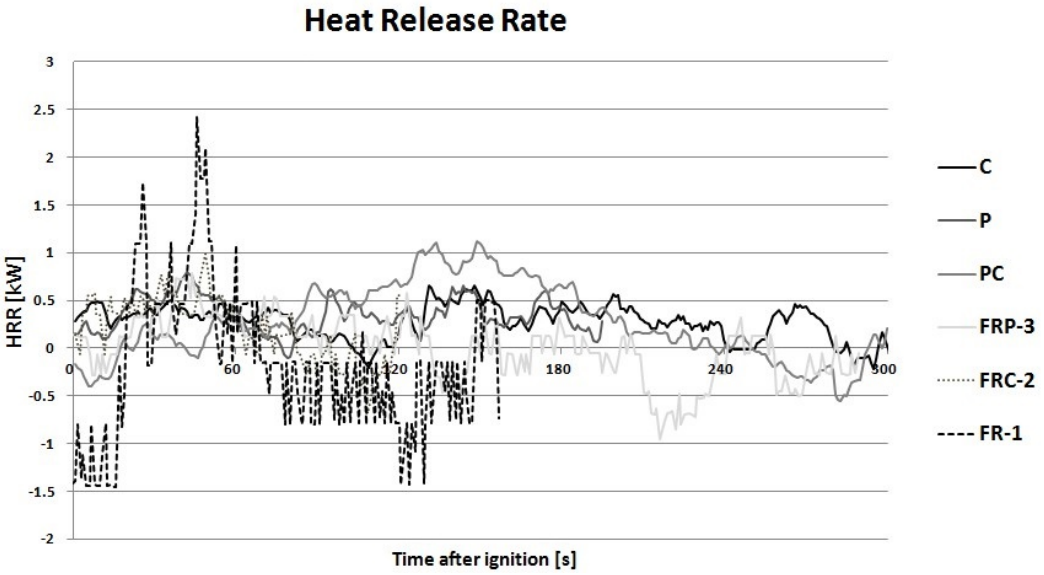

Figure 3.2: HRR for Polyester, Cotton and Polyester-Cottton blend.

A note taken during the experiments reveals that the NFRC appeared not burn identically due to a charred residue lattice being formed after the cotton burned away, this limited the oxygen flow and the combustion process appeared irregular and were uniquely each time. Figure 3.3 shows how this lattice looked and entrapped the combustion. Larger smoke production was also observed compared.

No explanation was found for FRM's inability to replicate the tests to satisfactory degree.
For most of the specimens are the repeatability shown between atleast one set and another, while some offers valid comparability between all three of the tests, examples of the first is provided below in Table 3.1. The repeatability of two, of any two and of all three, were 35%, 27% and 38%, respectively. This means that 100% of the test groups had atleast one in common, 62% test groups any two in common and 38% had all tests in common, by *'common'* it is meant the repeatability is shown.
An example of this is shown in Table 3.1 where M-1 compared with M-2 and M-3 are acceptable, while M-2 compared with M-3 is not - thus contributing to the 62%.

Figure 3.3: Picture of NFRC and how the cotton leaves a residue lattice protecting the foam.

Test		Test	ERD	EPC	SC
M-1	with	M-2	0.15	1.00	0.78
M-1	with	M-3	0.38	0.80	0.89
M-2	with	M-3	0.49	0.78	0.77

Table 3.1: Example of functional analysis result for methanol, gray is above limit value.

Those not able to show satisfactory reproducibility were not given great value in this result chapter. The heptane and polyester-cotton fabrics were the two materials showing best repeatability and the flame retarded foam and cotton fabric showed the least repeatability.
Overall, with 7 different products combined in 35 different ways and 75% of the test groups obeying the requirements, is the repeatability considered a partly success. Data is omitted used in the remaining chapter to prevent unnecessary sources of error and only the 26 test groups are used.

Note should be taken that tests were only done three times unless unforeseen event forced a fourth test e.g. measurement, calibration or human errors, and three tests are in it self limited.

3.3 Peak Heat Release Rate

All the factorial designs were set up identically to what was showed above in *Section 2.5 Analysis Methodology* for the foam.

The factorial analysis is set up for NFR, PC and H with respect to PHRR in Table 3.2.

	PC	H	PCH	PHRR
NFR	-1	-1	1	278
NFRPC	1	-1	-1	332
NFRH	-1	1	-1	515
NFRPCH	1	1	1	388
Effect:				
	-37	146	-91	

Table 3.2: Factorial analysis of NFR, PC and H.

The high positive effect of H indicates that the PHRR greatly increases as a result of adding heptane to the foam and the fabric, whereas the negative effect from the PC blend gives a negative response and translates into a lower PHRR. In the remaining experiment with PC fabric is the result different, the results are shown in Table 3.3.

The fabric effects are positive and increases the PHRR with respect to the foam. The trend is different for P and C with respect to both the FR and NFR foam where the effects are negative and PHRR is lowered by the fabrics. The method used to calculate the effects are identical to what was explained in Section 2.5 on page 14 and displayed above, merely presented in shortened format with only materials used and effect listed in Table 3.3 to 3.5. All tables identical to Table 3.2 are found in *Appendix F, Factorial Design for Time To Peak Heat Release Rate.*

NFR	PC	H	PCH
	-37	146	(-91)

FR	PC	H	PCH
	8	227	(-31)

NFR	PC	M	PCM
	22	60	(-31)

FR	PC	M	PCM
	52	97	(14)

Table 3.3: Factorial design analysis of PC fabric on PHRR

The factorial design in Table 3.3 shows that three out of four comparisons are receiving positive effects from both the fabric and accelerant(FRPCH,NFRPCM,FRPCM). The effect is greatest for the accelerants. This is to be expected from a potent fuels such as heptane but also methanol show large positive effects. The results for the combination of PCH can be interpreted as seen fit, and is therefore of less importance for the remaining of the analysis. An example of such, for argument sake: A negative effect shows the accelerant influences the fabric negatively and reduces its PHRR - or the more likely - the fabric effects the accelerant negatively and reduces its PHRR. In the case with PC and H it might be obvious that the accelerant does not affect the fabric negatively, but for other scenarios could it be more difficult to interpret hence placed in brackets but still included for sake of the factorial design completeness. The full factorial designs, such as displayed in Table 3.2, are found in *Appendix F, Factorial Design for Peak Heat Release Rate.*

The two tables for P and C, 3.4 and 3.5, respectively, shows how the fabric is reducing the PHRR or neutral at best, whereas the accelerants greatly increase it, shown with negative and positive effects, respectively.

The polyester-cotton blend shows different levels of influence compared to cotton and polyester fabrics. The ratio of 25/75% polyester cotton affects the foam in a negative way. Also is the PC blend able to sustain burning and spread flames over a vertical surface unlike the two other fabrics from which it is combined.

The effects are a result of the in-between relations between fabric, foam and accelerants and illustrate how the fabric reduces the PHRR - when comparing to without

NFRPH	P	H	PH
Effect:	-64	169	(-68)

FRPH	P	H	PH
Effect:	0	286	(25)

NFRPM	P	M	PM
Effect:	-6	80	(-11)

FRPM	P	M	PM
Effect:	-3	98	(21)

Table 3.4: Factorial design analysis of P fabric on PHRR

NFRCH	C	H	CH
Effect:	-97	166	(-71)

FRCH	C	H	CH
Effect:	-33	248	(-13)

NFRCM	C	M	CM
Effect:	-70	47	(-44)

FRCM	C	M	CM
Effect:	-15	82	(5)

Table 3.5: Factorial design analysis of C fabric on PHRR

fabric and only with heptane - which is greatly influenced by term in which the heptane is included in. It should be noted that FR did not show sufficiently repeatability, as previously mentioned, due to low HRR measurements, illustrated in Figure 3.2 on page 21. In general, this means that the materials unable to sustain flaming on their own are subjected to large increases when accelerants are applied, such as the Tables 3.3 to 3.5 shows, and the fabrics are at best a neutral component (effect of zero).
This analysis does not justify that the fabric and accelerant combination are increasing the PHHR of the foam, but merely that the accelerant effect is greatest and by so much that it cause the other results to look bad. An example of just that is the effect of P. The PHRR in descending order are NFRM > NFRPM > NFRP > NFR, $369 > 353 > 283 > 278$ (unit in kW/m^2), respectively, but is translated into effects of $-6kW/m^2$ and $-11kW/m^2$ for P and PM, respectively, despite both their PHHR are higher than NFR alone.

It is stressed that this does not alter the fact that accelerants shows a positive effect for all foam and fabric combinations.

3.4 Time To Peak

As previously, is the data for FR unreliable and the TTP is quite low for this experiment because the initial ignition source is the largest HRR measured. This results in a opaque analysis.
For completeness sake, the analysis for the FR result is included nonetheless. The factorial design for all fabrics are shown in Tables 3.6, 3.7 and 3.8. The PC fabric showed a clear influence on TTP with three positive effects and one negative. The fabric alone increase, but as stated should the values with FR foam be interpreted with caution. Even though the TTP is increased for FRPCM with an effect of $18s$, the PHRR from Table 3.3 is indicating a large positive effect of $97kW/m^2$ which is significant compared to the time delay of $18s$. This means that even though the

NFRPCH	PC	H	PCH
Effect:	49	-35	(-36)

FRPCH	PC	H	PCH
Effect:	49	-61	(-91)

NFRPCM	PC	M	PCM
Effect:	-18	-108	(37)

FRPCM	PC	M	PCM
Effect:	38	18	(-88)

Table 3.6: Factorial design analysis of PC on TTP in sec.

NFRPH	P	H	PH
Effect:	109	-44	(-45)

FRPH	P	H	PH
Effect:	-24	2	(-28)

NFRPM	P	M	PM
Effect:	119	-29	(-35)

FRPM	P	M	PM
Effect:	-59	38	(-63)

Table 3.7: Factorial design analysis of P on TTP in sec.

NFRCH	C	H	CH
Effect:	69	-47	(-49)

FRCH	C	H	CH
Effect:	-26	6	(-24)

NFRCM	C	M	CM
Effect:	77	-35	(-41)

FRCM	C	M	CM
Effect:	20	-40	(-140)

Table 3.8: Factorial design analysis of C on TTP in sec.

TTP is increased the PHRR also increased and over-all is there not indication of improved properties for FRPCM.
The FR, FRP and FRC experiments were not combustible beyond the initial ignition source and because of this gives inconclusive results in the analysis.
The TTP analysis for P and C shows that the addition of accelerants combined with fabric lowers the TTP in all comparison. The only combinations not showing decreased values in accelerant is FRPCM, but at the same time show methanol combined with any fabric and NFR decreased the TTP. At the same time, all the fabrics are increasing the TTP.

The method of analysis gives a general impression of how additional materials affect the TTP. Despite some inconsistencies, the accelerant alone or combined with fabric give a lower TTP in all tests indicating a drop. All of the TTP factorial designs can be found in *Appendix F Factorial Design for Time To Peak Heat Release Rate.*

A noteworthy reminder about the PHRR and TTP is that the accelerants in all experiments increased the PHRR and lowered the TTP for NFR tests. The fabrics

did all cases but one (NFRPCM) lower the PHRR for the NFR foam.
Even though this analysis is based on momentary values - and therefore can be misleading at glance - it leaves an accurate impression on how the different components affects each other when properly analysed.

3.5 Growth Rate

Combining the TTP and PHRR gives the growth rate, α, which was described in section 1.4, used in Equation 1.1 and re-written in Equation 3.1 seen below.

$$\alpha = \frac{PHRR}{TTP^2} \tag{3.1}$$

As previously mentioned, does the growth rate determine the growing rate of a fire in design fire used for fire safety design purposes. This makes it important, in terms of life safety and can greatly influence the number of fatalities of occupants if underestimated.

The growth rates for NFR foam with all fabrics and accelerants are showed in Table: 3.9. The increase in growth rates when Methanol is included are 199%, 170% and 91% with respect to tests without accelerant for polyester-cotton, polyester and cotton fabrics, respectively. Whereas the tests with Heptane show an increase of 326%, 318% and 327% with respect to tests without accelerant, for polyester-cotton, polyester and cotton fabrics, respectively.

Abbreviation	α $\frac{kW/m^2}{s^2}$
NFRPC	0.010
NFRPCM	0.029
NFRPCH	0.041
NFRP	0.008
NFRPM	0.021
NFRPH	0.032
NFRC	0.004
NFRCM	0.009
NFRCH	0.019

Table 3.9: Averaged rounded growth rates for all NFR tests, from *Appendix I*

This translates into an almost doubling at minimum, and a quadrupling at maximum depending on the accelerants and fabrics used.
The exact values for all NFR tests are found in *Appendix I Growth Rates*, including the mean values used in this section.

3.6 A priori Superposition Analysis

The superposition principle states that for all linear systems where A equal 1 and B equal 2 is A+B = 1+2.

In this section, an attempt is made to combine individual materials and compare them with the experiment corresponding to the combination e.g. NFR + H = NFRH with respect to the Heat Release Rate per Unit Area but simply referred to as HRR. Chow [50] and Chow et al. [51, 52] did some work on superposition and HRR of polymer on a posteriori basis and fitted empirical models to the obtained data, but just like Babrauskas were the experiments without accelerants. In this section, a priori methodology is attempted to fit the data solely based on the superposition principle, thus without attempting to fit it to with empirical factors and correlations. Different combinations of superposition are made, such as two or three materials compared against a single test containing them all.

3.6.1 Fabric and Accelerant Comparisons

Initially the simpler curve for PC with M and H is analysed and are showed in Figures 3.4 and 3.5. The initial peak value caused by the accelerant comparable to the one created by the fabric accelerant combinations. The following plateau is also present in both tests, although higher than the fabrics alone. The general resemblance in the curves are noticeable.

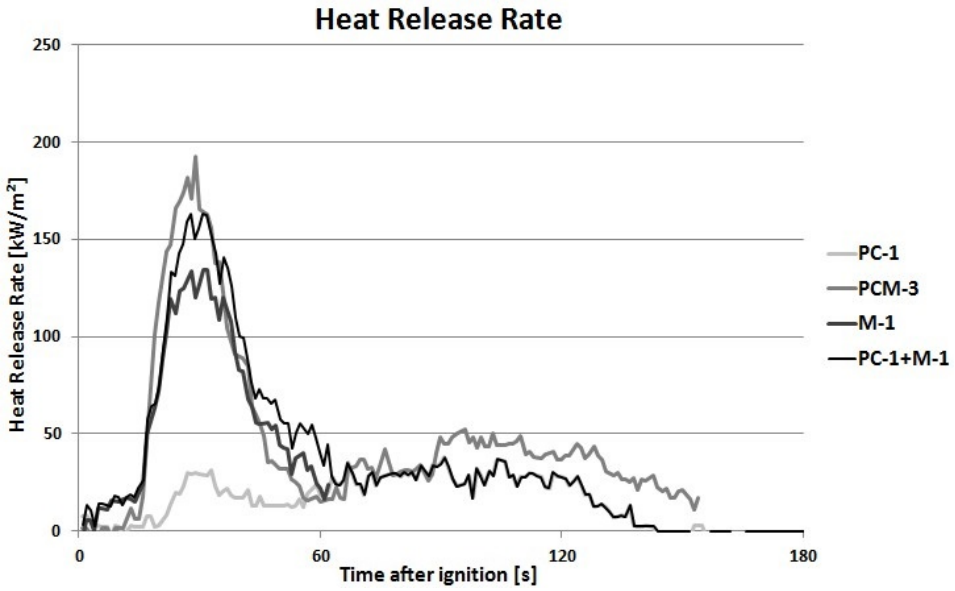

Figure 3.4: HRR for PCM including individual components.

	ERD	EPC	SC	Score
PCM	0.36	1.24	0.66	0.32
PCH	0.38	0.82	0.72	0.28

Table 3.10: Functional analysis for PCH and PCM.

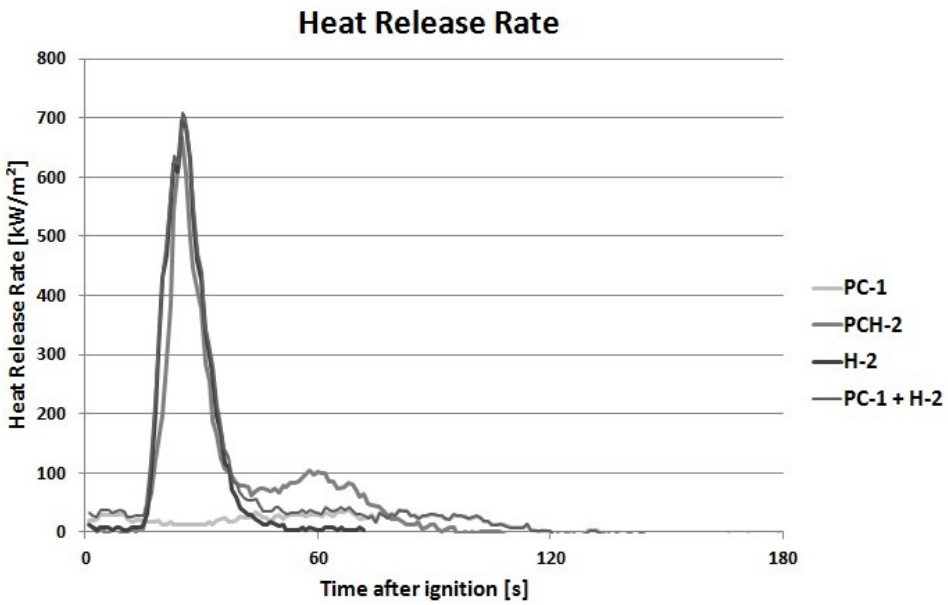

Figure 3.5: HRR for PCH including individual components.

The functional analysis does also agree with this, and all three parameters are within the limits for both test comparisons, as seen in Table 3.10. The scores are 0.32 and 0.28 for PCM and PCH, respectively. This indicates an average deviation of approximately 30% difference over the full duration of the curves. Because the two other fabrics, C and P, were unable to sustain flaming on their own they are not showed here because the comparison would just be between two accelerant curves with a small plateau after the initial accelerant peak. The scores are 0.22 and 0.17 for PCH and PCM, respectively with all parameters within limitations.

3.6.2 Analysis of all materials

The combination of one fabric, foam and accelerant gives 4 possible ways of combining by superposition, where one of them is all three materials added together and the remaining three combinations consist of two materials added with the third. These are listed in Table 3.11.

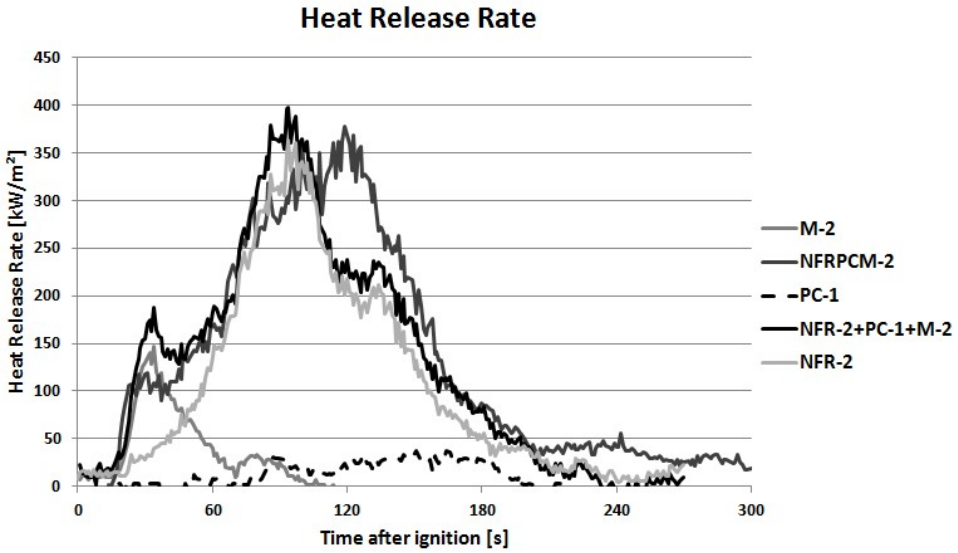

Figure 3.6: Functional analysis of NFRPCM and superposition position.

FoF + A	= FoFA
FoA + F	= FoFA
Fo + F+ A	= FoFA
F + FA	= FoFA

Table 3.11: Listing of materials producing same combination by superposition. Where abbreviations are: Fo is Foam, F is Fabric and A is Accelerant.

In total does this produce 4 combination a total of 48 combinations compared with 12 FoamFabricAccelerants abbreviated as FoFA as listed and explained in Table 3.11.

The HRR curve for the combined NFRPCM and individual components are illustrated in Figure 3.6 and shows how the combination of individual components correspond to the combined HRR. The functional analysis for all NFRPCM combinations are found in Table 3.12. It can be seen than a score less than 0.4 (indicating less than 40% difference over the full curve) - does not automatically mean it is acceptable in all parameters since it is an average value, but it made the identification of good results easier. The trend is that the relative difference and projection coefficient are within the acceptable limits suggesting that the overall values between the curves are good. The SC is below the limit in half of the tests suggesting two different shapes of the curves, despite the values being the same range. This could have been caused by too small data and time steps causing the oscillations in measurement to be significant - but to maintain a proper s/n ratio was nothing changed. The Polyester and Cotton fabric perform worse when comparing the superposition principle as showed in Table 3.13 and 3.14 where only a single parameter is within the limits, the EPC of NFRP+M and NFRC+M.

NFRPCM	ERD	EPC	SC	Score
NFRPC+M	0.82	1.56	-0.14	0.84
NFRM+PC	0.30	0.85	0.47	0.33
NFR+PC+M	0.23	0.86	0.69	0.23
NFR+PCM	0.22	0.84	0.76	0.23

Table 3.12: Functional analysis scores for NFRPCM.

NFRPM	ERD	EPC	SC	Score
NFRP+M	0.69	0.80	0.11	0.59
NFRM+P	1.93	0.30	-0.18	1.27
NFR+P+M	1.84	0.34	0.18	1.11
NFR+PM	1.42	0.41	0.44	0.86

Table 3.13: Functional analysis scores for NFRPM.

NFRCM	ERD	EPC	SC	Score
NFRC+M	0.50	0.90	-0.17	0.59
NFRM+C	2.05	0.28	-0.21	1.33
NFR+C+M	2.11	0.30	0.35	1.15
NFR+CM	1.98	0.32	0.16	1.17

Table 3.14: Functional analysis scores for NFRCM.

The full set of FR with M were showing a unsatisfactory correlation between all four possible test combinations, these are found in Table 3.15 to 3.17. The FR foam is difficult to predict by looking at individual materials because both the foam it self, but also two of the three fabrics fails to sustain flaming by it self causing close-to-zero HRR curves being added together and on top of that fail to show repeatability. Based on these experiments is ability to use the superposition principle on a priori basis with accelerants not possible.

FRPCM	ERD	EPC	SC	Score
FRPC+M	0.74	1.13	0.07	0.60
FRM+PC	0.82	3.52	0.43	1.30
FR+PC+M	0.74	1.08	-0.70	0.84
FR+PCM	0.82	0.81	-0.58	0.86

Table 3.15: Functional analysis scores for FRPCM.

FRPM	ERD	EPC	SC	Score
FRP+M	0.70	0.72	0.38	0.53
FRM+P	0.69	1.29	0.22	0.59
FR+P+M	0.58	0.74	0.24	0.53
FR+PM	0.60	0.66	0.73	0.40

Table 3.16: Functional analysis scores for FRPM.

FRCM	ERD	EPC	SC	Score
FRC+M	0.70	0.80	0.74	0.39
FRM+C	0.70	2.39	-0.11	1.07
FR+C+M	0.56	0.80	0.32	0.48
FR+CM	0.86	0.58	0.26	0.68

Table 3.17: Functional analysis scores for FRCM.

3.6.3 Total Heat Released

The last parameter analysed with respect to the values used for the design curve discussed in *Section 1.4 Design Fires* is the Total Heat Released (THR). The same combinations as in Section 3.6 where used to predict the HR from the superpositioned individual experiments to their corresponding combined experiment.

The Figures 3.7 to 3.9 show how the vertical columns with the individual components THR correspond to the horizontal value of its combined target value. Overall is the THR under-predicted by 31 % by all the methods. The general trend shows that the THR for the NFR foams with variable fabric and any accelerant is under-predicted by 12 %. The NFR with M and variable fabric was predicted to 7% less THR than the actual combined experiment yielded. The method best predicting the THR was the method of combining the foam and accelerant added to the fabric, labelled "FoA+F" in Figures 3.7 to 3.9. If considering NFR and FR results separately was the method with foam with fabric added acclerant best with only 2% under-prediction, but worst with 56% under-prediction with respect to the FR foam, the method is labelled "FoF+A". When comparing any combination involving FR foam the predicted THR was on average 50% under-predicted.

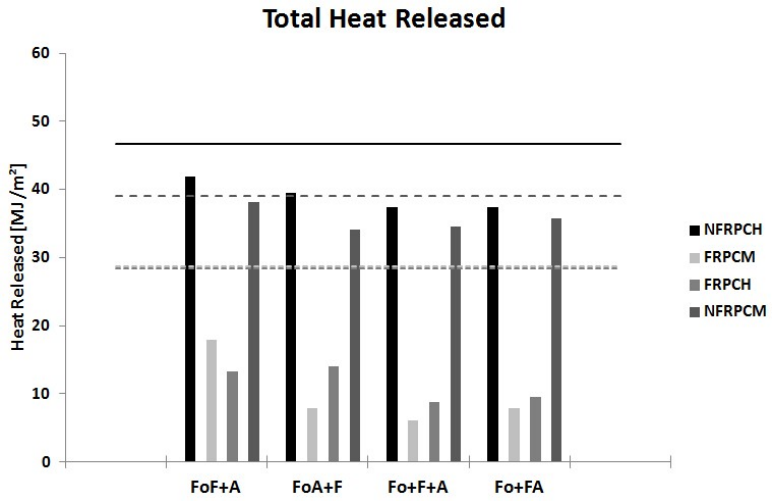

Figure 3.7: Total Heat Released for Cotton.

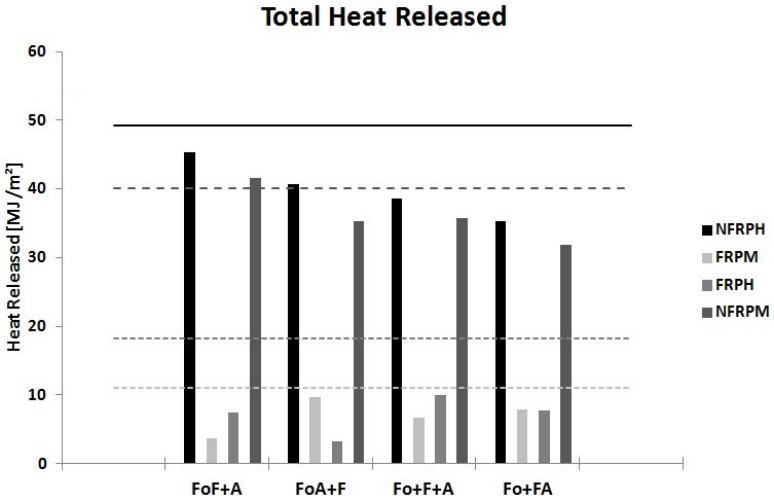

Figure 3.8: Total Heat Released for Polyester.

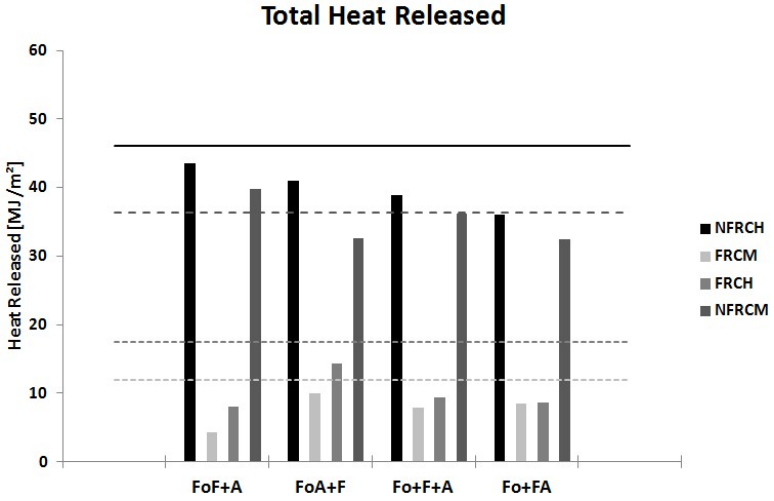

Figure 3.9: Total Heat Released for Polyester-Cotton blend.

The THR for the NFR foam can be predicted quite well with only 12% under-prediction on average. This means that the potential fuel load of these scaled experiments can be predicted by testing individual components. If FR foam is to be predicted a multiplication of a factor two is on average required to estimate the THR by the combined test is it not useful to take the superposition values but multiply with it a factor of two.

Further studies

The superposition principle revealed that adding two or more curves together to predict the combined effect is difficult and especially for the materials difficult to ignite, such as FR, C and P. Also offset and delays of individual specimens are reviled when looking at the graphs behind the factorial and functional analyses values. Figure 3.10 shows how the initial accelerant-caused peak was over-predicted and how the NFR foam grows at a slower rate than the combined specimen. This means that even though the peak is lower, more energy was released than the superposition principle predicted. Eventually, the THR is roughly the same.

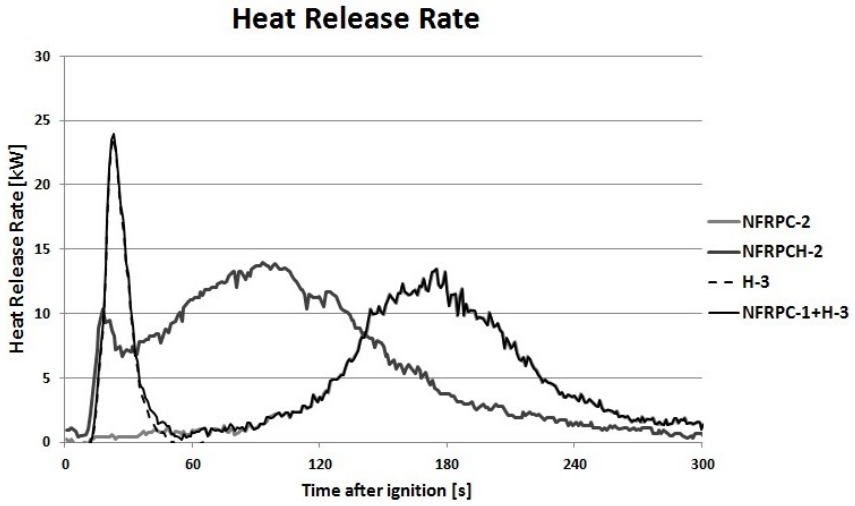

Figure 3.10: HRR for NFRCH including individual components.

The growth rate of the initial peaks are corresponding quite well and the peak values of the foams are also corresponding quite well. Further studies could use the data already gathered and analyse the growth rate α values for the superposition results with the combined results. An example is showed in Figure 3.11 where lines have been added to indicate the growth rates of the different curves and sections. The trend lines are linear their peak minus 90sec, thus, from 0-90sec (without accelerant peak) and from 90sec to 180sec for the two curves, respectively. The linear trends is just for illustrative purposes.
The trend of these two lines have the same slopes of 0.156 kW/s^2 suggesting they

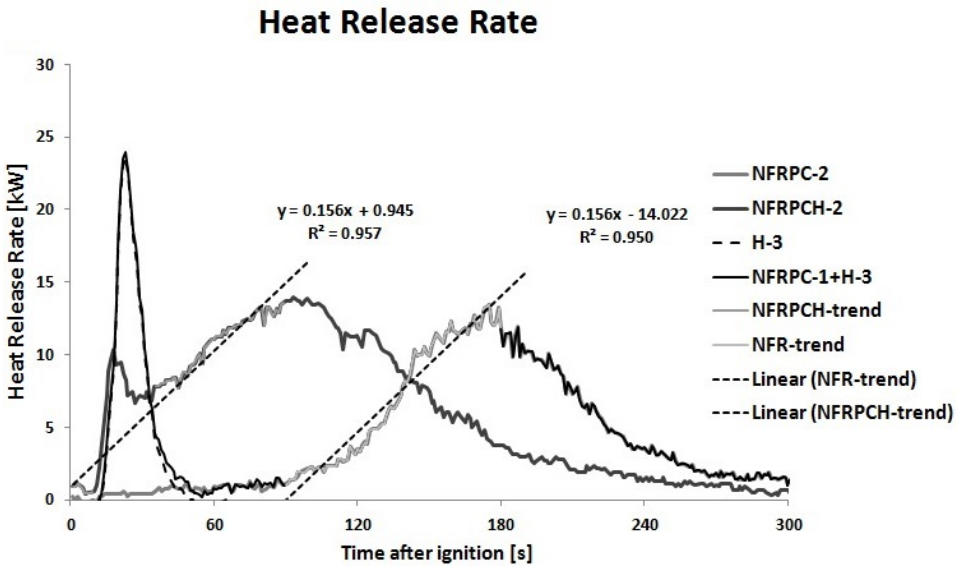

Figure 3.11: Growth rate analysis of NFRPCH.

grow similar, but different offset, which is confirmed visually in Figure 3.11.

Chapter 4

Discussions

Firstly, the conducted experiments were done under the assumption that it was the 'first large item' to ignite and therefore is the material behaviour under radiation not enlightened in this thesis. Secondly, this also means that the behaviour and superposition principle might predict differently under a radiative source such as a cone heater. And finally, are these small scale experiments and extrapolation should always be done with care since not everything can be scaled at the same time.
The experiments are conducted under as uniform conditions as possible, but accompanied with experiments are uncertainties, and this is no different.

4.1 General

If a sofa is targeted and a liquid accelerant is used as part of the ignition source it is evident from these experiments that it increases the peak heat release rate, decrease the time to reach this peak value, creating a higher growth rate, thus creating more dangerous conditions and more of a challenge for the fire safety design. The larger heat release rate increase the risk of flame spread and therefore also flashover will happen earlier. Flame retarded foam limited the effect and the ability to self extinguish meant the duration and heat released was less than for standard foam. It should be pointed out, that without accelerant was the flame retarded foam unable to sustain flaming. Previous research by Janssens [23] on upholstered furniture showed that the accelerant worked equivalent to a large ignition source burner and that "*The intensity of the ignition source will markedly affect weather an item of upholstered furniture, or mockup, will or will not ignite.*" confirming the findings in this work with respect to the peak heat release rate and heat released by flame retarded foam with accelerants compared to without accelerants. The experiments also showed how two of the three fabrics reduced the peak heat release rate for both foams. This is contradictory with the results found by Babrauskas *et al* [8] research which used a methenamine pill as ignition source for the full scale mock-up configurations with various fabrics, and foams. In their work, the foam with flame retardance exhibited higher heat release rates with three out of four fabrics tested. Compared with Babrauskas *et al* did the effect of the flame retardant seem different

as it was found impossible to sustaining flaming on its own in this thesis. Also, the two fabrics not increasing the peak heat release rate were also not able to sustain flaming by them self on a vertical surface. The fabrics ability to self extinguish on a vertical surface might be the reason for this discrepancy but was not confirmed.

There are some uncertainties associated with experimental work and these have been included as much as possible in the appendix, but it is believed by the author that all experiments were conducted under the same conditions thus allowing for internal comparison and the conclusions would not change if conducted elsewhere.
The carbon monoxide analyser was out of order and therefore the degree of clean combustion was not possible to assess, but could have showed a relationship between heat release rate and incomplete combustion (carbon monoxide concentration) and the difference between the foams. Especially for the unrepeatable test group of NFRC where the oxygen was limited by the lattice, maybe the yields would have provided some answers. The heat release rate was calculated by using appropriate calculations methods without carbon monoxide concentrations known, and therefore is the lack of known carbon monoxide not a problem with respect to heat release rate.

The repeatability shown for most of the test groups show that the internal validity is good, and the consistency of the execution of the experimental procedure helped make this possible.
The use of two acceletants was done because the knowledge of arsonist choice of liquid accelerants is limited. They were chosen to represent a wide range of the energy-content spectra with their very different energy content, and it was showed how they behaved as accelerant qualitatively in general and how they influenced the curves quantitatively. Since the knowledge of accelerants is limited is the external validity not as good as the internal. The results here only represent how methanol and heptane affects these fabrics and foams, where the heptane is very powerful and can be put in the same energy content regime as gasoline, and methanol being in close rage to alcohols (ethanol), but doesn't say anything about how gasoline or ethanol would behave with any certainty.

The functional analysis limits taken from Galea *et al* [48] were used for evacuation usage, but due to lack of values used for experimental comparison were these adopted for this works as well. It is a possibility that changes should be done to the limit values for experiments when more research have been done on the subject.

The ignition source could have been chosen differently and been more potent until sustained flaming was obtained by the test specimens. This could have been a Bunsen-burner with a known heat release rate which could easily be subtracted from the obtained data. It could have been interesting to keep the thickness contra mass of the foams identical and observe the impact of a more dense foam with respect to accelerants.

4.2 Recommended Future Studies

Additional research with accelerants and upholstered furniture materials is recommended on the basis of gaining additional information based on the uncertainties in predictability shown in this thesis. Methods could be scaling the sample size differently and investigating impact of change of the samples. A study with similar products ignited with a cone heater to see the difference between different heat fluxes is also recommended.

To improve the knowledge of accelerants behaviour in upholstered furniture it is important to maintain as many parameters constant as possible at one time and study the effects. Therefore, could identical foams with different thickness or different fabrics but with same density, be of interest.

Also the use of a smaller hood to measure smaller heat release rates such as the fabrics where flame height was limited could have been of interest to gain better curves for PC.

The ability to apply and ignite the accelerants consistently as possible is tricky, and the delay between applying accelerants and ignition could vary and further research could show the importance of this.

It is recommended that further studies are made on a posteriori analysis method with accelerants to find an empirical correlation between multiple fabrics, foams and accelerants.

The increases in growth rates with an accelerant included were shown for all the standard non flame retarded foams and therefore important to further study and validate. It is recommended to tests these factors of increase with full scale experiments to see if correlations are present.

Chapter 5

Conclusions

Different numerical analyses were used in order to assess the heat release rate curve for several components commonly used in upholstered furniture with and without accounting for accellerants. The heat release rate curves were obtained using small-scale experiments of 19.9x19.9cm sample size. The experiments were conducted under a hood connected to a oxygen analyser at the department of fire safety's fire laboratory at Lunds University. A Yates order was set up and randomised to prevent drifting in equipment influencing the results. The randomised order was used to dictate the order of experiments conducted.

The used fabrics were of cotton, polyester and 25%polyester-75%cotton blend with densities of 160, 400 and 183 g/m^2 respectively. The used foams were $22kg/m^3$ standard non flame retarded foam and $31kg/m^3$ flame retarded foam purchased at a common Danish sowing supplies shop. Heptane and methanol were used as accelerants to imitate possible additions to the ignitions source of an arsonist. The samples were consistently ignited by use of a small piece of cardboard in the centre.

The functional analysis was used to show repeatability of the three times replicated experiments except for a few non-ignitable test groups such as the flame retarded foam and polyester fabric. It was showed that 75% of the test groups had acceptable resemblance with atleast one of the other tests done within that group. Data without repeatability was not considered important and was not used for most analysis. The heat release rate curves were hardest to replicate for the fabrics and the flame retarded foam, and heptane tests were the easiest to replicate. A total of 24 out of 35 test groups were showing repeatability and were used throughout the thesis for comparison and analysis.

The factorial analysis was used to identify factors of importance with respect to: peak heat release rate and time to peak heat release rate. This gave a quantitative value from the influence between fabric and accelerant individually and when combined. The fabric results were less conclusive because they both increased and lowered time to peak and peak heat release rate at inconsistently. It was showed that both accelerants increased the peak heat release rate for all foams and lowered

the time to ignition for all non flame retarded foams.

The functional analysis was also used to analyse the superposition of individual components for both heat release rate and total heat released.
For combinations of fabrics and accelerant was it possible to get agreeable comparisons by adding the two heat release rate curves. This was found to be true for combinations of P+M, P+H, PC+M and PC+H.
For the full sets including Fo+F+A was it shown that it was only possible for one out of the 12 possibilities. Non-flame retarded foam with polyester-cotton blend with methanol (NFRPCM) was the only test group in which the superposition principle predicted the behaviour of the curve for the individual components as it would for the combined test. Based on this is it not possible to use the superposition principle to predict the accelerants contribution to an upholstered furniture component such as a cushion.
The total heat released was predictable with a 12% difference for the non flame retarded on average but 50% under-predicted for the tests including flame retarded foam.

The magnitude of increases in growth rates for all the three fabrics with any of the two accelerants were found to be substantial and between double and quadruple compared to tests without accelerant. Because life safety is determined by the ratio between RSET and ASET, and the ASET is highly dependent on the growth rate, is it paramount to get this parameter correct.
It was found that if an accelerant was used as part of the ignition source the increase in growth rate was to such an extend it is assessed unwise to ignored in a design phase. Prior to this, is it assumed that a risk assessment on the likelihood of an arson attack scenario is done, and if found likely - the growth rate of the design fire should be altered to correspond better to this scenario.

By accounting for accelerants in the design phase where assessed likely would the structural resistance and integrity also be designed in such a manner that it would limit the spread beyond the room of origin and potentially save money in repairs and replacements after a fire occurrence.

Chapter 6

Bibliography

[1] R. L. Aplert. Calculation of response time of ceiling-mounted fire detectors. *Fire Technology*, 8:181 – 195, 1972, http://dx.doi.org/10.1007/BF02590543.

[2] E.E. Zukoski, Toshi Kubota, and Baki Cetegen. Entrainment in fire plumes. *Fire Safety Journal*, 3(3):107 – 121, 1981, http://dx.doi.org/10.1016/0379-7112(81)90037-0.

[3] Gunnar Heskestad. Virtual origins of fire plumes. *Fire Safety Journal*, 5(2):109 – 114, 1983, http://dx.doi.org/10.1016/0379-7112(83)90003-6.

[4] Bernard J. McCaffrey. Purely buoyant diffusion flames: Some experimental results. *NIST*, 1979, http://fire.nist.gov/bfrlpubs/fire79/PDF/f79001.pdf.

[5] Vytenis Babrauskas and Richard D. Peacock. Heat release rate: The single most important variable in fire hazard. *Fire Safety Journal*, 18(3):255 – 272, 1992, http://dx.doi.org/10.1016/0379-7112(92)90019-9.

[6] Clayton Huggett. Estimation of rate of heat release by means of oxygen consumption measurements. *Fire and Materials*, 4(2):61–65, 1980, http://dx.doi.org/10.1002/fam.810040202.

[7] W.J. Parker. Calculations of the heat release rate by oxygen consumption for various applications. *Journal of Fire Sciences*, 2(5):380–395, 1984, http://dx.doi.org/10.1177/073490418400200505.

[8] V. Babrauskas and J. F. Krasny. Fire behavior of upholstered furniture. Technical report, NBS(NIST), 1985, http://fire.nist.gov/bfrlpubs/fire85/PDF/f85003.pdf. Gaithensburg, MD.

[9] V. Babrauskas. *Full-Scale Heat Release Rate Masurements*, chapter 5, pages 93–111. Elsevier Applied Science, 1992, http://fire.nist.gov/bfrlpubs/fire92/PDF/f92028.pdf.

[10] Gordon H. Damant. Flammability of soft furnishings. what's happening in california? *Journal of Fire Sciences*, 8(5):313–330, 1990, http://dx.doi.org/10.1177/073490419000800501.

[11] Marty Ahrens. Home structure fires. NFPA, 2013, http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Occupancies/oshomes.pdf.

[12] Björn Sundström, editor. *Fire Safety of Upholstered Furniture - the final report on the CBUF research programme.* The European Commission of Measuring and Testing, 1995.

[13] Department for Communities and Local Government. Fire statistics great britain - tables 25-28. 2012, https://www.gov.uk/government/publications/fire-statistics-great-britain-2011-to-2012.

[14] Department for Communities and Local Government. Fire statistics great britain 2011 to 2012. 2012, https://www.gov.uk/government/publications/fire-statistics-great-britain-2011-to-2012.

[15] Greenstreet Berman Ltd. A statistical report to investigate the effectiveness of the furniture and furnishings (fire) (safety) regulations 1988. Technical report, Consumer and Competition Polity Directorate, BIS, 2009, http://www.berr.gov.uk/files/file54041.pdf.

[16] Swedish Civil Constingencies Agency (MSB). *The Swedish Rescue Service in Figures.* 2008, https://www.msb.se/RibData/Filer/pdf/25586.pdf.

[17] State of California Department of Consumer affairs. Technical bulletin 133. *Flammability Test Procedure for Seating Furniture for Use in Public Occupancies*, 1991.

[18] British Standards Institution. Fruniture and furnishing (fire) (safety) regulations 1988. *1988 Nr. 1324 Parliment Hearing*, July 1988.

[19] V. Babrauskas. *Upholstered Furniture: Prediction by Correlations*, chapter 15, pages 519–543. Elsevier Applied Science, 1992, http://fire.nist.gov/bfrlpubs/fire92/PDF/f92017.pdf.

[20] Marcelo M. Hirschler and Saleem Shakir. Comparison of the fire performance of various upholstered furniture composite combinations (fabric/foam) in two rate of heat release calorimeters: Cone and ohio state university instruments. *Journal of Fire Sciences*, 9(3):223–248, 1991, http://dx.doi.org/10.1177/073490419100900303.

[21] Omar Harrami and Colin McIntyre. *Fire and Fire Protection in Homes and Public Buildings.* Swedish Chemical Inspectorate, January 2006, http://kemi.se/Documents/Publikationer/Trycksaker/Rapporter/Rapport1_06.pdf.

[22] Henri E. Mitler and King-Mon Tu. Effect of ignition location on heat release rate of burning upholstered furniture. *NIST*, 1994, http://fire.nist.gov/bfrlpubs/fire94/PDF/f94035.pdf.

[23] Marc L. Janssens. Reducing uncertainty of quantifying the burning rate of upholstered furniture. Technical report, Southwest Research Institute, 2012, https://www.ncjrs.gov/pdffiles1/nij/grants/239050.pdf.

[24] James A. Gallagher. Interliner effect on the fire performance of upholstery

materials. *Journal of Fire Sciences*, 11(1):87–105, 1993, http://dx.doi.org/10.1177/073490419301100105.

[25] British Standard. Furniture - assessment of the ignitability of upholstered furniture - part 1: Ignition source smoldering cigarette. *BS EN 1021-1:2006*, 2006.

[26] British Standard. Furniture - assessment of the ignitability of upholstered furniture - part 2: Ignition source match flame equivalent. *BS EN 1021-2:2006*, 2006.

[27] Nichola Tyler, Theresa A. Gannon, Lona Lockerbie, Tracy King, Geoffrey L. Dickens, and Calem De burca. A firesetting offense chain for mentally disordered offenders. *Criminal Justice and Behavior*, 2013, http://dx.doi.org/10.1177/0093854813510911.

[28] Office of the Deputy Prime Minister. *Fire Statistics, United Kingdom, 2004*. ODPM Publications, 2004, http://capic.swan.ac.uk/wp-content/uploads/2012/09/Fire-Data-Fire-Statistics-UK-2004.pdf.

[29] Nils Johansson, Patrick van Hees, Margaret S. McNamee, and Micheal Strömgren. A cost-benefit analysis of fire protection systems designed to protect against exterior arson fire in schools. *9th International Conference on Performance-Based Codes and Fire Safery Design Models*, 2012, http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=2855846&fileOId=2855923.

[30] P. L. E. Richards. Characterising a design fire for a deliberate lit fire scenario. Master's thesis, University of Canterbury, 2008, http://ir.canterbury.ac.nz/handle/10092/1779.

[31] Ben Evarts. Intentional fires. NFPA, 2012 http://www.nfpa.org/~/media/Files/Research/NFPA%20reports/Major%20Causes/osintentional.pdf.

[32] The Geneva Association Risk & Incurance Economics. World fire statistics. Informational Bulletin of the World Fire Statistics Centre, October 2010, http://www.f-e-u.org/upload/statistics/worldfire/WorldFireStatistics-26-October2010.pdf.

[33] Arne Kallstenius. European guideline: Preventing arson - information to young people. CFPA Europe, Martch 2004, http://www.cfpa-e.eu/wp-content/uploads/files/guidelines/Guideline_No_8_2004.pdf.

[34] Brian J. Meacham. The evolution of performance based codes and fires safety design methods. *NIST, U.S Department of Commerce*, 1998, http://fire.nist.gov/bfrlpubs/fire98/PDF/f98125.pdf.

[35] Henrik Bjelland. *Engineering Safety - With applications to fire safety design of buildings and road tunnels*. PhD thesis, University of Stavanger, 2013, http://brage.bibsys.no/xmlui/handle/11250/182347.

[36] Energy and Building Ministry. *Building Regulations BR04*. 2004.

[37] Leif Staffansson. *Selecting Design Fires*. Number Report 7032. Lund University, 2010.

[38] Björn Karlsson and James G. Quintiere. *Enclosure Fire Dynamics*. Taylor and Francis Group, 1999.

[39] SFPE & NFPA. *SFPE Engineering Guide to Performance-Based Fire Protection*. Taylor and Francis Group, 2007.

[40] Martin Nilsson. Nils Johansson and Patrick van Hees. A new method for quantifying fire growth rates using statistical and empirical data – applied to determine the effect of arson. *Fire Safety Science-Draft Proceedings of the 11th International Symposium. Christchurch. New Zealand*, 2013, http://www.iafss.org/publications/fss/11/44/view.

[41] Martin Nilsson, Håkan Frantzich, and Patrick van Hees. Selection and evaluation of fire related scenarios in multifunctional buildings considering antagonistic attacks. volume 2:3. Fire Science Reviews, Juli 2013, http://link.springer.com/article/10.1186%2F2193-0414-2-3.

[42] Vytenis Babrauskas. *Ignition Handbook*. Fire Science Publishers, WA USA, 2003.

[43] http://carpenter.com/index.php/us/en/foam/foam-glossary. Foam manifacturer. 29-04-2014.

[44] The International Organization for Standardization. Reaction-to-fire tests - heat release, smoke production and mass loss rate. *ISO 566-1:2002*, 2002.

[45] Based on William H. Twilley and Vytenis Babrauskas work at NIST, editors. *User's Guide for the Cone Calorimeter*. Fire Testing Technology Limited.

[46] Marc L Janssens. Measuring rate of heat release by oxygen consumption. *Fire Technology*, pages 280–282, 1991, http://dx.doi.org/10.1007/BF01038449.

[47] Richard D. Peakcock. Paul A. Renke. William D. Davis. Walter W. Jones. Quantifying fire model evacuation using functional analysis. *Fire Safety Journal*, 33:167–184, 1999.

[48] Edwin Richard Galea. Steven Deere. Robert Brown and Lazaros Filippidis. An evacuation validation data set for large passenger ships. *Pedestrian and Evacuation Dynamics Conference*, pages 109–123, 2012, http://www.iafss.org/publications/fss/11/208/view.

[49] Öivind Andersson. *Experiment! Planning, Implementing and Interpreting*. A John Wiley & Sons, Ltd, 1 edition, 2012. Lund University.

[50] W.K. Chow. Combining heat release rates of combustibles. *Journal of Applied fire Science*, 17(3):235–244, 2007, http://dx.doi.org/10.2190/AF.17.3.b.

[51] W.K. Chow and H.W. Au Yeung. On the superposition of heat release rate for polymeric materials. *Architectural Science Review*, 46(1):145–150, 2003, http://www.bse.polyu.edu.hk/researchCentre/Fire_Engineering/summary_of_output/journal/IJEPBFC/V6/p.168-180.pdf.

[52] W.K. Chow and S.S. Han. Superposition of heat release rate curves for combustibles with bench-scale tests. *Polymer Testing*, 25(1):75 – 82, 2006, http://dx.doi.org/10.1016/j.polymertesting.2005.09.016.

[53] B.J. McCaffrey and G. Heskestad. A robust bidirectional low-velocity probe for flame and fire application. *Combustion and Flame*, 26(0):125 – 127, 1976, http://dx.doi.org/10.1016/0010-2180(76)90062-6.

[54] Dougal Drysdale, editor. *SFPE Handbook of Fire Protection Engineering, Chapter 1, Volume 3,*. NFPA, 2002.

[55] K McGrattan R. Peacock and A. Hamins. Verification and validation of selected fire models for nuclear power plant applications. *Volume 2: Experimental Uncertainty*, 2007.

Appendix

Appendix A

Experimental Procedure

The experiments were conducted as consistently as possible in terms of storage, preparation and execution. All the materials were stored in the same room with assumed uniform conditions in terms of relative humidity and temperature. The samples were placed in a 20 by 20cm wide and long separable steel container. It allowed for the top to be exposed while all other surfaces remaining covered to minimize edge effect and ignition of larger surface area than planned, illustrated in Figure A.1.

The fabrics were placed on a aluminium covered block of Rockwool and inserted into the metal frame. This was done to prevent the underlying Rockwool from absorbing the accelerants and working as a kind of wig instead of allowing it to freely burn as the accelerant behaves when burned alone, illustrated in A.2.
The foams were also placed in the steel container and placed on top of a aluminium-covered gypsum board to ease cleaning and maintaining a high execution rate.

The accelerants were poured into 9 Ø5cm aluminium containers located in similar locations as when applied to foams and fabrics, containers are illustrated in Figure A.3 on 52.
The accelerant was applied with caution and precision, illustrated in Figure A.4 on page 52.

Figure A.1: Closed steel frame containing a sample

Figure A.2: Plyester-cotton blend after experiment.

Figure A.3: 9 $\varnothing$ 5cm aluminium containers used for accelerants.

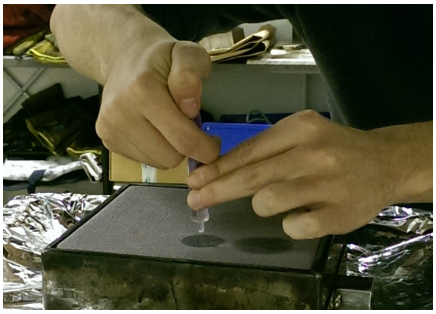

Figure A.4: Accelerant being applied with syringe.

Appendix B

Initial Accelerant Study

An initial study was made to identify the quantity of accelerants required in the experiments. A NFRPC-sample laid the basis for the tests.

The choice was based on the two materials ability to maintain a sustained flame and spread flames. Heptane was tested because it was the more potent accelerants of the two and safety measures were also considered during the initial tests to prevent damage to personal as well as equipment caused by the flames.

Before the quantity was determined, a method of applying the accelerants consistently was required. A $10ml$ syringe was a obvious choice since it allowed for a relative accurate transfer of desired accelerant with an accuracy of half ml. Attempts were made with locations, shaped like a 5 on a dice, a 3 by 3 and 4 by 4 square, but ultimately the 3 by 3 square with origin in the centre of the foam was adapted in marking up of each specimen before being tested to allow for same location application. The 9 locations yielded a better and more even distribution compared to the 5 locations and less of a hassle compared to the 4 by 4.

Figure B.1: Picture of FR foam with accelerant markings.

The result of three tests, without, with $4ml$ and with $8ml$ heptane, respectively, are shown in Figure B.2. It was noted that the difference in terms of PHRR got affected with the quantity of heptane, as shown in Figure B.2. The 3 by 3 scheme made the choice of applying $9ml$, one millilitre in each location the obvious one. The 4 by 4 grid, with an additional location in the center, was also analysed in order to determine the effect on the HRR with each $1/2ml$ in 16 locations and $1ml$ in the center beneath the ignition point, this is illustrated in Figure B.3. The difference between the 3x3 grid and 4x4 grid was considered negligible. The 3x3 grid with $1ml$ accelerant at each locations, was chosen because it was faster to apply accelerants accurately.
The diagonal of the specimens were $28cm$, and markings were made at 25 - 50 and 75% along the diagonal, thus, 7, 14 and $21cm$ from the corner, respectively, as illustrated in Figure B.1 with crosses.

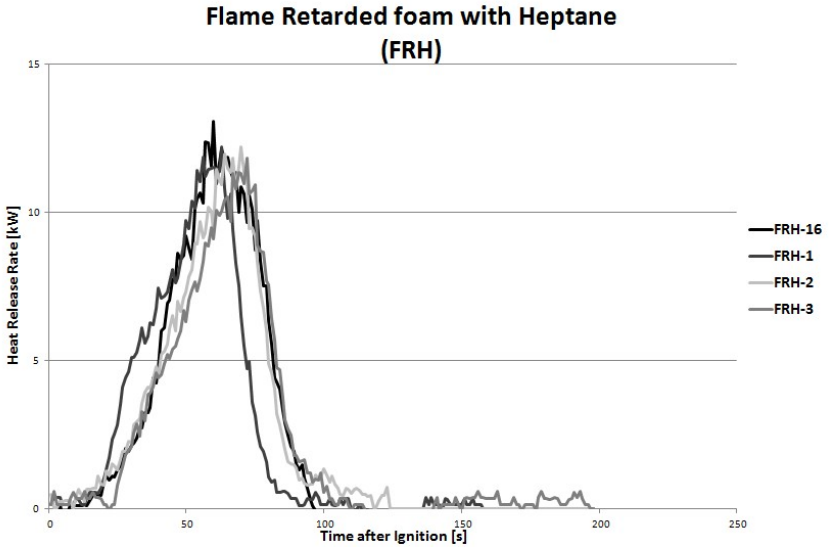

Figure B.3: HRR curve from tests with 9 and 16 accelerant locations.

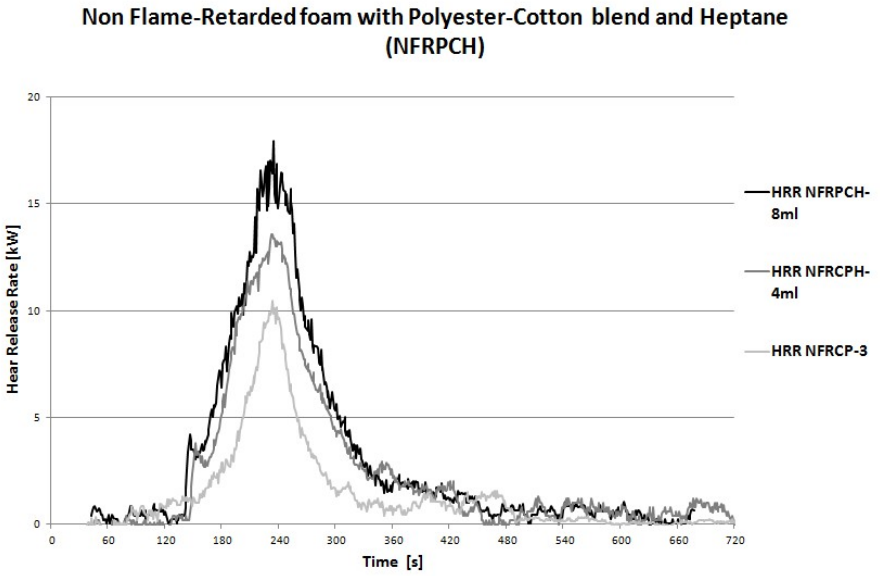

Figure B.2: HRR curve comparison between none, 4ml and 8ml heptane.

Based on an averagely assumed couch measuring in the range of $2m$ by $1m$ by $1.5m$ in length, width and height, respectively, the vertical back rest and horizontal seating provides roughly $4m^2$ of exposed surface area to be poured over with an accelerant. The amount of the accelerant is calculated in Equation B.1, under the assumption that a $1L$ bottle is used to transport the accelerant by the arsonist without being too suspicious looking.

$$\frac{0.5L}{2m^2} = 0.250L/m^2 \tag{B.1a}$$

$$250mL/m^2 \cdot (0.199m)^2 = 9.90ml \tag{B.1b}$$

Based on the amount brought by an arsonist in a common unsuspiciously looking bottle, the decision to use $9ml$ seemed to be a good estimate.

Appendix C

Calculation Procedures

Before being able to calculate the HRR by Equation 2.4 in Chapter 2 other measured values were required to be converted. The calculations were done by use of Excel.

On basis of the work done by Huggett [6] was the calculations done following Janssens procedure [46].

The saturation pressure is calculated using the temperature of the ambient environment and solution fitted to the Clausius-Clapeyron equation, in Equation C.1.

$$p_s = exp\left(23.2 - \frac{3816}{-46 + T_0}\right) \tag{C.1}$$

where the ambient temperature, T_0 is in Kelvin. The ambient temperature is calculated by taking the average temperature measured $50s$ before ignition.
The gas extracted from the duct was filtered through silica gel and drierite to prevent unwanted moisture entering the analyser in the form of e.g. water. The mole fraction of water in the incoming air was calculated using equation C.2 as a function of temperature and relative humidity in ambient conditions.

$$X^0_{H_2O} = \frac{RH}{100} \cdot \frac{p_s}{p_0} \tag{C.2}$$

where RH is the relative humidity given in per cent[%], the saturation pressure, p_s is given in [Pa], and the ambient pressure, p_0 is also given in [Pa]. The relative humidity was obtained from weather reports in the Lund area, value might vary locally but was not considered significant.
The conversion from the voltage measured by the analyser into Oxygen [O_2] and Carbon dioxide [CO_2] was done by linear correlations between know limits provided by: oxygen wall tap, nitrogen wall tab and bottled CO_2. The limit values are found in C.1

	High		Low	
	[Concentration]	[Voltage]	[Concentration]	[Voltage]
O_2	20.95%	9.800 V	0.0 %	2.253 V
CO_2	500ppm	2.402 V	0.0 ppm	2.001 V

Table C.1: Calibration limits.

The correlations between volt and percent were calculated by use of equations C.3.

Slope

$$\alpha = \frac{n\sum(xy) - \sum x \sum y}{n\sum x^2 - (\sum x)^2} \tag{C.3a}$$

Offset

$$\beta = \frac{\sum y - \alpha \sum x}{n} \tag{C.3b}$$

Trendline formula:

$$y = \alpha x + \beta \tag{C.3c}$$

Where x is the voltage measured, and the y is the known concentration. Concentration of oxygen and carbon dioxide was determined to be $X_{O_2} = 0.0278 \cdot [Volt] - 0.0625$ and $X_{CO_2} = 0.0012 \cdot [Volt] - 0.0025$, respectively. The oxygen depletion factor ϕ, is the ratio of which incoming air in completely depleted from oxygen, and calculated in equation C.4.

$$\phi = \frac{X^0_{O_2}\left(1 - X_{CO_2}\right) - X_{O_2}\left(1 - X^0_{CO_2}\right)}{\left(1 - X_{O_2} - X_{CO_2}\right) X^2_{O_2}} \tag{C.4}$$

where all values are concentration in volume fraction, e.g. 0.01 equivalent to 1%. Superscript indicated with a zero indicated ambient values, determined by an average over the first $50s$ prior to ignition. Other values were also measured from incoming exhaust gases.
The molecular weight of incoming air and oxygen, M_a and M_{O_2}, respectively, one is dependent of the incoming water vapour, the other is a tabulated value, both calculated in EquationC.5.

Incoming air

$$M_a = 29\left(1 - X^0_{H_2O}\right) + 18 \cdot X^0_{H_2O} \tag{C.5a}$$

Oxygen

$$M_{O_2} = 32 \tag{C.5b}$$

where M_a and M_{O_2} are in kg/mol.
The mass flow rate is a function of temperature and pressure difference in the exhaust duct, calculated by use of Equation C.6. The density of exhaust gases is calculated by the ideal gas law as $353/T_e$ [38].

$$m_e = \frac{A \cdot k_c}{f(Re)} \cdot \sqrt{2\rho_e \Delta p} \tag{C.6}$$

where A is the area and in m^2, k_c is the shape factor assumed to be 0.9 [23] , f(Re) is the function of the Reynolds number and is assumed to be 1.08 [23] due to simplicity, ρ_e is the density of gas in the exhaust duct in kg/m^3, Δp is the change in pressure across the probe in the exhaust duct and directly measured in kPa.
The HRR at a given time is then calculated as

$$\dot{Q} = E \cdot \frac{\phi}{1 + \phi\,(\alpha - 1)} \cdot m_e \cdot \frac{M_{O_2}}{M_a} \left(1 - X^0_{H_2O} - X^0_{CO_2}\right) X_{O_2} \tag{C.7}$$

where E is $13100 kJ/kg_{O_2}$ and α is fixed as 1.105 [23].

Appendix D

Uncertainty Analysis

An uncertainty analysis of HRR was also conducted in order to establish to what degree the results were valid.
Two different kinds of uncertainties were identified with respect to the measurement, and two with respect to computational assumptions and a known variation. The uncertainties from differences in weather conditions during and between experiments. The effects of the time between experiments and general material inconsistencies and heterogeneity are not considered but have in general been tried minimized by vigilant experimental procedures.
A know variation of $0.49g$ on the load scale was pre-determined by previous calibrations done in the laboratory. This means that the density calculations of cardboard and fabrics are influenced by this to some extend since they were of quite low mass. The fabric densities change with approximately $\pm 6g/m^2$ and the cardboard with $\pm 2kg/m^3$, but are generally considered insignificant.
In the calculation procedure in Section Calculation Procedures are two values, α and $f(Re)$, used to determine the HRR. α ranges from 1.21 to 1.00 for pure hydrogen and carbon, respectively, in dry air. 1.105 is recommended and true for methane and suggested used for other fuels as well, but is not verified for all. The function of the Reynolds number, $f(Re)$ is used to calculate the mass flow. It is assumed to be 1.08, which is true for full scale experiments where the Reynolds number is higher than 1000. For smaller scale experiments this assumption is no longer valid, as illustrated in Figure D.1, show how the value increase at lower Reynolds numbers. $f(Re)$ is nonetheless assumed to be 1.08 because the time required to iterate each measured value for all experiments was estimated too time consuming.

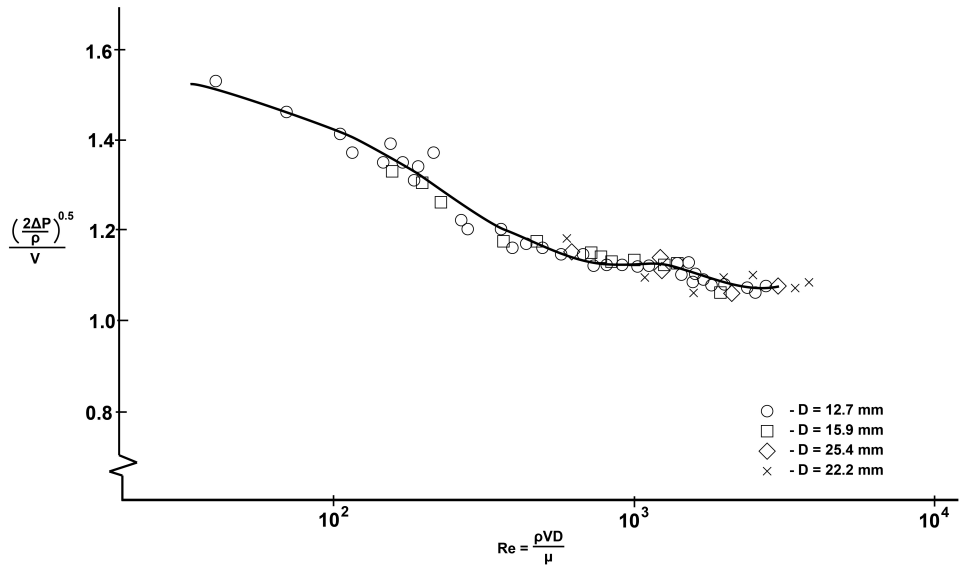

Figure D.1: Prope response versus Reynolds number. Inspired by McCaffrey & Heskestad [53]

The calibration of the gas analyser was done frequently and based on the methods described in Section C Calculation Procedures. The wall tap with oxygen was revealed to be containing oxygen in the range between 20.50 and 20.95% contrary to previous beliefs of uniform 20.95% content. The relationship between measured voltage and correlated oxygen concentrations is illustrated in Figure D.2. This means that at low HRR if the drop in oxygen were low and the voltage remained high, the difference in actual oxygen concentration could have been different compared to if higher drops in oxygen is measured. Because it is a difference in oxygen measured, the actual influence of this is limited as shown in Figure D.3 where the HRR is decreased by $0.6kW$ or $15kW/m^2$ corresponding to 2.7% at its peak, but otherwise unnoticeable.

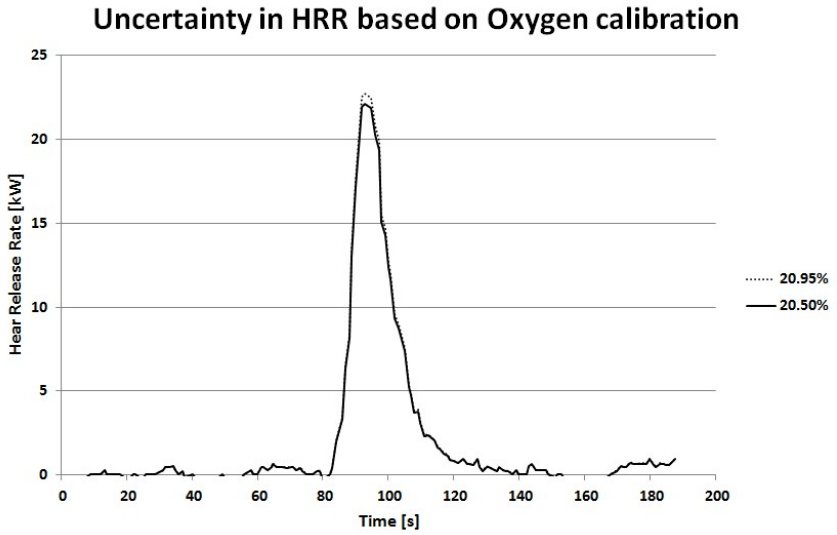

Figure D.3: Effect of calibration uncertainty on HRR.

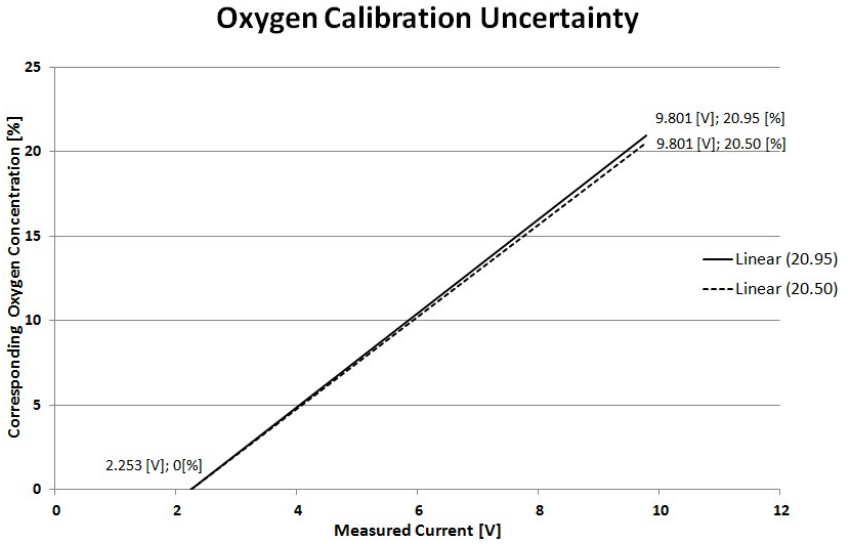

Figure D.2: Uncertainty related to oxygen consumption

The oxygen consumption method was used to calculate the HRR of a methane burner to compare measurement uncertainties between it and the flow-meter. The gas burner was controlled with a flow-meter, and a manufactures correlation between flow and HRR was used for $2kW$ intervals. The relationship between calculated HRR from oxygen consumption and HRR based on measured methane flow is illustrated in Figure D.4 with a linear trend plotted to show if over or under prediction is occurring.
The HRR based on oxygen consumption was done by use of Equation 2.4 on page 12 with energy released per kg oxygen burned replaced with 12500 instead of 13100 since the fuel is known. This value was calculated by use of Equation D.2. The

HRR for the flow measurement was calculated by use of Equation D.1

$$\dot{Q} = \text{Voltage} \cdot C \cdot K \cdot \rho_{methane} \cdot \Delta H_{methane} \tag{D.1a}$$

Where K is:

$$K = \frac{K_{actual}}{K_{ref}} = \frac{K_{methane}}{K_{propylene}} = \frac{0.75}{0.40} \tag{D.1b}$$

Where the Voltage is the measurement from the flow-meter in volt $[V]$, C is correlation between litre per min and volt measured $[\frac{L/min}{Volt}]$, K is a constant transforming the flow from the calibration gas to the actual gas, adapted from flow-meter manual, ρ is the density of methane in $[kg/m^3]$ and ΔH is the effective heat of combustion in $[kJ/kg]$ found to be $50000kJ/kg_{CH_4}$ [54].

$$E = \frac{\Delta H}{r_0} = \frac{50000}{\frac{(12+4\cdot 1)}{(2\cdot 16\cdot 2)}} = \frac{50000}{4} = 12500[kJ/kg_{O2}] \tag{D.2}$$

Where Δh is the heat of combustion for methane $[kJ/kg]$, r_0 is the stoichiometric air to fuel ration [-].
Figure D.4 shows that the range in which the oxygen consumption method is predicting the HRR is much wider than the range predicted by the flow measurements, this seen by the elongated horizontal spread compared to the vertical spread. This was also confirmed by McGrattan *et al* [55], but he also points out that the effective heat of combustion is difficult to predict and is a source of larger uncertainty than the flow itself. The standard deviations from the calibration experiment are displayed in Table D.1.

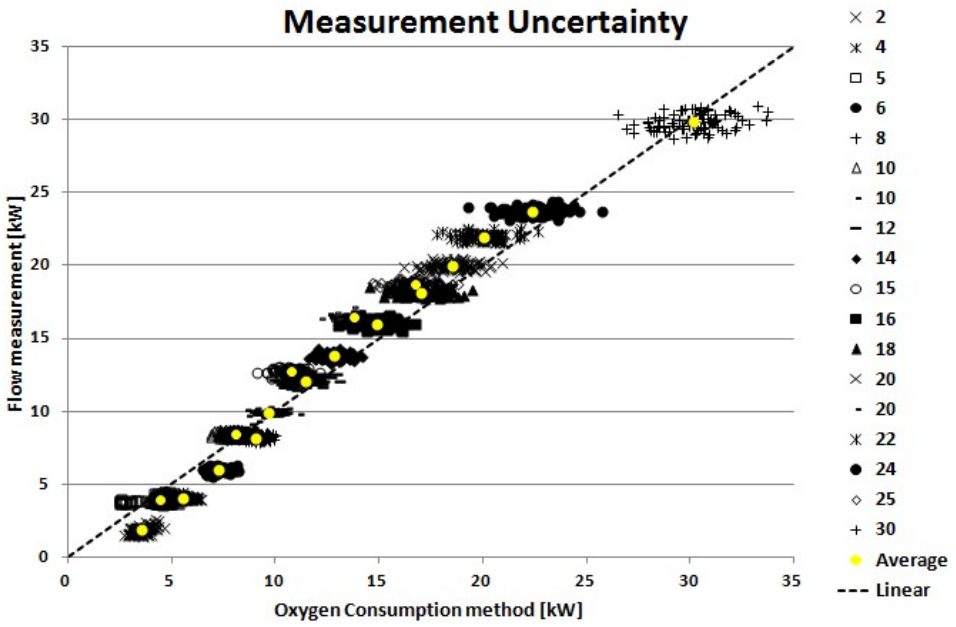

Figure D.4: Uncertainty related to calibration

It is noticeable from looking at Figure D.4, that the calculated HRR for low HRRs(less than $12kW$)are over predicted. Between 12-14kW does the prediction change for unknown reasons and the HRR is under-predicted with a growing difference until $26kW$ where the HRR of all experiments were below. This trend is equal for all experiments conducted and is regarded as not imposing a significant change in terms of over-all trends, analysis or conclusions.

Method	2kW	4kW	6kW	8kW	10kW	12kW
Oxygen	0.47	0.49	0.53	0.56	0.64	0.83
Flow	0.29	0.13	0.17	0.20	0.26	0.31
	16kW	18kW	20kW	22kW	24kW	30kW
Oxygen	0.92	1.21	1.15	1.19	1.46	1.94
Flow	0.31	0.3	0.31	0.3	0.33	0.76

Table D.1: Standard deviation in kW for pre-determined HRRs,
for both calculation methods.

The standard deviation is increasing for the oxygen consumption as the HRR increases, whereas the flow measurement maintain a fairly constant standard deviation except for last data series where the flow was at its limit. The combustion efficiency, χ, was set to 0.76 because a rule of thumb says it should be between 0.6 and 0.8 for fuels [38].

The uncertainties identified in this Appendix can be of some importance. The fluctuations in calculated HRR with respect to flow measurements show a large range of values measured to the same flow. Generally is the 10% which the ± 5 % of 13.1 MJ/kg_{O_2} accounts for, is the largest uncertainty with respect to HRR calculations.

Appendix E

Repeatability analysis

Test	compared with	Test	ERD	EPC	SC	Score	
C-1		C-2	1.06	0.27	0.00	0.93	Bad
C-1		C-3	1.22	0.15	-0.31	1.13	Bad
C-2		C-3	0.71	0.93	0.21	0.52	Bad
P-1		P-2	0.88	0.99	0.20	0.56	Bad
P-1		P-3	1.07	0.24	0.21	0.87	Bad
P-2		P-3	1.13	0.27	0.14	0.91	Bad
PC-1		PC-2	0.78	0.71	-0.01	0.69	Bad
PC-1		PC-3	0.79	1.03	0.21	0.54	Bad
PC-2		PC-3	0.92	0.72	-0.12	0.77	Bad
CH-1		CH-2	0.16	1.13	0.99	0.10	Good
CH-1		CH-3	0.20	1.15	0.98	0.12	Good
CH-2		CH-3	0.16	1.10	0.98	0.06	Good
PH-1		PH-2	0.12	0.96	0.98	0.06	Good
PH-1		PH-1R	0.46	0.85	0.75	0.29	Bad
PH-1R		PH-2	0.40	0.90	0.82	0.23	Good
PCH-1		PCH-2	0.19	1.12	0.98	0.11	Good
PCH-1		PCH-3	0.21	1.16	0.97	0.13	Good
PH-2		PCH-3	0.16	1.02	0.97	0.07	Good

Table E.1: Repeatability based on functional analysis, table-1.

Test	compared with	Test	ERD	EPC	SC	Score	
NFR-2		NFR_2	0.21	1.21	0.88	0.18	Good
NFR-2		NFR_3	0.56	1.42	0.59	0.46	Bad
NFR_2		NFR-3	0.53	1.16	0.62	0.35	Bad
	Only 1 FR test		-	-	-		
NFRP-1R		NFRP_2	0.17	1.11	0.71	0.19	Good
NFRP-1R		NFR-3	0.28	1.09	0.55	0.27	Bad
NFRP_2		NFR-3	0.27	0.97	0.44	0.28	Bad
NFRC_1		NFRC_2	0.44	0.90	0.15	0.46	Bad
NFRC_1		NFRC-3	0.37	0.80	0.53	0.35	Bad
NFRC_2		NFRC-3	0.41	0.79	0.41	0.40	Bad
NFRPC-1		NFRPC-2	0.17	0.99	0.70	0.16	Good
NFRPC_1		NFRPC-3	0.27	1.22	0.78	0.24	Good
NFRPC-2		NFRPC-3	0.28	1.21	0.73	0.25	Good
	Only 1 FRP test		-	-	-		bad
	No FRC values		-	-	-		bad
FRPC-1		FRPC-2	0.53	0.72	0.12	0.56	Bad
FRPC-1		FRPC-3	0.39	1.19	0.21	0.46	Bad
FRPC-2		FRPC-3	0.47	1.38	0.19	0.55	Bad
NFRPH-1		NFRPH-2	0.30	0.86	0.76	0.23	Good
NFRPH-1		NFRPH-3	0.35	0.82	0.84	0.23	Good
NFRPH-2		NFRPH-3	0.28	0.92	0.63	0.24	Good
NFRCH-1		NFRCH-2	0.80	0.74	0.48	0.52	Bad
NFRCH-1		NFRCH-3	0.84	0.67	0.47	0.57	Bad
NFRCH-2		NFRCH-3	0.20	0.93	0.69	0.19	Good
NFRPCH-1		NFRPCH-2	0.12	0.97	0.89	0.09	Good
NFRPCH-1		NFRPCH-3	0.21	0.95	0.59	0.22	Bad
NFRPCH-2		NFRPCH-3	0.20	0.97	0.61	0.20	Good
FRH-1		FRH-2	0.45	0.89	0.52	0.35	Bad
FRH-1		FRH-3	0.50	0.88	0.48	0.38	Bad
FRH-2		FRH-3	0.13	1.02	0.84	0.10	Good
FRM-1		FRM-2	0.61	1.03	0.12	0.51	Bad
FRM-1		FR-3	0.40	1.16	0.52	0.35	Bad
FRM-2		FRM-3	0.56	0.82	0.29	0.48	Bad

Table E.2: Repeatability based on functional analysis, table-2.

Test	compared with	Test	ERD	EPC	SC	Score	
NFRPM-1		NFRPM-2	0.12	1.02	0.59	0.18	Bad
NFRPM-2		NFRPM-3R	0.18	0.94	0.63	0.20	Good
NFRPM-2		NFRPM-3	0.20	0.92	0.73	0.18	Good
NFRCM-1		NFRCM-2	0.35	0.87	0.58	0.30	Bad
NFRCM-1		NFRCM-3	0.16	0.99	0.63	0.18	Good
NFRCM-2		NFRCM-3	0.48	0.92	0.51	0.35	Bad
NFRPCM-1		NFRPCM-2	0.21	1.00	0.78	0.14	Good
NFRPCM-1		NFRPCM-3	0.20	1.05	0.62	0.18	Good
NFRPCM-2		NFRPCM-3	0.18	1.03	0.60	0.18	Good
FRPH-1		FRPH-2	0.26	0.89	0.90	0.16	Good
FRPH-1		FRPH-3	0.21	0.93	0.86	0.14	Good
FRPH-2		FRPH-3	0.23	1.01	0.92	0.11	Good
FRCH-1		FRCH-2	0.50	0.76	0.89	0.28	Bad
FRCH-1		FRCH-3	0.61	0.72	0.91	0.33	Bad
FRCH-2		FRCH-3	0.23	0.97	0.79	0.16	Good
FRPCH-1		FRPCH-3	0.19	1.09	0.87	0.14	Good
FRPCH-1		FRPCH-3	0.18	1.14	0.86	0.15	Good
FRPCH-2		FRPCH-3	0.22	1.02	0.83	0.15	Good
FRPM-1		FRPM-2	0.42	0.92	0.85	0.22	Bad
FRPM-1		FRPM-3	0.44	0.80	0.83	0.27	Bad
FRPM-2		FRPM-3	0.36	0.82	0.83	0.23	Good
FRCM-1		FRCM-2	0.50	0.82	0.56	0.37	Bad
FRCM-1		FRCM-3	0.51	0.80	0.51	0.40	Bad
FRCM-2		FRCM-3	0.24	0.95	0.72	0.19	Good
FRPCM-1		FRPCM-2	0.60	0.67	0.47	0.49	Bad
FRPCM-1		FRPCM-3	0.26	0.84	0.67	0.25	Good
FRPCM-2		FRPCM-3	0.30	1.11	0.62	0.26	Good
NFRH-1		NFRH-2	0.15	0.95	0.87	0.11	Good
NFRH-1		NFRH-3	0.16	0.94	0.85	0.13	Good
NFRH-2		NFRH-3	0.16	0.97	0.90	0.10	Good
NFRM-1		NFRM-2	0.19	0.90	0.81	0.16	Good
NFRM-1		NFR-3	0.29	0.90	0.64	0.25	Good
NFRM-2		NFRM-3	0.17	1.01	0.76	0.14	Good

Table E.3: Repeatability based on functional analysis, table-3.

Test	compared with	Test	ERD	EPC	SC	Score	
PM-1		PM-2	0.16	1.07	0.86	0.13	Good
PM-1		PM-3	0.23	0.92	0.79	0.14	Good
PM-2		PM-3	0.23	0.86	0.93	0.15	Good
CM-1		CM-2	0.35	1.10	0.87	0.19	Good
CM-1		CM-3	0.27	1.13	0.93	0.16	Good
CM-2		CM-3	0.27	0.97	0.95	0.13	Good
PCM-1		PCM-2	0.44	0.92	0.79	0.24	Bad
PCM-1		PCM-3	0.29	0.95	0.95	0.18	Good
PCM-2		PCM-3	0.35	0.91	0.95	0.16	Good
H-4		H-5	0.20	1.04	0.92	0.11	Good
H-4		H-3	0.56	0.93	0.62	0.34	Bad
H-5		H-3	0.41	0.96	0.80	0.21	Good
M-1		M-2	0.15	1.0	0.78	0.12	Good
M-1		M-3	0.38	0.80	0.89	0.23	Good
M-2		M-3	0.49	0.78	0.77	0.31	Good

Table E.4: Repeatability based on functional analysis, table-4.

Appendix F

Factorial Design Set-up

Foam	Cover	Accelerant	Abbreviation	Abbreviation
0	0	0	-	
1	0	0	F1	NFR
2	0	0	F2	FR
0	1	0	C1	P
1	1	0	F1C1	NFRP
2	1	0	F2C1	FRP
0	2	0	C2	C
1	2	0	F1C2	NFRC
2	2	0	F2C2	FRC
0	3	0	C3	PC
1	3	0	F1C3	NFRPC
2	3	0	F2C3	FRPC
0	0	1	A1	H
1	0	1	F1A1	NFRH
2	0	1	F2A1	FRH
0	1	1	C1A1	PH
1	1	1	F1C1A1	NFRPH
2	1	1	F2C1A1	FRPH
0	2	1	C2A1	CH
1	2	1	F1C2A1	NFRCH
2	2	1	F2C2A1	FRCH
0	3	1	C3A1	PCH
1	3	1	F1C3A1	NFRPCH

Table F.1: Factorial design set-up, table-1

Foam	Cover	Accelerant	Abbreviation	Abbreviation
0	0	2	A2	M
1	0	2	F1A2	NFRM
2	0	2	F2A2	FRM
0	1	2	C1A2	PM
1	1	2	F1C1A2	NFRPM
2	1	2	F2C1A2	FRPM
0	2	2	C2A2	CM
1	2	2	F1C2A2	NFRCM
2	2	2	F2C2A2	FRCM
0	3	2	C3A2	PCM
1	3	2	F1C3A2	NFRPCM
2	3	2	F2C3A2	FRPCM

Table F.2: Factorial design set-up, table-2

Factorial Design for Time To Peak Heat Release Rate

	PC	H	PCH	
FR	-1	-1	1	46
FRPC	1	-1	-1	186
FRH	-1	1	-1	76
FRPCH	1	1	1	35
Effect:	49	-61	-91	

	PC	M	PCM	
FR	-1	-1	1	46
FRPC	1	-1	-1	186
FRM	-1	1	-1	146
FRPCM	1	1	1	103
Effect:	48	8	92	

	P	H	PH	
FR	-1	-1	1	46
FRP	1	-1	-1	44
FRH	-1	1	-1	76
FRPH	1	1	1	26
Effect:	-26	6	-24	

	P	M	PM	
FR	-1	-1	1	46
FRP	1	-1	-1	44
FRM	-1	1	-1	146
FRPM	1	1	1	26
Effect:	-61	41	-59	

	C	H	CH	
FR	-1	1	-1	46
FRC	1	-1	-1	49
FRH	-1	1	-1	76
FRCH	1	1	1	23
Effect:	-25	2	-28	

	C	M	CM	
FR	-1	-1	1	46
FRC	1	-1	-1	49
FRM	-1	1	-1	146
FRCM	1	1	1	25
Effect:	-59	38	-63	

Table F.3: Factorial design for TTP for FR foam in *sec*.

	PC	H	PCH	
NFR	-1	-1	1	88
NFRPC	1	-1	-1	173
NFRH	-1	1	-1	90
NFRPCH	1	1	1	102
Effect:	48	-35	-36	

	PC	M	PCM	
NFR	-1	-1	1	88
NFRPC	1	-1	-1	184
NFRM	-1	1	-1	92
NFRPCM	1	1	1	114
Effect:	59	-33	-37	

	P	H	PH	
NFR	-1	-1	1	88
NFRP	1	-1	-1	206
NFRH	-1	1	-1	90
NFRPH	1	1	1	111
Effect:	69	-47	-49	

	P	M	PM	
NFR	-1	-1	1	88
NFRP	1	-1	-1	206
NFRM	-1	1	-1	92
NFRPM	1	1	1	131
Effect:	78	-36	-40	

	C	H	CH	
NFR	-1	1	-1	88
NFRC	1	-1	-1	242
NFRH	-1	1	-1	90
NFRCH	1	1	1	153
Effect:	108	-44	-46	

	C	M	CM	
NFR	-1	-1	1	88
NFRC	1	-1	-1	242
NFRM	-1	1	-1	92
NFRCM	1	1	1	178
Effect:	120	-30	-34	

Table F.4: Factorial design for TTP for NFR foam in *sec*.

Factorial Design for Peak Heat Release Rate

	PC	H	PCH	
NFR	-1	-1	1	309
NFRPC	1	-1	-1	332
NFRH	-1	1	-1	504
NFRPCH	1	1	1	388
Effect:	-46	126	-70	

	PC	M	PCM	
NFR	-1	-1	1	309
NFRPC	1	-1	-1	332
NFRM	-1	1	-1	361
NFRPCM	1	1	1	360
Effect:	12	40	-12	

	P	H	PH	
NFR	-1	-1	1	309
NFRP	1	-1	-1	283
NFRH	-1	1	-1	504
NFRPH	1	1	1	383
Effect:	-73	148	-48	

	P	M	PM	
NFR	-1	-1	1	309
NFRP	1	-1	-1	283
NFRM	-1	1	-1	361
NFRPM	1	1	1	352
Effect:	-17	61	9	

	C	H	CH	
NFR	-1	1	-1	309
NFRC	1	-1	-1	253
NFRH	-1	1	-1	504
NFRCH	1	1	1	347
Effect:	-106	146	-50	

	C	M	CM	
NFR	-1	-1	1	309
NFRC	1	-1	-1	253
NFRM	-1	1	-1	361
NFRCM	1	1	1	255
Effect:	-81	27	-25	

Table F.5: Factorial design for PHRR for NFR foam in kW/m^2.

	PC	H	PCH	
FR	-1	-1	1	44
FRPC	1	-1	-1	82
FRH	-1	1	-1	302
FRPCH	1	1	1	279
Effect:	8	227	-31	

	PC	M	PCM	
FR	-1	-1	1	44
FRPC	1	-1	-1	82
FRM	-1	1	-1	124
FRPCM	1	1	1	293
Effect:	54	96	16	

	P	H	PH	
FR	-1	-1	1	44
FRP	1	-1	-1	20
FRH	-1	1	-1	302
FRPH	1	1	1	330
Effect:	2	286	26	

	P	M	PM	
FR	-1	-1	1	44
FRP	1	-1	-1	20
FRM	-1	1	-1	1
FRPM	1	1	1	26
Effect:	-61	41	-59	

	C	H	CH	
FR	-1	1	-1	44
FRC	1	-1	-1	24
FRH	-1	1	-1	302
FRCH	1	1	1	259
Effect:	-31	247	-11	

	C	M	CM	
FR	-1	-1	1	44
FRC	1	-1	-1	24
FRM	-1	1	-1	124
FRCM	1	1	1	111
Effect:	-16	84	4	

Table F.6: Factorial design for PHRR for FR foam kW/m^2.

Appendix G

Ranked Order of Experiments

Original Number	Abbreviation	Value
87	NFRCM-3	2.20
19	FR-1	2.72
66	FRP-3	4.06
32	PM-2	4.69
67	FRPC-1	4.79
75	NFRCM-3	5.30
60	NFRPC-3	5.99
11	C-2	6.03
17	NFR-2	6.26
25	CM-1	6.56
47	FRH-2	6.79
88	NFRPH-2	6.80
3	H-3	6.84
59	NFRPC-2	9.67
34	PCH-1	12.00
35	PCH-2	12.17
54	NFRC-3	12.91
42	NFRH-3	14.05
24	CH-3	15.08
89	FRCH-2	16.10
88	FRCH-1	16.60
104	FRPCM-2	16.97
100	FRPCH-1	18.02
43	NFRM-1	18.60
99	FRPM-1	18.87

Original Number	Abbreviation	Value
16	NFR-1	19.98
74	NFRCM-2	20.02
39	PCM-3	20.62
31	PM-1	21.36
95	FRPH-2	21.79
10	C-1	21.84
27	CM-3	23.72
46	FRH-1	24.75
48	FRH-3	25.38
7	P-1	25.90
36	PCH-3	27.66
15	PC-3	27.97
30	PH-3	28.10
80	NFRPM-2	28.49
76	NFRPH-1	29.28
29	PH-2	30.66
64	FRP-1	31.36
57	NFRP-3	31.85
52	NFRC-1	32.15
61	FRC-1	32.22
84	NFRPCH-3	33.30
101	FRPCH-2	34.08
12	C-3	34.11
4	M-1	34.89
69	FRPC-2	36.82

Table G.1: Ranked order of experiments, table-1.

Original Number	Abbreviation	Value
53	NFRC-2	36.83
49	FRM-1	38.43
9	P-3	41.3
20	FR-2	42.42
79	NFRPM-1	44.33
14	PC-2	45.11
33	PM-3	46.95
96	FRPH-3	47.42
105	FRPCM-3	48.97
1	H-1	51.82
71	NFRCH-2	52.47
6	M-3	53.65
13	PC-1	54.89
102	FRPCH-3	55.81
65	FRP-2	57.98
92	FRCM-2	59.10
90	FRCH-2	59.41
37	PCM-1	61.11
83	NFRPCH-2	61.98
103	NFRPCM-1	62.97
85	CH-2	66.24
23	NFRPC-1	66.99
58	NFRPC-1	67.70
97	FRPM-1	68.04
55	NFRP-1	71.39
21	FR-3	72.23
56	NFRP-2	72.37
44	NFRM-2	72.54
81	NFRPM-3	73.32
68	FRPC-2	74.11
91	FRCM-1	74.42
82	NFRPCH-1	77.19
70	NFRCH-1	77.20
73	NFRCM-1	77.89
40	NFRH-1	78.27
5	M-2	78.77
18	NFR-3	78.97
93	FRCM-3	79.66
38	PCM-2	80.22
28	PH-1	80.59
98	FRPM-2	81.76
50	FRM-2	82.30
63	FRC-3	82.32
45	NFRM-3	83.16
62	FRC-3	84.03
2	H-2	84.82
86	NFRPCM-2	85.30
51	FRM-3	85.36
94	FRPH-1	88.96
22	CH-1	90.65
72	NFRCH-3	91.57
26	CM-2	94.76
41	NFRH-2	95.39
8	P-2	97.71
78	NFRPH-3	97.75

Table G.2: Ranked order of experiments, table-2

Appendix H

Functional Comparison Analysis

NFRPM	ERD	EPC	SC	NOTE	Score
NFRP_2+M-1	0.69	0.80	0.11		0.58
NFRM-2+P1	1.93	0.30	-0.18		1.31
NFR-2+P-1+M-2	1.84	0.34	0.18		1.07
NFR-2+PM-2	1.42	0.41	0.44		0.77
NFRP_2+M-1	0.40	0.87	0.62	NFRP_2 -71s	0.27
NFR-2+P-1+M-2	0.35	1.08	0.69	NFR-2 + 60s	0.23
NFR-2+PM-2	0.33	0.81	0.87	NFR-2 +30s	0.16

NFRPH	ERD	EPC	SC	Score
NFRP_2+H-3	0.98	0.51	0.15	0.75
NFRH-3+P1	0.95	0.52	-0.07	0.85
NFR-2+P-1+H-3	0.79	0.57	0.84	0.34
NFR-2+PH-1	0.66	0.61	0.80	0.31

NFRPM	ERD	EPC	SC	Score
FRP-3+M-1	0.70	0.72	0.38	0.50
FRM-3+P-1	0.69	1.29	0.22	0.56
FR-1+P-1+M-2	0.58	0.74	0.24	0.31
FR-1+PM-2	0.60	0.66	0.73	0.32

FRPH	ERD	EPC	SC	Score
FRP-1+H-3	0.84	0.58	0.79	0,38
FRH-2+P-1	0.98	0.51	-0.09	0.86
FR-1+P-1+H-3	0.84	0.58	0.80	0.38
FR-1+PH-1	0.81	0.59	0.90	0.32

Table H.1: Functional analysis of polyester.

NFRCM	ERD	EPC	SC	Score
NFRC-3+M1	0.50	0.90	0.11	0.50
NFRM-3+C-1	2.05	0.28	-0.21	1.38
NFR-2+C-1+M-2	2.11	0.30	0.35	1.07
NFR-2+CM-1	1.98	0.32	0.16	2.26

NFRCH	ERD	RPC	SC	Score
NFRC-3+H-3	1.03	0.49	-0.17	0.93
NFRH-3+C-1	1.83	0.28	-0.11	1.25
NFR-2+C-1+H-3	0.54	0.83	0.53	0.36
NFR-2+CH-2	1-47	0.39	0.39	0.82

NFRCM	ERD	EPC	SC	Score
FRC-1+M-1	0.70	0.80	0.74	0.34
FRM-3+C-1	0.70	2.39	-0.11	1.12
FR-1+C-1+M-2	0.56	0.80	0.32	0.46
FR-1+CM-1	0.86	0.58	0.26	0.64

FRCH	ERD	EPC	SC	Score
FRC-2+H-3	1.04	0.48	0.78	0.46
FRH-2+C-1	0.92	0.54	0.06	0.76
FR-2+C-1+H-3	1.04	0.48	0.85	0.42
FR-1+CH-2	0.87	0.57	0.84	0.36

Table H.2: Functional analysis of cotton.

NFRPCM	ERD	EPC	SC	NOTE	Score
NFRPC-2+M-1	0.82	1.56	-0.14		0.86
NFRM-3+PC-1	0.30	0.85	0.47		0.30
NFR-2+PC-1+M-1	0.23	0.86	0.69		0.19
NFR-2+PCM-3	0.28	0.84	0.76		0.19
NFRPC-2+M-1	0.29	1.10	0.74	NFRPC - 60s	0.19

NFRPCH	ERD	EPC	SC	NOTE	Score
NFRPC-2+H-3	0.92	0.64	0.03		0.75
NFRH-3+PC-1	0.42	0.90	0.54		0.31
NFR-2+PC-1+H-3	0.54	0.83	0.52		0.37
NFR-2+PCH-3	0.45	0.86	0.59		0.31
NFRPC-2+H-3	0.27	1.09	0.75	NFRPC+80s, 50% H	0.18
NFR-2+PC-2+H-3	0.39	1.13	0.62	50% H	0.27
NFR-2+PCH-3	0.33	1.16	0.71	50% H	0.22

NFRPCM	ERD	EPC	SC		Score
FRPC-2+M-1	0.74	1.13	0.07		0.60
FRM-3+PC-1	0.82	3.52	0.24		0.42
FR-1+PC-1+M-1	0.74	1.08	-0.70		0.86
FR-1+PCM-3	0.82	0.81	-0.58		0.90

FRPCH	ERD	EPC	SC		Score
FRPC-2+H-3	0.87	0.64	0.50		0.52
FRH-2+PC-1	0.48	1.03	0.24		0.43
FR-1+PC-1+H-3	0.94	0.57	0.62		0.49
FR-1+PCH-3	0.82	0.69	0.61		0.44

Table H.3: Functional analysis of polyester-cotton blend.

Appendix I

Growth Rates

NFRP_1	NFRP_2	NFRP-3	NFRP
0.008	0.007	0.008	0.008
NFRPM-1	NFRPM-2	NFRPM-3	NFRPM
0.021	0.020	0.021	0.021
NFRPH-1	NFRPH-2	NFRPH-3	NFRPH
0.034	0.027	0.035	0.032
NFRC_1	NFRC_2	NFRC-3	NFRC
0.003	0.006	0.005	0.004
NFRCM-1	NFRCM-2	NFRCM-3	NFRCM
0.010	0.005	0.010	0.009
NFRCH-1	NFRCH-2	NFRCH-3	NFRCH
0.035	0.009	0.013	0.019
NFRPC_1	NFRPC-2	NFRPC-3	NFRPC
0.009	0.011	0.008	0.010
NFRPCM-1	NFRPCM-2	NFRPCM-3	NFRPCM
0.030	0.027	0.030	0.029
NFRPCH-1	NFRPCH-2	NFRPCH-3	NFRPCH
0.035	0.049	0.038	0.041

Table I.1: Growth rates for all tests.

Appendix J

Gathered Raw NFR Data

NFR_1	NFR_2	NFR_3	NFR
252	310	272	278
NFRP_1	NFRP_2	NFRP-3	NFRP
356	334	367	352
NFRPM-1	NFRPM-2	NFRPM-3	NFRPM
356	334	367	352
NFRPH-1	NFRPH-2	NFRPH-3	NFRPH
363	396	390	383
NFRC_1	NFRC_2	NFRC-3	NFRC
257	230	271	253
NFRCM-1	NFRCM-2	NFRCM-3	NFRCM
258	247	261	255
NFRCH-1	NFRCH-2	NFRCH-3	NFRCH
384	306	352	347
NFRPC_1	NFRPC-2	NFRPC-3	NFRPC
353	336	307	332
NFRPCM-1	NFRPCM-2	NFRPCM-3	NFRPCM
369	378	334	360
NFRPCH-1	NFRPCH-2	NFRPCH-3	NFRPCH
384	348	431	388

Table J.1: PHRR for NFR tests in kW/m^2. Table 1

NFRM-1	NFRM-2	NFRM-3	NFRM
344	382	356	361
NFRH-1	NFRH-2	NFRH-3	NFRH
469	538	505	504

Table J.2: PHRR for NFR tests in kW/m^2. Table 2

NFR_1	NFR_2	NFR_3	NFR
105	96	106	103

NFRP_1	NFRP_2	NFRP-3	NFRP
131	129	131	130
NFRPM-1	NFRPM-2	NFRPM-3	NFRPM
131	129	131	130
NFRPH-1	NFRPH-2	NFRPH-3	NFRPH
104	120	105	110

NFRC_1	NFRC_2	NFRC-3	NFRC
301	197	240	246
NFRCM-1	NFRCM-2	NFRCM-3	NFRCM
159	212	240	204
NFRCH-1	NFRCH-2	NFRCH-3	NFRCH
104	189	162	152

NFRPC_1	NFRPC-2	NFRPC-3	NFRPC
193	175	190	186
NFRPCM-1	NFRPCM-2	NFRPCM-3	NFRPCM
111	119	106	112
NFRPCH-1	NFRPCH-2	NFRPCH-3	NFRPCH
104	84	106	98

NFRM-1	NFRM-2	NFRM-3	NFRM
93	95	88	92
NFRH-1	NFRH-2	NFRH-3	NFRH
91	89	91	90

Table J.3: TTP for all NFR tests in s.

NFR_1	NFR_2	NFR_3	NFR
0.023	0.033	0.024	0.027

NFRP_1	NFRP_2	NFRP-3	NFRP
0.008	0.007	0.008	0.008
NFRPM-1	NFRPM-2	NFRPM-3	NFRPM
0.021	0.020	0.021	0.021
NFRPH-1	NFRPH-2	NFRPH-3	NFRPH
0.034	0.027	0.035	0.032

NFRC_1	NFRC_2	NFRC-3	NFRC
0.003	0.006	0.005	0.004
NFRCM-1	NFRCM-2	NFRCM-3	NFRCM
0.010	0.005	0.010	0.009
NFRCH-1	NFRCH-2	NFRCH-3	NFRCH
0.035	0.009	0.013	0.019

NFRPC_1	NFRPC-2	NFRPC-3	NFRPC
0.009	0.011	0.008	0.010
NFRPCM-1	NFRPCM-2	NFRPCM-3	NFRPCM
0.030	0.027	0.030	0.029
NFRPCH-1	NFRPCH-2	NFRPCH-3	NFRPCH
0.035	0.049	0.038	0.041

NFRM-1	NFRM-2	NFRM-3	NFRM
0.040	0.042	0.046	0.043
NFRH-1	NFRH-2	NFRH-3	NFRH
0.057	0.068	0.061	0.043

Table J.4: Growth rate for all NFR tests in $(kW/m^2)/s^2$.

Link to all raw data
$http://www.dropbox.com/sh/ds7kqhkf9uw2i37/6M_AbVT8pn/$