Fire Models and Design Fires

An Experimental Investigation on the Influence of Thermal Feedback on Pre-flashover Fires

Annemarie Poulsen

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Preface

This thesis is submitted as a partial fulfillment of the requirements for the Danish Ph.D. degree. The study has taken place at the Department of Civil Engineering at the Technical University of Denmark (DTU Byg), in the period from March 2008 to February 2012. Associate Professor Lars Schiøtt Sørensen (DTU Byg) was originally the principal supervisor of this project and Professor Kristian Hertz (DTU Byg) was co-supervisor together with Mr. Kurt Munk (Rockwool International A/S). Lars Schiøtt Sørensen left DTU in April 2009 after which Kristian Hertz took over as principal supervisor. Associate professor Grunde Jomaas (DTU Byg) has been co-supervisor from the end of 2011. I was associated to the National Research Council Canada, Institute for Research in Construction (NRC-IRC) as a visiting worker from May 2009 to April 2010, during which Dr. Alex Bwalya kindly hosted two research stays that total 14 weeks.

This thesis is in partial based written on basis of the appended papers and research report.

Kgs. Lyngby, February 2012

Annemarie Poulsen

Preface to the published version

This thesis was defended at a public defense on June 15th 2012. The opponents were Dr. Björn Karlsson, Iceland Construction Authority, Iceland, Prof. José Torero, University of Edinburgh, UK and Prof. Franco Bontempi, Università degli Studi di Roma "La Sapienza", Italien. Subsequently the Ph.D. degree was awarded from the Technical University of Denmark.

Compared to the original submitted version of this thesis minor editorial corrections have been implemented, and the status of paper #2 have changed from submitted to published online.

Kgs. Lyngby, December 2012

Annemarie Poulsen

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A very special thanks goes to Dr. Alex Bwalya for kindly inviting me to stay at NRC-IRC, and for many fruitful discussions on fire testing as well as sharing experimental result with me. Also I would like to thank NRC-IRC for partitioning in a joint research project including 3 full scale experiments performed for this Ph.D. project.

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Last, but not least, I am very grateful for the loving support of my dear family Mathias and Henrik.

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Abstract

The aim of this project is to perform an experimental study on the influence of the thermal feedback on the burning behavior of well ventilated pre-flashover fires. For the purpose an experimental method has been developed. Here the same identical objects are tested under free burn conditions and in two different rooms, which only are varied by linings of significantly different thermal inertia. As all linings were non-combustible the heat release rate could be found without the influence of thermal feedback and for two different levels of thermal feedback. The ISO 9705 Room Corner Test facility was chosen as the same measuring equipment could be used for all the tests. Using this method, 10 experiments were performed with three different sizes of heptane pools and three experiments were carried out with a block of flexible polyurethane foam. In addition to these 13 experiments, 16 experiments carried out by Carleton University and NRC-IRC performed on seven different types of fire loads representing commercial premises, comprise the tests used for the study.

The results show that for some of the room test the thermal feedback occurring in the room tests did increase the heat release rate compared to free burn test for pre-flashover fires. Two phenomena were observed, that relate well to theory was found. In an incipient phase the heat release rate rose with the temperature of the smoke layer/enclosure boundaries, and the magnitude of the increase was found to depend on the flammability properties of the burning object. This can be described by a simple model.

A rapid increase of the heat release rate commenced after the incipient phase. This is seen as a thermal runaway caused by the energy gain in the smoke layer exceeding the energy that can be lost through the boundaries. The onset point of thermal runaway was found to depend on the thermal inertia of the linings as well as the flammability parameters of the burning object. This correlates well with theory. At the onset point of thermal runaway the smoke layer temperature was found to be as low as 300 °C for linings with very low thermal inertia, which makes the onset point significantly below the traditional flashover criterion for the smoke layer of 5-600°C. This indicates that caution should be used when using this criterion for rooms with very low thermal inertia. The increase of the heat release rate after the onset of thermal feedback did not seem to be dominated by either temperature of the smoke layer/enclosure boundaries or the type of materials of the burning object.

Given the profound difference between room burn conditions and free burn, the results show that free burn results should also be used with caution for prediction of pre-flashover design fires in rooms.

Resumé

Dette projekts formål er ved forsøg at undersøge ændringen af brandeffekten som følge af tilbagestråling fra rummet for en velventileret brand før overtænding. Til formålet er der uviklet en eksperimentel metode, hvor der for det samme objekt udføres ét forsøg i det fri (kørt under et emfang) og to forsøg i rum, der varieres i form af beklædningens termiske inerti. Da alle beklædninger er ubrændbare, kan brandeffekten for det samme objekt dermed bestemme uden tilbagestråling samt ved to forskellige niveauer af tilbagestråling. Det blev valgt at benytte ISO 9705 Room Corner prøvnings-metoden til at udføre forsøgene, da alle prøvningerne her kan udføres med samme måleudstyr. Ved brug af denne metode, er der udført 10 forsøg med 3 størrelser af kar med heptan og 3 forøg med én størrelse polyuretanskum til møbler. Hertil kommer data fra 16 forsøg foretaget af Carlton University og NRC fra forsøg med 7 forskellige oplag svarende til butikker.

Resultaterne viser, at tilbagestålingen vil forøge brandeffekten før overtænding, og dermed vil en brand kunne udvikle sig hurtigere, end hvad der bestemmes, hvis denne effekt ikke tage i betragtningen. Forsøgene viser, at der opstår to fænomener, der begge kan forklares via teorien. Det første er en indledende fase, hvor brandeffekten gradvist forøges som funktion af temperaturer i røglag/beklædninger samt de brandtekniske egenskaber af det brændende objekt. I denne fase viser forsøgene, at den forøgede brandeffekt kan estimeres ud fra en simpel model. Estimater på materiale data til brug for modellen foreligger i litteraturen.

Efter den indledende fase opstår en meget hurtig stigning af brandeffekten. Dette ses som en termisk instabilitet som følge af, at energien der tilføres røglaget overstiger energien, der kan bortledes via beklædninger og åbninger. Efter den termiske instabilitet er indtruffet, viser forsøgene, at ændringen i brandeffekt ikke længere er domineret af temperaturen i røglag/beklædninger, ligesom ændringen i brandeffekten heller ikke kan relateres til typen af materialer, der brænder. Forsøgene viser dog, at startpunktet for den termiske instabilitet er afhængig af beklædningernes termiske inerti og de brandtekniske egenskaber af det brændbare objekt. Dette kan forklares af teorien. For beklædninger med lav termisk inerti opstod den termiske instabilitet for røglagstemperaturer ned til 300 °C. Dette er specielt interessant da temperaturen er væsentlig under røglagskriteriet for overtænding på 5-600 °C. Det indikere at dette kriterium bør benyttes varsomt for beklædninger med lav termisk inerti.

På grund at den grundlæggende forskel mellem brandforsøg kørt i det fri og forsøg kørt i rum viser resultaterne tillige at man skal være varsom med at bruge forsøg fra det fri til at estimere design brande i rum.

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Part I Introduction

1 Introduction

1.1 Background

Many countries around the world favor the adoption of performance-based building codes due to the well-documented benefits in fire safety, design flexibility, cost, and quality that can be achieved. A performance-based approach to fire safety evaluation and design of buildings is an elaborate process consisting of many steps and requires the use of decision-making tools based on analytical and computational methods [1]. The selection of the design fire is one of the most important steps in this process [1], as it represents the basis for the prediction of the safety of the occupants in the building, the structural stability, fire brigade intervention, property protection etc. Thus, the understanding and modeling of the design fire are important engineering tools in order to make a robust and cost effective building design.

How to select a design fire is an engineering task that has been described in several guidelines around the world. This study uses the ISO/TS 16733 guideline on “Selection of design fire scenarios and design fires” [2] as a general approach. This guideline has general descriptions without national choices, as well as it has been used as a background document for many national guidelines.

1.2 The concept of the design fires

The design fire represents the development of a fire course in terms of heat release rate, temperature, toxic yields and fire load density [2] for a given design fire scenario. Besides the design fire, a design fire scenario includes a description of the building or a part of the building, means of fire protection, occupancy and interaction between these parameters [2]. Typically design fire scenarios are also selected in relation to relevant fire safety objectives, which could be life safety of the occupants, avoiding structural collapse or ensuring safe fire brigade intervention as described in national regulations [3]. In addition, design fire scenarios should also address possible change in a lifetime of the building. Therefore it is often needed to investigate several design fire scenarios and design fires in order to make a robust performance based design of a building.

A design fire is typically divided into several phases including: the initial phase, the growth phases, flashover, the fully developed fire, decay and extinction. In the incipient phase the fire is small and in most cases located to one item. The duration will depend on the ignition source and type of combustibles. When the fire is large enough, the fire may start propagating and thus go into the growth phase characterized by an increasing but still localized fire [2]. During this stage the fire may gradually spread to other objects. As the fire builds up it will at some point become a threat to the occupants. Eventually the fire may reach flashover, which is a short transition stage under which most combustibles will ignite and the fire is no longer restricted to a localized fire [4]. At this stage, the rate of heat release, temperature, smoke production and smoke toxicity increase rapidly, until a further increase is restricted by ventilation or fuel [4]. Flashover also represents a point in the fire course where: a) occupants have no chance of survival in the room of fire origin b) the time when tenability conditions in adjacent spaces will be threatened, c) the beginning of the thermal assault on the structure due to elevated temperatures, and d) a point when fire service intervention in the fire room is considerably limited.

After flashover has occurred the fire will be fully developed (also called post-flashover), which is a stage where a substantial steady burning rate takes place and the fire usually is controlled by ventilation or in more rare cases by the amount of fuel [2]. This stage of the design fire scenario will mostly aim at investigating structural failures. Eventually as the fuel has burned out the fire will decay and be extinguished.

1.3 Selection of design fires

Given the design fire scenarios, the design fires are selected based on information on the type and position of the actual combustibles, but also information on the room such as size, ventilation or different means of fire protection should be taken into consideration when the design fire is selected [2]. Therefore the design fire should reflect the phenomena occurring during the fire course related to the room and means of fire protection.

In order to define the design fire an appropriate model has to be found. Generally fire models are often divided into the two regimes depending on whether they are fuel controlled or ventilation controlled.

The fuel controlled design fire (also called the well ventilated fire) is defined by the type of combustibles in the room. Here the fuel is both inventory and building products [2]. In Europe the building products are subject to legislation with regards to fire safety enforced by The Construction Products Directive (Council Directive 89/106/EEC), this is seldom the case for normal inventory; therefore inventory generally cannot be related to classes. The ISO guideline [2] suggests that pre-flashover design fires often can be selected based on engineering judgments of the heat release rate from the possible combustible objects in the room (inventory and linings).

For the inventory, data on the heat release rates are available from tests with mainly single objects and can be found in handbooks [5]. These data are mostly found by the use of measuring the oxygen consumption [6] for free burn condition, which could be conducted under the exhaust hood of the ISO 9705 Room Corner test [7] or the furniture calorimeter [8]. Lately, room fire results have also been published for single items representative of domestic premises [9] and fire loads representing different types of commercial premises [10]. In the literature there are also examples, where reasonable results have been obtained on modeling the fire development of an object by CFD based on experimental results [11].

Choosing a design fire based on specific information on the type of combustible items in a room is not a simple process. An a-priori investigation found that for well described inventory, engineering judgments among well qualified fire safety engineers there was a considerable scatter in the modeled design fires. Furthermore, predictions of test results were poor [12]. Therefore, the uncertainties of the engineering choices are obvious and in practice it also requires good ethics of the designer.

Many guidelines similar to the ISO guideline [2] use of the t-squared fires, where the heat release rate is found as:

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

Where α is a constant and t is the time.

The t-squared is often defined by the rate at which the fire grows as slow, medium, fast and ultra fast. Values of α and examples are given in Table 1.1

Table 1.1 Values of growth rates and examples of inventory [2]

Growth rate	α (kW/s²)	Example
Slow	0.003	Floor covering
Medium	0.012	Shop Counters
Fast	0.047	Bedding
Ultra-fast	0.19	Upholstered furniture

The t-squared fire has been found to be a fair representation of the burning characteristic of the growth phase of several free burning items [13]. Some countries also have guidelines [14, 15] that suggest α-values, which may be applied for specific uses in building design as a representation of the inventory whereas linings are generally not included. This may be a practical approach to ensure a given set of input data for modeling and thus limiting the uncertainties due to engineering judgment, but the t-squared fire only relates to the burning object and does not take either risk or room effects as thermal feedback into consideration [16].

The growth of the fuel controlled fire may continue into flashover, but it may also be limited by the amount of fuel present in the room or by ventilation before flashover.

The ventilation controlled fire is characterized by the amount of oxygen that can enter the room, which is also described by the ventilation factor $A_O \cdot \sqrt{H_O}$ where A_O is the area of the openings and H_O is the height of the openings [17]. As it is found that one kg O_2 by an average will release 13.1 MJ [18] the heat release in the room can be estimated, giving a simple approach for defining the ventilation controlled fire. This approach also decouples the fire model from the precise type of combustibles, as a fire model can be defined based on the ventilation factor and the fire load density representative of the fire that gives the duration of the fire. For fully developed fires, this approach together with simple assessments of the heat lost via boundaries and openings is the basis of the parametric time temperature as can be found in the Eurocodes [19].

It is also important to be able to predict the onset of flashover, as it represents a significant change in the fire behavior. Flashover is, however, not a single physical event that can be precisely described [4], but it can be seen as a transition phase covering several processes such as: Fire spread caused by sudden increase in the fire size due to the radiant ignition of adjacent combustibles [20], rapid surface flame spread on an object [21], thermal runaway (sometimes referred to as burning instability) caused by the thermal feedback from the warm enclosure and smoke layer [21], spontaneous ignition of unburned gases in the hot smoke layer due to direct contact with the fire plume [20], and an increase of the oxygen supply for under-ventilated rooms [21].

Traditionally, it has been found that a rapid fire spread to adjacent objects is the dominant process in causing flashover [21]. Based on this assumption, criteria for the onset of flashover have been established as uniform temperatures in the smoke layer of 5-600°C or an incident heat flux to the floor of 20kW/m^2 [2, 22]. For the assessment of fire tests, ignition of crumpled paper on the floor or flames exiting the opening has also commonly been used as indicators [22].

The mentioned smoke layer temperature criterion is also used as basis for predicting flashover by respected fire models such as Thomas' model [23], Babrauskas' model [24] and the model developed by McCaffrey, Quintiere and Harkleroad (MQH) [25]. These models predict the critical heat release rate needed to cause flashover based on energy balance considerations. None of the three models, however, handles the actual development of the heat release rate in the room, which has to be decided on by the fire engineer.

1.4 The influence of thermal feedback

The ISO guideline [2] also specifies that free burn experimental data should be used with caution for prediction of room burn fires, as preheating and thermal feedback may enhance the burning rate, and thus lead to more severe fires. More detailed information is, however, not given on this matter.

In fire safety design it has, at least in Denmark, become common practice to use free burn fire tests for the assessment of the pre-flashover design fire, perhaps because no other guidance is available to do otherwise. In this context it should be mentioned that both Thomas [23] and Babrauskas [24] argued that heat release rates from free burn fire tests could be used at input values for their models. This could justify the practice of using free burn values.

Further information on thermal feedback in relation to the development of the heat release rate can; however be found in the literature. Fundamentally the thermal feedback is the net heat flux to the surface of a burning object origin from hot gasses and hot room boundaries. To describe the influence of the thermal feedback on the heat release rate, the heat release rate must be defined. In general, the pre-flashover fire the heat release rate of the fire $\dot{Q}_F$ can be found as [26]:

$$\dot{Q}_F = A_F \cdot \Delta H_{eff} \cdot \dot{m}''_F \tag{1.2}$$

where $\dot{Q}_F$ is the total heat release rate, A_F is the area of the burning object, ΔH_{eff} is the effective heat of combustion and $\dot{m}''_F$ is the fuel mass loss rate per unit area. Any change of the heat release rate may take place as a consequence of changes of the burning area or change of the fuel mass loss rate, whereas the heat of combustion can be taken as a constant [26].

For a well-ventilated fire the fuel mass loss rate changes with the heat flux to the burning surface. The heat flux may increase due to higher flame emission, as it is generally seen for pool fires with increasing diameter [24], or the heat flux may also increase due to thermal feedback related to the heat flux from the smoke layer and enclosure boundaries [27]. Therefore thermal feedback may increase the burning rate of the ignited area. The burning area may change due to surface flame spread, ignition of other object or burnout. As thermal feedback may increase the surface temperature by preheating surfaces not jet ignited an increased flame spread rate can be expected [27], and thus the ignited area may also increase due to thermal feedback. It can therefore be seen that the heat release rate is a compounded variable that in more ways are dependent on the thermal feedback.

An experimental investigation [28] on upholstered furniture has shown that an effect of thermal feedback can be expected for pre-flashover room burns. It was found that the heat release rates increased in room tests (ISO Room corner test facility) compared to free burn heat release rates, if the free burn peak was above 450 - 600 kW. As this test facility generally is found not to lead to flashover at levels below 1000 kW [29], the test also indicates that thermal feedback will increase the heat release rate even before flashover. That thermal feedback is important for upholstered furniture or mattresses are of specific interest as these are often found to be the first ignited object in fatal fires [30]. Therefore it implies that it may be a problem to ignore the effect of thermal feedback for pre-flashover fires.

Furthermore, Thomas et al. [31] showed by theory how thermal feedback can increase the burning rate, and how this effect can lead to a thermal runaway as the heat gained in the room exceeded the heat that could be lost. At the onset of thermal runaway the burning rate would increase rapidly and create a “jump” that is also associated with flashover. Their initial analyses showed that thermal runaway in theory could happen at smoke layer temperatures in the range of 300 °C to 650 °C. Their analyses also showed that the burning rate at the onset of thermal runaway may have increased by approximately 50 % compared to free burn conditions. Thomas [23] also argued that an increase of 50 % of the heat release rate per unit area makes thermal feedback less important compared to fire spread when flashover is investigated. Therefore, he found that heat release rates from free burn tests could be used for the assessment of flashover.

Similar theoretic models assessing thermal runaway have been developed [32, 33], and by parameter studies they have shown that the onset of thermal runaway is dependent on thermal inertia [34, 35], assumed discharge coefficients [36] and aspect ratio [37]. On the other hand, a request for experimental validation has also been expressed [27, 35].

As thermal runaway, as mentioned earlier, also is associated with flashover it is interesting to relate the models for thermal runaway to the traditional flashover models. It is obvious that the models for thermal runaway take more parameters into consideration when assessing the heat balance, as the impact of thermal feedback (fuel response) is included. As the onset of thermal runaway is indicated to occur at room temperatures as low as 300 °C, it could be questioned whether using a flashover criterion of a smoke layer temperature 5-600 °C is a robust choice covering most building designs.

Finally it should be mentioned that it has been attempted to reproduce the results of fire tests where thermal feedback was present by CFD modeling [38-40]. This was done without any success.

The impact of the thermal feedback on the burning rate has been investigated for fully developed fires at a stable burning rate by Utiskul [41]. He found a reasonable correlation between theoretic models and small scale experiments taking both oxygen reduction and thermal feedback into consideration.

Besides increasing the heat release rate, thermal feedback can also preheat surfaces still not ignited, and thus the flame spread rate may increase. This has in principal been explained by Quintiere [27], as he shows how flame spread will increase for concurrent and opposed flow due to decreasing difference between the surface temperature and the ignition temperature. He also explains how this may lead to a thermal runaway as the increased burning area will increase the gained heat compared to a free burn situation.

1.5 Research objectives

The previous sections argued that the common practice of using free burn heat release as a basis for selection of pre-flashover design fire can be questioned, as thermal feedback can increase the heat release rate, as well as flame spread rates may be increased due to pre-heating. Also, it was found that onset of thermal runaway caused by the thermal feedback may occur before traditional flashover criteria would predict.

It is therefore evident that the practice of using free burn values as a basis for a prediction of a design fire may to some point influence the fire safety of a building, because a faster fire development may possibly lead to the situation that tenability criteria are met earlier in the fire course, as well as flashover may occur sooner than expected.

One of the parameters mentioned is that the onset of thermal runaway is dependent on the thermal inertia of the linings of the enclosure. Lately there has been increasing requirement for thermal insulation of buildings in order to reduce the energy losses from buildings. This will typical lower the thermal inertia of the building, especially if the insulation is applied directly on walls or ceiling. This might, according to theory, affect the onset of thermal runaway.

It is therefore identified that thermal feedback may influence the fire safety of a building. Principal models are available, but these require experimental validation. Also it is found that CFD models have not been able to reproduce the effect of thermal feedback.

Therefore, the research objectives are by use of experiments to investigate the influence of thermal feedback on the burning behavior of pre-flashover well-ventilated fires. This will be carried out in relation to:

- the change of the heat release rate,
- the influence of changing linings on the onset point of thermal runaway and
- secondarily, the changes in flame spread on a horizontal surface.

In addition, the results will be compared to existing theory on thermal feedback.

As limitation of oxygen may reduce the effect of thermal feedback only well ventilated fires are considered. Also, only non-combustible linings are considered.

1.6 Outline of the thesis

Part I is this introduction.

Part II presents the experimental investigations, including selecting of the test method for assessing thermal feedback and results of the individual experiment.

Part III summarizes the experimental results in general and relates the findings to design fires. Finally, conclusions are made and future work is proposed.

Part IV presents appended papers, research report and poster. It should be noted that the contents of the appended papers and report are included in part II and III.

Part II Experimental investigation

2 Experimental investigation

As mentioned in the introduction, the aim of the experimental investigation is to determine the influence of the thermal feedback from the room on the burning behavior of an object in a well-ventilated pre-flashover room fire.

Before the experiments can be performed an experimental setup should be designed with a view to generate thermal feedback and the onset of thermal runaway, and measurement should be made to document the phenomena and if possible the causes.

2.1 Selection of the experimental setup

A new experimental setup was developed in order to determine the effect of the thermal feedback. But before the experimental setup is selected, the theory on heat release rate in room fires is shortly reviewed to select an appropriate experimental setup.

As mentioned in the introduction, the heat release rate can be found as described by equation (1.2):

$$\dot{Q}_F = A_F \cdot \Delta H_{eff} \cdot \dot{m}''_F \tag{1.2}$$

As also mentioned in the introduction, the heat release rate is a compounded variable which is among others dependent on the size of the burning area and the mass loss rate per unit area, and any changes of either parameter will affect the heat release rate.

In relation to mass loss rate, this can be expressed as a function of the net heat flux $\dot{q}''_{net}$ to the surface and the heat of gasification L_g [26] as:

$$\dot{m}''_F = \frac{\dot{q}''_{net}}{L_g} \tag{2.1}$$

For a burning object under the influence of external heating from a room, the net heat flux to the burning object can be found as the sum of the radiative and convective heat flux from the flame and the external heating from hot room boundaries and hot gasses. For a well-ventilated fire, it has been suggested (see equation 2.2) that the fuel mass loss rate in a room fire can be estimated as the free burn mass loss rate related the heat flux from the flame plus a contribution from the external heat flux from the room [41]:

$$\dot{m}''_F = \dot{m}''_{F,0} + \frac{\dot{q}''_{ext}}{L_g} \tag{2.2}$$

Here $\dot{m}''_{F,0}$ is the free burn mass loss rate per unit area and $\dot{q}''_{ext}$ is the total external heat flux per unit area to the burning surface from the smoke and the compartment walls. Data on L_g and $\dot{m}''_{F,0}$ can for liquids and selected material be found from the literature as the SFPE handbook [42]. For other types of materials these information can also be obtained from small scale tests as the cone calorimeter [43].

The total external heat flux to the burning object depends on temperatures of smoke layer and boundaries as well as appropriate view factors and the absorption of external flux by the flames and unburned fuel gases [32]. This project is limited to pre-flashover well-ventilated fires. As described later in this section, this was experimentally achieved by ensuring that a two zone situation was present during the experiments. For a two zone model the external radiation from the smoke layer and boundaries can be assessed as:

$$\dot{q}''_{ext} = \sigma \cdot \varepsilon_g \cdot \left(T_g^4 - T_s^4\right) + \sigma \cdot \left(1 - \varepsilon_g\right) \cdot \left(T_w^4 - T_s^4\right) \tag{2.3}$$

where T_g is the average smoke layer temperature, T_w is an average temperature of the upper hot boundaries, T_s is the surface temperature of the burning object, σ is Stefan Boltzmann's constant and ε_g is the emissivity of the smoke layer. It should be noted that equation (2.3) assumes black body boundaries and fuel and that there is no blockage from unburned gases or absorption from the flames. The view factors are also assumed to be 1 which will apply for a horizontal surface, whereas vertical surfaces will have reduced view factors. As such, it can be seen that horizontal surfaces are more subjective to thermal feedback from the room.

Combining equation (2.1) and (2.3) the fuel heat release rate under the influence of thermal feedback could be estimated as:

$$\dot{Q}_F \approx \dot{Q}_{F,0} + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\sigma \cdot \varepsilon_g \cdot \left(T_g^4 - T_s^4\right) + \sigma \cdot \left(1 - \varepsilon_g\right) \cdot \left(T_w^4 - T_s^4\right)}{L_g} \right) \tag{2.4}$$

Here $\dot{Q}_F$ is the total heat release rate from the burning object, $\dot{Q}_{F,0}$ is the total heat release rate from the free burning object

In order to evaluate experimental results, it is found reasonably to estimate the total heat release as [32]:

$$\dot{Q}_F \approx \dot{Q}_{F,0} + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\alpha \cdot \sigma \cdot \left(T^4 - T_s^4 \right)}{L_g} \right) \tag{2.5}$$

Here, α is a factor between 0 and 1 including view factor and a lumped value emissivity/absorption for linings, fuel, and gas. T is the room temperature, which has to be selected based on information on the emissivity of the smoke layer. From equation (2.3) it can be seen that if the emissivity of the smoke layer is small, most of the radiation will be related to the wall temperature. If the emissivity is large most of the heat flux will come from the smoke layer.

Equation (2.5) is a central equation in the selection of the experimental setup. The equation shows explicitly that the room heat release rate is a strong function of the room temperatures, and that the room burn heat release rate can be found as the free burn heat release rate plus a contribution from the room.

Therefore the experimental setup has been chosen as follows:

- A two-zone division of the room should be reached, which represents a pre-flashover non-ventilation controlled fire.
- Equation (2.5) states that the influence of the thermal feedback can be found as the heat release rate for a burning object under free burn conditions plus a contribution from the external heat flux from linings and smoke layer. Therefore, both free burn and room burn conditions are investigated, and the free burn is used as a benchmark for the room burn conditions.
- Room burn tests are performed with different linings with substantial different thermal inertia. By lowering the thermal inertia, the room temperature will increase, as linings with lower thermal inertia will accumulate less energy. Thereby the thermal feedback is changed without changing any other parameters, and any change in the burning behavior can be related to the thermal feedback. This will also allow to see if matching room temperatures gives equal heat release rates, as it should be according to equation (2.5). This way the free burn heat release rate can also be decupled from equation (2.5) and in principles an investigation of the effect of the thermal feedback can be done without free burn tests.
- Performing test on similar objects in rooms with linings of substantial different thermal inertia also allows investigating if and when a thermal runaway may occur as well as the dependency of the thermal inertia on the onset of thermal runaway (flashover) can be investigated.
- Non-combustible linings are chosen to avoid additional heat release rate from the linings. Combustible linings may also change the heat loss, as the same heat loss cannot be expected for an ignited surface [23].

- The room temperature may also be changed by changing ventilation conditions of the room as done by Pierce et al. [40], but this was not chosen as it may influence the emissivity of the smoke layer and the position of the smoke layer for the same heat release rate of the fires.
- Full scale tests were preferred to avoid scaling.
- The burning object is chosen to have a horizontal position to maximize the view factor between fuel and the smoke layer/enclosure boundaries. Also precautions should be taken to ensure that the view factor is not changed considerably during the experiment.
- The burning object should, if possible, be positioned in the middle of the room to limit asymmetric thermal feedback caused by differences in wall temperatures as found by other experimental investigations [38, 39], where the effect of position in the room was studied. This way plume entrainment for the room burn would also be less affected by walls and thereby giving the best basis for a comparison to the free burn plume.
- It should be possible to identify the burning area to ensure that the heat release rates can be related to the same burning areas.
- Measurements should be made of the burning behavior that allows for a comparison between room burn behavior and free burn behavior. Also it should be investigated if a jump in the development of the heat release rate would occur, which could indicate that an onset of thermal runaway is taking place. Preferably measurement of the different scenario under which the same object burns should be made by the use of the same instrumentation in order to limit uncertainties related to reproducibility. Also measurements should be made of lining temperatures as well as smoke layer temperatures in order to estimate the external heat flux.

Based on these considerations the ISO Room Corner Test [7] was chosen as an experimental setup. A principal sketch can be seen from Figure 2.1. The test facility was originally developed to investigate the burning behavior of linings products by measuring the heat release rate until flashover. The test facility is well established and has commonly been used in the research community to investigate room fires as e.g. in the CBUF project [44]. Also the uncertainties of the measuring equipment are well described and calibration procedures are available from the standard.

In relation to this study, the ISO Room Corner test facility [7] can provide data on the heat release rate for both room burn conditions and free burn conditions if the burning object is positioned under the hood by use of the same equipment. The locations for the burning objects are marked on the sketch in Figure 2.1.

The burning behavior can, according to equation (2.5), be found as the heat release rate, but also mass loss rate can also supply the information as the two values only differ by the heat of combustion, which is a value that in many cases can be found by small scale test such as the cone calorimeter [43]. Therefore it is preferred to measure both, if possible. However, in rooms it can be difficult to measure the mass loss rate as scales may have to be protected against the heat.

In the Room Corner test facility the heat release rate is found by the use of oxygen consumption [6]. Here, the concentrations of O_2, CO_2 and CO (optimal) are measured in the measuring section in the duct (see Figure 2.1) and used for calculation of the heat release rate. Generally the uncertainty of oxygen consumption is found to be 5-10 % [6].

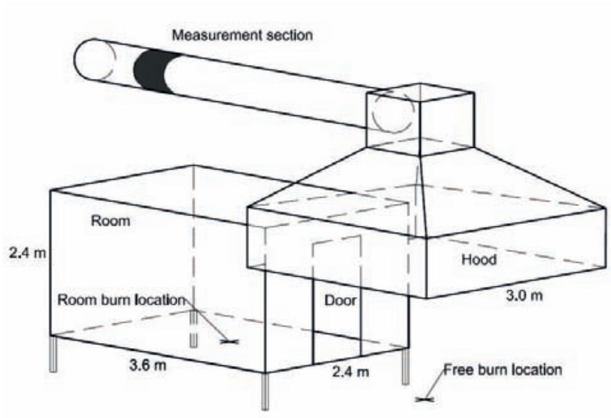


Figure 2.1. Principal sketch of the experimental setup.

According to equation (2.5) the external heat flux can be found as a function of a room temperature which can be either the temperature of the hot surfaces in the upper layer or the smoke layer depending on smoke layer emissivity. Temperature recordings are performed by the use of thermocouple trees and measurements of lining temperatures. Generally two thermocouple trees are used and positioned in opposite corners as room temperatures may differ across the room. More information on the precise type and location of thermocouples can be found in the sections about the specific experiments.

Heat fluxes are measured to support the temperature measurements. Due to the position of the fuel it is not possible to measure the heat flux to the center of the floor, which would have been ideal in order to measure to the thermal feedback.

Video recordings of the burning behavior, such as smoke layer height, flame shapes and ignition of crumpled paper on the floor, are made to support to measurement.

2.2 The experimental series

Two series of experiments are designed and performed to investigate the influence of thermal feedback.

The first test series was performed on heptane pools contained in different sizes of steel pans. This way different fixed areas could be tested and give information on the heat release rate per unit area as well as thermal runaway. It is realized that heptane does not represent a common piece of inventory, but as heptane is a well-defined liquid, for which a lot of data are available, and it will serve as a good benchmark to show the influence of thermal feedback. More detailed information can be found in Chapter 3. The tests are also presented and analyzed in appended paper#1 and poster#1.

The second test series was performed on flexible polyurethane. As mentioned in the introduction, flexible polyurethane is an important material to investigate, as furniture and mattresses are often found to be the first ignited object in many fatal fires [30]. Also, previous experiments have shown that upholstered furniture is sensitive to thermal feedback for pre-flashover fires [28]. In this test series horizontal positioned blocks are ignited in one end of the block. This way flame spread can be observed as well as heat release rate per unit area once flame spread is completed. More detailed information can be found in Chapter 5. The experimental results are also presented in the appended NRC-IRC research-report.

Carleton University and National Research Council, Canada, NRC-IRC had previously carried out the test programs Design Fires of Commercial Premises Phase 1 and 2 (DFCP1 and DFCP2) in order to investigate design fires for commercial premises [45-47]. These tests were all performed in room size test facilities and varied in fire loads (representing commercial fire loads) as well as thermal inertia of the linings. Some of the test went to flashover. Therefore these tests serve as a basis for studying the influence of linings and type of materials at the onset of thermal runaway. More information can be found in Chapter 4 and the analysis of flashover is also presented in the appended paper#2.

The tests and their contribution to the experimental investigations are shown in Table 2.1

Table 2.1. Experimental investigations

Test	HRR/m^2	Flame spread	Thermal runaway
Heptane	+	-	+
Polyurethane	+	+	-
DFCP1 and DFCP2	(+)	(+)	+

3 Heptane experiments

The aim of these heptane experiments is to provide information on the effect of thermal feedback in a pre-flashover well ventilated room fire with a fixed burning area, to avoid influence of changing area. Also the experiments should provide information on the influence of changing lining materials in relation to the onset of thermal runaway.

The experiments were carried out at the EFIC-laboratories. The laboratories are accredited by The Danish Accreditation and Metrology Fund – DANAK to perform fire tests according to ISO 9705 [7] and the test facility has been evaluated in round robin tests.

3.1 Experimental setup

As discussed in Chapter 2 the experimental setup should fulfill the following criteria:

- The facility should comply with the ISO 9705 Room Corner test facility [7].
- For the same burning object, free burn tests should be performed under the hood, and two room tests should be carried out with linings varied in terms of substantially different thermal inertia.
- Measurement should include heat release rate, mass loss rate, lining temperatures, smoke layer temperature and heat flux.

Two different linings were used. Lining 1 was non-combustible mineral wool with density, thermal conductivity and heat capacity of approximately 90 kg/m^3, 0.05 W/mK and 0.8 kJ/kgK, respectively, giving a thermal inertia ($k \cdot \rho \cdot c$) of approximately 0.0036 kW^{2}s/m^{4}K^2. This material was chosen as it would remain stable during the test irrespectively of room temperatures, has a low thermal inertia that quickly can lead to high room temperatures and has a limited contribution to the heat release in the room. Lining 2, also non-combustible, was light weight concrete blocks covered with a thin plaster (the walls of the test room), which was dry as it had gone through heating in past tests. Lining 2 was estimated to have a density of 600 kg, a thermal conductivity of 0.15 W/mK [48] and a heat capacity of 1.0 kJ/kgK, yielding a thermal inertia for lining 2 of 0.090 kW^{2}s/m^{4}K^2.

The heat release rates were based on measurements in the duct and calculated according to ISO 9705 [7] with a corrected E-value of heptane (12.6 MJ/kg O_2)

[50]. Mass loss rate was recorded using a scale with a maximum capacity of 80 kg and an uncertainty of 50 g. During the free burn tests the scale was positioned underneath the pan and protected by a substrate. The room was lifted 0.55 m above the main floor, which allowed for a hole to be drilled in the test room floor and, as a result, the scale could be positioned underneath the room and as such be protected from the heating in the room, see Figure 3.1.

The room temperatures were recorded by two thermocouple trees in opposite corners of the room at a distance of 0.4 m from the walls, see Figure 3.2. The vertical spacing between the thermocouples was 200 mm throughout the entire height of the room, see Figure 3.1. Surface temperatures were measured at the back wall by thermocouples located 1.0 m and 2.0 m above the floor. All thermocouples were type K with an uncertainty of less than 1 K.

A heat flux meter (HF 1) was positioned 5 cm from the object pan facing upwards towards the smoke layer, as shown in Figure 3.2. Vertically, the heat flux meter was positioned 3 cm below to top of the outer pan. In the room tests the heat flux to the back wall (HF 2) was measured facing the fire in a horizontal direction at 1.2 m above the floor, see Figure 3.1. The heat fluxes were measured with a Gardon gage model no. 64-5-18 from Medtherm Corporation with an absorbance of 0.92 and a maximum range of 50 kW/m^2 with an uncertainty of less than 3 %.

All measurements were recorded every 5 seconds.

All test equipments were calibrated prior to the experiments.

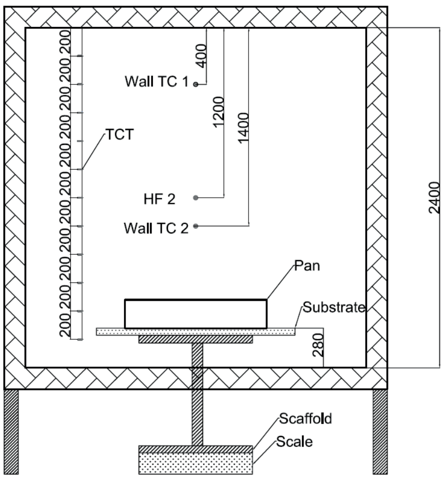


Figure 3.1. Room burn test setup, section, HF is heat flux gauge, TC is thermocouple and TCT is thermocouple tree. Units are in mm.

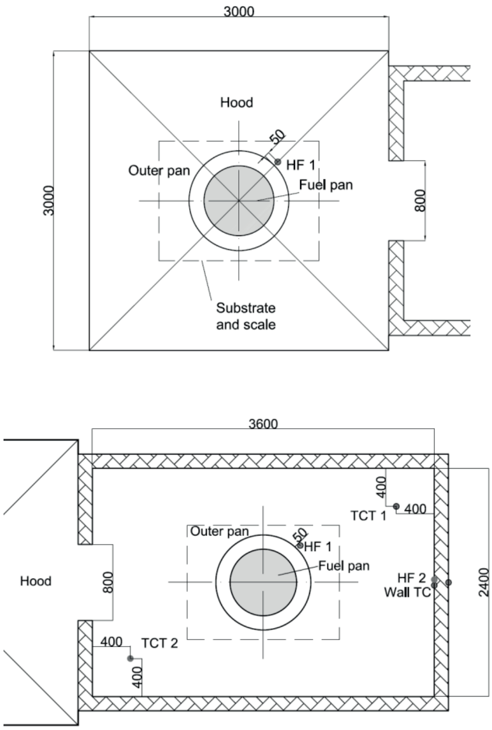


Figure 3.2. Free burn, plan (upper panel) and room burn, plan (lower panel) HF is heat flux gauge, TC is thermocouple and TCT is thermocouple tree. Units are in mm.

The type of heptane used for these tests was an isomeric mixture, which allowed for minor impurity of the heptane. This was considered less important, as the burning object is a pool fire repeated under different conditions and no specific material data should be derived from the tests.

In order to select pool sizes, threshold values of flame height and room temperatures were used. Previous fire tests [39] have indicated that an increase of the heat release rate could be expected when flames impinge the ceiling. The ISO 9705 room has a ceiling height of 2.4 m. As the pans were placed on a scaffold as a part of the measurements of mass loss rate, the height from the initial surface of the liquid to the ceiling was approximately 2 m. Therefore 2 m is used as a threshold for mean flame height.

Parameter analysis using simple models for prediction of the onset of a thermal runaway showed that thermal runaway could happen for a pool fire at room temperatures as low as 350 °C [31]. Therefore, this temperature is used as threshold for the room temperature.

In order to predicts orders of magnitudes of the expected flame heights and room temperatures preliminary estimates of these values were made by the use of simple approximations.

Mass loss rates were estimated by equation (3.1) to be able to predict the free burn heat release rate. The equation is based on free burn fires using data and models as presented by Babrauskas [24]:

$$\dot{m}'' = \dot{m}''_\infty (1 - e^{-k\beta D}) \tag{3.1}$$

Where $\dot{m}''_\infty$ is an empirical factor (corresponding to the mass loss rate for a pool diameter of 0.2 m) depending on the type of liquid, k is the absorption extinction coefficient for the flame, β is the "mean beam-length corrector" and D is the diameter of the pool. For heptane $\dot{m}''_\infty$ is found to be 0.101 kg/m^{2}s and $k\beta$ found to be 1.1 m^{-1}[24]. Equation (3.1) is based on the theory that increasing pool sizes will have larger burning rates due to larger heat flux from the flames. The method is an approximation for this purpose as it does not reflect room effects or lip effects that may occur during the tests.

The mean flame height L_f was estimated based on Heskestad's [50] method as:

$$L_f = 0.235 \dot{Q}_F^{2/5} - 1.02D \tag{3.2}$$

Equation (3.1) and (3.2) are only valid for free burn conditions. No correlations are, however available for room burn conditions. In the absence of better correlation, the free burn correlations are used for the preliminary estimates.

Finally the increase of the smoke layer temperatures is found using the MQH correlation [25]:

$$\Delta T = 6.85 \left(\frac{\dot{Q}_F^2}{h_k \cdot A_T \cdot A_0 \cdot \sqrt{H_0}} \right)^{1/3} \tag{3.3}$$

Here A_T is the interior surface area of the room, A_0 is the area of the openings, H_0 is the height of the opening and h_k is the effective heat transfer coefficient found as:

$$h_k = \sqrt{\frac{k \cdot \rho \cdot c}{t}} \tag{3.4}$$

In relation to the estimates done here, it is noted that h_k should be found as an average for all surfaces including the floor for this particular model, and that the model is only valid up to 600 °C [25].

In order to find the room temperature, time is set to 10 or 15 minutes, as these were the expected burning periods that were used for the assessment of the amount of heptane (see below). Also, it is realised that by using free burn values as input for the model, the temperatures can be seen as a lower level as higher temperatures can be expected if there is an effect of the thermal feedback.

The estimated values can be seen from Table 3.1 for the three pool sizes (0.35 m, 0.50 m and 0.70 m diameter). By using the two thresholds it can be seen that flame are not expected to reach the ceiling for the small and medium pool size, whereas the large pool size is expected to have flames impinging the ceiling. The table also show that both the small pool sizes are expected to have room temperatures significantly below the threshold of 350 °C regardless of the type of lining. For the medium pool size, the temperature for lining 1 is slightly above the threshold, whereas the room temperature for lining 2 is slightly below the threshold. For the large pool size the room temperature is above the threshold for both linings. Therefore an effect of thermal feedback could be expected for the large pool in both room test and for the medium pool for lining 1, but not for lining 2. No effect was expected for the small pan.

The experimental test series comprised 10 experiments with varying pool sizes, lining materials and amounts of liquid burning under free burn and room burn conditions, as shown in Table 3.1.

Table 3.1 Experimental matrix with expected temperature results

Test no.	Pan Diameter (m)	Amount of heptane (l)	Mean flame Height (m)	Mass Loss Rate) (kg/m^2s)	Temperature lining 1 (Mineral wool) (°C)	Temperature lining 2 (Light weight Concrete) (°C)
1	0.70	25	2.75	0.054	Free burn	Free burn
2	0.70	25	2.75	0.054	(720)	-
3	0.70	25	2.75	0.054	-	560
4	0.50	10	1.70	0.043	Free burn	Free burn
5	0.50	10	1.70	0.043	390	-
6	0.50	10	1.70	0.043	-	310
7	0.50	15	1.70	0.043	-	330
8	0.35	4	1.25	0.032	Free burn	Free burn
9	0.35	4.2	1.25	0.032	200	-
10	0.35	4.2	1.25	0.032	-	160

The pans were made of carbon steel with a thickness of 3 mm and had lip heights of 152 mm for the small pan and 200 mm for the rest of the pans. The amount of liquid was chosen to allow for approximately 10 minutes duration of burning, except for one experiment where an additional 50 % of liquid was added. This leaves exposed lips on the pan of 110 mm for the small pan, 150 mm and 125 mm for the medium pan and 135 mm for the large pan. The exposed lip height increased during the tests as the fuel burned away. As the purpose of this test series is to investigate the thermal feedback, heating up of the test specimen is allowed for. Any procedure that might cool down the test specimen, such as continuous fuel filling to avoid lip effects [24, 51] or diluting with water to prevent overheating [49], was avoided. It is realized that the lip will be heated by the flames and some additional heat will transfer to the heptane. This implies that the burning rate from the tests may not be comparable with other test on heptane, but the free burn tests comparisons should provide sufficient benchmarking.

The amount of liquid, especially in the large pan experiments, is substantial and any breakage of the pan due to overheating could be critical to the test facility and the operating personnel. To reduce the consequences of this possible failure mode, the pans were placed in a larger pan to collect any spillage. The fuel pans with diameters of 0.35 m and 0.50 m were placed in an outer pan with a diameter of 0.70 m and the fuel pan with a diameter of 0.70 m was placed in an outer pan with a diameter of 1.0 m.

3.2 Experimental results and discussion

3.2.1 Large pool experiments (0.70 m)

During the room burn tests flames were observed to impinge the ceiling and exit the door opening. Also, crumpled newspaper on the floor was ignited in both tests. These phenomena are generally known to indicate flashover [22] and as such a transition to a post-flashover fire occurred during the fire tests. For lining 1, flames were observed exiting the door and the crumpled newspaper ignited after 3½ minutes and 2 minutes, respectively, and for lining 2 after 8 minutes (sparse) and 7 minutes, respectively. To protect the test equipment the experiment with lining 1 was terminated after 6 minutes and the experiment with lining 2 was terminated after 12 minutes, as violent burning occurred. A more or less constant smoke layer was observed at a height of approximately 1.1 m to 1.2 m above the floor during both room tests.

The results of the heat release rate measurements for all three tests as a function of time are shown in Figure 3.3 and measurements of the mass loss rate (averaged over 35 second as a floating average over 7 points) are shown in Figure 3.4. The results show that the fire initially develops similarly for all three tests. The heat release rates for the free burn test were not constant but increased slightly during the test. After approximately 2 minutes a rapid increase took place for lining 1. For lining 2, the heat release rate increased slightly compared to free burn in the beginning of the test. After approximately 10 minutes a rapid increase occurred. For both lining 1 and 2 the rapid increase continued until the fires were extinguished. The rapid increase can be seen as thermal runaway, TR.

The mass loss rate (Figure 3.4) follows the same trend as the heat release rate, though the difference between lining 2 and the free burn is less evident. An average of the free burn mass loss rate is found to be 0.044 kg/m^{2}s which is less than the predicted mass loss rate of 0.054 kg/m^{2}s (see Table 3.1).

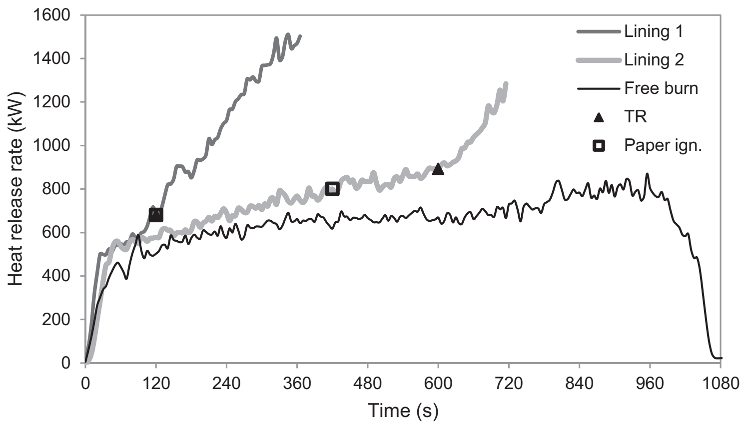


Figure 3.3. Heat release rate versus time for a pool diameter of 0.70 m.

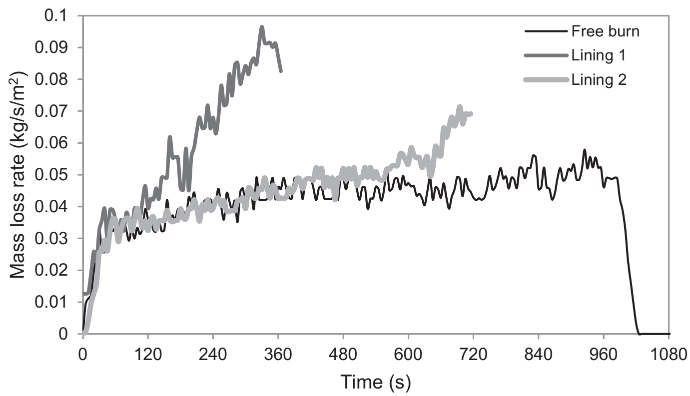


Figure 3.4. Mass loss rate versus time for a pool diameter of 0.70 m

The heat release rate is not an exact measured value, but calculated based on measurements made in the measuring section (see Figure 2.1) of the consumed O_2

and the produced CO_2, Both values are shown versus time in Figure 3.5. It can be seen how the consumption of O_2 (upper panel) has an inverse relation to the heat release rate, and how the CO_2 (lower panel) is directly related to the heat release rate, as it should be.

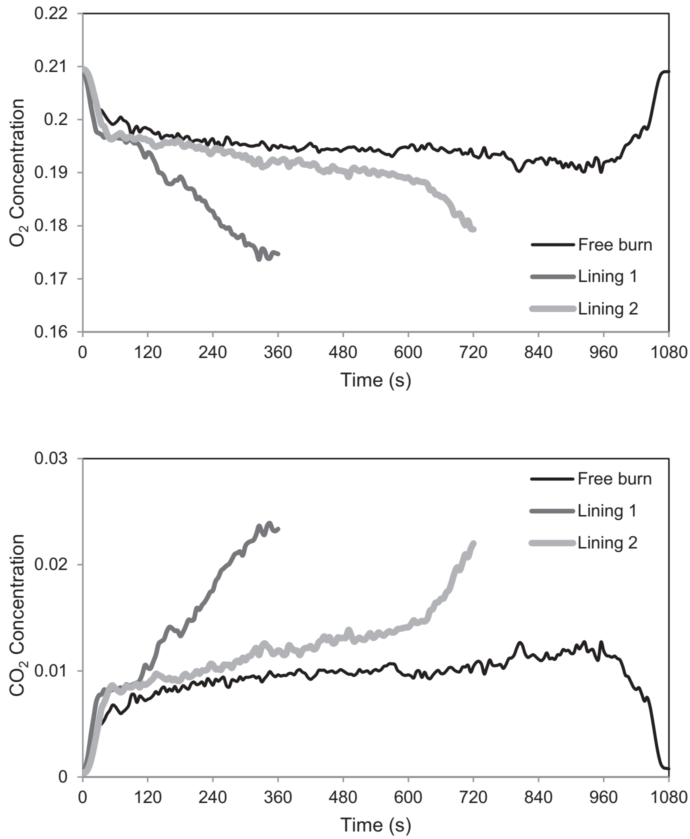


Figure 3.5. O_2 (upper panel) and CO_2 (lower panel) versus time for a pool diameter of 0.70 m

Table 3.2 reports the effective heat of combustion, ΔH_{eff}, calculated from the total mass loss and total heat release. The table shows that the effective heats of combustion in the room tests are comparable for all three tests. The values are within reasonably range of the theoretical value of 44.6 MJ/kg [24]. Therefore, the heat of combustion is found not to be influenced by whether the test is done as free burn or room burn.

Table 3.2. Estimates of the effective heat of combustion, ΔH_{eff} for pool a diameter of 0.70 m

Test no	Duration (s)	Total Heat Release (MJ)	Total Mass Loss (kg)	ΔH_{eff} (MJ/kg)
1, Free burn	1005	679	16.7	40.6
2, Lining 1	365	334	7.9	42.1
3, Lining 2	720	537	12.4	43.2

In order to further investigate the heat of combustion, the values are plotted versus time in Figure 3.6 for the free burn test and for the test with lining 2. These tests are chosen as the average heat of combustion differ the most for these two tests. The figures shows that the heat of combustion by an average is constant with time, disregarding that thermal runaway took place in the test with lining 2. This also shows that combustion efficiency was not affected by the occurrence of thermal runaway. The same result is also found for the test with lining 1, which is not reported here.

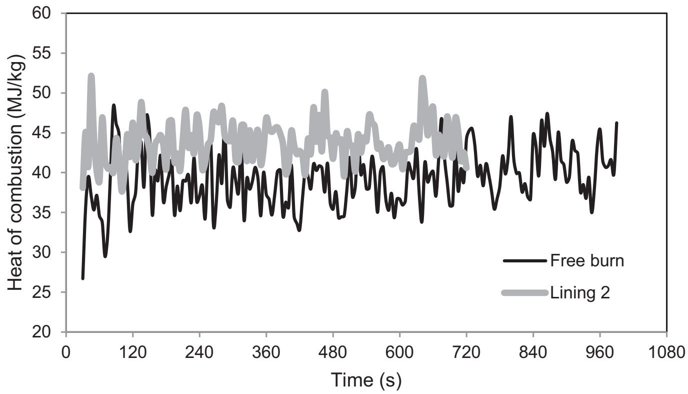


Figure 3.6. Heat of combustion, ΔH_{eff} versus time for a pool diameter of 0.70 m

A fundamental assumption for this experimental series is that the fires should apply to a two-zone model and not be ventilation controlled. Figure 3.7 shows a clear horizontal division of the room temperatures in two zones during the test. This correlates well with the visual observation of a clear layer below a smoke layer, and confirms that using a two-zone model is a reasonable assumption. The time for Figure 3.7 is taken as the time for the crumpled paper to ignite as this was the first indication of flashover. Thus, the two-zone assumption is valid at least until this time. Figure 3.7 also shows that smoke layer temperatures were higher for lining 2 than for lining 1 at the time for ignition of the crumpled paper, whereas lower level temperatures are comparable especially at the level of the pan (0.3-0.5 m above the floor).

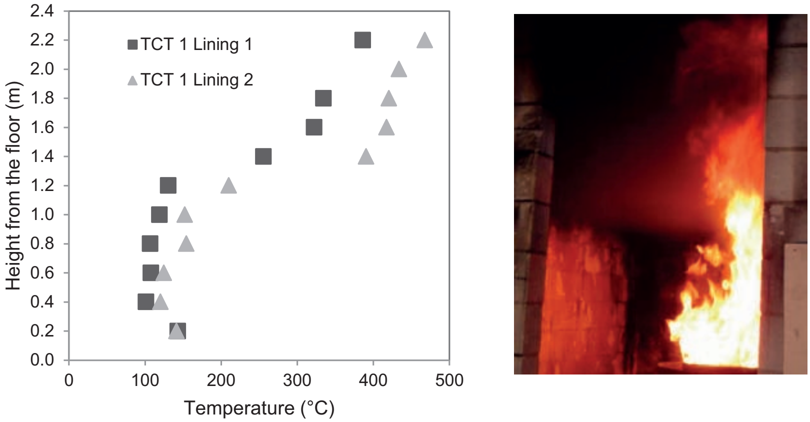


Figure 3.7. Vertical temperature distribution at TCT 1 at time of ignition of crumpled paper (lining 1; 2 min and lining 2; 7 min) and photo illustrating the division of layers.

Figure 3.8 shows the development with time of the average smoke layer temperature, SLT, (upper panel) and temperatures measured at the back wall (lower panel). The smoke layer temperature is calculated as the average output from thermocouples placed from 1.6 m to 2.2 m above the floor. The wall temperatures are measured in the smoke layer 2.0 m above the floor (WTC1) and below the smoke layer 1.0 m above the floor (WTC2). The figure shows that for the test with lining 1, the temperature rose linearly during the test, which followed the trend of the heat release rate after the first three minutes of the test. For lining 2 the temperature rise does not have a linear form and the temperature increase after the initial growth period was slower compared to the heat release rate for lining 1. The lower panel also show that the temperature measured below the smoke layer is relatively smaller for lining 2 than for lining 1 when compared to temperatures measured in the smoke layer.

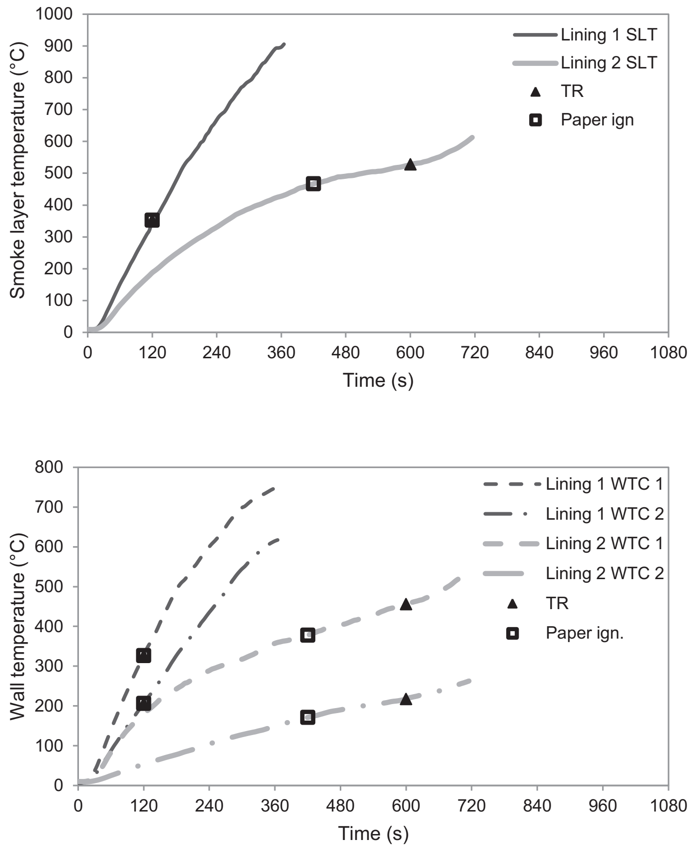


Figure 3.8. Temperature in the smoke layer, SLT (upper panel) and wall temperatures (lower panel) for a pool diameter of 0.70 m. WTC1 is at 2.0 m and WTC 2 is at 1.0 m.

The heat fluxes measured at the substrate and at the back wall are given in Figure 3.9 (averaged over 35 second as a floating average over 7 points). The figure shows that the heat fluxes increased rapidly and almost linearly for lining 1, whereas the heat fluxes for lining 2 had a significantly slower growth rate between the initial growth period and the time for onset of thermal runaway.

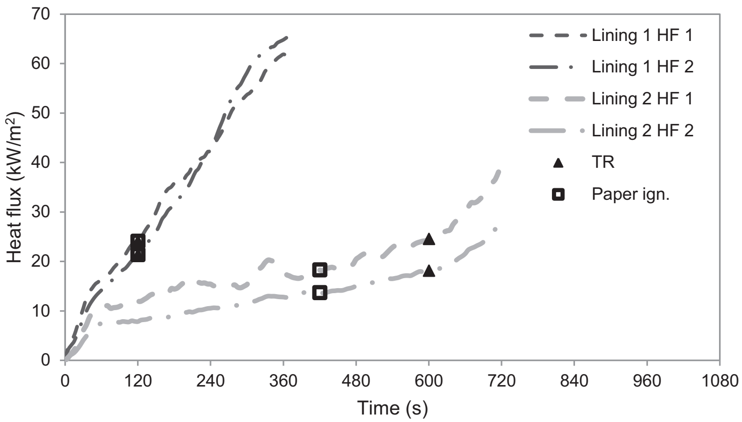


Figure 3.9. Heat flux for a pool diameter of 0.70 m. HF 1 is positioned horizontally on the substrate and HF 2 in positioned vertically on the back wall 1.2 m above the floor.

The ignition of the crumpled paper and the onset of thermal runaway are seen as key phenomena, as they indicate significant changes in the burning behavior as compared to the free burn. Therefore, data on measurements when these phenomena occurred are summarized in Table 3.3. The table shows that the time for paper ignition and onset of thermal runaway generally occurs at lower temperatures for lining 1 than for lining 2. Only measurements of the lower wall temperature, WTC 2, and the heat flux measured at the substrate have comparable levels at the onset of the thermal runaway, whereas the wall temperatures are comparable at the time of paper ignition. It can also be seen that the measurements of the wall temperatures generally are closer to each other for both linings than the smoke layer temperature, and that the smoke layer temperature and the upper wall temperatures are comparable for lining 1 but not for lining 2.

Table 3.3. Summary of measurements at time of ignition of crumpled paper and at estimated time for the thermal runaway (TR) for pool a diameter of 0.70 m.

	TR		Paper ignition	
	Lining 1	Lining 2	Lining 1	Lining 2
Time (s)	120	600	120	420
HRR (kW)	679	893	679	800
SLT (°C)	352	528	352	467
WTC 1 (°C)	327	456	327	378
WTC 2 (°C)	206	218	206	171
HF 1 (kW/m^2)	24	25	24	18
HF 2 (kW/m^2)	21	18	21	14

3.2.2 Medium pool experiments (0.50m)

In the room test, the flames did not reach the ceiling instantaneously upon ignition, but later in the test the flame would periodically touch the ceiling. For the tests with lining 1 and lining 2-2 (lining 2 with additional 50 % heptane), the flames impinged the ceiling more constantly towards the end of the test. No flames were observed exiting the door opening, and the smoke layer was observed to be at approximately 1.1 to 1.2 m above the floor for all room tests. Ignition of crumpled paper was not investigated.

Measurements of the heat release rate (see Figure 3.10) show that all 4 tests with the medium pool size followed the same trend up to about 6 minutes. It can be argued that the reason for the peak towards the end of the tests is a consequence of the fact that the heptane fuel layer is being thin at this point. As a result, both the liquid and the pan have warmed up which will lead to an increase of the evaporation rate. This is supported by visual observations of boiling at the end of the tests.

The average free burn mass loss rate for the steady state of the test was 0.043 kg/m^2s, which is in very good agreement with the predicted mass loss rate (see Table 3.1).

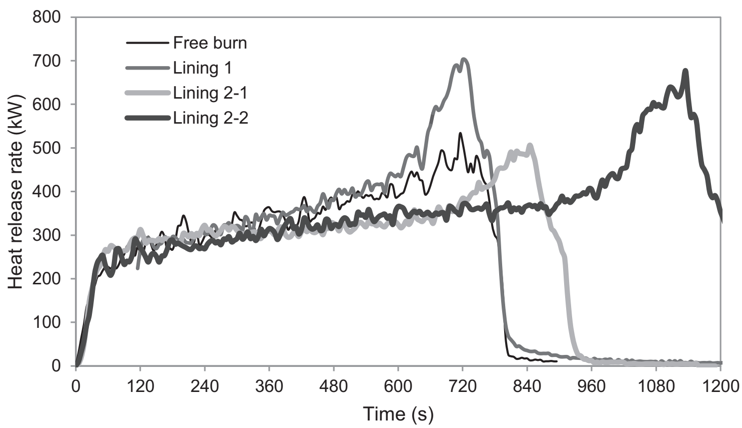
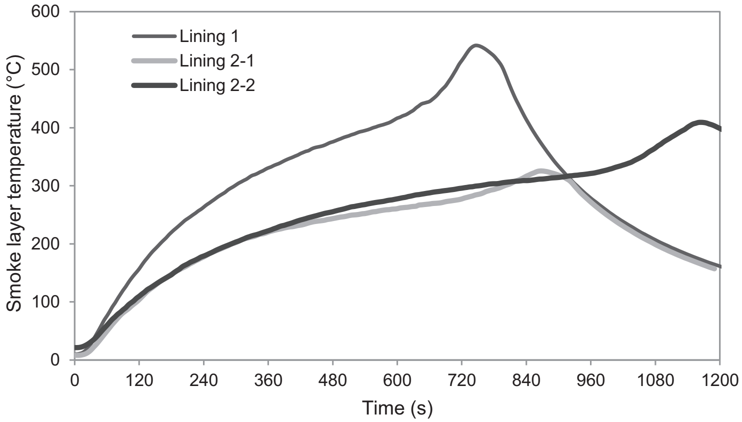


Figure 3.10. HRR versus time for a pool diameter of 0.50 m

The effective heat of combustion has been estimated and is listed in Table 3.4. The results show that tests with lining 2 and the free burn test has comparable levels of heat of combustion, whereas and the test with lining 1 had a larger effective heat of combustion. The differences between levels of heats of combustion are not uncommon and compares to what is reported from other test series [39].

Table 3.4. Estimates of the effective heat of combustion, ΔH_{eff} for a pool diameter of 0.50 m.

Test no.	Duration (s)	Total Heat Release (MJ)	Total Mass Loss (kg)	ΔHeff (MJ/kg)
4, Free burn	810	271	6.6	40.8
5, Lining 1	760	N/A	6.6	47.0
6, Lining 2-1	900	253	6.6	38.1
7, Lining 2-2	1240	398	10.1	39.3



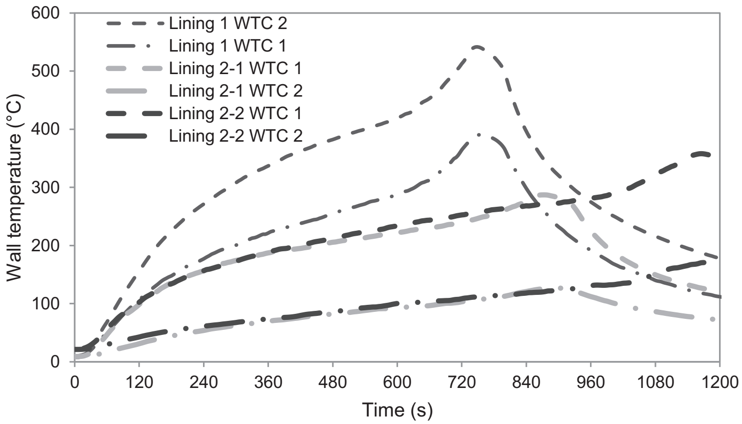


Figure 3.11. Temperature in the smoke layer, SLT (upper panel) and wall temperature (lower panel) for a pool diameter of 0.50m.

Figure 3.11 plots the experimental results for the average smoke layer temperature in the upper panel and the wall temperatures for the three room tests in the lower panel. It can be seen that the temperatures follow the trend of the heat release rate. In this test series the difference between the upper and the lower wall thermocouples are comparable for all three tests.

Figure 3.12 shows that a rapid increase of the heat fluxes took place for lining 1 when the HF 1 value (next to the pool) reached 25 kW/m^2. At this level of heat flux thermal runaway was observed for the large pool tests, which indicates that thermal runaway may have taken place during the peaking, but the test results do not show any clear evidence of a thermal runaway. The two tests with lining 2 did not show any rapid increase, though a certain increase took place at the end when the heat release rates peaked. It should also be noted that the free burn heat flux measured close to the pool (HF 1) was significantly lower than all the three room tests.

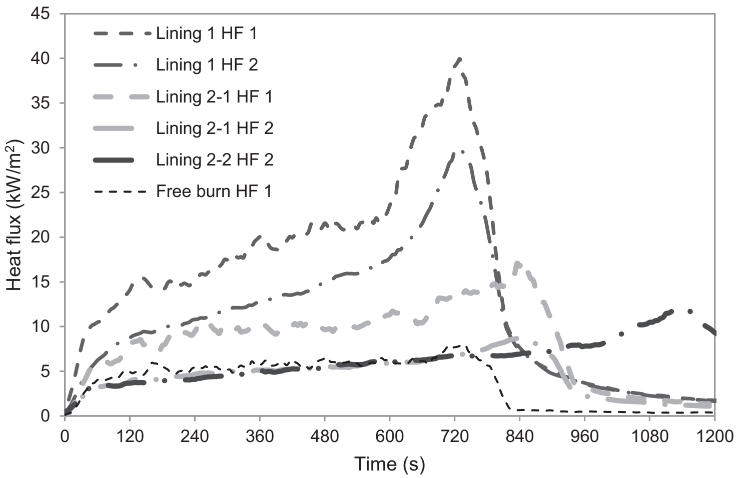


Figure 3.12. Heat flux for a pool diameter of 0.50 m. HF 1 is positioned horizontally on the substrate and HF 2 is positioned vertically on the back wall 1.2 m above the floor.

Summarizing the results of the experimental data for the medium pool fires it is found that some effect of thermal feedback is found for lining 1 but no evidence of an effect is found for lining 2.

The peak values are summarized in Table 3.5. It can be seen from this table and also by utilizing Figure 3.11, that smoke layer temperatures and upper wall temperatures are almost identical for lining 1, whereas differences of more than 10 percent are observed for lining 2. It is also noteworthy that the heat fluxes are substantially higher in the tests with lining 1 than in any of the other tests.

Table 3.5. Summary of measured peak values for pool a diameter of 0.50 m

	Free burn	Lining 1	Lining 2-1	Lining 2-2
HRR (kW)	533	703	507	677
Time [a)] (s)	715	720	845	1135
SLT (°C)	-	542	325	409
WTC 1 (°C)	-	541	287	358
WTC 2 (°C)	-	391	127	171
HF 1 (kW/m^2)	8	40	17	N/A
HF 2 (kW/m^2)	-	30	9	13

[a)] The time is for peak HRR.

3.2.3 Small pool experiments (0.35 m)

The experimental results (see Figure 3.13) of the heat release rates for the small pool shows that the free burn heat release rate was larger than the heat release rates for the two room burn tests, and that the heat release rates for the two linings were comparable. Therefore, no effect of thermal feedback is found.

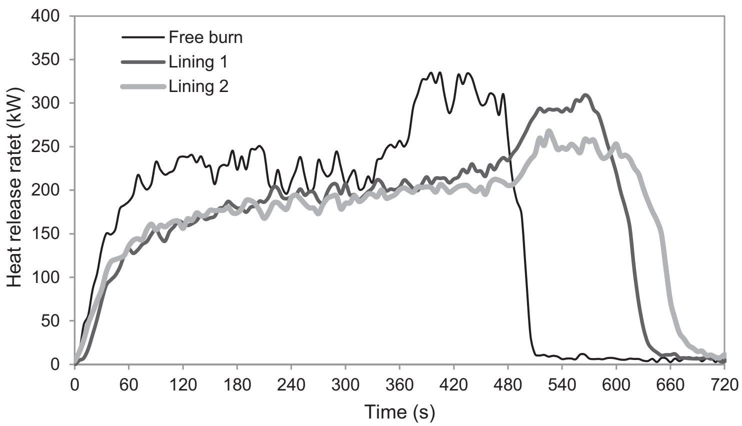


Figure 3.13. HRR versus time for a pool diameter of 0.35m

An average free burn mass loss rate for the steady state period was found to 0.056 kg/m^{2}s which is considerably higher than the expected value of 0.032 kg/m^{2}s. This difference will be discussed further in the summary in section 3.2.4.

3.2.4 Comparisons of experimental results

A clear effect of thermal feedback can be found for both linings for the large pool and a minor effect is found for lining 1 for the medium pool, but no effect is found for lining 2 for the medium pool and for the small pool. This compares well with the expected results as predicted in Table 3.1. As flames were impinging the ceiling for the large pool test and a significant thermal feedback was found, the results are also matching the observations made by Parkes [40].

The thermal feedback was found to result in both an initial increase of the heat release rate as compared with the results from the free burn, and in thermal runaway. In this test series the onset of thermal runaway occurred for the large pool at a smoke layer temperature of 350°C for lining 1 and 525°C for lining 2. This supports the theory that lower thermal inertia should result in lower onset temperature of thermal runaway [34, 35].

In general the results of the test for the large pan shows that the heat release rate can increase compared to free burn as a consequence of thermal feedback even before flashover occurs.

For the small pool tests and for lining 2 for the medium pool tests, the room heat release rates are smaller than those measured in the free burn tests. This observation compares well with the test results obtained by Thomas et al. [38] and Parkes [39] as in some of their experiments the free burn heat release rates were larger than the room burn heat release rates.

Mass loss rates found in the free burn tests and the predicted mass loss rates from Table 3.1 are compared in Table 3.6. The table shows that mass loss rates found from the test were the same for the large and medium pools, whereas the small pan had a higher mass loss rates. As can be seen from equation (3.1) the theory [24] predicts the mass loss rate to increase with larger diameters. This correlation with pool diameter was not observed, as the smallest pool had the largest mass loss rate, which is a striking difference. The deviation could be due to lip effects, which are reported to be able to give either higher or lower mass loss rates [24]. Lips effects are however presence in both room burn and free burn test and should not contribute to any difference in the comparison between the room burn and the free burn experiments.

Table 3.6. Free burn MLRs from tests compared to predicted values

	Large pool (kg/m^2s)	Medium pool (kg/m^2s)	Small pool (kg/m^2s)
Test	0.044	0.043	0.056
Prediction	0.054	0.043	0.032

Ventilation is also reported [51] to be able to increase mass loss rate due to better mixing of oxygen and fuel, and it is expected that the ventilation is better in the free burn experiments and thus that the mass loss rate for these experiments is higher than that found in the enclosure tests.

3.3 Evaluation of thermal feedback

For well ventilated room fires it has been indicated that two key differences may occur as a consequence of thermal feedback from the room as illustrated in Figure 3.14. The first is a slight increase of the room burn heat release rate as compared to the free burn heat release rate in an incipient period. The second difference is the possibility of a thermal runaway onset point, defined as the point where the rate of heat gained in the smoke layer is significantly larger than the rate of heat losses from the enclosure.

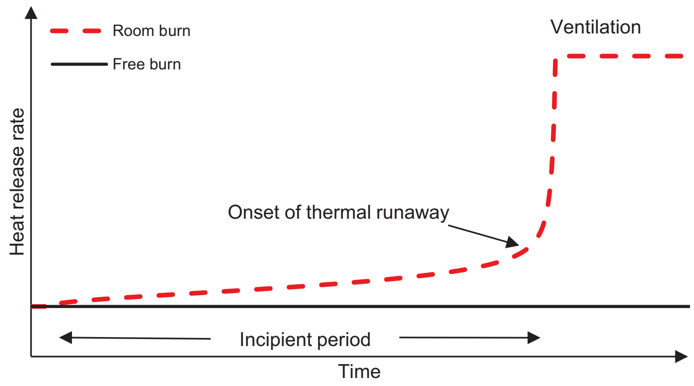


Figure 3.14. Principal differences in room burn and free burn HRR

In the incipient period the heat release can be found according to equation (2.5) that describes that the heat release rate is strongly dependent on the room temperature. The equation also shows that equal room temperatures should give equal heat release rates irrespectively of lining materials, given that room size and ventilation is unchanged. To see if this can be reproduced by the tests for the large pool, the heat release rates are plotted against the room temperature in Figure 3.15. The room temperature is chosen as the wall temperature for the following reasons. From Table 3.3 it can be seen that the wall temperatures differs less from each other at the time of paper ignition than the smoke layer temperatures do. This is supported by the vertical temperature distribution in the room plotted in Figure 3.7, as temperatures in the smoke layer differs substantially at this point, whereas temperatures measured below the smoke layer are more uniform.

Figure 3.15 shows that by comparing the heat release rate and the wall temperatures, it can be seen that the different linings show similar results until the onset of thermal runaway, at which point the two materials yield drastically different results. Therefore the results show that equal room temperatures gives equal heat release rate before thermal runaway, but not after. This indicates that equation (2.5) can be used before thermal runaway, but not after. After thermal runaway it is, however, found from Figure 3.3 that the developments of the heat release rates for the two rooms are comparable. The reason is not obvious.

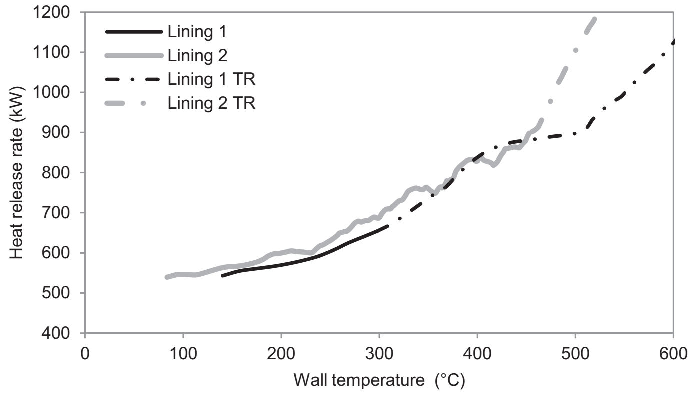


Figure 3.15. Comparisons of heat release rates and wall temperatures for the 0.70m pool

In order to further investigate equation (2.5) the heat release rate $\dot{Q}_{F,calc}$ is calculated using the measured free burn heat release rate, wall temperature and heat of combustion as input values. α is assumed to be 1 and L_g is assumed to be constant over time to 520 kJ/kg [42], and thus independent of the pan. Figure 3.16 plots the measured heat release rate, $\dot{Q}_{F,meas}$, versus the calculated heat release rate, $\dot{Q}_{F,calc}$, for the large pool, and it is seen that there is a reasonable correlation with the calculated values being somewhat higher than the measured ones. A linear fit to the two curves has a slope of 0.6, which indicates that, the estimate on α/L_g is too high, and therefore either α is smaller than unity, L_g is larger than assumed, or they are both different than assumed.

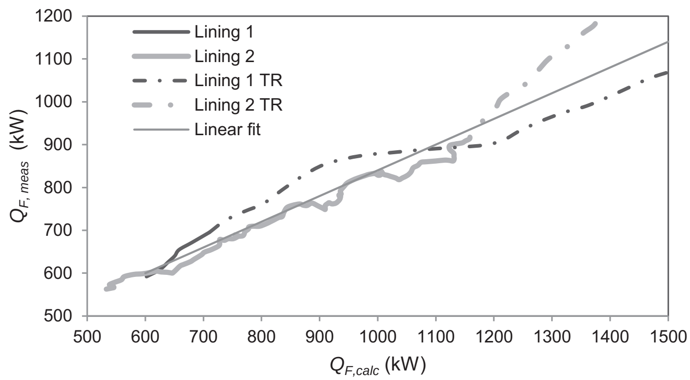


Figure 3.16. Comparison of measured and calculated heat release rate for the 0.70m pool. TR indicates that thermal runaway has occurred.

If, however, $\dot{Q}_{F,0}$ in equation (2.5) is seen as a constant and not a measured value from the free burn test, a better linear correlation is found for both linings between $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ until the onset point of thermal runaway, as seen in Figure 3.17. After the onset of thermal runaway no good correlation is found between the two curves in Figure 3.17. $\dot{Q}_{ext,calc}$ represents the heat release rate arising from the external heat flux and is found as the second term of equation (2.5). This suggests that equation (2.5) can express the development of the heat release rate for a room fire as long as $\dot{Q}_{F,0}$ is taken as a constant corresponding to the heat release rate at $T=T_s$ for a room test and not a free burn test on the same item. Before the onset of thermal runaway the slope of the curves is approximately 0.85.

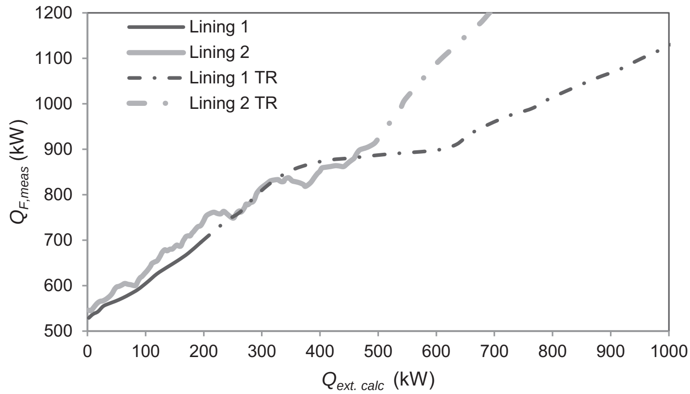


Figure 3.17. Comparison of measured HRR and calculated external HRR for the 0.70 m pool. TR indicates that thermal runaway has occurred.

Utiskul [41] found equation (2.5) to work on his data based on free burn measurements. It should be noticed that his free burn fires were constant and not slightly increasing as in this case. This, supported by the differences found for mass loss rate for the three pool sizes, indicates that free burn values should be used with caution as experimental conditions, such as ventilation, differ from the free burn tests to the room burn tests.

Using equation (2.5) as suggested with an α value of 0.85 can also be used to explain why no effect of thermal feedback was found for the small and medium pool for the tests with lining 2. As pool sized decrease the wall/smoke layer temperature will also decrease as a consequence of the energy balance. Decreasing both parameters has an influence on the second term of equation (2.5) and consequently the effect of the thermal feedback. This is illustrated in Figure 3.18, showing how the heat release rate calculated by the use of equation (2.5) together with smaller pool diameters and lower wall temperatures (200 °C and 300 °C for the small and medium pool, respectively), gives a very small increase of the heat release rate. This is in contrast to the large pool that reaches 460 °C at the onset point of thermal runaway leading to a significant increase of the heat release rate. A similar correlation can be found for lining 1.

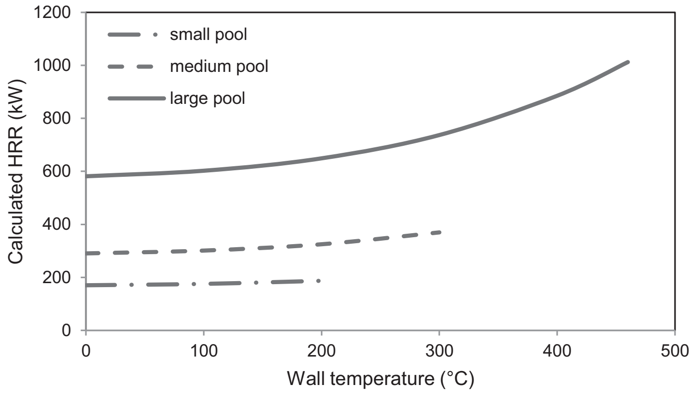


Figure 3.18. Calculated HRR for the three pool sizes for lining 2.

Whether a fire will reach thermal runaway or not can be determined from an energy balance for the room. The onset of thermal runaway can happen when the heat gained, *G*, by the hot layer from the fire exceeds the heat lost, *L*, by mass flow out of the opening and the heat lost by accumulation of heat by the linings. In the literature [31, 33], this onset point is also determined by the temperature for which the gradient of *G(T)* exceeds the gradient of *L(T)* in a Semenov diagram. The heat gained, *G*, can be expressed by equation (2.5). As $\dot{Q}_{F,0}$ is independent of temperature, the gradient of *G(T)* for an object with a fixed area can be estimated as

$$\frac{dG}{dT} \sim k_G \cdot T^3 \tag{3.4}$$

Here k_G is a constant including the parameters of the second term of equation (2.5). The heat lost from the smoke layer (neglecting radiation losses) can be estimated as:

$$L(T) \sim h_k \cdot A_u \cdot (T - T_0) + \dot{m}_{out} \cdot c_p \cdot (T - T_0) \tag{3.5}$$

where A_u is the surface area of the walls and ceiling covered by the smoke layer, h_k is the effective heat transfer coefficient of the linings, $\dot{m}_{out}$ is the mass flow out of the room and c_p is the heat capacity of air. For a steady smoke layer height $\dot{m}_{out}$ is assumed to be constant as well as it can be assumed to be constant for temperatures between 400 and 1000 K [31]. Thus the gradient of the heat loss can be estimated as:

$$\frac{dL}{dT} \sim h_k \cdot A_u + \dot{m}_{out} \cdot c_p \approx h_k \cdot A_u + k_m \quad (3.6)$$

Comparing equation (3.4) and (3.6) a linear correlation between h_k and T^3 can be expected at the onset of thermal runaway, suggesting that linings with lower thermal inertia will lead to lower room temperatures at the onset of thermal runaway.

As thermal runaway occurs later for lining 2 than for lining 1, and as such at higher room temperature and heat release rate (see Table 3.3), it supports a correlation between h_k and T. Estimates on h_k and T^3 are plotted in Figure 3.19. The figure indicates that a linear correlation may be achieved, but as only two sets of data are available no definite conclusions are made based on the test data. Comparing the results found with findings in the literature the results generally compares well with the simulation made by Graham et al. [35]. They show that lower thermal inertia will lead to lower onset temperatures for thermal runaway as well as their figure 5 indicates that a linear correlation could be found between a dimensionless room temperature to the third power and a dimensionless thermal inertia of the lining materials.

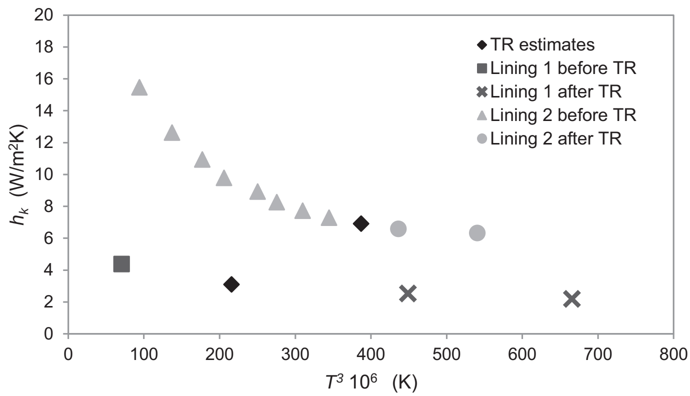


Figure 3.19. Correlation between the effective heat transfer coefficient, h_k, and the room temperature, T^3 for a pool diameter of 0.70 m

3.4 Summary

10 heptane pool experiments were performed in free burn conditions and in a room with two different linings (mineral wool and light weight concrete) in order to study the effect of thermal feedback on pre-flashover well ventilated fires.

The experimental results showed that the heat release rate may be affected by thermal feedback before flashover. Two phenomena related to the development of the heat release rate that relate well with theory were found. In an incipient period the heat release rate rose as a function of the wall temperature of the upper zone irrespectively of the thermal inertia of the linings. A rapid increase of the heat release rate commenced after the incipient period. This rapid increase is seen as a thermal runaway caused by the energy gained in the upper layer exceeding the energy that can be lost through the boundaries. The wall/smoke layer temperature did not seem to be a dominant factor in deciding the heat release rate after the onset point of thermal runaway. The thermal inertia was found to influence the onset point of thermal runaway as lower thermal inertia leads to lower onset point of thermal runaway. For the lining 1 (mineral wool) the onset point was met at a wall temperature of 330 °C corresponding to a smoke layer temperature of 350 °C and for lining 2 (light weight concrete) the wall temperature was 460 °C and the smoke layer temperature was 530 °C

Traditionally the heat release rate in a room fire has been proposed to be the sum of the free burn heat release rate in addition to a contribution from the heat flux induced by the room. This cannot be reproduced by the tests. Also, for experiment where thermal feedback was not observed a difference was found between room burn and free burn.

It is therefore found that free burn measurements should be used with caution for design fire calculations as not only enclosure effects, but also the specific wall linings can be expected to influence the outcome of a room fire.

4 A Study of the onset of flashover

The heptane experiments described in Chapter 3 showed that the heat release rate increased due to thermal feedback from the room. For the larger pool sizes the increase of the heat release rate resulted in the onset of thermal runaway, that for rooms with low thermal inertia (mineral wool) was found to start at a wall temperature of 330 °C and a smoke layer temperature of 350 °C. This makes the temperature at the onset point significantly below the traditional flashover criterion of flashover of 500-600 °C [2], which is the criterion that is commonly used for fire engineering models [23-25].

Heptane is, however, a highly flammable liquid, so no direct correlation can be made to normal types of occupancy.

In order to investigate this further, two series of large scale room fire experiments carried out by Carleton University and the National Research Council Canada, NRC-IRC [10] have been studied. The two series had similar fire loads representative of contemporary commercial premises and the fire rooms were comparable in sizes and ventilation. The linings (non-combustible) were changed between the two tests series, and thereby was the thermal inertia changed significantly. This way the tests allow for a comparison of the fire development with different types of linings for normal classes of occupancy.

4.1 Experimental setups

The two experimental programs were named “Design Fires for Commercial Premises Phase 1 (DFCP1) and Phase 2 (DFCP2). The DFCP1 and DFCP2 programs were intended to study pre-flashover and post-flashover fires, respectively.

The DFCP1 test program utilized an experimental setup comparable to the ISO Room Corner test [7]. The principal setup is shown in Figure 4.1. The walls and ceiling of the room were lined with cement board and the floor was made of concrete slabs giving the room a thermal inertia $(\rho \cdot c \cdot k)$ of approximately 0.85 kW^2s/m^4K and a thermal inertia of approximately 0.60 kW^2s/m^4K for the walls and ceiling.

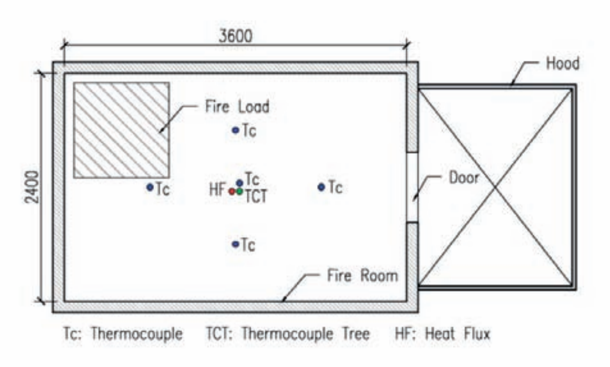


Figure 4.1 Plan of the experimental setup for the DFCP1 program [47]. Units are in mm.

The experimental setup for the DFCP2 program was a little different than the experimental setup used for DFCP1 as higher temperatures were expected as the fires were allowed to develop into fully developed fires. The fire room, see Figure 4.2 had a depth of 3.6 m, a width of 2.75 m and a height of 2.4 m, giving a floor area of 9.9 m^2. There was one door opening to the room with a height of 2.2 m and a width of 0.9 m. The door was connected to a 1.2 m wide and more than 10m long corridor leading to an exhaust hood. The linings on the walls and ceiling were made of ceramic fibers and the floor was made of concrete slabs giving the room an approximate thermal inertia $(\rho \cdot c \cdot k)$ of 0.37 kW^2s/m^4K, whereas the thermal inertia for the ceiling and walls was only approximately 0.02 kW^2s/m^4K

In both experimental setups, measurements, which relate to flashover predictions, were made of the heat release rate, incident heat flux to the floor and temperatures measured 25 mm below the ceiling, T_c as well as room temperatures by a thermocouple tree in the middle of the room for the DFCP1 setup and a corner at the door for the DFCP2 setup. In addition ignition of crumpled paper on the floor was also recorded for the DFCP2 tests. Further information on the experimental setup and instrumentation can be found in [10, 46, 47].

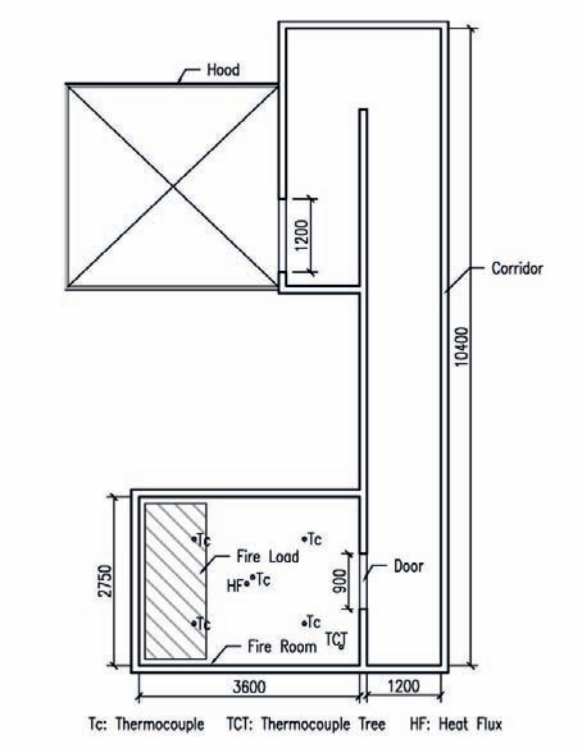


Figure 4.2 Plan of the experimental setup for DFCP2 [47]. Units are in mm.

The fire loads differed in type of material and arrangement. The type of fire loads in the DFCP1 and DFCP2 programs were based on a recent survey of fire loads in commercial premises in Canada [45] dividing the fire loads into 7 different categories, see Table 4.1 composed of different mixtures of plastic/rubber/textiles and wood/celluloses. The fire load density ranged from 661 MJ/m^2 to 4,900MJ/m^2. In the DFCP1 tests the fire loads were arranged as a single bundle simulating each respective retail group on a 1m^2 footprint positioned in the right back corner of the room, see Figure 4.1.

In the DFCP2 tests, two identical fuel packages, each having approximately the same size as in the DFCP1 tests, were used, except in the shoe store scenario, which used only one fuel package. The fuel packages were positioned in the back of the room, see Figure 4.2. The ignition source was the same in both DFCP1 and DFCP2. In DFCP 2 the first fuel package was ignited at the opposite side of the second fuel package, so that the second fuel package was ignited by the energy released from the first fuel package.

By the use of traditional fire safety engineering models it can theoretically be estimated at which levels of heat release flashover could occur and when the room would be ventilation controlled. These two values give theoretical estimates of the range of heat release rates in which flashover is expected to occur.

The heat release rate need to cause flashover is found by the use of Thomas model [23] as:

$$\dot{Q}_{FO} = 7.8 \cdot A_T + 378 \cdot A_O \cdot \sqrt{H_O} \tag{4.1}$$

Thomas based his model on the assumption of a smoke layer of 600 °C would case flashover. Therefore his model predicts the heat release rate that is needed to raise the room temperature to this level. He includes loss through openings and boundaries taken as the heat that could be lost from a concrete wall after 10 minutes of heating.

The heat release rate at the ventilation limit is found based on an assessment of the airflow, and thus the oxygen flow into the fire room as [48]:

$$\dot{Q}_{vent} = 1.518 \cdot A_O \cdot \sqrt{H_O} \tag{4.2}$$

It can be seen that the two heat release rates are not directly comparable, as the ventilation limits only are functions of the ventilation factor, whereas Thomas' model, also relates to the surface area of the room. The difference can also be explained by the difference between the two phenomena as the ventilation limit is assumed only to be dependent on the oxygen supplied from airflow through the openings. The heat release rate needed to cause flashover is defined by a room temperature that depends both on the heat lost via airflow out of the room and heat lost to the enclosure. Therefore, no explicit correlation is expected.

In total the two series comprises 16 fire tests, see Table 4.1. The table shows how fire loads and thermal inertia changes between the different test, and also how the theoretically estimated values for the heat release rate at flashover and ventilation limit changes from room to room.

Table 4.1 Experimental matrix

Test room	Test object	Fire load[a)]	Thermal inertia room/walls and ceiling (kW^2s/m^4K)	Estimated HRR at ventilation limit (kW)	Estimated HRR at flashover (kW)
DFCP1	Computer show room (COM)	812 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Storage room (STO)	2,320 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Clothing store 1 (CLO1)	661MJ (1 m2)	0.85/ 0.60	3,430	1,200
	Clothing store 2 (CLO2)	661 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Clothing store 3 (CLO3)	661 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Toy store (TOY)	1,223 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Shoe storage (SHO)	4,900 MJ (1 m2)	0.85/ 0.60	3,430	1,200
	Book store (BOO)	5,305 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
	Fast food (FAS)	881 MJ ($1\ m^2$)	0.85/ 0.60	3,430	1,200
DFCP2	Computer show room (COM)	1,624 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490
	Storage room (STO)	4,640 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490
	Clothing store 3 (CLO3)	1,322 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490
	Toy store (TOY)	2,446 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490
	Shoe storage (SHO)	4,900 MJ ($1\ m^2$)	0.37/ 0.02	4,460	1,490
	Book store (BOO)	10,610 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490
	Fast food (FAS)	1,762 MJ ($2\ m^2$)	0.37/ 0.02	4,460	1,490

[a] The area in parentheses represent the horizontal projection of the fire load.

4.2 Experimental results and discussion

The experimental results are presented as the heat release rates versus time, as well as the heat release rates at different traditional flashover criteria. These criteria are chosen as a room temperature of 600 °C and a heat flux to the floor of 20 kW/m^2 as these are commonly used for engineering assessments [2] as well as 600 °C is also found to be the basis of Thomas' model. Also, the tests allowed for investigation of ignition of crumpled paper, therefore this is also investigated.

In the literature, it is mentioned that temperatures for different tests are measured in different ways [22]. In some tests the room temperatures were measured at 10 mm or 25 mm below the ceiling, while others were reported to be an average room temperature or maximum temperature. In this study of flashover, it is chosen to distinguish between the different ways of measuring the temperature.

All the used criteria are defined in Table 4.2.

Table 4.2. Flashover criteria

Flashover criteria FOC	Heat release rate when
T_C = 600°C	The temperature exceeds 600°C measured 25mm below the ceiling
T_{slt} = 600°C	The smoke layer temperature exceeds 600°C
HF	The incident heat flux to the floor exceeds 20kW/m^2
Ignition of paper (IP)	Crumpled paper on the floor ignites

4.2.1 Observations from the design fires for commercial premises – phase 1 experiments (DFCP1)

The experimental results are presented for four different types of fire loads, representing different characteristic developments of the heat release rate, see Figure 4.3. The computer showroom represented a fire burning for a long time with a low intensity, and the clothing store represented a fire that increases progressively until it peaks at around 1100 kW and burns out. The heat release rate for the book store increased progressively after a long initial phase, but in this case the fire stabilized at around 800 kW and stayed at this level until it was extinguished due to safety of the test equipment. For the shoe storage test, the heat release rate rose quickly and the fire was extinguished, as it went to flashover. Besides differing in the development of heat release rate, the book store also differed from the other fire loads, as this fire load is composed purely of wood/celluloses. This indicated, as expected, that the composition of the fire load controlled the fire development.

Figure 4.3 also plots the points were the traditional criteria for flashover are met. Only the criteria for temperatures were met. The shoe storage reached the criteria at a heat release around 1,500 kW during a rapid increase of the heat release rate, whereas the book store reached the criteria at around 1,000 kW. The book store test did not show any sign of flashover at the time for meeting the criterion or after the criteria were met. After the criterion was met the heat release rate and temperature decreased. Therefore, result for the book store cannot be taken as representative of flashover and only one of the tests was found to reach flashover. The heat release rate found when the flashover criterion was met (1,500 kW) was higher than what was predicted prediction by the Thomas' model (1,200 kW). Therefore the result was within the range of what the Thomas' model can predict.

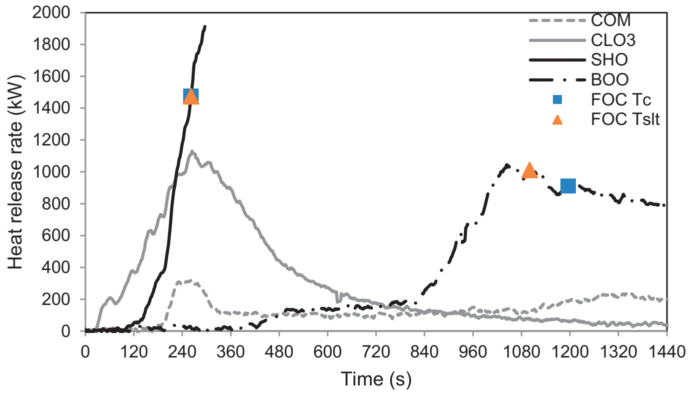


Figure 4.3. Heat release rate versus time and heat release rates at various flashover criteria, DFCP1

4.2.2 Design fires for commercial premises – phase 2 (DFCP2)

Observations

The fire development for the same four types of fire loads as presented for DFCP1 are shown in Figure 4.4. All the fire tests had a growing phase followed by a rapid increase of the heat release rate leading to flashover. From here on the fires continued burning as fully developed fires for one to ten minutes, depending on the fire load density, before the decay phase began followed by burnout. The other tests in the DFCP2 program not reported here also reached flashover and had similar developments of the heat release rate. The growing phases were in all cases around a couple of minutes except for the book store test, which, as for the DFCP1 test, had a significantly longer growing phase. As all the tests in the DFCP2 program showed the same trend in the development of the heat release rate only one characteristic fire development was found and not several as for the DFCP1 tests.

Figure 4.4 also shows that the traditional flashover criteria in general were met during the rapid increase of the heat release rate at a range of 1,500 kW to 2,600 kW, which in some cases were close to the peak heat release rate. The book store differed as one criterion (ceiling temperature) was met at the beginning of the rapid increase and at a significantly lower level. If the criteria in general should indicate the onset of flashover as the start of a rapid increase of the heat release rate, it would have been expected that some of the criteria would have been met around the end of the growth phase or the beginning of the rapid increase of the heat release rate curve, and not all during or close to the end of the rapid increase.

All the peak heat release rates were measured to be in a narrow range from 2,400 kW to 2,700 kW, which is significantly less than the predicted value of 4,460 kW. The difference may be caused by the corridor restricting oxygen supply to the room as well as saturation of the hood, but no certain answer can be given at this point.

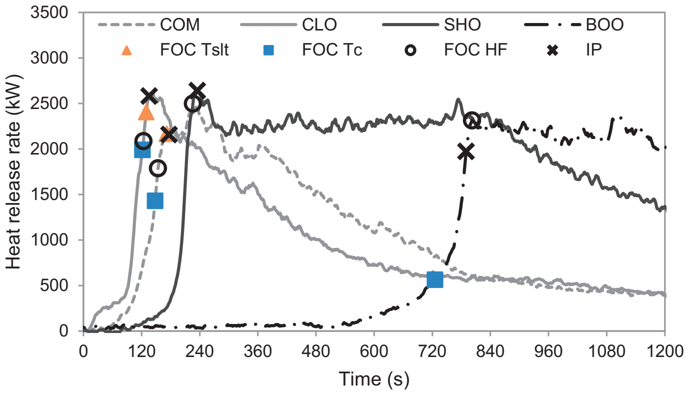


Figure 4.4. Heat release rate versus time and heat release rates at various flashover criteria, DFCP2

Flashover Investigation

In order to further investigate the rapid development of the heat release rate found for the DFCP2 tests, the heat release rates versus time for all seven tests are plotted in Figure 4.5. The time is changed and set to zero when a rapid increase of the heat release rate starts. This point is found as the time where the heat release rate increases more than 25 kW/s. It can be seen that the heat release rate curves are more or less alike from the onset of the rapid increase, indicating that the compositions of the fire load were not a dominating factor from this point on. This is in contrast to the DFCP1 tests, where the fire load seemed to dominate the fire development. Therefore the onset of the rapid increase of the heat release rate for the DFCP2 tests also represents a significant change in the fire development occurring early in the fire course that is not found for the DFCP1 tests.

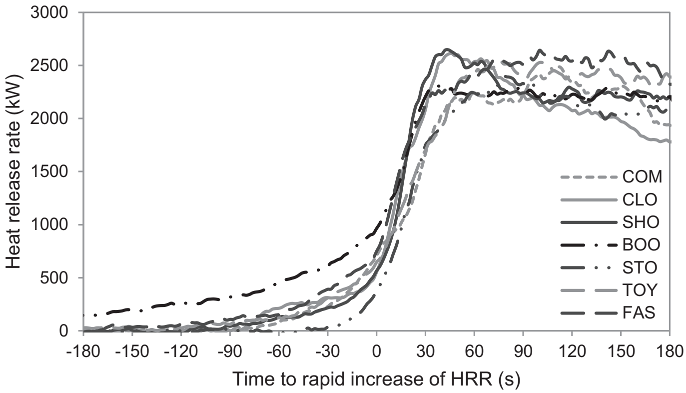


Figure 4.5. HRR versus time correlated to the onset of the rapid increase (thermal runaway) of the HRR, DFCP2.

To support the assessment of thermal runaway the ceiling temperatures versus time for the onset of rapid increase is shown in Figure 4.6. The figure shows that for three out of four tests a rather rapid increase of the temperature takes place, which is in line with the development of the heat release rate. The increase of the temperatures are, however, not as distinct as increase of the heat release rate.

The book store, however, behaves considerable different compared to the other three tests. For this test the temperature is considerably higher at the time t = 0, (time for the start of rapid increase of the heat release rate) and there is no change of the temperature development after this point. The temperature development only changes when the fire becomes ventilation controlled. It was expected that the temperature for the book store test should be higher at t = 0, as a consequence of the energy balance as the fire growth time is longer and the heat release rate is higher at t = 0 in Figure 4.6. It would have been expected that some of change of the temperature would follow the rapid increase of the heat release rate. The ceiling temperatures did eventually increase to the same level as the other tests, which indicate that the temperatures should have been measured correctly. Therefore Figure 4.7 shows that for the book store there does not seem to be a correlation between the heat release rate and the temperature at the time where thermal runaway is predicted to occur.

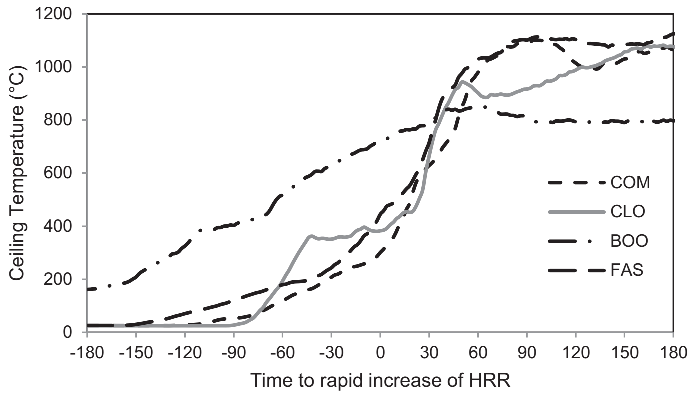


Figure 4.6. Ceiling temperature versus time correlated to the onset of rapid increase of HRR

The rapid increases of the heat release rate occurring in these experiments are seen as a thermal runaway. At the onset point, the heat release rates were in the range of 550 to 700 kW, except for the book store (965 kW), see Table 4.3 and the temperatures measured below the ceiling were in the range of 300-420°C (considerably higher for the book store (725°C)).

Table 4.3. Measured HRR and ceiling temperatures at the onset of thermal runaway.

Test	Time from ignition (s)	HRR (kW)	Tc (°C)
Computer Showroom (COM)	122	710	300
Storage room (STO)	68	560	n/a
Clothing store (CLO3)	94	555	380
Toy store (TOY)	268	650	n/a
Shoe storage (SHO)	192	565	n/a
Book store (BOO)	766	965	725
Fast food (FAS)	156	690	420

The temperatures at the onset of thermal runaway are plotted together with traditional flashover criteria in Figure 4.7. The figure shows that for three out of four tests, the thermal runaway occurred before any of the flashover criteria, as it should be. In the book store test, on the other hand, the temperature criterion was met before thermal runaway occurred.

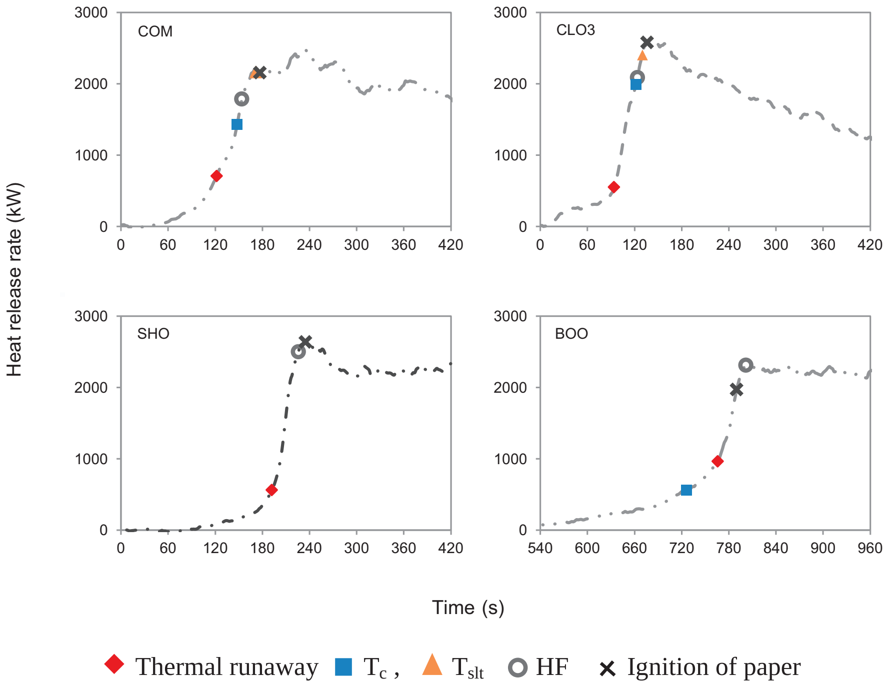


Figure 4.7. HRR versus time at different flashover criteria compared to the fire development, DFCP2. The criterion for thermal runaway is also inserted.

During the tests it was in most cases observed that ignition of the second fuel package appeared as radiation ignition at the top of the second fuel package, quickly followed by ignition of crumpled paper, which also means that the second fuel package ignited during the rapid increase of the heat release rate. As such, the start of the rapid increase occurred before significant fire spread was observed. Therefore, in most cases, only one fuel package was needed to cause the onset of thermal runaway. The traditional flashover criteria are generally related to fire spread [21]. This may also explain why the traditional criteria for flashover were met during the rapid increase and not around the start. As the start of the flashover process found in these tests are not directly caused by fire spread, using heat release rates found at the traditional criteria for flashover would overestimate the actual heat release rate that was needed for the onset of flashover. Therefore, these values should not be taken as representative of the onset of flashover in the sense that flashover represents a rapid increase of the heat release rate, but an assessment of fire spread.

It should be mentioned that for the book store test, fire spread seems to be the dominating process in causing flashover, indicating that for fire loads composed only of wood/cellulose the traditional temperature criterion should be valid for predicting flashover. Thomas' model [23] is, however, not able to predict the heat release rate at 600°C for the book test (550 kW). This may be because Thomas assumes the linings to be of concrete and not ceramic fibers which were used in the tests. Concrete linings will allow for a much larger energy loss and thus a higher heat release rate would be needed to give the required temperature.

4.2.3 Comparison of the test series

The test results showed for the DFCP1 tests that the fires developments were mostly dependent on the composition of the fire load. This was only the case in the growth phase for the DFCP2 tests, as a thermal runaway took place for the DFCP2 test after, in most cases, a relatively short growth phase. For the DFCP2 test it was also found that the second fuel package, in most tests, ignited during the rapid increase of the heat release rate. Taking the heat release rate for DFCP2 tests until ignition of the second fuel package and comparing these curves to the DFCP1 tests, it is possible to study the influence of changing non-combustible linings for comparable objects, as the test room for the DFCP1 and DFCP2 test are comparable in size and ventilation. As the tests also are categorized by the different compositions of the fires load, it is also possible to study the influence of the different flammability parameters.

Influence of the Thermal Inertia.

The heat release rate from the DFCP1 tests and the DFCP2 tests are compared in Figure 4.8. To eliminate the influence of difference in the ignition phase, the time on the graphs is set to zero when the heat release continuously exceeds 30kW, and the DFCP2 tests are only plotted for the part of the experiment that takes place before the second fuel package ignites. As only one fuel package was tested for the shoe storage in the DFCP2 tests, the full graph is shown. Therefore, the graphs show the burning behavior of comparable fuel packages with comparable fire loads. The onset of thermal runaway (rapid increases of heat release rates) is also marked.

Figure 4.8 shows that there is a significant difference in the burning behavior for all types of combustibles except the book store, as the heat release rate for the DFCP2 tests increased significantly compared to the DFCP1 tests. In all three cases thermal runaway is found to occur shortly after the deviation between the heat release rate curves starts and before the second fuel package ignites. After the thermal runaway occurred, the difference between the heat release rates for the two test series, as expected, became more pronounced. This indicates that the increase of the heat release rate associated with the onset of thermal runaway was related to thermal feedback.

This is not the case for the book store where the heat release rate curves are comparable almost until the second fuel package ignites, which is about the same time as the onset of thermal runaway is estimated.

As the thermal inertia was the only varied parameter for the shown period of the four fire tests, the results show that lowering the thermal inertia caused both the increase of the heat release rate and subsequently flashover for three out of four tests. Thus, the results are in line with the results from the heptane tests that show that thermal runaway is dependent on the thermal inertia of the lining. This result is also supported by results obtained from models [34, 34]. The effect of changing the thermal inertia of the linings could also in principles be explained by the use of a Semenov diagram as lowering the thermal inertia will lower the loss curve. Consequently, the critical temperature for causing thermal runaway and the heat release rate associated with this temperature may also decrease.

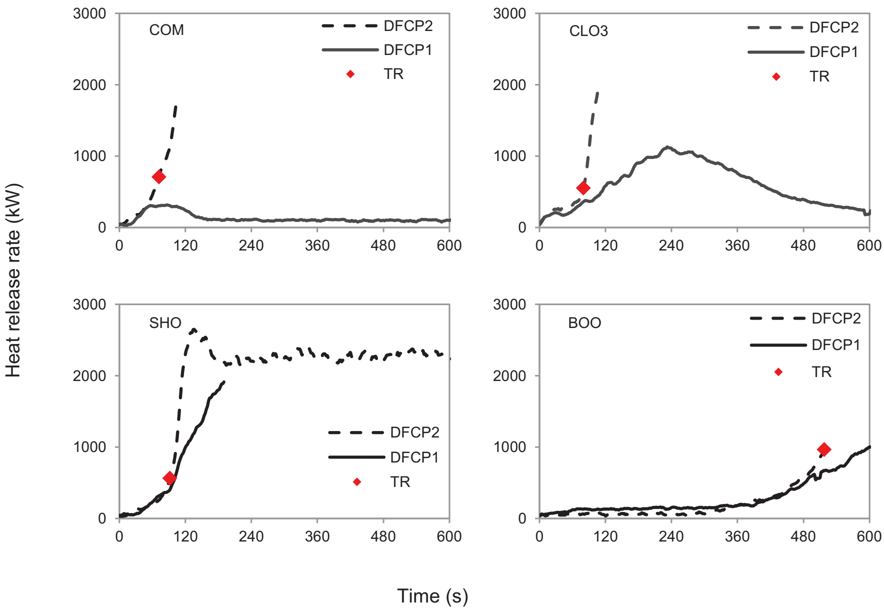


Figure 4.8. Comparison of HRR versus time between DFCP1 and DFCP2. TR is thermal runaway

At the onset of thermal runaway the room temperature for these tests (except the book store) were around 300-420°C (see Table 4.3). Therefore the results also support that by lowering the thermal inertia thermal runaway could occur at significantly lower temperature than the traditional flashover criteria of 5-600°C and that the traditional criteria do not in all cases implicitly take thermal feedback into consideration. This is the same result as found for the heptane pools, which show that thermal feedback may be a dominant process in bringing about flashover, also for other combustibles than pool fires. The results further show that thermal runaway need to be considered when assessing flashover for highly insulated buildings with low thermal inertia.

Influence of the Type of Material

Figure 4.8 showed that three out of four test resulted in thermal runaway before the second fuel package was ignited. The test that deviated on this point was the book store test. This corresponds well to the difference in temperatures at the onset of flashover by thermal runaway, as this happened at a higher temperature (725°C) for the book store than for the other tests (300-420°C). The fire load in the book store was composed of pure wood/cellulose, whereas the other types of fire loads also included various amount of plastics, food, textiles and rubber/leather.

From equation (2.5), (3.4) and (3.6) it can be seen that there may be a linear correlation between $(\Delta H_{eff}/L_g)$ and the room temperature T^3 for a fixed burning area in the same room. The correlations shows that for materials with a low ratio of $(\Delta H_{eff}/L_g)$ a higher room temperature is needed to give the same gradient of the heat gained in the Semenov diagram, and therefore materials with a low ratio of $(\Delta H_{eff}/L_g)$ will be less sensitive to thermal feedback than materials with a higher ratio. This is also indicated by Quintiere [27] in his figure 5. For charring solids such as wood the effective heat of combustion, ΔH_{eff}, will normally be in the range of 5-15 MJ/kg [26] and the heat of gasification, L_g, will be in the range of 5-8 MJ/kg [26]. For melting, non-charring solid such as plastic materials, ΔH_{eff} and L_g would be in the range of 20-40 MJ/kg and 1-3 MJ/kg, respectively [26]. Thus, $(\Delta H_{eff}/L_g)$ for melting, non-charring solids can be an order of magnitude larger than for charring solids. This difference in the composition of the fire load may therefore also influence the difference in the onset temperature of thermal runaway, and as such indicate why thermal runaway is not evident for the book store test.

4.3 Summary

Two series of full scale room fire tests comprising 16 experiments are used for a study of the onset of flashover. The fire loads were varied and represented seven different commercial applications and linings were varied with two non-combustible linings with significantly different thermal inertia were used. The test results showed that by lowering the thermal inertia and thereby increasing the thermal feedback, a thermal runaway occurred before significant fire spread; but only for objects composed of a mixture of plastic/rubber/textiles and wood/celluloses. In these cases the onset of thermal runaway was found to occur at room temperatures in the range 300-420°C. This supports that the room temperature at the onset of thermal runaway was strongly dependent on the thermal inertia, which confirms the results from the heptane experiments.

The low room temperatures at the onset of thermal runaway also show, that this cannot in all cases implicitly be predicted by the traditional flashover temperature criterion of 500-600°C. As this traditional flashover criterion often is a basis for simplified traditional models, as well as these models uses simplified assessments of the energy balance, these models cannot be expected to predict the onset of flashover as found by the tests. In these cases models including thermal feedback should be applied.

For fire loads composed of pure wood/celluloses the onset of flashover occurred about the same time as fire spread irrespectively of linings and at significantly higher room temperatures (725°C). This can be explained by flammability parameters showing that wood/celluloses are less sensitive to thermal feedback.

5 Polyurethane experiments

In the previous chapters it has been shown that thermal feedback may affect the heat release rate before flashover. The heptane tests identified two key phenomena that relate well to theory. In an incipient phase the heat release rate will increase as a function of the upper room temperature. A rapid increase of the heat release rate seen as a thermal runaway may commence after the incipient phase. The temperature at the onset point of thermal was by the heptane tests was found to be dependent of the thermal inertia of the linings. This was confirmed by the study of the onset of flashover with fire loads representative of commercial premises. These tests also showed that the type of combustibles can influence the onset point of thermal runaway. It was indicated that this could be explained by the ratio between the heat of combustion and the heat of gasification, as materials with a low ratio less will be less sensitive to thermal feedback. The flashover study could however not give more direct information on the effect of thermal feedback on the pre-flashover fire.

In order to further investigate the effect of thermal feedback on development of the heat release rate for pre-flashover fires, the polyurethane experiments were designed. The aim of the polyurethane tests was to support findings from the heptane tests regarding burning rate, and in addition to this, to study the influence of thermal feedback on the flame spread rate.

The experimental investigation has been carried out in collaboration with The National Research Council Canada, Institute of Research in Construction. The tests were performed in their laboratories and the test results have been reported in a NRC research report [52], which is also appended this thesis.

5.1 Test specimen

In order to make the best correlation to the heptane experiments a similar experimental setup should be used. In addition to this the experimental setup should allow for recording of the flame spread rate.

The first part of the selection of the experimental setup for this test series was the choice of type and size of the polyurethane block to be tested.

In order to select the right test specimen the nature of flexible polyurethane was briefly studied. Flexible polyurethane foam is not a generic material but can differ in composition, density and some types may be fire retarded by different means. Generally it is found that flexible polyurethane at ignition is a solid material, but the material has a complex burning behavior once ignited. After ignition it will collapse structurally into an overheated low viscous liquid that may turn into a pool fire [53]. Much effort [53-55] has been made in investigating the melting and burning behavior using small scale test as the cone calorimeter [43]. Also flame spread has been investigated in a free burn condition [56].

The type of polyurethane used in this study was therefore chosen to be the same as that used for constructing a mock-up sofa in a previous project [57] conducted at NRC-IRC. This was done in order to take advantage of existing experimental data of burning behavior found by the use of the cone calorimeter [43] as well as intermediate size free-burn experiment with a 610 x 610 x 100 mm horizontally positioned block placed on shallow aluminum pan. The intermediate test was performed under a calorimeter hood.

From the existing test an average effective heat of combustion, ΔH_{eff} was found to be approximately 28 MJ/kg. The intermediate size experiment showed that for a central ignition, the heat release rate was increasing progressively irrespectively until a peak of 298 kW (800 kW/m^2) followed by a rapid decay. Often tests from the cone calorimeter can give information about the heat of gasification, L_g for this specific type of foam. Unfortunately the previous test did not supply sufficient information to estimate the heat of gasification.

The size of the test specimen was found to ensure that the flame spread rate could recorded as well as an effect of thermal feedback could be expected.

In order to find a threshold for the size of the block a previous investigation [28] on upholstered furniture was used. This investigation showed that for Room Corner tests [7] an effect of the thermal feedback could be expected for peak heat release rates 450-600 kW. A lower threshold was therefore chosen as a free burn heat release rate of 500 kW.

On this background the size of the test specimen was chosen to be 1.2 m long and 0.6 m wide. It should be noted that the length of the block also was restricted by flame spread recordings through the door of the room corner. This gives a total area of the top of 0.72 m^2 and an expected peak heat release rate of 570 kW based on the results from the intermediate test. The thickness was chosen to be 0.2 m to prolong the duration of the burning period, and thus give more time to detect an influence of the thermal feedback.

The test specimen is chosen to be in a horizontal position to get the maximum view factor to the ceiling and smoke layer, and the block of polyurethane was placed in a steel pan (1.4 m x 0.8 m and 0.05 m lips) to keep the melted substance into a restricted area.

The dimensions and mass of each tested polyurethane block are given in Table 5.1.

Table 5.1. Dimensions of test specimens.

Specimen number	Length (mm)	Width (mm)	Thickness (mm)	Mass (kg)	Density (kg/m^3)
1	1213	600	203	4.760	32.2
2	1201	609	204	4.812	32.2
3	1206	601	204	4.702	31.8

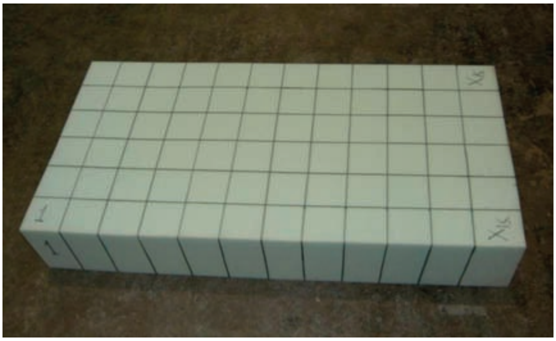


Figure 5.1. Photograph of the PUF block showing the 100 mm grid marks.

A 100 mm square grid was drawn on the surface of the polyurethane block (Figure 5.1) for the purpose of measuring the rate of surface flame spread. In the room test some of the lines were marked at the ends with aluminum tape in order to be recognized by infra-red recoding.

5.2 Experimental setup

The experimental setup was based on a facility comparable to the ISO-9705 room corner test [7]. As described in Chapter 2 one test should be performed as free burn under the hood and two room tests should be performed in the room with changing linings. Thus a total of three fire tests were performed, see Table 5.2. The different lining materials used were a 12.7 mm thick cement board with a density of approximately 1257 kg/m^3 and a 50 mm thick mineral wool with a density of approximately 100 kg/m^3. The mineral wool was mounted on a substrate of cement board with steel pins. The thermal inertias ($k \cdot \rho \cdot c$) for the cement board and mineral wool were approximately 0.6 and 0.004 W^{2}s/K^{2}m^4, respectively. None of the linings had been subject to prior heating.

Table 5.2. Experimental matrix

Test No.	Specimen No.	Experimental setup	Expected room temperature[(a)] (°C)
1	2	Free-burn	-
2	1	Room test – Cement board	330
3	3	Room test – mineral wool	430

a) The temperatures were calculated as expected temperature for 3 minutes steady burning at a heat release rate of 500 kW using the MQH relation as described by equation (3.3).

To be able to record flame spread, the polyurethane block was ignited at the short end. The ignition source was developed through a set of preliminary tests were performed (see the appended research report appendix 1). For the first test a 19 kW T-single flame burner was used. The melt flow was found to be undesirable for the study. For the second preliminary test the heat output was changed to 75 kW. In this test the burner ignited a large part of the surface allowing little area to investigate flame spread as well as it appeared that the burner gas flow was affecting the flame spread. Therefore the final burner configuration was a dual flame T-burner (propane) with a horizontal flame to ignite the polyurethane and a vertical flame to attenuate the horizontal flame and provide a balance of the heat release rate output, see Figure 5.2.

Figure 5.2. Picture of the burner

The total strength of the burner was 75 kW. The burner was positioned at the end of the block 33 mm vertically and 75 mm horizontally from the edge of the block. The preliminary tests showed that the peak heat release rate was in the range of 500-600 kW, which is just above the lower threshold. It was therefore decided not to extinguish the burner during the test. This way, the burner would add to the heat release rate as a second burning object. It was also realized that the burner would ignite more than 1/3 of the length of the test specimen. The advantage would be that the flame spread would be finished by the time that melting would make the flame base sink to the bottom of the pan. This way the flame spread would not be affected by melting.

As the heat release rate was expected just to be slightly over the lower threshold it was decided to downsize the room to increase the room temperature. This was done by reducing the length of the room from 3.6 m to about 2.8 m as well as the door was reduced in height by a 0.5 m sill leaving the opening with the dimensions of 0.74 m wide and 1.5 m height. This should increase the expected room temperature by 40-50°C compared to the standard room corner test setup, giving expected room temperatures of 330°C for the cement board lining and 430°C for the mineral wool lining, see Table 5.2. Thus the room temperatures were expected to be below the flashover criterion of 500-600°C. Also, the ventilation limit for the reduced scale room was approximately 2 MW using equation (4.2), so ventilation limiting should not influence the results.

The mineral wool had a thickness of 50 mm, and thus reducing the width of the room. Therefore the length of the room was increased by 28 cm giving a total length of 3080 mm compared to the cement board experiments in order to have the same volume of the room. Detailed interior dimension for the room lined with cement board and mineral wool can be found in Figure 5.3 and Figure 5.4.

The test specimen (block and pan) was positioned 750 mm above the floor. For the room tests the pan was positioned with the center line 1800 mm from the wall with the opening, see Figure 5.3 and Figure 5.4 and for the free burn test, the pan was positioned below the hood, see Figure 5.5.

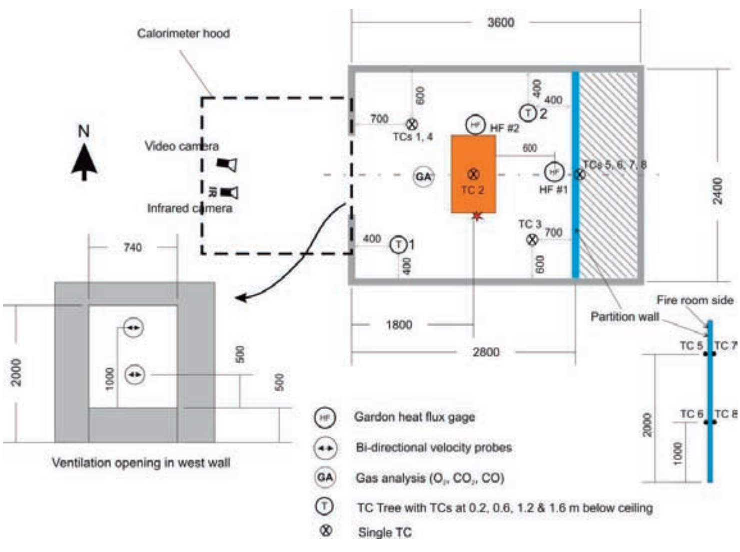


Figure 5.3 Room burn tests setup with cement board lining

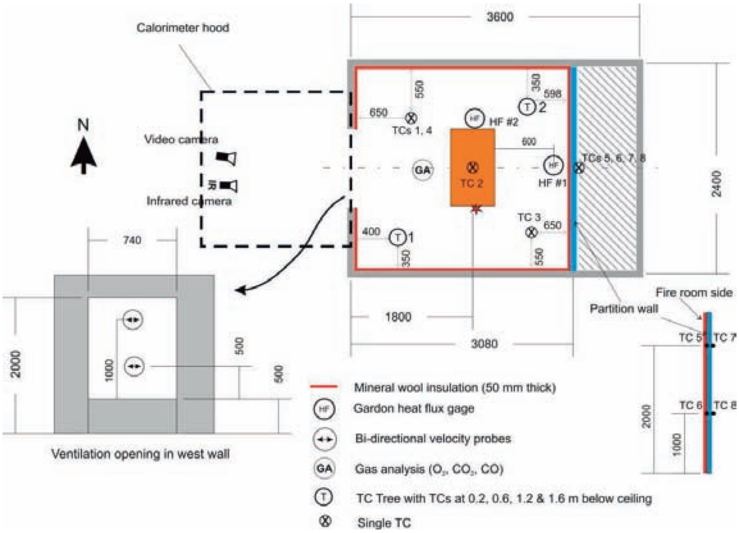


Figure 5.4 Room burn test setup, mineral wool lining

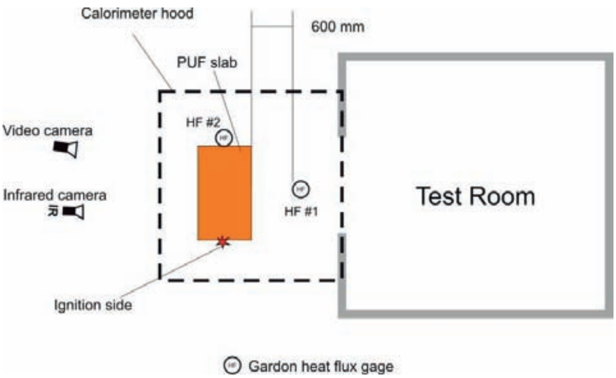


Figure 5.5 Free burn test setup

Measurements relevant to the investigation of the thermal feedback were made of heat release rate, temperatures and heat flux. No good solution was found to measure mass loss rate in the room. Therefore this value could not be measured.

The heat release rate was found by the use of gas analysis from measurements of CO_2, CO and O_2 in the duct using standard E-values.

Temperatures were measured in the room in two thermocouple trees in opposite corners at 0.2, 0.6, 1.2 and 1.6 m below the ceiling. As the length of the room was increased for the test with mineral wool it was decided to fix the distance from the burning object and change the distance to the walls accordingly. In the other two corners the temperatures were measured 0.2 m below the ceiling. Position from the walls can be found from Figure 5.3 and Figure 5.4. All thermocouples were type K.

A Gardon heat flux gauge (HF#1) was placed 600 mm from the pan 1.2 m above the floor facing horizontally towards the fire. Another Gardon heat flux gauge (HF#2) was positioned at the end of the pan (opposite the ignition side) facing upwards towards the smoke layer. These heat flux measurements were repeated for all three test setup. The heat flux gauge had an upper range of 150 kW/m^2.

In addition, the experiments were recorded by video and infrared (IR) camera type JENOPTIC VarioCAM HiRes. Information on the IR camera can be found in Table 5.3. The recording by the IR camera was done with an interval of two second.

Table 5.3. Technical data for the VarioCAM® IR camera

Spectral sensitivity	Temperature range	Measurement accuracy	Thermal resolution (at 30°C)
7.5 – 14 μm	-40°C - 2,000°C	0°C - 120°C: ± 1.5 K >120°C: ±2%	<60 - 80 mK

Further measurements were made of smoke production for all three tests and for the two room test the velocity through the door and gas concentrations of CO_2, CO and O_2 in the room were also recorded. The measurements will not be presented here, but can be found in the appended research report.

A 16 bit Solartron (Schlumberger) Instruments distributed data acquisition system with 3595 series isolated measurement pods (each having 100 channels) and a personal computer interface was used to record all measurements directly to a hard disk drive at specified intervals. All temperature data were instantly processed by the data acquisition system and recorded as temperature values with an accuracy of better than 1°C. Outputs from heat flux gauges, pressure transducers, gas analyzers and the smoke meter were recorded as either direct current (DC) voltage or current values and were converted by applying the appropriate calibration constants after each experiment. The sensitivity of the data acquisition system for voltage and current measurements is 1 μV and 10 nA, respectively. All data were recorded with an interval of two seconds.

A special test procedure was developed for these experiments in order to measure pre and post conditions as well as burner output at each test. The procedure was as follows. Pre-test measurements were made for 60 seconds before the burner was ignited. The burner was kept on for 60 seconds before it was extinguished. Hereafter the block was placed in the middle of the pan and the burner was ignited again. When burnout was observed, the burner continued burning for 60 seconds after which the burner was turned off. In order to record post-test data additional 60 seconds were measured. Thus predictions could be made of the setback time for the measurements in the duct as well as to record any drift in the measurements of the heat release rate. The test procedure used is given in Table 5.4

Table 5.4. Planned test procedure (sequence and timing of events)

Time (sec)	Event	Comment
0	Start data logger	Record pre-ignition conditions
60	Light burner (without specimen)	Measures of burner output
120	Switch-off burner	
180	Place specimen in pan	Measures initial specimen mass
240	Re-light burner (to ignite polyurethane block)	This is where the actual test starts
Wait until complete burnout		
+ 60	Stop burner	
+ 60	Stop measurements	Measures end conditions and allows for correction of any drift in measurements

Prior to the experiments a calibration test was made of the gas analyzer using a propane burner with three output levels (198 kW, 286 kW and 441 kW) according to NRC procedure.

5.3 Experimental results

5.3.1 Flame spread

The flame spread was found visually by the use of IR recordings as the position of the flame front with time. Especially in the room tests, the recordings were associated with some uncertainties, as the lines on the surface of the test specimen, as oppose to the free burn, were difficult to recognize. Therefore the results should be seen as trend more than exact results.

The observations showed that the flame quickly was spreading to the center of the test specimen for both free burn and room burn. Therefore only the results from the observations of flame spread over the second half of the test specimen will be presented. One of the pretests (with a 19 kW burner) was also recorded with the IR camera. The results from this test will also be presented to support the free burn test.

The observations of the position of the flame front moving over the surface with time are given in Figure 5.6 (upper panel). Time is set to zero when the flame front passes the middle of the test specimen. The lower panel shows an estimate of the flame spread rate found based on the time it takes the flame front to travel between two observations. From the figure it can be seen that the both free burn tests and both the room burn tests are comparable. The flame front for the free burn tests travels slightly slower over the surface for the free burn tests than the room burn tests. The difference is, however, only signification when the flame front is approaching the end of the test specimen. Here the average flame spread rate for the room burn test over the last 20 cm is 25 mm/s in contrast to the free burn, where the average flame spread rate is about 9-10 mm/s.

Therefore the tests show that the flame spread in the room tests increase at a higher rate at the end of the tests than the free burn tests, whereas the flame spread rates are comparable at the start. It should also be noted that the free burn flame spread rate is not constant, but slightly increasing, which corresponds well with theory, as the heat release rate and thus the heat flux from the flames will increase as the fire grows [21].

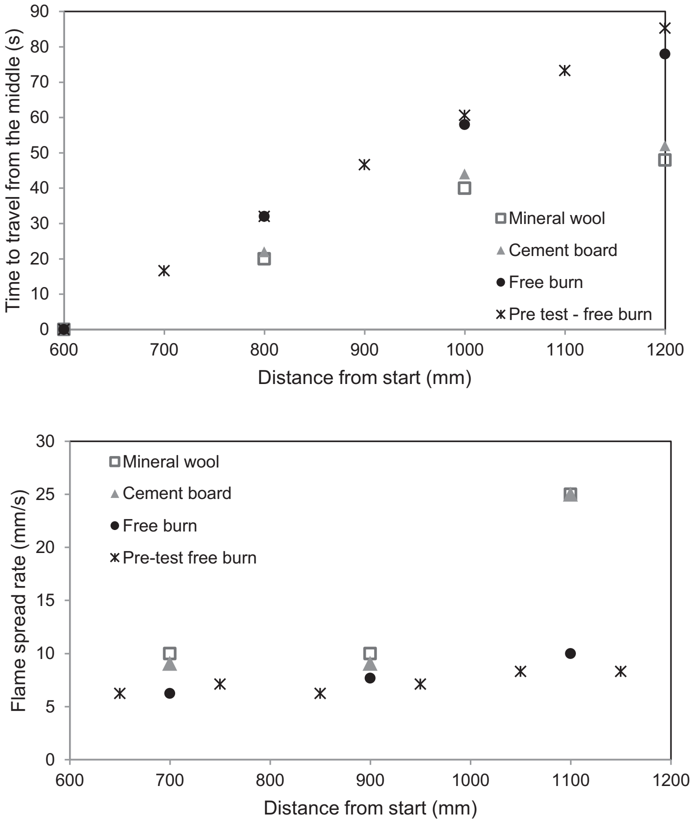


Figure 5.6. Position of the flame front with time (upper panel) and estimated average flame spread rates (lower panel).

In theory the initial flame spread should be comparable for the free burn test and the room burn test in the absence of initial thermal feedback in the room. This is not the case here. It was, however, observed that even early in the room tests, a smoke layer was building up. Figure 5.7 shows digital images 44 seconds after ignition for both room tests. It can be seen that the room temperature was already at that time building significantly up for the test with mineral wool lining. Also, for the test with cement board, the smoke layer is building up but at a lower temperature. This cannot explain the difference found at the start. At this stage it can only be explained by the difference in the test setup, which among other things differs significantly in ventilation conditions. Here it should also be noted that similar differences were also found for the heptane tests.

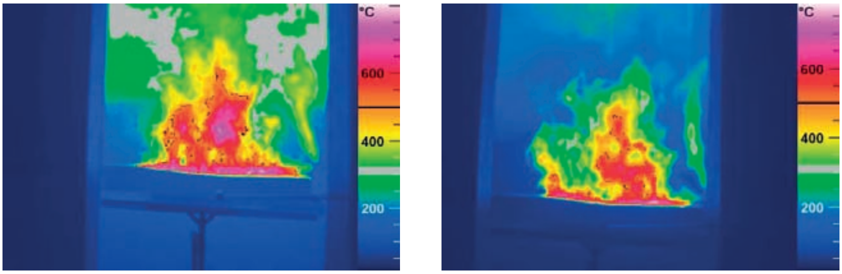


Figure 5.7. Thermal image of the room test 44 seconds after ignition. (Left picture is test with mineral wool and right picture is with cement board).

Finally it was observed that structural collapse of the foam did not happen to a larger extent before flame spread was completed

5.3.2 Measurements of heat release rates, temperatures and heat flux

The measured heat release rates (including burner output) versus time are presented in Figure 5.8 as a floating average of 10 seconds (5 measurements). Also the point where the full surface was ignited is plotted. Initially the heat release rates were comparable for all three tests. After about 1 minute a difference was found as the heat release rate for the test with mineral wool continued to increase linearly but more rapid rate than to two other tests. The test with mineral wool lining peaked at 930 kW followed by a sudden decay. The development of the heat release rate for the free burn test and the test with cement board lining were comparable and both peaked at approximately 500 kW followed by a decay, which is also considerable slower than for the test with mineral wool linings. As such the peak heat release rate for the test with mineral wool was increased about 90 % compared to free burn and the test with cement board. The test with cement board lining had a little larger peak than the free burn test, but the difference is not considered significant due to uncertainties in the measurements of heat release rate (5-10 % [6]) The growth rate for the cement board lining was slightly faster and the peak was reached before the free burn test, which can be explained by the faster flame spread for the room test.

As only the linings and thus the thermal feedback was changed between to two room tests, the tests showed that the thermal feedback may have increased the heat release rate for the test with mineral wool lining. The free burn test and the room test with cement board were, however, comparable except for minor differences related to flame spread.

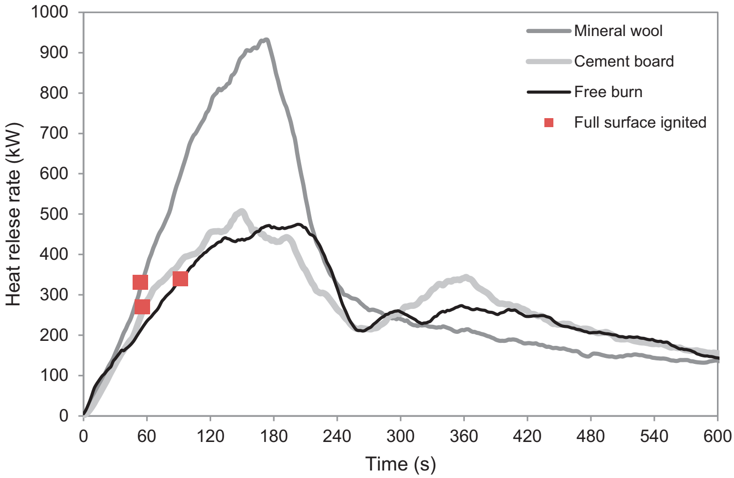


Figure 5.8. Heat release rate versus time.

The cement board test had a second but smaller peak. For the free burn test only fluctuations occurred after the first peak. In all test a deflection of the pan was observed to start around the time for the peak heat release rate, see Figure 5.9.

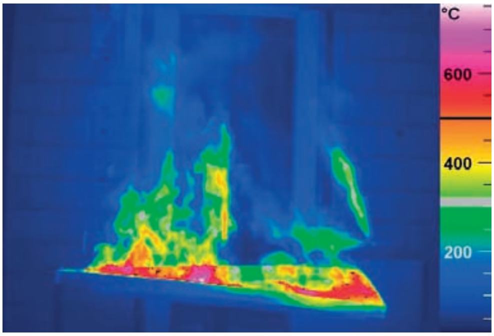


Figure 5.9. Thermal image of the deflection of the pan and separation of molten polyurethane for the free burn test

The deflection caused opposite corners to move up/down and two pools were formed in opposite corner. This together with unconsumed polyurethane around the edged may have caused the second peak/fluctuations in the test with cement board and the free burn test. Whether the deformation of the pan also influenced the peak heat release rate is unknown. It is however noteworthy that peak heat release rates for the two pre-tests were considerably higher (500-600 kW without burner). In these pre-tests no deformations were observed.

It should also be noted, that no second peak was found for the test with linings of mineral wool. This, together with visual observations, indicates that all the polyurethane was consumed during the first peak for this test.

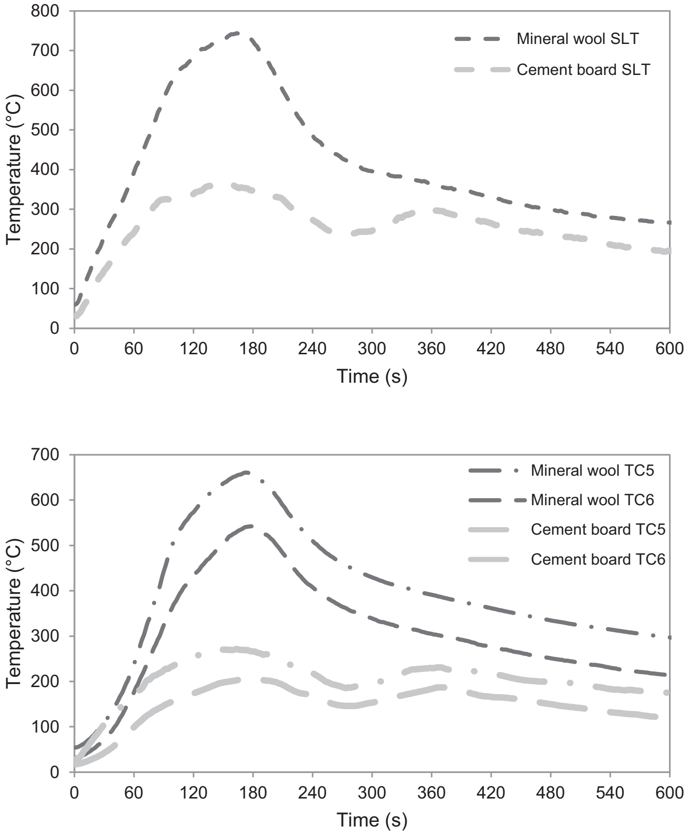


Figure 5.10 Measured temperatures for the smoke layer temperature, SLT (upper panel) and back wall temperatures (lower panel), TC5 is at 2.0 m and TC6 is at 1.0 m above the floor

Figure 5.10 shows the development with time of the smoke layer temperature, SLT in the upper panel and the back wall temperatures are shown in the lower panel. The smoke layer temperature is found as the average of the thermocouple positioned 0.2 and 0.6 m below the ceiling in both thermocouple trees. The wall temperature TC5 is measured 2.0 m above the floor and TC6 is measured 1.0 m above the floor.

Generally, the smoke layer temperatures follow the trend of the heat release rates. The lining temperatures are also, as expected, significantly higher for the mineral wool test, than for the cement board test. Peak values are given in Table 5.6.

The changes in the heat flux with time is shown in Figure 5.11, where measurements from the heat flux gauge facing horizontal toward the flames (HF#1) are shown in the upper panel and measurement from the heat flux gauge facing vertically towards the smoke layer (HF#2) are shown in the lower panel.

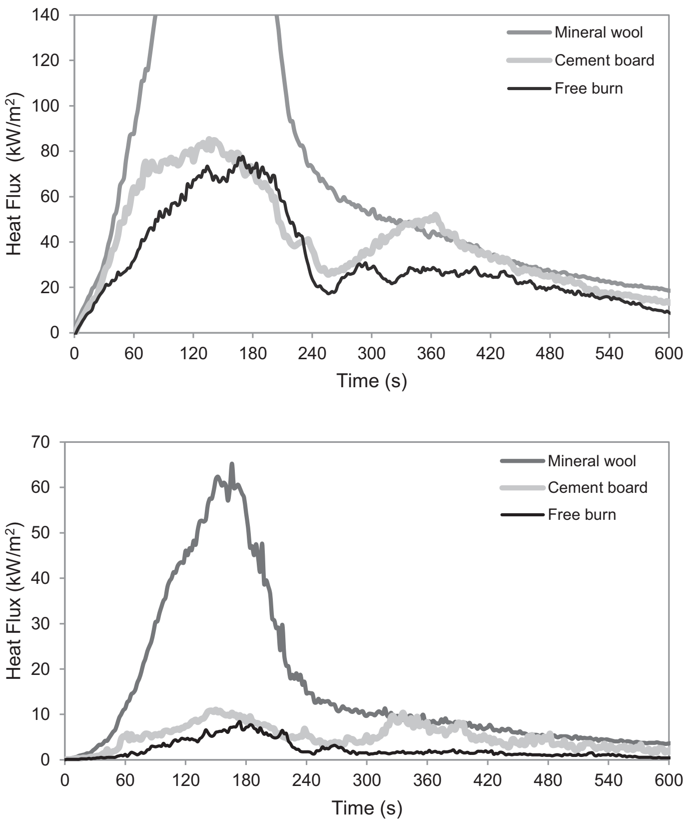


Figure 5.11 Measured heat flux facing horizontally 0.6 m from the pan, HF#1 (upper panel) and facing vertically at the end of the pan, HF#2 (lower panel)

For both heat flux gauges the heat flux is significantly higher for the room test with mineral wool lining as expected from temperature measurements. At a point HF #1 increase out of range of measurements for the test with mineral wool lining, therefore this part of the graph is omitted. It is noted, that HF#1 and 2 increases significantly faster for the room test with cement board compared to the free burn test, which again is related to the faster flame spread for the room test. Also the second peak for the test with cement board linings is more pronounced, emphasising that thermal feedback was present, but no evident effect can be determined from the heat release rate.

To summarize all the measurements, the value at the time for completed flame spread is given in Table 5.5 and all the peak values are given in Table 5.6.

Table 5.5 show the measurement at the time when flame spread is completed. It can be seen that heat release rate for all the tests are within reasonable range of each other, given the uncertainties of estimating the time via IR recordings as well as uncertainties in the measurements of the heat release rate. It can, however, be seen that heat fluxes are comparable for the free burn test and the test with cement board, whereas the test with mineral wool lining has significantly higher heat flux. This may indicate that an effect can be expected of thermal feedback already at this point, which may also be the reason for the higher heat release rate for the test with mineral wool lining compared to the test with cement board lining.

Table 5.5. Measurements at the time when flame spread is completed.

	Free burn	Cement board	Mineral wool
Heat release rate (kW)	339	270	331
Time (s)	96	56	54
Smoke layer temperature (°C)	na	233	354
Upper wall temp. (TC5) (°C)	na	154	174
HF#1 (kW/m^2)	54	56	81
HF#2 (kW/m^2)	2	5	9

The peak values in Table 5.6 show that comparable values are found for the free burn tests and the test with cement board lining, whereas the test with mineral wool lining has much higher values due to the increased heat release rate. It should also be noted that the smoke layer temperature has been raised to 744°C which is significantly above the traditional flashover criterion of 5-600°C.

Table 5.6. Peak values of measurements. Values in brackets are times for meeting the event.

	Free burn	Cement board	Mineral wool
Heat release rate (kW)	474 (204)	507 (150)	932 (172)
Smoke layer temperature (°C)	na	367 (154)	744 (164)
Upper wall temp. (TC5) (°C)	na	271 (164)	660 (174)
HF#1 (kW/m^2)	78 (166)	85 (136)	>150
HF#2 (kW/m^2)	8 (190)	11 (154)	65 (152)

Comparing the two tables it is found that the heat release rate increased significantly after flame spread is completed. From Figure 5.8 it can also be seen that the heat release rate continued growing at about the same rate after the flame spread is completed. Therefore complete flame spread does not seem to affect the rate of which the heat release rate increases in a significant way. In view of equation (1.2) this would be expected, indicating that the burning rate may be influenced by other factors. This increasing heat release rate was also observed in the previous intermediate test [57]. It should be noted that tests in the cone calorimeter indicate that the heat release rate for polyurethane may have two peaks, one just after ignition and one in the pool stage [55]. The latter tends have a significant the larger peak. As the block in both these tests and the intermediate scale test gradually collapses and turns into a pool stage this may explain the delay in the peak, therefore the increase of the heat release rate after complete flame spread rate cannot without further investigation be related to thermal feedback from the room.

5.4 Influence of thermal feedback

5.4.1 Flame spread

The influences of thermal feedback on flame spread rate can be seen as consequence of preheating of the surface. Flame spread can be assessed as successive ignitions of a small area heated by the flame. The flame spread rate v_p can for horizontal flame spread on a block of polyurethane be seen as opposed flame spread on a thermally thick object, which can be found as [26]:

$$v_p = \frac{4 \cdot \dot{q}_f''^2 \cdot \delta_f}{\pi \cdot (k \cdot \rho \cdot c) \cdot \left(T_{ig} - T_s\right)^2} \tag{5.1}$$

Where δ_f is the flame heating length, $\dot{q}_f''$ is the heat flux from the flame k is the thermal conductivity, ρ is the density and c is the heat capacity of the burning object. T_{ig} is the ignition temperature of the object and T_s is the surface temperature of the object prior to ignition. Equation (5.1) is a simple assessment developed on the assumption that $\dot{q}''_f$ is constant over δ_f, that no preheating has taken place, that the flame spread is constant, and that no deformation of the burning object takes place [21].

Equation (5.1) can however be used in at quasi-stage manner in order to investigate the influence of for example preheating [21]. Therefore it can be seen that as the surface temperature increases the flame spread rate will increase. As the surface temperature approaches the ignition temperature, the flame spread rate will in theory continue to increase to an asymptotic infinite fast flame spread rate [21]. It is suggested that this may happen when the external heat flux from the smoke layer reaches the flashover criterion of 20 kW/m^2 [21].

The previous section showed that the flame spread was faster in both room tests than free burn test, which may be caused by preheating. Measuring the preheating of a surface that may shrink is related with substantial uncertainties. As a substitute HF #2 is used. HF#2 is measured at the end of the pan facing the smoke layer. In Figure 5.12 the heat flux and flame spread rates are plotted together as a function of the position of the flame front. The figure shows a qualitative good correlation between the change in heat flux and flame spread rate for the free burn test and the test with mineral wool. The free burn has a slightly increasing flame spread rate and heat flux as the flame front travels over the surface. For the test with mineral wool a similar but more increasing correlation is found. It is noted, that for this test the heat flux was above 9 kW/m^2 when the flame front reaches the end of the block. Polyurethane has been reported [56] to ignite at this level for tests conducted in the cone calorimeter [44]. This indicates that the heat flux at the end of the block was close to a critical heat flux for ignition which supports that the thermal feedback did increase the flame spread rate in this test.

If the change in flame spread rate should have been caused by increasing thermal feedback similar increases in the heat flux and flame spread rates should be found for both room tests as flame spread rates are similar. This is not the case, as the increase of the heat flux is not the same for both room tests, though an increasing trend was found.

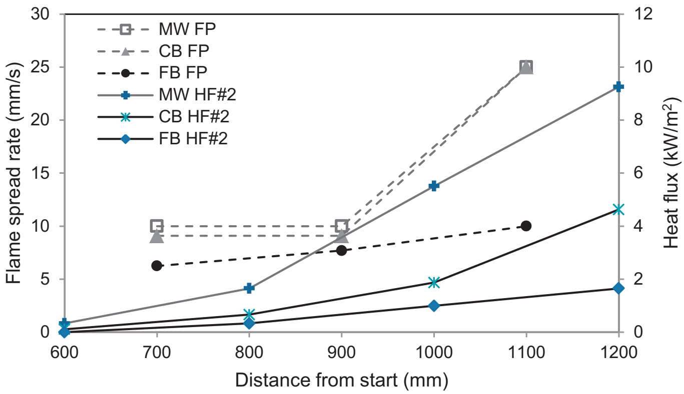


Figure 5.12. Comparison of flame spread rate and heat flux (HF #2) at the end of the pan for different positions of the flame position. MW is short for mineral wool, CB for cement board and FB for free burn.

From Figure 5.11 lower panel it can be seen that HF#2 has a small jump for the cement board test at the time where the flames reach the end of the block. This is also the same increase of the heat flux that is seen at the end in Figure 5.12. The jump is only found for test with the cement board. To further investigate this, an assessment is made in Figure 5.13 of the correlation between the upper room temperature (wall/smoke layer) to the forth power and the heat flux measurements (HF#2), to see if there are any irregularities between the heat flux and the temperature. From the figure it can be seen that for the mineral wool test a good linear correlation is found. For the test with cement board this correlation is not reproduced, indicating that the increase of the heat flux from 2 to 5 kW/m^2 may not be caused by radiation from the upper layer. Therefore a more correct value of the heat flux in Figure 5.12 for the cement board should be lower at the distance 1200 mm. Therefore the same correlation between the heat flux (thermal feedback) and the flame spread rate cannot be found for both room tests.

It is therefore found that the increase of the flame spread rate found it the room tests cannot explicitly be explained by thermal feedback. Further experiments will need to be made in order to do this. It is, however, evident that the flame spread is faster in the room tests than for free burn tests, and the room test with linings of mineral wool that the increased flame spread rate may be caused by thermal feedback.

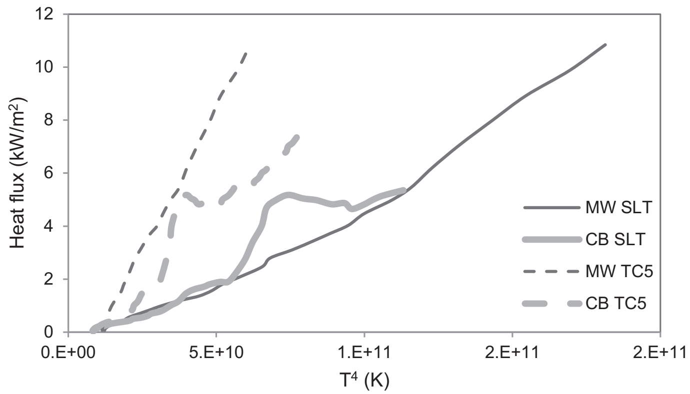


Figure 5.13. Correlation between heat flux measured at the end of the pan (HF#2) and the smoke layer temperature (SLT) and the upper wall temperature (TC5).

5.4.2 Heat release rate

The test with linings of mineral wool had significantly higher heat release rates than the free burn test, indicating that only this test was influenced by thermal feedback.

For the heptane tests a linear correlation was found between $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ where $\dot{Q}_{ext,calc}$ represents the second term of equation (2.5). To investigate if this also applies to the polyurethane $\dot{Q}_{ext,calc}$ is calculated on the following assumptions. First, the full surface should be ignited, to avoid any influence from changing area. T is taken to be the smoke layer temperature. The smoke layer temperature is used, as a good correlation is found between the smoke layer temperatures and the heat flux measured in a direction facing the smoke layer, see Figure 5.13. This good correlation is not found for the wall temperatures (TC5). This choice differs from the heptane tests, where the upper wall temperature gave the best fit. The difference can be explained by the differences in soot production. In the literature a smoke yield of approximately 0.2 g/g is reported for flexible polyurethane and 0.037 g/g is reported for heptane [58].

The surface temperature T_s is not known and assumed to be 350 °C based on IR recordings. Also the test with cement board linings had smoke layer temperatures of up to 365 °C without being affected by the thermal feedback. In the literature [59] a thermal degradation study in air have found that 90 % of the mass is lost between 245 °C and 365 °C, where the mass loss rate has significant peak at 341 °C, and thus supporting a choice of 350 °C. The heat of combustion is found based on the total heat release rate measurements and the mass of the foam as approximately 33 MJ/kg. The heat of gasification is estimated to be 2 MJ/kg [26] and α is set to 1. $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ are plotted against each other in Figure 5.14 for the period from the full surface involvement to the peak heat release rate. The figure shows a good linear correlation which supports that the correlation found for the heptane tests will also apply for the polyurethane test. The gradient of the curve is 0.9, indicating that the exact values of $\dot{Q}_{ext,calc}$ is overestimated.

The correlation between $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ corresponds well to the incipient period found for the heptane experiments. The heptane experiments also describe how a rapid increase of the heat release occurred after the incipient period. This rapid increase was seen as a thermal runaway. The thermal runaway was also seen in the plot between $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ (see Figure 3.17) as point where a linear correlation could not be established anymore. For the polyurethane test a good linear correlation is found until the peak heat release rate, and as no sudden rapid increase of the heat release rate is found, there is no evidence of thermal runaway.

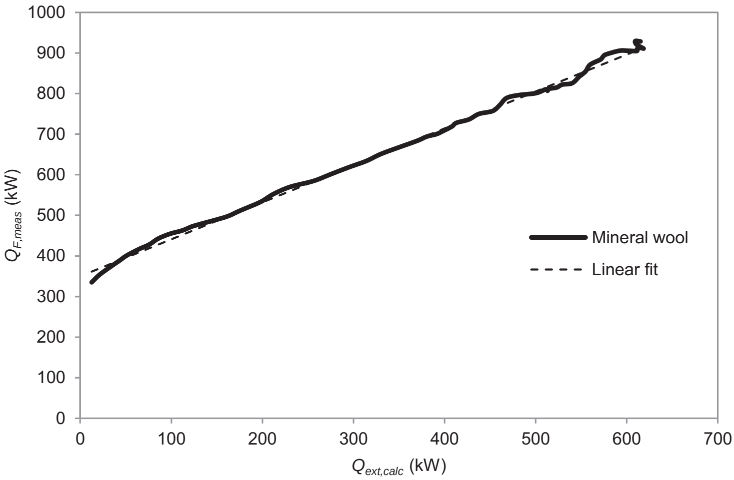


Figure 5.14. Comparison of measured heat release rate (without burner) and calculated external heat release rate for the test with mineral wool linings.

From equation (2.5) it can also be seen that the incipient period starts when the smoke layer temperature exceeds the surface temperature of the burning object. For polyurethane the surface temperatures is roughly estimated to 350 °C, which is significantly below the traditional criteria of smoke layer temperatures of 5-600 °C. Using the correlation found in Figure 5.14 for smoke layer temperatures of 500 °C and 600 °C, the thermal feedback gives an additional heat release rate of 125 kW and 260 kW, respectively. Thus it is found that the heat release rate for polyurethane will increase due to thermal feedback before flashover is predicted according to traditional criteria.

The correlation shown in Figure 5.14 suggests, as the heptane tests, that the calculated heat release rate can be found as a constant plus a contribution from the thermal feedback. As the free burn test and the test with cement board lining are not constant after full surface involvement, these two tests will lead to an overestimation of the heat release rate, if they were used as a basis for estimating the heat release rate for the test with mineral wool lining.

5.5 Summary

The experimental study on a block of flexible polyurethane showed that the heat release rate did increase due to thermal feedback before flashover would be predicted using traditional flashover criteria for smoke layer temperatures.

The test showed, as the heptane experiments, that the heat release rate rose as a function of the upper room temperature, but whereas the heptane test had the best fit for wall temperatures, the polyurethane tests had the best fit for the smoke layer temperature. This is explained by differences in the smoke yield.

The experiments with polyurethane support the heptane tests in that free burn tests may not be the best basis for prediction of the room the heat release rate in the room tests.

It was also the intention to study the flame spread rates. The experimental results showed that flame spread rates are faster in the room tests than the free burn tests. No direct correlation to the thermal feedback could be found.

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Part III Summary, conclusion and future work

6 Summary of results and relations to design fires

The research objectives of this study were to make an experimental study of the influence of thermal feedback on the burning behavior of pre-flashover well-ventilated room fires. This was carried out in relation to

- the change of the heat release rate,
- the influence of changing linings on the onset point of thermal runaway and
- secondarily, the changes in flame spread on a horizontal surface.

Also, the study was limited to well-ventilated, pre-flashover fires in rooms with non-combustible linings.

In order to carry out this study an experimental method was used and two experimental series were conducted according to the method. The results of these two test series, as well as data kindly supplied by NRC, constitute the data used for this study. The total program of test series was:

- 10 different full scale experiments of varying sizes of heptane pools tested under free burn conditions and in rooms, varying in terms of the thermal inertia of the linings. These tests were performed as a part of this project.
- 3 different full scale tests on a horizontal positioned block of polyurethane tested under free burn conditions and in rooms, varying in terms of the thermal inertia of the linings, as for the heptane tests. These tests were also performed as a part of this project.
- 16 experiments conducted as a part of the “Design Fires for Commercial Premises Part 1 and 2 Program” (DFCP1 and DFCP2) carried out by Carleton University and NRC-IRC. In these tests fire loads representing commercial premises were carried out in rooms varying in terms of the thermal inertia. No free burn tests were performed.

6.1 The experimental setup

The first part of the study aimed at developing an experimental method to isolate the effect of the thermal feedback from other types of impact on the burning behavior. The first step in developing this method was to study theory. Here it is suggested that the heat release rate in a room fire could be estimated as the heat release rate under free burn conditions plus a contribution from the thermal feedback, as formulated in equation (2.5)

$$\dot{Q}_F \approx \dot{Q}_{F,0} + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\alpha \cdot \sigma \cdot \left(T^4 - T_s^4\right)}{L_g} \right) \tag{2.5}$$

Based on this correlation, it was decided that identical objects should be tested under different conditions, including free burn conditions and room burn test. This way the free burn tests could give information about the first term of equation (2.5), as the second term could be found as the difference between room burn tests and free burn tests.

In addition, two room burn tests should be conducted with varying linings of substantially different thermal inertia. By changing the linings the room temperatures were changed, and thus the thermal feedback without changing any other parameters. Thereby the free burn heat release rate could be decoupled from equation (2.5) as equal room temperatures should give matching heat release rates. This would also indicate if the free burn heat release rate is the best way of estimating the first term of equation (2.5).

Changing the linings would also allow for a study of the influence of changing thermal inertia on the onset point of thermal runaway.

To measure the effect of the thermal feedback, heat release rates and temperatures in the room (wall and smoke layer) should be measured to supply the parameters in equation (2.5). Also, it was decided to measure mass loss rate to support the heat release rate, and heat flux was measured to support the temperature measurements.

The experimental setups used were similar to the ISO room corner test [7] in order to create pre-flashover, well-ventilated conditions.

From the experimental results, as explained further in the next section, it is learned that the profound differences in free burn conditions and room burn conditions means that free burn measurements were not the best fit for the first term in equation (2.5). A better fit would be the heat release rate measured at the time, when the room temperature exceeds the surface temperature. Also, the study on the flame spread rate indicated that even early in the experiment, a difference was found between room burn conditions and free burn conditions. Therefore it is found that the effect of thermal feedback may better be found from performing room burn tests with significantly different thermal inertia, as described by the method, than by comparing between free burn and room burn tests.

6.2 Summary and comparison of experimental results

6.2.1 Change of the heat release rates

This part of the study was performed by using three different sizes of round heptane pools (0.35 m, 0.50 m and 0.70 m) as benchmark tests. To see if the results from the heptane tests could be reproduced for a critical and common material, a block of flexible polyurethane (0.60 m x 1.20 m) was also studied. Both heptane pools and the polyurethane block were tested under free burn conditions, and in rooms with two different non-combustible linings. In both cases one of the linings was mineral wool, and the other type of lining was a light weight concrete for the heptane pools and cement boards for the polyurethane. For this part of the study, it was also ensured that the burning area was constant, to avoid any influence of changing area.

An effect of the thermal feedback was found in the room tests for the heptane test with the large pool (0.70 m) and the polyurethane test with mineral wool lining. For some of the heptane tests with the medium pool (0.5 m) there were weak indications of an effect of thermal feedback, but this was not evident, therefore no further analyses could be made on the these experiments. The remaining tests did not show any sign of an effect of thermal feedback.

The large pool fire tests confirmed that equal room temperatures should give matching heat release rates (see Figure 3.15). Also, a good linear correlation was found between the measured heat release rate and an external heat release rate calculated by the use of the second term of equation (2.5) using wall/smoke layer temperature as input. This correlation can be seen from Figure 6.1, where both tests with the large heptane pool as well as the polyurethane test with linings of mineral wool are shown. The heptane pool tests are shown for the period until thermal runaway was identified, and the polyurethane test is shown from the time of full surface ignition until the peak heat release rate was reached.

The linear correlation between the measured heat release rate and the calculated external heat release rate found in Figure 6.1 shows that the first term in equation (2.5) should be a constant.

Both the free burn heptane tests and the polyurethane test did, however, not have a constant heat release rate after the full surface was ignited. For the heptane test an attempt was made to calculate the heat release rate based on the free burn heat release rate (see Figure 3.16) and no good correlation was found.

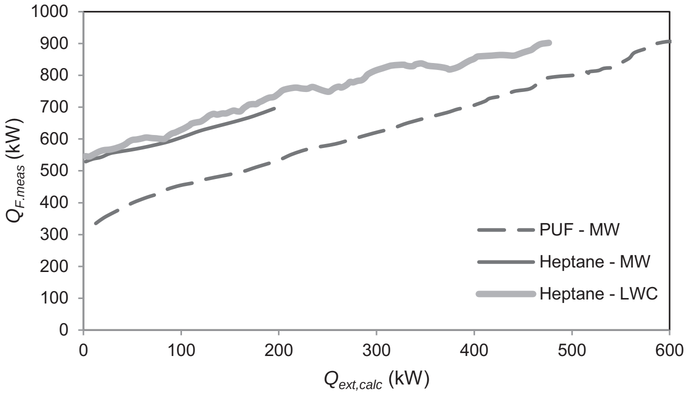

Figure 6.1. Comparison of measured heat release rate and calculated external heat release rate for the 0.70 m heptane pool and the polyurethane foam test. Extension MW shows that linings were of mineral wool and LWC shows that linings were of light weight concrete.

Based on both the heptane tests and the polyurethane test, it is therefore suggested that $\dot{Q}_{F,0}$ is taken as a constant offset value found as the heat release rate measured in the room at the time when the smoke layer/wall temperature exceeds the surface temperature. Therefore equation (2.5) may better be written as:

$$\dot{Q}_F \approx \dot{Q}_{TS} + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\alpha \cdot \sigma \cdot \left(T^4 - T_s^4 \right)}{L_g} \right) \tag{6.1}$$

Here $\dot{Q}_{TS}$ is the heat release rate for the object at the time when the upper room temperature exceeds the surface temperature of the burning object. The upper room temperature is either the surface temperature of the linings in the upper zone or the smoke layer temperature depending on emissivity of the smoke layer.

Using a constant offset value also means that any increase in the free burn heat release rate taking place after the time for T=T_s is neglected. For the polyurethane test this effect is illustrated in Figure 6.2. Here the offset value for the mineral wool test is plotted together with the development of the heat release rate for the test with mineral wool and the free burn test. From the figure it can also be seen that taking the free burn value and adding the effect of the thermal feedback may overestimate the room burn heat release rate.

As the effect of thermal feedback is present very early in all the three tests where an effect of thermal feedback was found, it would be interesting to see if the assessment of using $\dot{Q}_{TS}$ instead of $\dot{Q}_{F,0}$ also is valid for tests where T=T_s is not reached early in the test. According to equation (2.5) this should be the case.

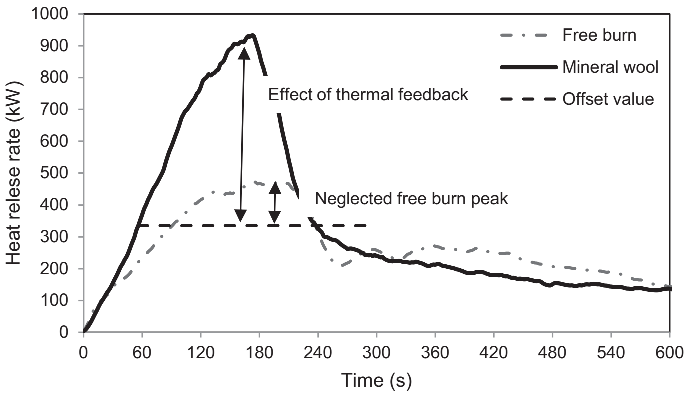

Figure 6.2. The difference between the offset value and the free burn heat release rate for the polyurethane test.

In relation to equation (6.1) the experiments show that α was found to be in the range of 0.85 and 0.9. This range was found based on estimated values of L_g. Therefore the test would support an α-value of 1.0. This also indicates that absorption/blockage of the thermal feedback from the flames/evaporating gasses can be neglected.

After the onset point of thermal runaway the heptane tests showed that equation (2.5) is no longer valid (see Figure 3.17), and thus that development of the heat release rate was no longer dominated by the wall/smoke layer temperature. Also, from the DFCP2 tests it was learned that the increase of the heat release rate was no longer dominated by the type of material burning. It was, however, found in both test series that the growth rates with time were similar after the onset point of thermal runaway. This growth rate was no reproduced between the experimental series.

For some of the tests it was evident that there was no effect of thermal feedback. For the polyurethane test with cement board lining this could be explained by the smoke layer temperature not exceeding the surface temperature of the fuel, and therefore there was no net heat flux to the burning surface from the room. For the heptane tests the room temperature in this case represented by the wall temperature, did exceed the surface temperature of the burning object. An analysis of the size of the pool and the measured wall temperature showed that the expected magnitude of the thermal feedback represented by the second term of equation (2.5) would be small (see Figure 3.18). This may explain why no effect of thermal feedback was present. It was also noted that the flames for these tests did not impinge the ceiling, which compares well to other experiences from pool fire tests, where no effect of thermal feedback was found [39].

As the free burn tests did not serve as a solid basis for estimating the room burn fire behavior, and as it was found that the free burn heat release rate in some instances (small heptane pool) would be larger than the heat release rate found in the room, the tests indicate that free burn experiments should be used with caution for prediction of room burn fire behavior.

6.2.2 Change of flame spread rate

Flame spread was only recorded for the polyurethane tests. The tests showed that the flame spread would be faster for the room burn than for the free burn. This difference was most significant as the flame front reached the end of the test specimen. Also, it was found that the free burn test had a slightly increasing flame spread rate, whereas the room flame spread rate would increase faster with time approaching a rather fast flame spread rate. No significant different was found between the two room tests regardless of significant different room temperature. Therefore the experimental data could not show any correlation to the thermal feedback. As a difference was found between free burn and room burn, the flame spread data support the use of room burn test for assessing design fires for rooms.

6.2.3 The onset of thermal runaway

This part of the study aimed at investigating the influence of the thermal inertia in relation to the onset of thermal runaway. This was done by evaluating the experimental results from the heptane tests and the DFCP1 and DFCP2 tests, as these tests allowed a comparison to similar fire loads test in similar room with two different linings having substantial thermal inertia. Thus a parameter analysis could show the difference in results caused by the change in thermal inertia.

In principle it has been proposed, that thermal runaway can be seen as a “jump” in the heat release rate [31] occurring in a room as the heat gained in the smoke layer from the fire, G exceeds the heat that can be lost from the smoke layer, L and the two curves plotted in a Semenov diagram are tangent. When these two criteria are met, a critical point is reached and a rapid increase of the heat release rate will take place, which in theory is only limited by ventilation. This critical point can therefore be characterized by a critical temperature satisfying both terms for the relations between heat gained and lost.

The heat gained is a function of the heat release rate which is a compounded variable that depends on several parameters. For a well-ventilated fire, an increase of the heat release rate can result from an increasing burning area (fire spread), an increasing heat release due to thermal feedback as explained in section 6.2.1 or a combination of both. The heat lost is the sum of losses through the boundaries caused by airflow out of the room, accumulation of energy in the linings or radiation losses to the floor or through the openings. This is a complex two-zone model that has been described in the literature [31-33].

Changing the thermal inertia of the linings will lower the loss curve in the Semenov diagram. Consequently, the critical temperature for causing thermal runaway and the heat release rate associated with this temperature may also decrease. More precise estimates found by the use of models that have indicated that lowering the thermal inertia of the linings lead to lower onset temperatures of thermal runaway [34, 35].

From the experimental results it was found that for both of the room tests with the large heptane pool and for the DFCP2 tests a sudden rapid increase of the heat release took place at some point in the fire course. This is seen as an onset point of thermal runaway.

For the heptane pools the onset point of thermal runaway was observed to occur at a smoke layer temperature of 350 °C and a wall temperature of 330 °C for the test with the mineral wool lining. For the light weight concrete lining the smoke layer temperature was 530 °C and the wall temperature was 460 °C.

For the DFCP2 tests with linings of ceramic fibers the onset points of thermal runaway were found for temperature (measured 20 mm below the ceiling) at around 300-420°C, but only for fire loads composed of a mixture of wood/cellulose and various amount of plastics, food, textiles and rubber/leather. For a fire load composed of pure wood/cellulose the onset of the rapid increase of the heat release rate did not occur until the room temperature reached 725 °C. For similar object tested as s part of the DFCP1 program with linings of cement board thermal runaway was not observed.

Thus the results confirm the model predicting that lowering the thermal inertia can give lower onset points of thermal runaway [34, 35].

A further investigation of the DFCP2 tests indicated that the onset point of thermal runaway was caused mainly by the thermal feedback increasing the heat release rate for fire loads composed of a mixture of wood/cellulose and various amount of plastics, food, textiles and rubber/leather. This was not the case for the fire load of pure wood/cellulose as fire spread, and thus a significant increase of the burning area, was causing the rapid increase of the heat release rate. It is therefore also found that the type of material has an influence on the critical temperature at the onset of thermal runaway. This can be explained by the gain curve, which can be described by the second term of equation (6.1). For materials such as wood the ratio between ΔH_{ef} and L_g is an order of magnitude lower than for example plastics and consequently the gradient of the gain curve is much lower for wood than for plastics. This also means that the gradient of the loss curve should be lower for fire loads of pure wood to cause thermal runaway.

It is also noted that the critical temperature was below the traditional flashover criterion of 5-600 °C at the onset point of thermal runaway for some of the tests with the low thermal inertia. This will be discussed in relation to design fires in the following section.

6.3 Influence of thermal feedback on pre-flashover design fires

The experimental study shows that some pre-flashover fires may be influenced by thermal feedback from the room. In these cases the effect of thermal feedback can be divided into two phenomena that correlate well with theory. These are:

- An incipient period, where the heat release raise as a function of the upper room temperature.
- An onset point of thermal runaway occurring as heat gained in the upper layer exceeds the heat that can be lost.

The experimental study also showed that the development of the heat release rate during the incipient period may be found based on equation (6.1). After the onset point of thermal runaway the equation is no longer valid.

Equation (6.1) was used for the assessment of the fire tests. In relation to an appropriate assessment of design fires in general equation (6.2) should be used. Equation (6.2) is a combination of equation (2.4) and (6.1), where α is set to one based on the experience from the experimental results.

$$\dot{Q}_F \approx \dot{Q}_{TS} + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\sigma \cdot \varepsilon_g \cdot \left(T_g^4 - T_s^4\right) + \sigma \cdot \left(1 - \varepsilon_g\right) \cdot \left(T_w^4 - T_s^4\right)}{L_g} \right) \qquad (6.2)$$

In view of equation (6.2) it is found that in order to predict the impact of thermal feedback (the second term of the equation) information is needed on the upper room temperature, the type of material, the area and the gas emissivity. In case that the view factor between the burning object and the smoke layer is not 1, equation (6.2) should be adjusted accordingly.

The upper room temperature can be found by the use of an appropriate model based on the energy balance for the room. It is important that the model takes the thermal inertia of the linings into consideration, as lowering the thermal inertia will give an increased upper room temperature, and thus a higher impact of thermal feedback. Therefore it is also important that popper input data is selected.

The type of burning material should be represented by the surface temperature of the burning object, the ratio between the heat of combustion and the heat of gasification ($\Delta H_{eff}/L_g$) and preferable also the smoke yield. The surface temperature is important at it gives the lower level for the starting point of the impact of thermal feedback. The ratio $\Delta H_{eff}/L_g$ gives the growth rate of the heat release rate due to the thermal feedback and the smoke yield can be used to determine the gas emissivity.

Quintiere [26] has divided the burning materials into 3 categories depending on their flammability parameters. Using these categories, see Table 6.1, the impact of thermal feedback may also be explained in relation to the type of materials. Starting with the surface temperature it can be seen, that for liquids, as heptane, an effect of thermal feedback may in principles be found at a rather low room temperature. For solids in general a higher room temperature would be needed to cause an effect of thermal feedback. The magnitude of the increase of the heat release rate is also, as mentioned, related to the ratio $\Delta H_{eff}/L_g$. This ratio is in the same range for liquids and melting solids as flexible polyurethane, whereas $\Delta H_{eff}/L_g$ is significantly lower for charring solids as wood. This correlates well to the book store in the DFCP2 tests where the fire load was composed of purely wood/cellulose. In this test no impact of thermal feedback was found before flashover, whereas an effect of thermal feedback was found before flashover for the heptane tests and the polyurethane tests.

Table 6.1. Typical material fire properties [26]

Group of materials	ΔH_{eff} (MJ/kg)	L_g (MJ/kg)	T_s (°C)
Liquids	20-40	0.5-1	100-400
Melting solids	20-40	1-3	250-400
Charring solids	5-15	5-8	350-500

The level of surface temperature may also be viewed in relation to the fire safety objectives.

Many countries favor a tenability criterion for life safety of 2.5 kW/m^2 [14, 15]. For a small room with a uniform smoke layer temperature this would apply to a smoke layer temperature of 185 °C assuming black body conditions. This implies that the occupants should be out of the room of fire origin, before an effect of thermal feedback would be found, if the fire load was composed of melting and charring solids. For larger rooms there may not be a uniform smoke layer temperature as temperatures may be higher close to the fire than far away from the fire. For these rooms there may be an effect of thermal feedback, but this would be more pronounced for melting solids due to the lower heat of gasification.

For assessing structural stability room temperatures may be much higher than 185 °C and therefore the impact of thermal feedback should be taken into consideration especially for fuel controlled fully developed fires.

In order to make a proper assessment of the design fire it should be determined if and when flashover occurs. For engineering purposes it has generally been accepted that the onset of flashover will take place when the smoke layer exceeds the flashover criterion of 500-600°C [2]. This would relate well to a sudden ignition of most combustible objects in a room [21], and as such to flame spread. Thereby other processes, which may contribute to the flashover process as thermal runaway caused by thermal feedback, are not considered directly.

The experimental investigation showed that for linings with low thermal inertia (mineral wool or ceramic fibers) thermal runaway did occur for a fire load of heptane and for fire loads composed of a mixture of wood/cellulose and various amount of plastics, food, textiles and rubber/leather. The temperature at the onset point was found to be in the range of 300 – 420 °C, which is significantly below the flashover criterion. The tests also indicated that the onset points of thermal runaway, primarily were dominated by the thermal feedback and not by fire spread. Fire spread occurred shortly after the onset points of thermal runaway and not just before, as would have been expected if fire spread should have caused flashover. This was not found for linings of more average thermal inertia as cement board or for fire load composed purely of wood/cellulose.

Therefore the tests show that the traditional criterion for smoke layer temperature is not always a conservative assumption, but there are cases where the thermal runaway initiated by thermal feedback also should be taken into consideration. This could be buildings with linings having fire loads of flammable liquids or melting solids and very low thermal inertia, as could be the case for highly insulated building.

As the traditional flashover criterion often is a basis for simplified traditional models as well as these models use simplified assessments of the energy balance, these models cannot be expected to predict the onset of flashover as found by the tests. In these cases models including thermal feedback as well as thermal runaway should be applied. This is especially important if the design fire is selected in order to show that flashover would not occur.

7 Conclusions and future work

7.1 Conclusion

This thesis aimed at an experimental study of the influence of thermal feedback on pre-flashover well-ventilated fire.

An experimental method was developed to measure the thermal feedback. This method included test on similar object tested under free burn conditions as well as room burn conditions. Two room burn tests with non-combustible linings were carried out for each object. Only the thermal inertia was varied between tests, and thus the magnitude of the thermal feedback was differed without changing other parameters. The experimental investigation showed that the method could isolate the influence of thermal feedback for further analysis, even without performing free burn tests. The experimental setup was primarily based on the ISO Room Corner test facility or fire rooms of similar sizes.

29 experiments were studied varying in type of combustibles and type of linings.

It is found that thermal feedback may increase the heat release rate for pre-flashover fires, but this is not always the case. Two phenomena that are well correlated with theory are found.

In an incipient phase the heat release rate will rise as a function of the temperature of the smoke layer/warm linings and the flammability parameters of the burning object. This can be described by a model, and estimates of the increasing heat release rate can be made for this phase.

A rapid increase of the heat release rate commenced after the incipient period. The rapid increase is seen as a thermal runaway that is caused by temperatures in the upper layer, as energy gain by the smoke layer exceeds the energy that can be lost through the boundaries. Neither wall temperature/smoke layer temperature nor type of burning materials seem to be the dominant factor in determining the heat release rate after thermal runaway has started.

The thermal inertia of the linings and flammability parameters are found to change the onset point of the thermal runaway as lower thermal inertia leads to lower temperatures and thus the times for thermal runaway. For linings with thermal inertia corresponding to what can be found for thermal insulation, the temperature in the upper zone was found to be in the range of 300 – 420 °C at the onset point of thermal runaway. As thermal runaway is also associated with flashover, the results show that thermal runaway may occur before the traditional flashover criterion of 500-600°C. As many simplified engineering models for assessing flashover use this criterion as a basis, these models should be used with caution.

Traditionally the heat release rate in a room fire has been proposed to be the sum of the free burn heat release rate in addition to a contribution from the heat flux induced by the room. This cannot be reproduced by the tests. A better basis is found to be the heat release rate measured under room burn condition at the time when the temperature of the smoke layer/warm linings exceeds the surface temperature of the burning object.

The experiments also indicated, supported by theory that the level for when thermal feedback should be considered for design fires, can be taken as the surface temperature of the burning object.

It was the intension to study the change in flame spread rates due to thermal feedback. The experiments showed that flame spread rates were faster in room than under free burn conditions. No correlation to the thermal feedback could be established.

Given the profound difference between the room burn tests and the free burn tests as well as the difference between room burn tests with varied linings, it is recommended to show great caution if free burn tests are to be used in design fire scenarios especially if no corrections are considered for thermal feedback.

7.2 Future work

In this part of a thesis one can wish for anything, but one has to be realistic.

Some of the things that I would have liked to investigate further are:

- Performing similar experimental series of other types of materials as solid charring object.
- It would also be of interest to perform tests where the surface temperature of the burning object was not exceeded right away, to confirm the validity of the offset value for equation (6.1).
- The experimental setup can be developed further in relation to estimation of thermal feedback. I only measured to wall temperatures in two positions. In future experiments the lining temperature should be measured in more places on the wall and on the ceiling.
- To decouple the experimental results from the from the room size, the experiments could be performed in other room sizes, preferable larger room.
- I did not succeed in finding a correlation between the increased flame spread rate in room and the thermal feedback. I find this important to investigate, as my results show that this happens early in the tests.

- My experiments were limited to non-combustible linings. In principles the same increase of the heat release rate due to thermal feedback should be found for combustible linings. Therefore it would be interesting also to include combustible linings.

Now I will leave it up to others to investigate this.

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Part IV Appended papers and report

Paper I

Experimental Study on the Burning Behavior of Pool Fires in Rooms with Different Wall Linings

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Experimental Study on the Burning Behavior of Pool Fires in Rooms with Different Wall Linings

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Abstract. An experimental test series, comprising 10 experiments with varying pool sizes, lining materials and amounts of liquid burning, was conducted under free burn and room burn conditions. The thermal feedback from the enclosure (ISO 9705 Room Corner Test facility) enhanced the burning rate of the pools and resulted in a thermal runaway in some of the runs. The onset of the thermal runaway, which can be associated with flashover, varied with all the input parameters. The lining with the lowest thermal inertia lead to the fastest increase in the heat release rate (HRR) in the enclosure and caused flashover in the shortest time. Given the profound difference between the enclosure tests and the free burn tests and also between enclosure tests with different linings, it is recommended to show great caution if free burn tests are to be used in design fire scenarios.

Keywords: Heptane pool fire, Thermal feedback, Large scale experiments, Enclosure fire, Thermal runaway

1. Introduction

Proper selection of a design fire is necessary for successful performance-based fire safety design, and one of the key data inputs for the design fire models is the heat release rate, HRR [1]. It has become common practice to use HRRs from free burn experiments for the input as such data are easy to obtain. However, the design fire should reflect the phenomena occurring during a fire and given the fact that the HRR is very sensitive to enclosure effects such as the oxygen level and the thermal feedback there is a need for input data from enclosure experiments in order to approach more realistic modeling of design fires [2].

The thermal feedback can increase the HRR per unit area, the flame spread rate, and hence lead to flashover in the room [3]. Still, the HRR for a pre-flashover fire has typically been assumed not to be dominated by the thermal feedback [4], even though the effect on the fire development has been recognized [5].

Several studies on intermediate and full scale pool fire experiments have compared the mass loss rate and the HRR in free burn versus room burn conditions. Thomas et al. [6] used a Room Corner test facility [7] to study the effect of

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quantity and position of ethanol pool fires. They found the level of the HRR to be dependent on the pool location and ranked the HRR magnitudes as front–back–centre in a descending order, with the HRR of the centre location being comparable to that of free burn test. In experiments with heptane pools in a ½ height room, Parkes [8] found that when the flames did not impinge the ceiling, the HRR was not significantly influenced by the thermal feedback from the room. By increasing the pan size, the flames impinged the ceiling and this resulted in an increase in both the flame's optical thickness and the room temperature. In the latter case the HRR increased as compared to the values from the free burn. Pierce et al. [9] restricted the ventilation for heptane pool fires by narrowing the door opening and found that the HRR was increased due to the enhanced smoke levels. These experimental series generally showed that the HRR levels in enclosures differ from the free burn values as a consequence of the thermal feedback from the walls and/or the smoke layer. Also, limiting the airflow can increase the room temperature and the emissivity of the smoke layer leading, to an enhancement of the thermal feedback.

Models show that a thermal runaway (sometimes referred to as thermal instability) can occur in enclosure fires [3, 10, 11]. The thermal runaway (heat gain surpassing heat losses) is also associated with flashover and theoretically the runaway is only controlled by the ventilation conditions. These models also indicate that enhanced levels of the HRR as compared to the free burn values can be critical for the pre-flashover fire development. By isolating different parameters the models have listed the aspect ratio [12], the thermal inertia of lining [13, 14] and the discharge coefficient [15] as parameters influencing the onset of flashover. Furthermore, the analyses generally mentioned that experimental validation was needed, which is in agreement with the fact that the CFD modeling in references [6, 8, 9] was unable to fully reproduce the results of the experimental tests.

This experimental study investigates the effect of the thermal feedback resulting from changes in the lining material and hence the thermal inertia of the enclosure and compares the results to the free burn conditions. The focus will be on the increase of the HRR per unit area. Therefore, only burning objects with a fixed surface area will be included in this study to avoid influence of flame spread. Further, oxygen limitations are avoided as much as possible, because oxygen limitations can lead to reduction of the HRR and may neutralize some of the effect of the thermal feedback [16]. Heptane was chosen as burning object as it is a material with well known combustion properties.

2. Experimental Setup

The main objective of the experiments was to investigate the impact of thermal feedback on the HRR of an object with a fixed area burning in a room in comparison with results from free burn experiments.

The experimental setup was chosen to be the ISO 9705 Room Corner Test facility [7] representing a small room that will not be ventilation controlled before flashover, see Figure 1. The size of the room and the hood as well as the design

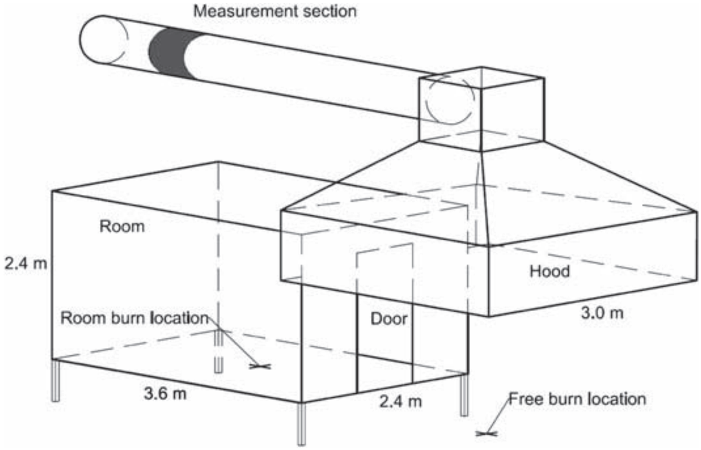

Figure 1. Principal sketch of the experimental setup.

and type of exhaust and measuring section was certified in accordance with the standard [7].

The test setup allowed for room tests and free burn tests under the same hood and thus enabled use of the same instrumentation for the HRR measurements.

The mass loss rate, MLR, was recorded using a scale with a maximum capacity of 80 kg and an uncertainty of 50 g. During the free burn tests the scale was positioned underneath the pan and protected by a substrate. The room was lifted 0.55 m above the main floor, which allowed for a hole to be drilled in the test room floor and, as a result, the scale could be positioned underneath the room and as such be protected from the heating in the room, see Figure 2.

As both the lining surfaces and the smoke layer can contribute to the thermal feedback to the burning object, both the surface temperature and the room temperatures were recorded. The room temperatures were recorded by two thermocouple trees in opposite corners of the room at a distance of 0.4 m from the walls, see Figure 3. The vertical spacing between the thermocouples was 200 mm throughout the entire height of the room, see Figure 2. Surface temperatures were measured at the back wall by thermocouples located 1.0 m and 2.0 m above the floor. All thermocouples were type K with an uncertainty of less than 1 K. The HRRs were based on measurements in the duct and calculated according to ISO 9705 [7]. The uncertainty of the measurements of HRR has been reported in the literature to be 10% or less [17].

A heat flux meter was positioned 5 cm from the object pan facing upwards towards the smoke layer, as shown in Figure 3. Vertically, the heat flux meter was positioned 3 cm below to top of the outer pan. In the room tests the heat flux to the back wall was measured facing the fire in a horizontal direction at 1.2 m above the floor, see Figure 2. The heat fluxes were measured with a Gardon gage model no. 64-5-18 from Medtherm Corporation with an absorbance of 0.92 and a maximum range of 50 kW/m^2 with an uncertainty of less than 3%.

All measurements were recorded every 5 s.

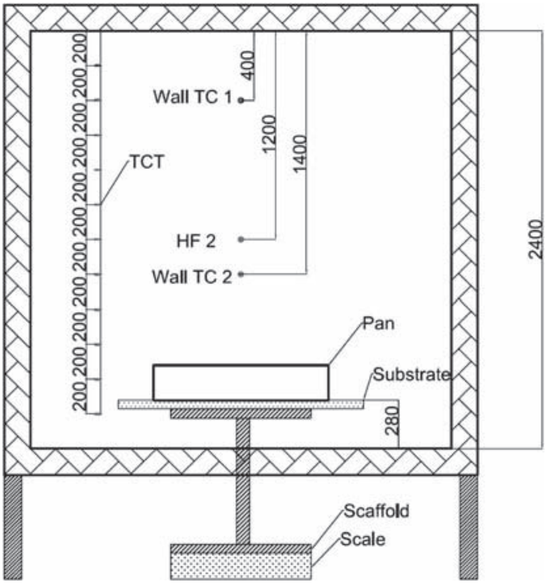

Figure 2. Room burn test setup, section. HF is heat flux gauge, TC is thermocouple and TCT is thermocouple tree. Units are in mm.

As different thermal inertia of the linings can give different room temperatures and thus different thermal feedback to the burning object, two different types of linings were used. Lining 1 was non-combustible stone wool with density, thermal conductivity and heat capacity of approximately 90 kg/m^3, 0.05 W/mK and 0.8 kJ/kgK, respectively, giving a thermal inertia ($k \cdot \rho \cdot c$) of approximately 0.0036 kW^{2}s/m^{4}K^2. This material was chosen as it would remain stable during the test irrespectively of room temperatures, has a low thermal inertia that quickly can lead to high room temperatures and has a limited contribution to the heat release in the room. Lining 2, also non-combustible, was light weight concrete blocks covered with a thin plaster (the walls of the test room), which was dry as it had gone through heating in past tests. The lining was estimated to have a density of 600 kg, a thermal conductivity of 0.15 W/mK and a heat capacity of 1.0 kJ/kgK, yielding a thermal inertia for lining 2 of 0.090 kW^{2}s/m^{4}K^2.

Heptane pools of different sizes (0.35 m, 0.50 m and 0.70 m diameter), ignited by a torch, were used as burning objects as this provides a set of fixed burning areas with a well-documented fuel. Previous fire tests [8] have indicated that an increase of the HRR could be expected when flames impinge the ceiling. The pool sizes were therefore chosen so that the calculated values of the flame height were below (the two smaller pans) and above the ceiling height (the largest pan).

The ISO 9705 room has a ceiling height of 2.4 m. As the pans were placed on a scaffold as a part of the measurements of mass loss rate the height from the initial surface of the liquid to the ceiling was approximately 2 m. Parameter analysis using simple models for prediction of the onset of a thermal runaway showed that thermal runaway could happen for room temperatures as low as 350°C [3]. By

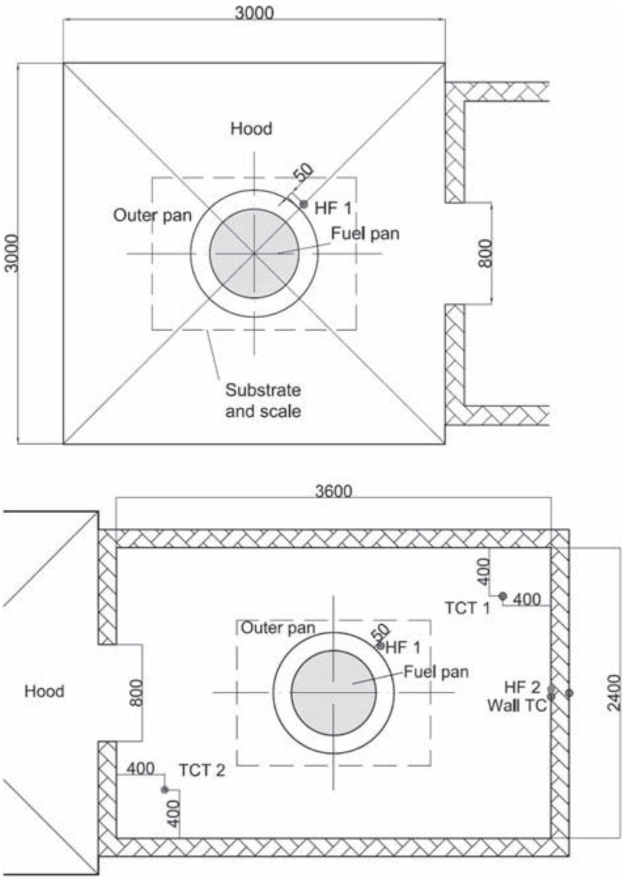

Figure 3. Free burn (*upper panel*) and room burn (*lower panel*) test setup, HF is heat flux gauge, TC is thermocouple and TCT is thermocouple tree. Units are in mm.

using these thresholds for room temperature and flame heights an effect of thermal feedback could be expected for the large pool in both room test and for the medium pool for lining 1, but not for lining 2. No effect was expected for the small pan.

The pan was placed in the middle of the room to minimize plume entrainment effects by the walls as well as local wall heating from impinging flames.

The experimental test series comprised 10 experiments with varying pool sizes, lining materials and amounts of liquid burning under free burn and room burn conditions, as shown in Table 1, which also provides estimates of room temperatures, mean flame heights and mass loss rates.

The pans were made of carbon steel with a thickness of 3 mm and had lip heights of 152 mm for the small pan and 200 mm for the rest of the pans. The amount of liquid was chosen to allow for approximately 10 min duration of burning, except for one experiment where an additional 50% of liquid was added. This

Table 1
Experimental Matrix with Expected Temperature Results Based on the Free Burn Model

Test no.	Pan diameter (m)	Amount of heptane (l)	Mean flame height[a] (m)	Mass loss rate[b] (kg/m^2s)	Temperature lining 1 (stone wool insulation)[c] (°C)	Temperature lining 2 (light concrete)[c] (°C)
1	0.70	25	2.75	0.054	Free burn	Free burn
2	0.70	25	2.75	0.054	720	–
3	0.70	25	2.75	0.054	–	560
4	0.50	10	1.70	0.043	Free burn	Free burn
5	0.50	10	1.70	0.043	390	–
6	0.50	10	1.70	0.043	–	310
7	0.50	15	1.70	0.043	–	310
8	0.35	4	1.25	0.032	Free burn	Free burn
9	0.35	4.2	1.25	0.032	200	–
10	0.35	4.2	1.25	0.032	–	160

[a] Flame heights are estimated for free burn fires using Heskestad theory [18]
[b] Mass loss rates are estimated for free burn fires using data and models presented by Babrauskas [19]
[c] The temperature is calculated as expected temperature increase for 10 min steady burning at the given mass loss rate (using the MQH model [20])

leaves exposed lips on the pan of 110 mm for the small pan, 150 mm and 125 mm for the medium pan and 135 mm for the large pan. The exposed lip height increased during the tests as the fuel burned away. As the purpose of this test series is to investigate the thermal feedback, heating up of the test specimen is allowed for. Any procedure that might cool down the test specimen, such as continuous fuel filling to avoid lip effects [19, 21] or diluting with water to prevent overheating [22], was avoided. It is realized that the lip will be heated by the flames and some additional heat will transfer to the heptane. This implies that the burning rate from the tests may not be comparable with other test on heptane, but the free burn tests comparisons should provide sufficient benchmarking.

The amount of liquid, especially in the large pan experiments, is substantial and any breakage of the pan due to overheating could be critical to the test facility and the operating personnel. To reduce the consequences of this possible failure mode, the pans were placed in a larger pan to collect any spillage. The fuel pans with diameters of 0.35 m and 0.50 m were placed in an outer pan with a diameter of 0.70 m and the fuel pan with a diameter of 0.70 m was placed in an outer pan with a diameter of 1.0 m.

3. Results and Discussion

3.1. Large Pool Experiments (0.70 m)

During the room burn tests flames were observed to impinge the ceiling and exit the door opening. Also, crumbled newspaper on the floor was ignited in both tests. These phenomena are generally known to indicate flashover [23] and as such a transition to a post-flashover fire occurred during the fire tests. For lining 1, flames were observed exiting the door and the crumbled newspaper ignited after 3½ min and 2 min, respectively, and for lining 2 after 8 min (sparse) and 7 min, respectively. To protect the test equipment the experiment with lining 1 was terminated after 6 min and the experiment with lining 2 was terminated after 12 min, as violent burning occurred. A more or less constant smoke layer was observed at a height of approximately 1.1 m to 1.2 m above the floor during both room tests.

The results of the HRR measurements (corrected for the E-value) for all three tests as a function of time are shown in Figure 4 and measurements of the MLR are shown in Figure 5. The results show that the fire initially develops similarly for all three tests. The HRRs for the free burn test were not constant but increased slightly during the test. After approximately 2 min a rapid increase toke place for lining 1. For lining 2, the HRR increased slightly compared to free burn in the beginning of the test. After approximately 10 min a rapid increase occurred. For both lining 1 and 2 the rapid increase continued until the fires were extinguished. The rapid increase can be seen as thermal runaway, TR.

The MLR (see Figure 5) follows the same trend as the HRR, though the difference between lining 2 and the free burn is less evident. An average of the free burn MLR is found to be 0.044 kg m^{-2} s^{-1} which is less than the predicted mass loss rate of 0.054 kg m^{-2} s^{-1} (see Table 1).

Table 2 reports the calculated effective heat of combustion, ΔH_{eff}, and show that the effective heats of combustion in the room tests are comparable for all three tests. The values are within reasonably range of the theoretical value of 44.6 MJ/kg [19]. Therefore, the heat of combustion is found not to be influenced by whether the test is done as free burn or room burn.

A fundamental assumption for this experimental series is that the fires should apply to a two-zone model and not be ventilation controlled. Figure 6 shows a clear horizontal division of the room temperatures in two zones during the test. This correlates well with the visual observation of a clear layer below a smoke

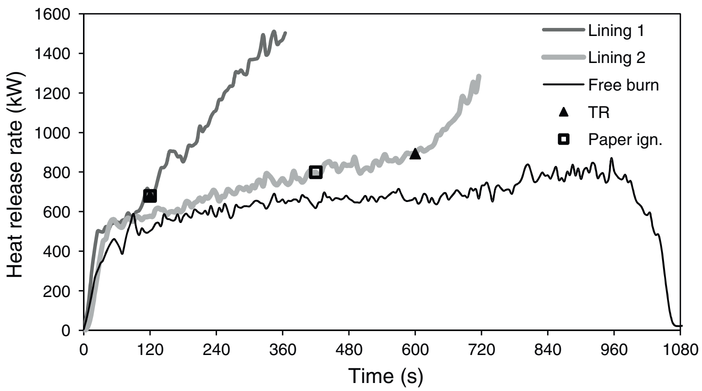

Figure 4. Experimental results of the HRR versus time for a pool diameter of 0.70 m.

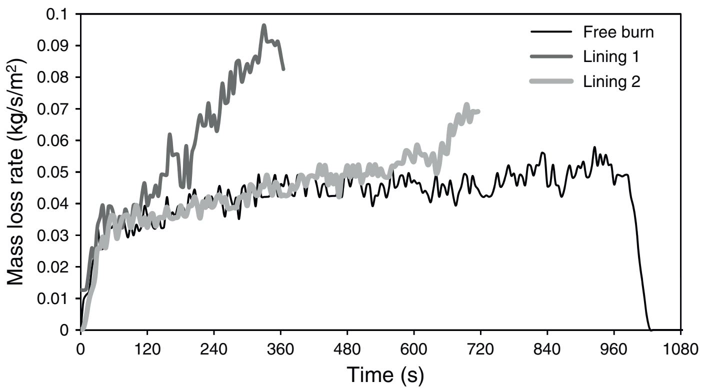

Figure 5. Experimental results for the MLR versus time for pool diameter of 0.70 m.

Table 2
Estimates of the Effective Heat of Combustion for Pool a Diameter of 0.70 m

Test no.	Duration (s)	Total heat release (MJ)	Total mass loss (kg)	ΔH_{eff} (MJ/kg)
1, Free burn	1005	679	16.7	40.6
2, Lining 1	365	334	7.9	42.1
3, Lining 2	720	537	12.4	43.2

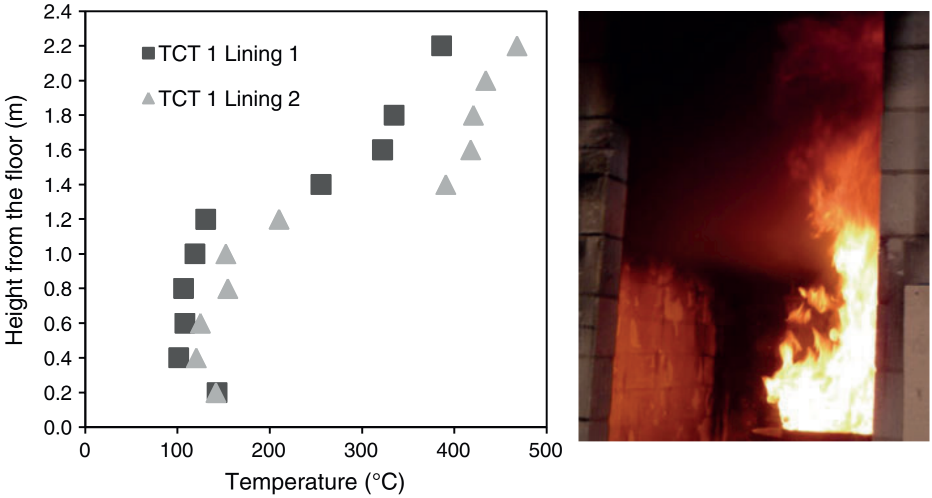

Figure 6. Measured vertical temperature distribution at TCT 1 at time of ignition of the crumbled paper (lining 1; 2 min and lining 2; 7 min) and photo illustrating the division of layers.

layer, and confirms that using a two-zone model is a reasonable assumption. The time for Figure 6 is taken as the time for the crumbled paper to ignite as this was the first indication of flashover. Thus, the two-zone assumption is valid at least until this time. Figure 6 also shows that smoke layer temperatures were higher for lining 2 than for lining 1 at the time for ignition of the crumbled paper, whereas lower level temperatures are comparable especially at the level of the pan (0.3–0.5 m above the floor).

Figure 7 shows the development with time of the average smoke layer temperature, SLT, (upper panel) and temperatures measured at the back wall (lower panel). The smoke layer temperature is calculated as the average output from thermocouples placed from 1.6 m to 2.2 m above the floor. The wall temperatures are measured in the smoke layer 2.0 m above the floor (WTC1) and below the smoke layer 1.0 m above the floor (WTC2). The figure shows that for the test with lining 1, the temperature rose linearly during the test, which followed the trend of the HRR after the first 3 min of the test. For lining 2 the temperature

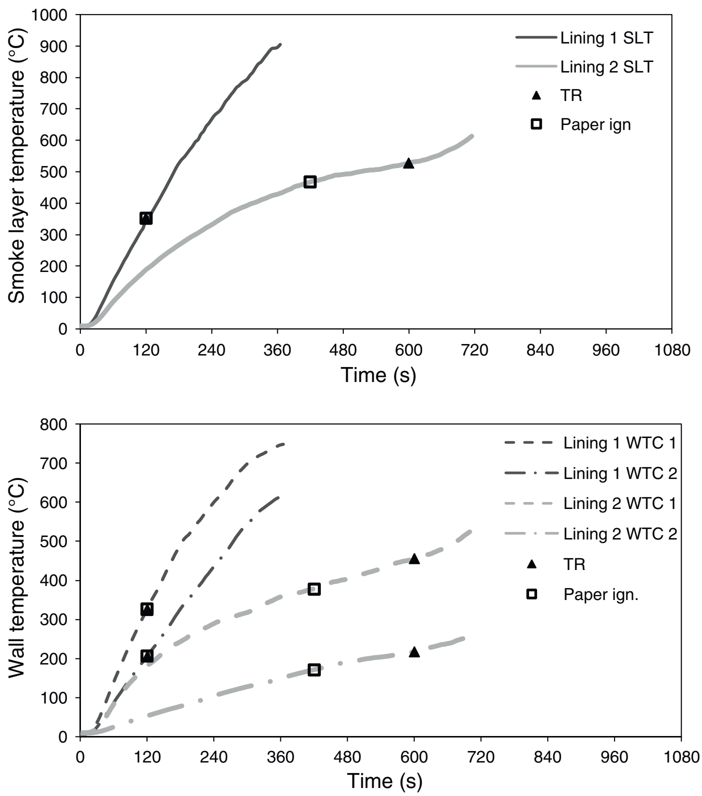

Figure 7. Experimental results for the temperature in the smoke layer, SLT (*upper panel*) and wall temperature (*lower panel*) for pool diameter of 0.70 m. WTC 1 is at 2.0 m and WTC 2 is at 1.0 m.

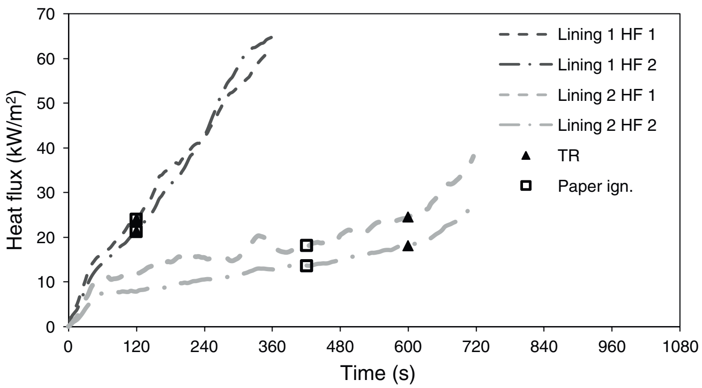

Figure 8. Experimental results for the heat flux for a pool diameter of 0.70 m. HF 1 is positioned horizontally on the substrate and HF 2 is positioned vertically on the back wall 1.2 m above the floor.

rise does not have a linear form and the temperature increase after the initial growth period was slower compared to the HRR than what is seen for lining 1. The lower panel also show that the temperature measured below the smoke layer is relatively smaller for lining 2 than for lining 1 when compared to temperatures measured in the smoke layer.

The heat fluxes measured at the substrate and at the back wall are given in Figure 8 (averaged over 35 s as a floating average over 7 points). The figure shows that the heat fluxes increased rapidly and almost linearly for lining 1, whereas the heat fluxes for lining 2 had a significantly slower growth rate between the initial growth period and the time for onset of thermal runaway.

The ignition of the crumbled paper and the onset of thermal runaway are seen as key phenomena, as they indicate significant changes in the burning behavior as compared to the free burn. Therefore, data on measurements when these phenomena occurred are summarized in Table 3. The table shows that the time for paper

Table 3
Summary of Measurements at Time of Ignition of Crumbled Paper and at Estimated Time for the Thermal Runaway (TR) for Pool a Diameter of 0.70 m

	TR		Paper ignition	
	Lining 1	Lining 2	Lining 1	Lining 2
Time (s)	120	600	120	420
HRR (kW)	679	893	679	800
SLT (°C)	352	528	352	467
WTC 1 (°C)	327	456	327	378
WTC 2 (°C)	206	218	206	171
HF 1 (kW/m^2)	24	25	24	18
HF 2 (kW/m^2)	21	18	21	14

ignition and onset of thermal runaway generally occurs at lower temperatures for lining 1 than for lining 2. Only measurements of the lower wall temperature, WTC 2, and the heat flux measured at the substrate have comparable levels at the onset of the thermal runaway, whereas the wall temperatures are comparable at the time of paper ignition. It can also be seen that the measurements of the wall temperatures generally are closer to each other for both linings than the smoke layer temperature, and that the smoke layer temperature and the upper wall temperatures are comparable for lining 1 but not for lining 2.

3.2. Medium Pool Experiments

In the room test, the flames did not reach the ceiling instantaneously upon ignition, but later in the test the flame would periodically touch the ceiling. For the tests with lining 1 and lining 2–2 (lining 2 with additional 50% heptane), the flames impinged the ceiling more constantly towards the end of the test. No flames were observed exiting the door opening, and the smoke layer was observed to be at approximately 1.1–1.2 m above the floor for all room tests. Ignition of crumbled paper was not investigated.

Measurements of the HRR (see Figure 9) show that all 4 tests with the medium pool size followed the same trend up to about 6 min. It can be argued that the reason for the peak towards the end of the tests is a consequence of the fact that the heptane fuel layer is being thin at this point. As a result, both the liquid and the pan have warmed up which will lead to an increase of the evaporation rate. The average free burn MLR for the steady state of the test was 0.043 kg m^2s^{-1}, which is in very good agreement with the predicted MLR.

The effective heat of combustion has been estimated and is listed in Table 4. The results show that tests with lining 2 and the free burn test has comparable levels of heat of combustion, whereas and the test with lining 1 had a larger effective heat of combustion. The differences between levels of heats of combustion are not uncommon and compares to what is reported from other test series [8].

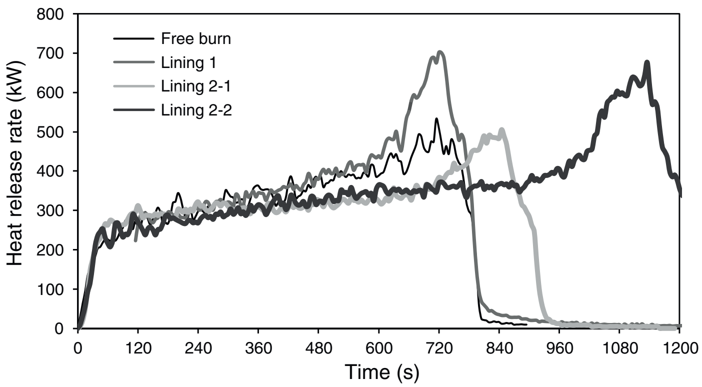

Figure 9. Experimental results of HRR versus time for at pool diameter of 0.50 m.

Table 4
Estimates of the Effective Heat of Combustion for Pool a Diameter of 0.50 m

Test no.	Duration (s)	Total heat release (MJ)	Total mass loss (kg)	ΔH_{eff} (MJ/kg)
4, Free burn	810	271	6.6	40.8
5, Lining 1	760	N/A	6.6	47.0
6, Lining 2–1	900	253	6.6	38.1
7, Lining 2–2	1240	398	10.1	39.3

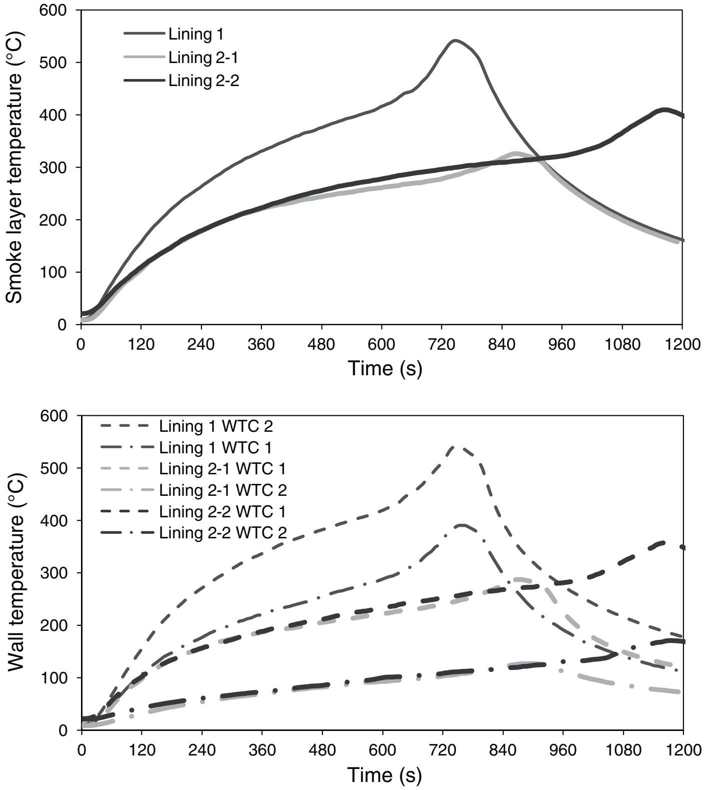

Figure 10. Experimental results for temperature in the smoke layer, SLT (*upper panel*) and wall temperature (*lower panel*) for a pool diameter of 0.50 m.

Figure 10 plots the experimental results for the average smoke layer temperature in the upper panel and the wall temperatures for the three room tests in the lower panel. It can be seen that the temperatures follow the trend of the HRR. In this test series the difference between the upper and the lower wall thermocouples are comparable for all three tests.

Figure 11 shows that a rapid increase of the heat fluxes took place for lining 1 when the HF 1 value (next to the pool) reached 25 kW/m^2. At this level of heat

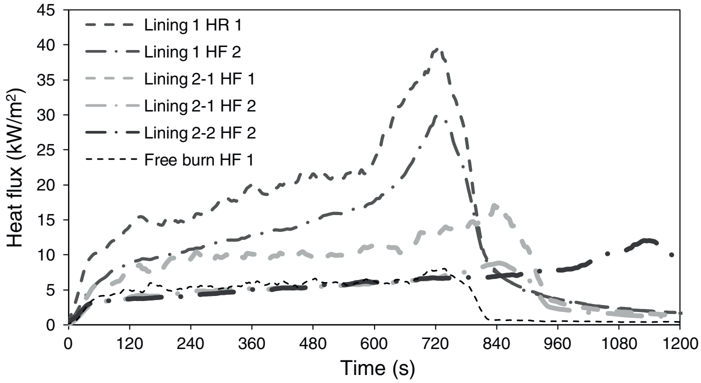

Figure 11. Experimental results of heat flux for a pool diameter of 0.50 m. HF 1 is positioned horizontally on the substrate and HF 2 is positioned vertically on the back wall 1.2 m above the floor.

flux thermal runaway was observed for the large pool tests, which indicates that thermal runaway may have taken place during the peaking, but the test results do not show any clear evidence of a thermal runaway. The two tests with lining 2 did not show any rapid increase, though a certain increase took place at the end when the HRRs peaked. It should also be noted that the free burn heat flux measured close to the pool (HF 1) was significantly lower than all the three room tests.

Summarizing the results of the experimental data for the medium pool fires it is found that some effect of thermal feedback is found for lining 1 but no evidence of an effect is found for lining 2.

The peak values are summarized in Table 5. It can be seen from this table and also by utilizing Figure 10, that smoke layer temperatures and upper wall temperatures are almost identical for lining 1, whereas differences of more than 10 percent are observed for lining 2. It is also noteworthy that the heat fluxes are substantially higher in the tests with lining 1 than in any of the other tests.

Table 5
Summary of Measured Peak Values for Pool a Diameter of 0.50 m

	Free burn	Lining 1	Lining 2–1	Lining 2–2
HRR (kW)	533	703	507	677
Time[a] (s)	715	720	845	1135
SLT (°C)	–	542	325	409
WTC 1 (°C)	–	541	287	358
WTC 2 (°C)	–	391	127	171
HF 1 (kW/m^2)	8	40	17	N/A
HF 2 (kW/m^2)	–	30	9	13

[a] The time is for peak HRR

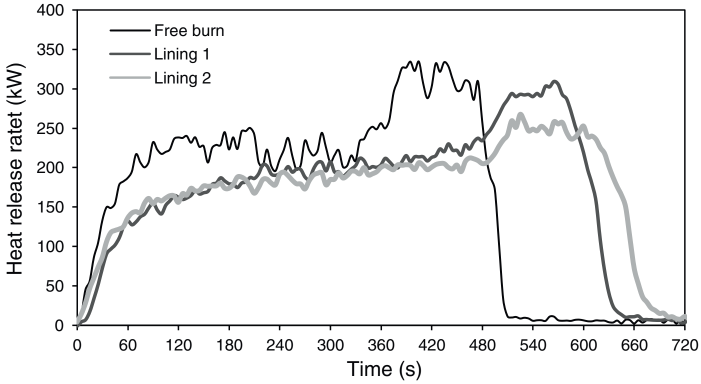

Figure 12. Experimental results of HRR versus time for a pool diameter of 0.35 m.

3.3. Small Pool Experiments (0.35 m)

The experimental results (see Figure 12) of the HRRs for the small pool shows that the free burn HRR was larger than the HRRs for the two room burn tests, and that the HRRs for the two linings were comparable. Therefore, no effect of thermal feedback is found.

An average free burn MLR for the steady state period was found to 0.056 kg m^{-2} s^{-1} which is considerably higher than the expected value of 0.032 kg m^{-2} s^{-1}. This difference will be discussed further in the summary in Section 3.4.

3.4. Comparisons of Experimental Results

A clear effect of thermal feedback can be found for both linings for the large pool and a minor effect is found for lining 1 for the medium pool but no effect is found for lining 2 for the medium pool and the small pool. This compares well with the expected results as predicted in Section 2. As flames were touching the ceiling resulting in significant thermal feedback the results are also matching the observations made by Parkes [8].

The thermal feedback was found to result in both an initial increase of the HRR as compared with the results from the free burn, and in thermal runaway. In this test series the onset of thermal runaway occurred for the large pool at a smoke layer temperature of 350°C for lining 1 and 525°C for lining 2. The onset point of thermal runaway could also be seen as the starting point of flashover [3]. This also means that the HRR can increase compared to free burn as a consequence of thermal feedback even before flashover occurs.

For the small pool tests and for lining 2 for the medium pool tests, the room HRRs are smaller than those measured in the free burn tests. This observations compares well with the test results obtained by Thomas et al. [6] and Parkes [8] as in some of their experiments the free burn HRRs were larger than the room burn HRR.

Table 6
Free Burn MLRs from Tests Compared to Predicted Values

	Large pool (kg m^{-2}s^{-1})	Medium pool (kg m^{-2}s^{-1})	Small pool (kg m^{-2}s^{-1})
Test	0.044	0.043	0.056
Prediction	0.054	0.043	0.032

Mass loss rates found in the free burn tests and the predicted MLRs from Table 1 are compared in Table 6. The table shows that MLRs found from the test were the same for the large and medium pools, whereas the small pan had a higher MLR. Theory [19] predicts the MLR to increase with larger diameters. This correlation with pool diameter was not observed, as the smallest pool had the largest MLR, which is a striking difference. The deviation could be due to lip effects, which are reported to be able to give either higher or lower MLR [21]. Lips effects are however presence in both room burn and free burn test and should not contribute to any difference in the comparison between the room burn and the free burn experiments.

Ventilation is also reported [21] to be able to increase MLR due to better mixing of oxygen and fuel, and it is expected that the ventilation is better in the free burn experiments and thus that the MLR for these experiments is higher than that found in the enclosure tests.

4. Phenomenological Description

For well ventilated room fires it has been indicated that two key differences may occur as a consequence of thermal feedback from the room as illustrated in Figure 13 [3]. The first is a slight increase of the room burn HRR as compared to the free burn HRR in an incipient period. The second difference is the possibility of a thermal runaway onset point, defined as the point where the rate of heat gained in the smoke layer is significantly larger than the rate of heat losses from

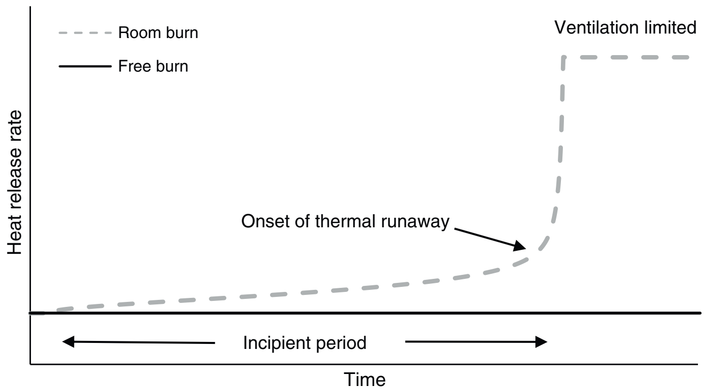

Figure 13. Principal differences in room burn and free burn HRRs.

the enclosure. Theoretically the thermal runaway point is only limited by ventilation [3] which is indicated as the final, horizontal part of the room burn HRR. Both phenomena were observed in our experiments, as can be seen in Figure 4.

The MLR and thus the HRR can be expressed as a function of the net heat flux to the liquid [19]. It has been suggested that the MLR in a room for a well ventilated fire can be estimated as the free burn MLR plus a contribution from the heat flux from the room [16]

$$\dot{m}''_{\mathrm{F}} = \dot{m}''_{\mathrm{F},0} + \frac{\dot{q}''_{\mathrm{ext}}}{L_{\mathrm{g}}} \tag{1}$$

here $\dot{m}''_{\mathrm{F}}$ is the MLR for the burning pool per unit area, $\dot{m}''_{\mathrm{F},0}$ is the free burn MLR per unit area, L_{g} is the heat of gasification of the fuel and $\dot{q}''_{\mathrm{ext}}$ is the total external heat flux per unit area to the liquid surface from the smoke and the compartment walls. L_{g} and $\dot{m}''_{F,0}$ can be found based on tests.

The total external heat flux to the pool surface depends on temperatures and of smoke layer and walls as well as appropriate view factors and the absorption of external flux by the flames and unburned fuel gasses [10]. For simplicity $\dot{q}''_{\mathrm{ext}}$ is roughly estimated as

$$\dot{q}''_{\mathrm{ext}} \approx \alpha \cdot \sigma \cdot \left(T^4 - T_s^4\right) \tag{2}$$

where T_{s} is the surface temperature of the liquid, σ is Stefan Boltzmann's constant, α is a factor between 0 and 1 including view factor and emissivity/absorption, and T is a room temperature that has to be chosen based on whether the smoke layer is optically thick or thin. For an optically thick smoke layer, the smoke layer temperature will be dominant, whereas for an optically thin smoke layer, the surface temperature will be dominant. The following expression based on (1) and (2) can be used to estimate the HRR

$$\dot{Q}_{\mathrm{F}} \approx \dot{Q}_{\mathrm{F},0} + A_{\mathrm{F}} \cdot \Delta H_{\mathrm{eff}} \cdot \left(\frac{\alpha \cdot \sigma \cdot \left(T^4 - T_{\mathrm{s}}^4\right)}{L_{\mathrm{g}}}\right) \tag{3}$$

here $\dot{Q}_{\mathrm{F}}$ is the total heat release rate from the burning pool, $\dot{Q}_{\mathrm{F},0}$ is the total heat release rate from the free burning pool, A_{F} is the area of the burning object and ΔH_{eff} is the effective heat of combustion.

Equation 3 shows explicitly that the room temperature is a dominant factor in determining the HRR in the room. The room temperature is dependent on the thermal inertia of the room, as linings with lower thermal inertia will accumulate less energy and thus leads to higher temperature increase of the smoke layer as a consequence of the energy balance. Thus it can be expected that rooms with lower thermal inertia will have higher HRRs than rooms with higher thermal inertia, but the HRRs should still be equal for matching room temperatures. It should also be noted that α is of importance, as the external heat flux may not affect a thick, sooty flame.

For the tests conducted on the large pool (0.70 m), Table 3 indicates that the wall temperatures should be used, as the wall temperatures differs less from each other at the time of paper ignition than the smoke layer temperatures do. This is supported by the vertical temperature distribution in the room plotted in Figure 6, as temperatures in the smoke layer differs substantially at this point, whereas temperatures measured below the smoke layer are more uniform.

Assuming L_g to be constant over time (estimated to 520 kJ/kg [24]) and independent of the pan and α to be 1, $\dot{Q}_F$ can be calculated from Equation 3 using the measured free burn HRR, wall temperature and heat of combustion as input values. Figure 14 plots the measured HRR, $\dot{Q}_{F,meas}$, versus the calculated HRR, $\dot{Q}_{F,calc}$, for the large pool, and it is seen that there is a reasonable correlation with the calculated values being somewhat higher than the measured ones. A linear fit to the two curves has a slope of 0.6, which indicates that, the estimate on α/L_g is too high, which indicates that either α is smaller than unity, L_g is larger than assumed, or they are both different than assumed.

If, however, $\dot{Q}_{F,0}$ in Equation 3 is seen as a constant and not a measured value from the free burn test, a better linear correlation is found for both linings between $\dot{Q}_{F,meas}$ and $\dot{Q}_{ext,calc}$ until the onset point of thermal runaway, as seen in Figure 15. $\dot{Q}_{ext,calc}$ represents the HRR arising from the external heat flux and is found as the second term of Equation 3. This suggests that Equation 3 can express the development of the HRR for a room fire as long as $\dot{Q}_{F,0}$ is taken as a constant corresponding to the HRR at $T = T_s$ for a room test and not a free burn test on the same item. Before the onset of thermal runaway the slope of the curves is approximately 0.85.

Utiskul [16] found Equation 3 to work on his data based on free burn measurements. It should be noticed that his free burn fires were constant and not slightly increasing as in this case. This, supported by the differences found for MLR for the three pool sizes, indicates that free burn values should be used with caution as

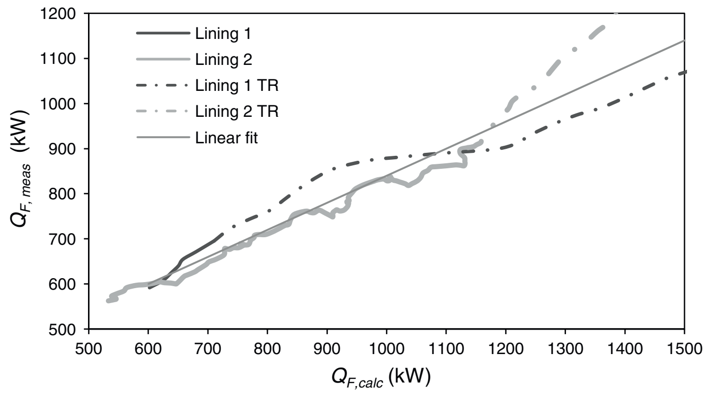

Figure 14. Comparison of the measured and calculated HRRs for the 0.70 m pool. Extension TR indicates that thermal runaway has occurred.

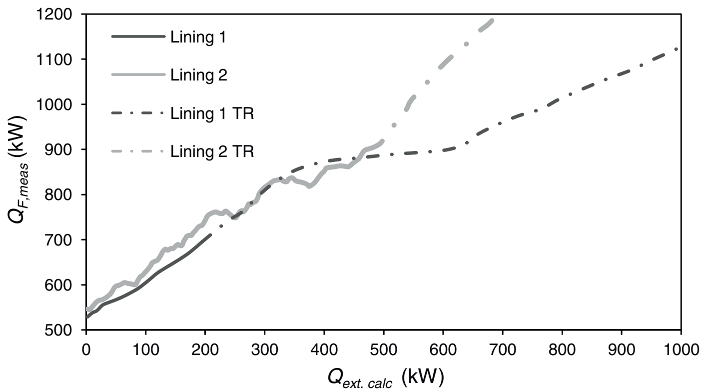

Figure 15. Comparison of the measured HRR and the calculated external HRR for the 0.70 m pool. Extension TR indicates that thermal runaway has occurred.

experimental conditions, such as ventilation, differ from the free burn tests to the room burn tests.

Whether a fire will reach thermal runaway or not can be determined from an energy balance for the room. The onset of thermal runaway can happen when the heat gained, G, by the hot layer from the fire exceeds the heat lost, L, by mass flow out of the opening and the heat lost by accumulation of heat by the linings. In the literature [3, 11], this onset point is also determined by the temperature for which the gradient of $G(T)$ exceeds the gradient of $L(T)$. The heat gained, G, can be expressed by Equation 3. As $\dot{Q}_{F,0}$ is independent of temperature, the gradient of $G(T)$ for an object with a fixed area can be estimated as

$$\frac{dG}{dT} \sim k_G \cdot T^3 \tag{4}$$

here k_G is a constant including the parameters of the second term of Equation 3. The heat lost from the smoke layer (neglecting radiation losses) can be estimated as

$$L(T) \sim h_k \cdot A_u \cdot (T - T_0) + \dot{m}_{out} \cdot c_p \cdot (T - T_0) \tag{5}$$

where A_u is the surface area of the walls and ceiling covered by the smoke layer, h_k is the effective heat transfer coefficient of the linings, $\dot{m}_{out}$ is the mass flow out of the room and c_p is the heat capacity of air. For a steady smoke layer height $\dot{m}_{out}$ is assumed to be constant as well as it can be assumed to be constant for temperatures between 400 K and 1000 K [3]. Thus the gradient of the heat loss can be estimated as

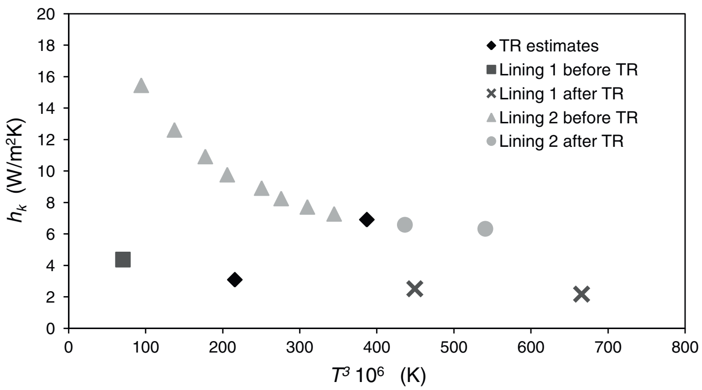

Figure 16. Correlation between the effective heat transfer coefficient, h_k, and the room temperature, T^3 for a pool diameter of 0.70 m.

$$\frac{dL}{dT} \sim h_k \cdot A_u + \dot{m}_{out} \cdot c_p \approx h_k \cdot A_u + k_m \tag{6}$$

Comparing Equations 4 and 6 a linear correlation between h_k and T^3 can be expected at the onset of thermal runaway, suggesting that linings with lower thermal inertia will lead to lower room temperatures at the onset of thermal runaway.

As thermal runaway occurs later for lining 2 than for lining 1, and as such at higher room temperature and HRR, it supports a correlation between h_k and T. Estimates on h_k and T^3 are plotted in Figure 16. The figure indicates that a linear correlation may be achieved, but as only two sets of data are available no definite conclusions are made based on the test data. Comparing the results found with findings in the literature the results generally compares well with the simulation made by Graham et al. [13]. They show that lower thermal inertia will lead to lower onset temperatures for thermal runaway as well as their Figure 5 indicates that a linear correlation could be found between a dimensionless room temperature to the third power and a dimensionless thermal inertia of the lining materials.

5. Summary

A series of heptane pool fire experiments were conducted in free burning conditions and in an enclosure with two different linings in order to study the effect of thermal feedback in enclosure fires. The experiments were designed to represent a two zone model not restricted by ventilation before flashover, thus avoiding oxygen reduction.

It is found that the HRR can be affected by the thermal feedback. Two HRR related phenomena that correlate well with the general theory were observed in this test series. We observed an incipient period where the HRR rose as a function of the wall temperature in the upper zone irrespectively of the thermal inertia of the linings. A rapid increase of the HRR commenced after the incipient period. The rapid increase is seen as a thermal runaway that is caused by temperatures in the upper layer, as energy gain by the smoke layer exceeds the energy that can be lost through the boundaries. The wall temperature/smoke layer temperature do not seem to be the dominant factor in determining the HRR after thermal runaway has started. The thermal inertia of the linings changes condition at the onset point of the thermal runaway as lower thermal inertia leads to lower temperatures and thus times for thermal runaway.

Traditionally the HRR in a room fire has been proposed to be the sum of the free burn HRR in addition to a contribution from the heat flux induced by the room. This cannot be reproduced by the tests. It is proposed that free burn measurements should be used with caution for design fire calculations as not only enclosure effects, but also the specific wall linings can be expected to influence the outcome of a room fire.

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Paper II

Evaluation of the Onset of Flashover in Room Fire Experiments

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Evaluation of the Onset of Flashover in Room Fire Experiments

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Abstract. Two series of full scale room fire tests comprising 16 experiments are used for a study of the onset of flashover. The fire loads were varied and represented seven different commercial applications and two non-combustible linings with significantly different thermal inertia were used. The test results showed that by lowering the thermal inertia and thereby lowering the heat loss from the room and at the same time increasing the thermal feedback, a thermal runaway occurred before significant fire spread; but only for objects composed of a mixture of plastic/rubber/textiles and wood/celluloses. In these cases the onset of thermal runaway was found to occur at room temperatures in the range 300°C to 420°C, supporting that the room temperature at the onset of thermal runaway is strongly dependent on the thermal inertia. It also shows that the onset of thermal runaway cannot in all cases implicitly be predicted by the traditional flashover temperature criterion of 500°C to 600°C. For fire loads composed of pure wood/celluloses the onset of flashover occurred about the same time as fire spread irrespectively of linings and at significantly higher room temperatures (725°C). This can be explained by flammability parameters making wood/celluloses less sensitive to thermal feedback.

Keywords: Flashover, Room fire experiments, Thermal runaway, Thermal feedback, Thermal inertia

1. Introduction

One or more design fires are typically selected in conducting a performance based design of a building [1]. An essential step in the selection of the design fires is the prediction of flashover, as flashover represents the culmination of untenable conditions in the room of fire origin, the beginning of a more severe thermal exposure of the structure (if there is sufficient fuel to support a fully-developed fire of a given duration) and the point where fire extinguishing intervention in the room of origin is considerably limited.

Flashover is not a single physical event that can be precisely described [2], but can be seen as a transition phase covering several process such as: fire spread caused by sudden increase in the fire size due to the radiant ignition of adjacent combustibles [3], rapid flame spread [4], thermal runaway (sometimes referred to

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as burning instability) caused by the thermal feedback from the warm enclosure and smoke layer [4], spontaneous ignition of unburned gases in the hot smoke layer due to direct contact with the fire plume [3], and an increase of the oxygen supply for under-ventilated rooms [4].

Flashover is also commonly referred to as a jump or rapid increase of the heat release rate which is limited by ventilation [5]. It has been proposed that the "jump" in the heat release rate can be explained by the onset of thermal runaway occurring in a room as the heat gained from the fire, G exceeds the heat that can be lost, L and the two curves plotted in a Semenov diagram are tangent [5, 6]. When these two criteria are met, a critical point is reached and a rapid increase of the heat release rate will take place, which in theory is only limited by ventilation. From here on the fire will continue as a ventilation controlled fully developed fire if sufficient combustibles are available. This critical point can therefore be characterized by a critical temperature satisfying both terms for the relations between heat gained and lost.

The heat gained is a function of the heat release rate which is a compounded variable that depends on several parameters. For a well-ventilated fire, an increase of the heat release rate can result from an increasing burning area (fire spread), an increasing heat release rate per unit area due to thermal feedback or a combination of both.

Traditionally, the focus has been on fire spread as the dominant mechanism causing flashover [5] and it has therefore been argued that design fires may be based on free burn values up to the onset of flashover [7, 8]. However, it is also realized that the thermal feedback from the room may increase the heat release rate even before flashover [5, 7].

Based on the assumption that flashover is caused by a rapid fire spread to adjacent objects in the room, criteria for the onset of flashover have been established as uniform temperatures in the smoke layer of 500°C to 600°C or an incident heat flux to the floor of 20 kW/m^2 [7, 9]. For the assessment of fire tests, ignition of crumpled paper on the floor or flames exiting the opening has also commonly been used as indicators [9].

The temperature criterion is also used as basis for predicting flashover in well-established fire models such as Thomas' model [10], Babrauskas' model [8] and the model developed by McCaffrey, Quintiere and Harkleroad (MQH) [11]. These models predict the critical heat release rate needed to cause flashover based on energy balance considerations. Babrauskas' model uses the ventilation factor as the only input, whereas Thomas' model includes the heat loss to the boundaries, represented by the heat loss that would be found for concrete wall after 10 min. MQH incorporates the thermal inertia of the linings as a variable to their model through a user defined temperature dependent heat transfer coefficient. Therefore, Thomas' and Babrauskas' models predict a constant critical heat release rate for a room, whereas the MQH model predicts the critical heat release rate to decrease with time. None of the three models, however, handles the actual development of the heat release rate in the room, which has to be decided on by the fire safety engineer. That is, the models focus on fire spread due to the chosen temperature criteria and do not take thermal feedback into consideration. This is also pointed out by Thomas [10], but he argues that the thermal feedback is less important than the fire spread. From here on these three models are called traditional models.

As building practices change over the years, it is therefore important to regularly review the validity of the general assumptions used for design guides. One of the more pronounced changes within the last decade has been an increased requirement for better thermal insulation of buildings, in order to reduce the energy losses from buildings. As a result, the thermal inertia of a modern building is typical lower than an older one, especially if the insulation is applied directly on walls or ceiling. By lowering the thermal inertia the possible heat lost from the room decreases and lowers the loss curve in the Semenov diagram. Consequently, the critical temperature for causing thermal runaway and the heat release rate associated with this temperature may also decrease.

The design of energy efficient buildings may also influence other parameters that are linked to the development of a room fire. For example, such buildings are known to have increased air tightness as compared to older buildings. As a result, these constructions will, in addition to lowering the heat losses from the building, also limit the access of oxygen to the fire room, which in turn will affect the dynamics of a fire. Although an experimental investigation into these topics would be worthwhile, this paper will focus on the impact of lowering thermal inertia of the linings on the fire development.

Recent large scale room fire tests with heptane pools [12] showed that the heat release rate increased due to thermal feedback from the room without any fire spread. For larger pool sizes the increase of the heat release rate led to a thermal runaway, which for rooms with low thermal inertia was found to start at a critical temperature (wall temperature) of 330°C. This may, however, not be the same for standard inventory for normal occupancy classes. In order to investigate if this is the case, two series of large scale room fire experiments with fire loads representative of contemporary commercial premises [13] have been evaluated. The two series had comparable fire room sizes but had linings that were made of cement board in one series and ceramic fibers in the other series, which allows for a comparison the fire development with different types of linings. In the following section, a brief description of the experimental setup and the fire loads are given. Section 3 presents the test results as heat release rates at different flashover criteria in relation to the actual fire development, and test results are discussed in relation to the influence of thermal feedback with respect to the thermal inertia of the linings and the type of material of the burning object. Finally, the discussion will also refer to fire spread and more traditional criteria used for prediction of flashover.

2. Experimental Programs

Two large scale experimental programs "Design Fires for Commercial Premises—Phase 1 (DFCP1) and Phase 2" (DFCP2) [13] are reviewed and analyzed.

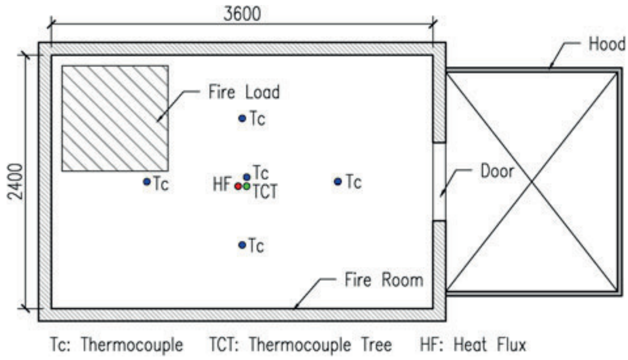

Figure 1. Plan of the experimental setup for the DFCP1 program [15]. Units are in mm.

2.1. Experimental Setups

The DFCP1 program was intended to study pre-flashover fires. The test program utilized an experimental setup comparable to the ISO Room Corner test [14]. The principal setup is shown in Figure 1. The room had a depth of 3.6 m a width of 2.4 m and a height of 2.4 m, and the door was 2.0 m high and 0.8 m wide. The walls and ceiling of the room were lined with one layer of cement board and the floor was made of concrete slabs giving the room a thermal inertia $(\rho \cdot c \cdot k)$ of approximately 0.85 kW^2s/m^4K with a thermal inertia of approximately 0.60 kW^2s/m^4K for the walls and the ceiling. Measurements related to flashover predictions were heat release rate, temperatures (measured 25 mm below the ceiling and room temperatures by a thermocouple tree in the center of the room) as well as incident heat flux to the floor. The heat release rate was found by the use of oxygen consumption calorimetry based on measurements of O_2, CO_2 and CO and the data was corrected for delay time. Further information on the experimental setup and instrumentation can be found in [13, 15].

The DFCP2 program was designed to study post flashover fires. Therefore, a different room than that used for DFCP1 was utilized, see Figure 2. The room had a depth of 3.6 m, a width of 2.75 m and a height of 2.4 m, giving a floor area of 9.9 m^2. There was one door opening to the room with a height of 2.2 m and a width of 0.9 m. The door was connected to a 1.2 m wide and more than 10 m long corridor leading to an exhaust hood. The linings on the walls and ceiling were made of one layer of ceramic fibers and the floor was made of concrete slabs giving the room an approximate thermal inertia $(\rho \cdot c \cdot k)$of 0.37 kW^2s/m^4K, whereas the thermal inertia for the ceiling and walls only was approximately 0.02 kW^2s/m^4K. Measurements related to flashover were temperatures (25 mm under the ceiling and in a corner thermocouple tree), heat release rate, incident heat flux to the floor, and times to ignition of crumpled paper on the floor. As for the DFCP1 experiment, the heat release rate was found by oxygen consumption calorimetry and was corrected for the delay time corresponding to this particular

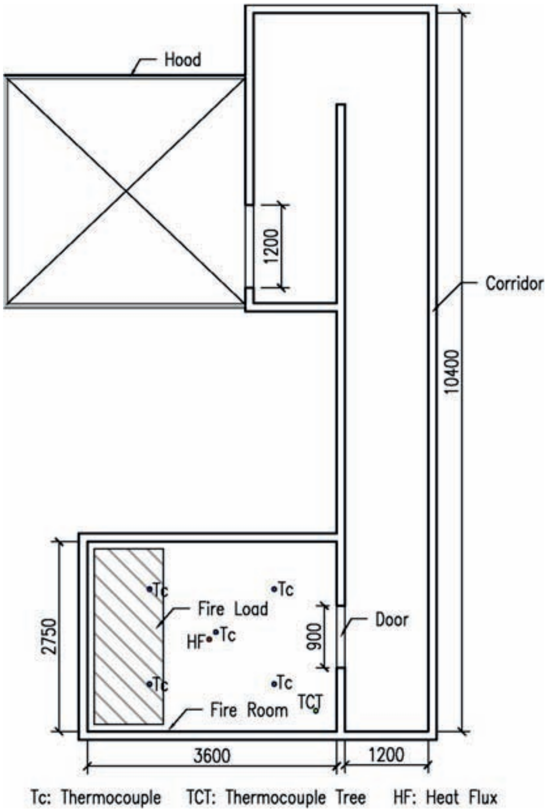

Figure 2. Plan of the experimental setup for DFCP2 [16]. Units are in mm.

experimental setup. More detailed information on the experimental setup and instrumentation can be found in [13, 16].

2.2. Fire Loads

The fire loads differed in type of material and arrangement. The type of fire loads in the DFCP1 and DFCP2 programs were based on a recent survey of fire loads in commercial premises in Canada [17] dividing the fire loads into seven different categories, see Table 1, composed of different mixtures of plastic/rubber/textiles and wood/celluloses. The fire load density ranged from 0.66 GJ/m^2 to 4.9 GJ/m^2. In the DFCP1 tests, the fire loads were arranged as a single bundle simulating each respective retail group on a 1 m^2 footprint positioned in the right back corner of the room, see Figure 1.

In the DFCP2 tests, two identical fuel packages, each having approximately the same size as in the DFCP1 tests, were used, except in the shoe store scenario, which used only one fuel package. The fuel packages were positioned in the back of the room, see Figure 2. The ignition source was the same in both DFCP1 and

Table 1
Experimental Matrix

Test room	Test object	Fire load[a]	Thermal inertia room/walls and ceiling (kW^2s/m^4K)	Estimated HRR at flashover[b] (MW)	Estimated HRR at ventilation limit[c] (MW)
DFCP1	Computer showroom (COM)	0.81 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Storage room (STO)	2.3 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Clothing store 1 (CLO1)	0.66 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Clothing store 2 (CLO2)	0.66 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Clothing store 3 (CLO3)	0.66 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Toy store (TOY)	1.2 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Shoe storage (SHO)	4.9 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Book store (BOO)	5.3 GJ (1 m^2)	0.85/0.60	1.2	3.4
	Fast food (FAS)	0.88 GJ (1 m^2)	0.85/0.60	1.2	3.4
DFCP2	Computer show room (COM)	1.6 GJ (2 m^2)	0.37/0.02	1.5	4.5
	Storage room (STO)	4.6 GJ (2 m^2)	0.37/0.02	1.5	4.5
	Clothing store 3 (CLO3)	1.3 GJ (2 m^2)	0.37/0.02	1.5	4.5
	Toy store (TOY)	2.4 GJ (2 m^2)	0.37/0.02	1.5	4.5
	Shoe storage (SHO)	4.9 GJ (1 m^2)	0.37/0.02	1.5	4.5
	Book store (BOO)	10.6 GJ (2 m^2)	0.37/0.02	1.5	4.5
	Fast food (FAS)	1.8 GJ (2 m^2)	0.37/0.02	1.5	4.5

[a] The area in parentheses represent the horizontal projection of the fire load
[b] Estimated using the Thomas equation [10]
[c] Estimated as $1.518 \cdot A_O \cdot \sqrt{h_O}$ [18] where A_o is the area of the opening and h_o is the height of the opening

DFCP2. In DFCP2 the first fuel package was ignited at the opposite side of the second fuel package.

2.3. *Experimental Matrix*

In total the two series comprise 16 fire tests, see Table 1. The table shows how fire loads and thermal inertia changes between the different test, and also how the theoretically estimated values for the heat release rate at flashover and ventilation limit changes from room to room. The two values give theoretical estimates of the range of heat release rates in which flashover is expected to occur. The estimated flashover values found using Thomas' model represent the lower level for the expected occurrence of flashover and the ventilation limits represent the level where the theoretical heat release rates no longer rise. The values are not directly comparable as the ventilation limits only are a function of the ventilation factor, whereas Thomas' model, also relates to the surface area of the room. The difference can also be explained by the difference between the two phenomena as the ventilation limit is assumed only to be dependent on the oxygen supplied from airflow through the openings of the room and the oxygen flowing into the room is fully consumed by the fire. The heat release rate needed to cause flashover is

Table 2
Flashover Criteria

Flashover criteria FOC	Heat release rate when
T_C = 600°C	The temperature exceeds 600°C measured 25 mm below the ceiling
T_{slt} = 600°C	The smoke layer temperature exceeds 600°C
HF	The incident heat flux to the floor exceeds 20 kW/m^2
Ignition of paper (IP)	Crumpled paper on the floor ignites

defined by a temperature that depends both on the heat lost via airflow out of the room and heat lost to the enclosure. Therefore, no explicit correlation is expected.

3. Experimental Results and Discussion

The experimental results are presented as the heat release rates versus time, as well as the heat release rates at different flashover criteria, as defined in Table 2.

In the literature, it is mentioned that temperatures for different tests are measured in different ways [9]. In some tests the room temperatures were measured at 10 mm or 25 mm below the ceiling, while others were reported to be an average room temperature or maximum temperature. In this study of flashover, we distinguish between the different ways of measuring the temperature.

3.1. Observations from the DFCP1 Experiments

The experimental results are presented for four different types of fire loads, representing different characteristic developments of the heat release rate, see Figure 3. The computer showroom represented a fire burning for at long time with a low intensity, and the clothing store represented a fire that increases progressively until it peaks at around 1.1 MW and burns out. The heat release rate for the book store increased progressively after a long initial phase, but in this case the fire stabilized at around 0.80 MW and stayed at this level until it was extinguished due to safety of the test equipment. For the shoe storage test, the heat release rate rose quickly and the fire was extinguished, as it went to flashover. Besides differing in the development of heat release rate, the book store also differed from the other fire loads, as this fire load is composed purely of wood/celluloses. This indicated, as expected, that the composition of the fire load controlled the fire development. Also, it was observed during the fire tests that burning only took place on the surface of the burning object.

Figure 3 also plots the points were the traditional criteria for flashover are met. Only the criteria for temperatures were met. The shoe storage reached the criteria at a heat release around 1.5 MW during a rapid increase of the heat release rate, whereas the book store reached the criteria at around 1.0 MW. The book store test did not show any sign of flashover at the time or after the criteria were met and that a slight decrease of the heat release rate and temperature was found after

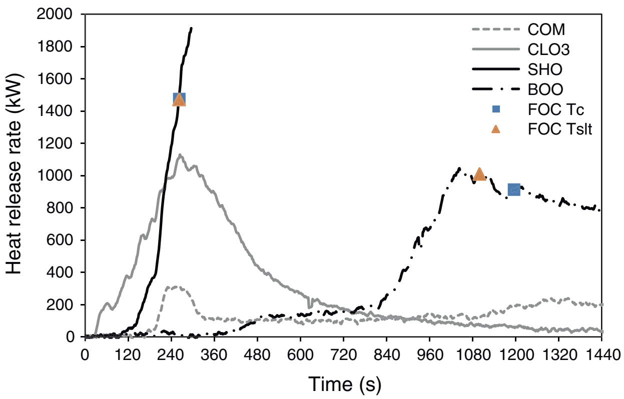

Figure 3. Heat release rate versus time and heat release rates at various flashover criteria, DFCP1.

meeting the criteria. Therefore, result for the book store cannot be taken as representative of flashover and only one of the tests is found to represent flashover. The heat release rate found when the flashover criterion was met (1.5 MW) is higher than what is predicted prediction by Thomas' model (1.2 MW). Therefore the result was within the range of what the Thomas' model can predict. Further information on other measured values, such as room temperatures, can be found in two other studies [13, 15].

3.2. Design Fires for Commercial Premises: Phase 2 (DFCP2)

3.2.1. Observations. The fire development for the same four types of fire loads as presented for DFCP1 are shown in Figure 4. All the fire tests had a growing phase followed by a rapid increase of the heat release rate leading to flashover. From here on the fires continued burning as fully developed fires for 1 min to 10 min, depending on the fire load density, before the decay phase began followed by burnout. After flashover occurred, the room filled with smoke and massive burning took place both in the room as well as in the corridor outside the room. The other tests in the DFCP2 program not reported here also reached flashover and had similar developments of the heat release rate. The growing phases were in all cases around a couple of minutes except for the book store test, which, as for the DFCP1 test, had a significantly longer growing phase. As all the tests in the DFCP2 program showed the same trend in the development of the heat release rate only one characteristic fire development was found and not several as for the DFCP1 tests.

Figure 4 also show that the traditional flashover criteria in general were met during the rapid increase of the heat release rate at a range of 1.5 MW to 2.6 MW, which in some cases were close to the peak heat release rate. The book store differed as one criterion (ceiling temperature) was met at the beginning of the rapid increase and at a significantly lower level. If the criteria in general should indicate the onset of flashover as the start of a rapid increase of the heat

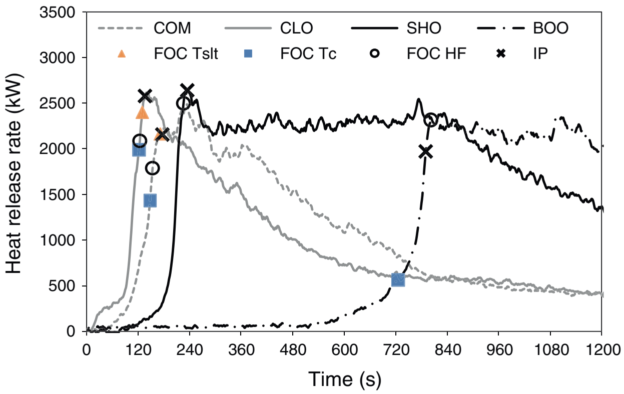

Figure 4. Heat release rate versus time and heat release rates at various flashover criteria, DFCP2.

release rate, it would have been expected that some of the criteria would have been met around the end of the growth part or the beginning of the rapid increase of the heat release rate curve, and not all during or close to the end of the rapid increase. This was only the case for the book store test where the criterion for the ceiling temperature was met around the start of the rapid increase.

All the peak heat release rates were measured to be in a narrow range from 2.4 MW to 2.7 MW, which is significantly less than the theoretically estimated value of 4.5 MW. The difference may be caused by the corridor restricting oxygen supply to the room as well as saturation of the hood, but no certain answer can be given at this point. It should also be mentioned that the theoretical estimate of the ventilation limit is based on an ideal assumption where the airflow to the room is only being restricted by the opening, as well as a full consumption of all the oxygen flowing into the room. Therefore, the theoretical estimate can only be used as a rough prediction of the upper bound of energy that may be released in the room, and is not expected to have a perfect match with the measured values in this particular experimental setup.

Further information on other measured values as room temperatures can be found in two other publications [13, 16].

3.2.2. Flashover Investigation. In order to further investigate the rapid development of the heat release rate found for the DFCP2 tests, the heat release rates versus time for all seven tests are plotted in Figure 5. The time is changed and set to zero when a rapid increase of the heat release rate starts. This point is found as the time where the heat release rate increases more than 25 kW/s. It can be seen that the heat release rate curves are more or less alike from the onset of the rapid increase, indicating that the compositions of the fire load were not a dominating factor from this point on. This is in contrast to the DFCP1 tests, where the fire load seemed to dominate the fire development. Therefore the onset of the rapid increase of the heat release rate for the DFCP2 tests also represents a significant

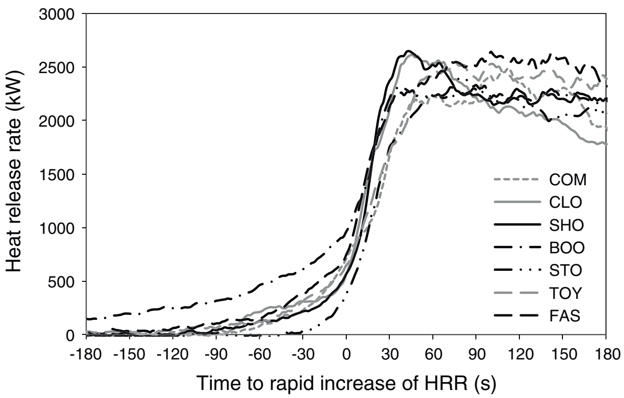

Figure 5. HRR versus time correlated to the onset of the rapid increase (thermal runaway) of the HRR, DFCP2.

Table 3
Measured HRR and Ceiling Temperatures at the Onset of Thermal Run-away

Test	Time from ignition (s)	HRR (kW)	T_c (°C)
Computer showroom (COM)	122	710	300
Storage room (STO)	68	560	n/a
Clothing store (CLO3)	94	555	380
Toy store (TOY)	268	650	n/a
Shoe storage (SHO)	192	565	n/a
Book store (BOO)	766	965	725
Fast food (FAS)	156	690	420

change in the fire development occurring early in the fire course that is not found for the DFCP1 tests.

The rapid increases occurring in the DFCP2 experiments are seen as a thermal runaway. At the onset point, the heat release rates were in the range of 550 kW to 700 kW, except for the book store (965 kW), see Table 3, and the temperatures measured below the ceiling were in the range of 300°C to 420°C [considerably higher for the book store (725°C)].

The temperatures at the onset of thermal runaway are plotted together with traditional flashover criteria in Figure 6. The figure shows that for three out of four tests, the thermal runaway occurred before any of the flashover criteria, as should be. In the book store test, on the other hand, the temperature criterion was met before thermal runaway occurred.

During the tests it was in most cases observed that ignition of the second fuel package appeared as radiation ignition at the top of the second fuel package, quickly followed by ignition of crumpled paper, which also means that the second fuel package ignited during the rapid increase of the heat release rate. As such, the start of the rapid increase occurred before significant fire spread was observed.

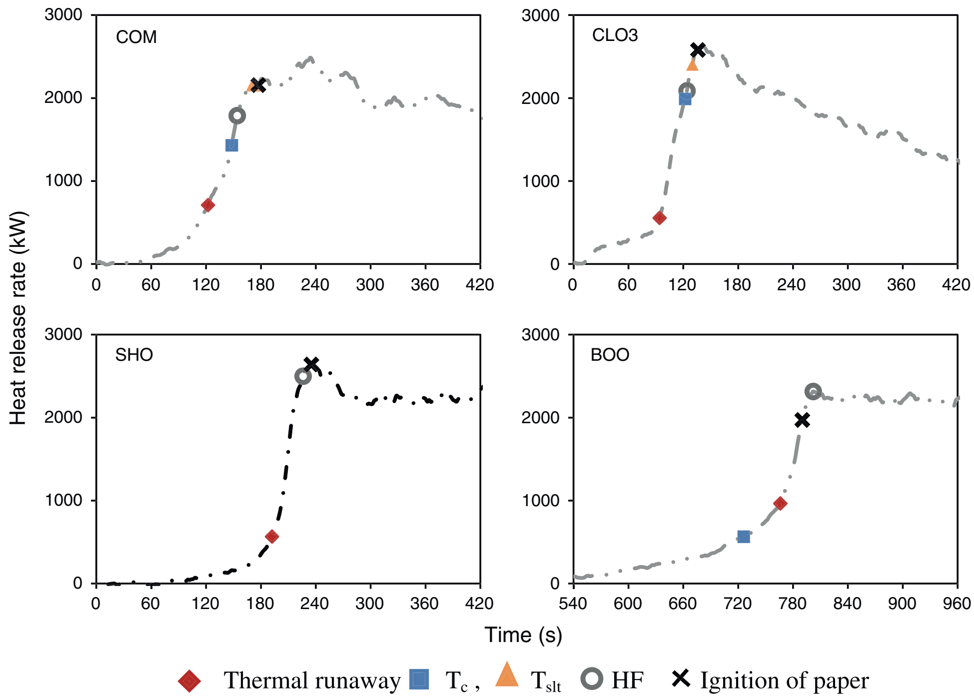

Figure 6. HRR versus time at different flashover criteria compared to the fire development, DFCP2. The criterion for thermal runaway is also inserted.

Because the traditional criteria generally are related to fire spread, this may also explain why the traditional criteria for flashover were met during the rapid increase and not around the start. It should however also be noticed, that as flashover is not directly caused by fire spread, using heat release rates found at the traditional criteria for flashover would overestimate the actual heat release rate that was needed for the onset of flashover. Therefore, these values should not be taken as representative of the onset of flashover, but an assessment of fire spread.

As the traditional models for prediction of the heat release rate needed to cause flashover is based on a temperature criterion of 500°C to 600°C and uses simplified assessments of the energy balance, these models cannot be expected to predict the onset of flashover, which for the DFCP2 tests in most cases occurred at significantly lower temperatures. Instead models also taking thermal runaway into consideration could be used [5, 19, 20].

It should be mentioned that for the book store test, fire spread seems to be the dominating process in causing flashover, indicating that for fire loads composed only of wood/celluloses the traditional temperature criterion should be valid for predicting flashover. Thomas' model [10] is, however, not able to predict the heat release rate at 600°C for the book test (550 kW). This may be because Thomas assumes the linings to be of concrete and not ceramic fibers which were used in the tests. Concrete linings will allow for a much larger energy loss and thus a higher heat release rate would be needed to give the required temperature.

3.3. Comparison of the Test Series

The test results show that for the DFCP1 tests the fires developments were mostly dependent on the composition of the fire load. This was only the case in the growth phase for the DFCP2 tests as a thermal runaway took place for the DFCP2 test after, in most cases, a relatively short growth phase. For the DFCP2 test it was also found that the second fuel package, in most tests, ignited during the rapid increase of the heat release rate. Taking the heat release rate for DFCP2 tests until ignition of the second fuel package and comparing these curves to the DFCP1 tests, it is possible to study the influence of changing non-combustible linings for comparable objects, as the test room for the DFCP1 and DFCP2 test are comparable in size and ventilation. As the tests also are categorized by the different compositions of the fires load, it is also possible to study the influence of the different flammability parameters.

3.3.1. Influence of the Thermal Inertia. Four different types of fire loads (computer showroom, clothing, shoe storage and book store) from the DFCP1 test and DFCP2 tests are compared in Figure 7. To eliminate the influence of difference in the ignition phase, the time on the graphs is set to zero when the heat release continuously exceeds 30 kW. The heat release rates for the DFCP2 tests are only plotted for the part of the experiment that takes place before the second fuel package ignites. As only one fuel package was tested for the shoe storage in the DFCP2 tests, the full graph is shown. Therefore, the graphs show the burning behavior of comparable fuel packages with comparable fire loads. The thermal runaway (rapid increases of heat release rates) is also marked.

Figure 7 shows that there is a significant difference in the burning behavior for all types of combustibles except the book store, as the heat release rate for the DFCP2 tests increased significantly compared to the DFCP1 tests. In all three cases thermal runaway is found to occur shortly after the deviation between the heat release rate curves starts and before the second fuel package ignites. After the thermal runaway occurred, the difference between the heat release rates for the two test series became more pronounced, even before fire spread to the next fuel package. This is not the case for the book store where the heat release rate curves are comparable almost until the second fuel package ignites, which is about the same time as thermal runaway is found.

As the thermal inertia was the only varied parameter for the shown period of the four fire tests, the results show that lowering the thermal inertia caused both the increase of the heat release rate and subsequently flashover for three out of four tests. Thus, the results are in line with previous pool fire experiments [12] and are supported by models [21, 22] which by isolating parameters, have shown that the critical temperature at the onset of thermal runaway is strongly dependent on the thermal inertia.

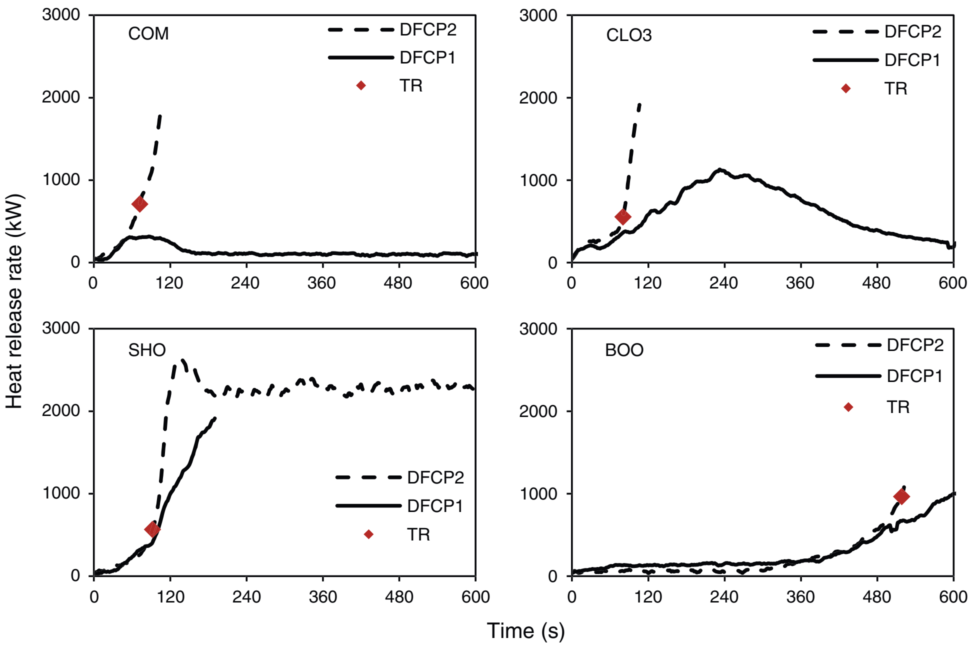

Figure 7. Comparison of HRR versus time between DFCP1 and DFCP2. TR is thermal runaway.

At the onset of thermal runaway the room temperature for these tests (except the book store) were around 300°C to 420°C (see Table 3). Therefore the results also support that by lowering the thermal inertia thermal runaway could occur at significantly lower temperature than the traditional flashover criteria of 500°C to 600°C and that the traditional criteria do not in all cases implicitly take thermal feedback into consideration. This is the same result as was found for the heptane pools [12] which shows that thermal feedback may be a dominant process in bringing about flashover also for other combustibles than pool fires. The results further show that thermal runaway need to be considered when assessing flashover for highly insulated buildings with low thermal inertia.

3.3.2. Influence of the Type of Burning Material. Figure 7 showed that three out of four test resulted in thermal runaway before the second fuel package was ignited. The test that deviated on this point was the book store test. This corresponds well to the difference in temperatures at the onset of flashover by thermal runaway, as this happened at a higher temperature (725°C) for the book store than for the other tests (300°C to 420°C). The fire load in the book store was composed of pure wood/cellulose, whereas the other types of fire loads also included various amount of plastics, food, textiles and rubber/leather.

At the onset of thermal runaway, an approximate linear correlation may be found between the ratio of the effective heat of combustion and the heat of gasification ($\Delta H_{eff}/L_g$) and the room temperature T^3 for a fixed burning area in the same room (see equations 4 and 6 in [12]). The correlation show that for materials with a low ratio of ($\Delta H_{eff}/L_g$) a higher room temperature is needed to give the same gradient of the heat gained in the Semenov diagram, and therefore that a material with a low ratio of ($\Delta H_{eff}/L_g$) is less sensitive to thermal feedback that materials with a higher ratio.

For charring solids such as wood the effective heat of combustion, ΔH_{eff}, will normally be in the range of 5 MJ/kg to 15 MJ/kg and the heat of gasification, L_g, will be in the range of 5 MJ/kg to 8 MJ/kg [23]. For melting, non-charring solid such as plastic materials, ΔH_{eff} and L_g would be in the range of 20 MJ/kg to 40 MJ/kg and 1 MJ/kg to 3 MJ/kg, respectively [23]. Thus, ($\Delta H_{eff}/L_g$) for melting, non-charring solids can be an order of magnitude larger than for charring solids. This difference in the composition of the fire load and, thus flammability parameters, may therefore also influence the difference in the onset temperature of thermal runaway, and as such indicate why thermal runaway is not evident for the book store test.

4. Summary

Two series of full scale room fire tests comprising 16 experiments are used for a study of the onset of flashover. The fire loads were varied and represented seven different commercial applications and two non-combustible linings with significantly different thermal inertia were used. The test results showed that by lowering the thermal inertia and thereby at the same time lowering the heat loss from the room and increasing the thermal feedback, a thermal runaway occurred before significant fire spread; but only for objects composed of a mixture of plastic/rubber/textiles and wood/celluloses. In these cases the onset of thermal runaway was found to occur at room temperatures in the range 300°C to 420°C. This supports that the room temperature at the onset of thermal runaway was strongly dependent on the thermal inertia. It also shows that the onset of thermal runaway cannot in all cases implicitly be predicted by the traditional flashover temperature criterion of 500°C to 600°C. As the traditional flashover criterion often is a basis for simplified traditional models as well as these models uses simplified assessments of the energy balance, these models cannot be expected to predict the onset of flashover as found by the tests. In these cases models including thermal feedback as well as thermal runaway should be applied.

For fire loads composed of pure wood/celluloses the onset of flashover occurred about the same time as fire spread irrespectively of linings and at significantly higher room temperatures (725°C). This can be explained by flammability parameters making wood/celluloses less sensitive to thermal feedback.

This influence of the thermal inertia in bringing about flashover is also important to acknowledge as increasing requirements for thermal insulation can lower the thermal inertia especially if thermal insulation is mounted on the inner surfaces of the rooms. For these buildings the starting point of flashover may not always be found by the use of the temperature criteria for flashover.

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Research Report

An Experimental Study of the Effect of Thermal Radiation Feedback on the Room Burning Behavior of Horizontal Blocks of Polyurethane Foam

Annemarie Poulsen and Alex Bwalya

NRC-IRC Research Report IRC-RR-309

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An Experimental Study of the Effect of Thermal Radiation Feedback on the Room Burning Behaviour of Horizontal Blocks of Polyurethane Foam

Research Report No. 309

Date: July 6th, 2011

Authors: Annemarie Poulsen and Alex Bwalya

Institute for Research in Construction
Fire Research Program

Abstract

This report presents the results of three fire experiments (one free-burn and two room tests) that were carried out to investigate the influence of thermal radiation feedback on the rate of surface flame spread and heat release rate (HRR) for a horizontal block of furniture-grade non-fire-retarded polyurethane foam measuring 1200 x 600 x 200 mm and weighing approximately 4.8 kg. The room tests were conducted in a small compartment measuring 2400 mm wide x 2800 mm deep x 2400 mm high with a rectangular vent (opening under a calorimeter hood) measuring 740 mm wide x 1500 mm high (a ventilation limit of approximately 2000 kW) located in one of the 2400 mm walls. The room was lined with one of two different non-combustible materials – 12.7 mm thick cement board or 50 mm thick mineral wool insulation – with substantially differential thermal inertias in order to subject the test specimen to one of two thermal environments. Measurements were taken to quantify the temporal variation of heat release rates (HRRs), smoke density, radiant heat flux, temperatures and the concentration of O_2, CO_2 and CO in the test room. The tests were also recorded using an infrared camera in order to determine the surface rate of flame spread.

The free-burn peak HRR was found to be 498 kW at 172 s from ignition, plateauing at this value for approximately 34s before it rapidly declined. The peak HRR for the test conducted with a cement board room lining was 526 kW at 159 s from ignition (with immediate decline), while that for a mineral wool insulation lining was 965 kW at 176 s (with immediate decline). The maximum room temperatures for the tests with cement board and mineral wool linings were 435 ℃ and 850 ℃, respectively. The results indicated that for the test with a cement board lining, there was no significant change in the peak HRR compared to the test conducted under free-burn conditions. Lowering the thermal inertia (with a mineral wool lining) resulted in a considerably greater (~ 90%) increase in peak HRR compared to the other two tests, which confirmed that radiation feedback from hot layer and walls was responsible for the dramatic increase in the peak HRR.

From the analysis of data record with an infrared camera, it was found that surface flame spread rates were higher (~ 12 mm/s) when the PUF was burning in the room than under free-burn conditions (~ 8 mm/s), regardless of the lining material used.

An Experimental Study of the Effect of Thermal Radiation Feedback on the Room Burning Behaviour of Horizontal Blocks of Polyurethane Foam

by

Annemarie Poulsen[1] and Alex Bwalya[2]

1 Introduction

During the last decade many countries adopted performance-based fire regulations for the design of buildings. As part of the documentation of fire safety, the designer may select one or more design fires based on the knowledge of the expected occupancy. One of the key parameters that must be defined is the evolution of the heat release rate (HRR), which defines the temperature conditions in the room or building.

Much data on fire growth and HRR rates for burning items are available in the literature. However, most of the data has limitations as the experiments were conducted in open conditions, and therefore enclosure effects such as radiation feedback from the hot gas layer and surrounding walls are not reflected. During a room fire, radiation feedback is believed to have an impact on fire development. Radiation feedback can affect the rate of surface flame spread, burning rate and, consequently, the rate of fire growth and onset of critical events such as flashover [1]. One group of variables known to have a significant effect on the radiation feedback are the thermal properties of the wall lining materials since different values of thermal inertia will affect the temperature levels in the smoke layer and the room surfaces.

This report presents the results of fire experiments with horizontal blocks of polyurethane foam (PUF) conducted as part of a joint research project between NRC-IRC's Fire Research Program and The Technical University of Denmark, department of civil engineering, DTU Civil Engineering. The experiments were also part of the Thesis work on *Fire Models and Design Fires* for the first author, a PhD candidate at DTU Civil Engineering, who was a visiting worker at NRC-IRC.

2 Objectives

The aim of the experiments was to study the effect of radiation feedback on surface flame spread, rate of fire growth and peak HRR during the pre-flashover phase of a fire. For this reason a test conducted in the open, under the calorimeter hood (also referred to as a "free-burn test"), and two room fire tests were conducted with identical blocks of non fire retarded polyurethane foam (PUF), which is commonly used in the manufacture of upholstered furniture. The room tests had non-combustible linings with vastly different thermal inertia to subject the test specimen to one of two thermal environments. The thermal radiation feedback is in this context understood to occur due to radiation from the smoke layer below the ceiling and heated walls.

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3 Test specimens

The test specimen was required to be sized so that the resulting fire did not exceed a heat release rate of approximately 1000 kW, which was the flashover threshold for the small room used in this study [2]. The type of PUF material used in the study was the same as that used for constructing a mock-up sofa in a previous project [3] conducted at NRC-IRC in order to take advantage of existing experimental data in preliminary estimates of burning behaviour. In that project, a free-burn experiment with a 610 x 610 x 100 mm PUF block placed on shallow aluminum pan resulted in a fire with a peak HRR of 298 kW. Based on these results, it was estimated that a PUF block of approximately twice the size would produce a free-burn HRR of slightly greater than 500 kW, which has been indicated as a minimum value at which the effects of thermal feedback would be expected to occur in a small room [4]. Therefore, the dimensions of the PUF block was chosen to be 1,200 mm long x 600 mm wide x 200 mm thick. The dimensions and mass of each PUF block are given in Table 1. A 100 mm square grid was drawn on the surface of the PUF block (Figure 1) for the purpose of measuring the rate of surface flame spread.

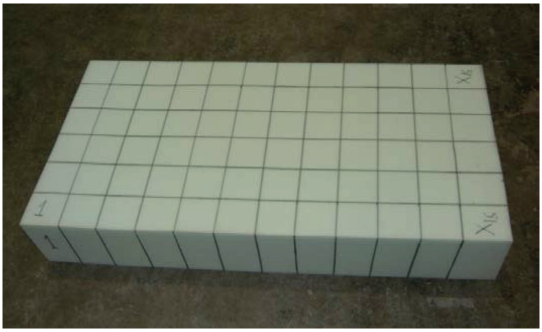

Figure 1. Photograph of the PUF block showing the 100 mm grid marks.

Table 1. Dimensions of test specimens.

Specimen number	Length [mm]	Width [mm]	Thickness [mm]	Mass [kg]	Density [kg/m^3]
1	1213	600	203	4.760	32.2
2	1201	609	204	4.812	32.2
3	1206	601	204	4.702	31.8

4 Experimental Design

The test facility was comparable to the ISO-9705 room calorimeter [5], but the depth of the standard room was reduced from 3600 mm to 2800 mm while the width and height each remained

2400 mm. This was done to lower the flashover threshold since preliminary tests showed that the free-burn HRR was only expected to be slightly greater than 500 kW. A ventilation opening of 740 mm wide x 1500 mm high was provided in one of the 2400 x 2400 mm walls. The opening was directly under a fume hood, which was connected to an exhaust duct having a diameter of 406 mm.

Two preliminary tests (presented in Appendix A) were conducted to refine the test setup (including the position and strength of the burner) and test procedures.

The experimental matrix consisted of three tests: one free-burn test and two room tests. In the room tests the wall and ceiling lining materials were varied in order to alter the radiation feedback. The non-combustible lining materials used were 12.7 mm thick cement board with a density of approximately 1257 kg/m^3 and 50 mm thick mineral wool with a density of approximately 100 kg/m^3. The mineral wool insulation was attached to the cement board lining. The thermal inertias ($k \cdot \rho \cdot c$) for the cement board and mineral wool were approximately 0.6 and 0.004 W^2s/K^2m^4, respectively

Table 2 lists the three experiments that were conducted with identical pieces of PUF.

Table 2. List of experiments conducted.

Test No.	Specimen No.	Type	Room Lining
1	2	Free-burn	NA[1]
2	1	Room test (uninsulated)	Cement board
3	3	Room test (insulated)	Mineral wool

[1] Not applicable (free-burn test was conducted under the hood).

Previous experiments [3] showed that the PUF had a tendency to melt and form a pool on the pan after it was ignited. Only a small amount of char residual was left on the pan in those experiments. Therefore, to contain the melt-pool and limit the burning area, the test specimen was placed on a steel pan measuring 1400 mm long x 800 mm wide x 50 mm deep. The pan was supported on a 750 mm high load-cell apparatus that was designed to measure mass loss, see Figure 2.

Based on the results of preliminary experiments (Appendix A), the burner was designed so that it produced two flames of approximately equal strength and having a total HRR of 75 kW: a horizontal flame to ignite the PUF block and a vertical flame to attenuate the horizontal flame and provide the balance of the burner HRR output, see Figure 3. The burner was left on for the entire duration of each test.

Figure 2. Photograph of pan and load cell.

Figure 3. Photograph of dual-flame T-burner.

4.1 Instrumentation

Figure 4 is an illustration of the floor plan and instrumentation of the test setup for the free-burn experiment. The test specimen was located directly under the hood to allow combustion products to be collected. Measurements of mass flow rate, gas temperature and concentrations of oxygen, carbon dioxide and carbon monoxide were taken in the exhaust duct to facilitate calculation of the heat release rate by using an oxygen consumption method [6]. The smoke density was measured in the duct using a pulsed white light meter. In addition, the mass loss rate of the test specimen and heat flux at two different locations was recorded. One heat flux gauge (HF#1) was positioned in a vertical plane at a distance of 600 mm from the pan and height of 1200 mm above the floor facing the flames. The second heat flux gauge (HF#2) was positioned in a horizontal plane at the end of the pan facing upwards towards the hood. The tests were also recorded using an infrared camera to aid the study of flame spread.

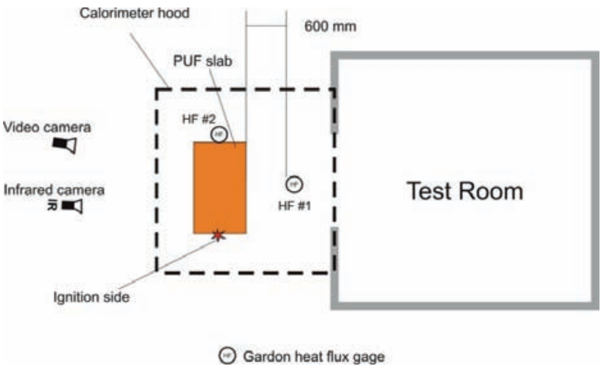

Figure 4. Layout of instrumentation for the free-burn Test 1.

Figure 5 shows the layout of instrumentation for Test 2. The depth of the standard room was reduced to 2800 mm by constructing a light-weight frame partition wall using cement board. The instrumentation was repeated from Test 1 (free-burn). In addition to these measurements, temperatures in the room were recorded at different locations in the room as shown in Figure 5. TCs nos 1, 2 and 3 were positioned at 200 mm below the ceiling whereas TC no. 4 was installed at a height of 200 mm above the floor. TC's 5 to 8 were mounted on the back wall to measure surface temperatures inside the room and on the backside of the lining. Two thermocouple trees were installed in opposite corners.

Figure 6 shows the layout of instrumentation for Test 3. All surfaces in the room, except for the floor, were covered with a layer of 50 mm thick mineral wool insulation. In order to maintain the same volume of the room as in Test 2, the depth of the room was extended by 280 mm before the mineral wool insulation was installed. The instrumentation was the same as that used in Test 2, except that the thermocouple trees were adjusted to give the same relative positions (eg. distance from the pan, walls and ceiling) as those in Test 2.

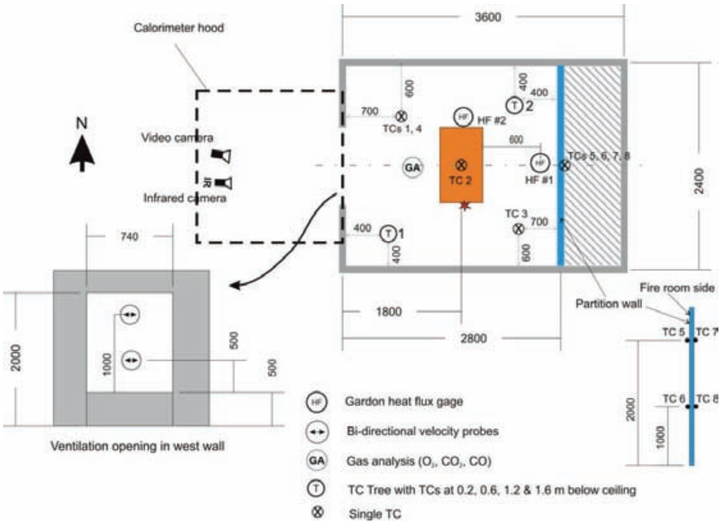

Figure 5. Room burn test setup with cement board lining (Test 2).

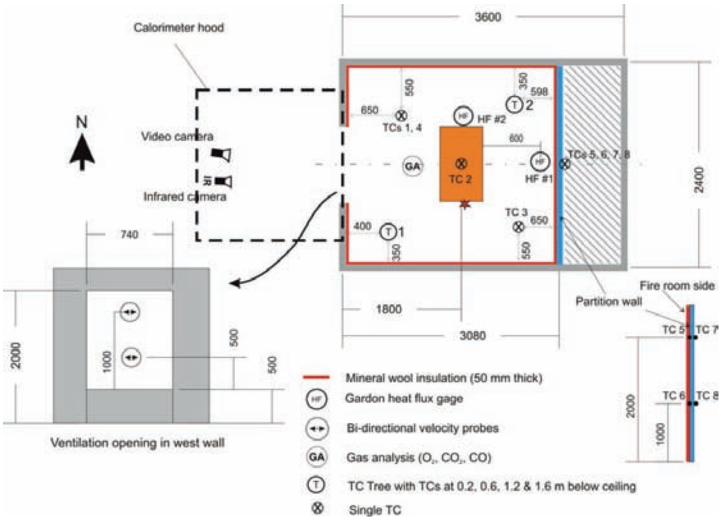

Figure 6. Room burn test setup with mineral wool insulation (Test 3).

The Infrared camera used was a JENOPTIK VarioCAM HiRes infrared (IR) camera incorporating a 16 bit micro bolometer (an uncooled thermal detector) with 384 x 288 pixels. Additional technical data for the IR camera are given in Table 3.

Table 3. Technical data for the VarioCAM® IR camera.

Spectral sensitivity	Temperature range	Measurement accuracy	Thermal resolution (at 30°C)
7.5 – 14 μm	-40°C - 2,000°C	0°C - 120°C: ± 1.5 K >120°C: ±2%	<60 - 80 mK

4.2 Data Acquisition System

A 16 bit Solartron (Schlumberger) Instruments distributed data acquisition system with 3595 series isolated measurement pods (each having 20 channels) and a personal computer interface was used to record all measurements directly to a hard disk drive at specified intervals. All temperature data were instantly processed by the data acquisition system and recorded as temperature values with an accuracy of better than 1°C. Outputs from heat flux gauges, load cells, pressure transducers, gas analyzers and the smoke meter were recorded as either direct current (DC) voltage or current values and were converted by applying the appropriate calibration constants after each experiment. The sensitivity of the data acquisition system for voltage and current measurements is 1 μV and 10 nA, respectively.

4.3 Test procedure

The dual-flame propane T-burner was positioned at 75 mm from the edge of the PUF block and 33 mm above the surface of the block. The test procedure is given in Table 4; it was designed to measure pre- and post-test conditions (including burner output) for each test.

Table 4. Planned test procedure (sequence and timing of events).

Time (sec)	Event	Comment
0	Start data logger	Record pre-ignition conditions
60	Light burner (without specimen)	Measures of burner output
120	Switch-off burner	
180	Place specimen in pan	Measures initial specimen mass
240	Re-light burner (to ignite PUF block)	This is where the actual test starts
	Wait until complete burnout	
+ 60	Stop burner	
+ 60	Stop measurements	Measures end conditions and allows for correction of any drift in measurements

5 Results and Discussion

5.1 Measurements

The measured HRR profiles are presented in Figure 7 and the measurements of smoke density are presented in Figure 8. The HRR results show that Test 1 (free-burn) and Test 2 (cement board lining) had two peaks, whereas Test 3 (mineral wool lining) only had one significantly greater peak. The second HRR peak was likely caused by a combination of two factors: a) burning of unconsumed PUF material around the edges of the block after the material in the central area was initially consumed; and b) deflection of the pan (observed to occur around the time that the peak HRR was reached), which caused the molten PUF to collect at the opposite ends of the pan.

Tests 1 and 2 had comparable fire growth rates and HRR profiles, but there was no considerable increase in HRR in Test 2 due to room effects – Test 2 was only slightly quicker in reaching the peak (498 kW at 172s in Test 1 versus 526 kW at 159 s in Test 2). Test 1 exhibited a plateaued peak lasting 34s before the HRR begun to decline. A second peak of 499 kW occurred at 206 s (towards the end of the plateau). However, considering that the accuracy of HRR measurements using the oxygen consumption method [6] is not better than 5%, the first peak HRR value of 498 kW is here considered to be more important in describing the rate of fire growth in Test 1, i.e. within the stated margin of error, there is a negligible difference between 498 kW and 499 kW, but selecting the second peak HRR value would give an inaccurate impression of the rate of fire growth leading up to the peak.

The measurements of smoke density show similarities with the HRRs except that the first peak for the test with mineral wool lining is not significantly larger than the other two tests, which may suggest that smoke production may be a function of combustion stoichiometry and material properties given that the same material was used in all of the tests. Further research and analysis is needed to determine if the trend of HRR magnitudes should have been repeated. Detailed information about peak values is given in Section 5.5.

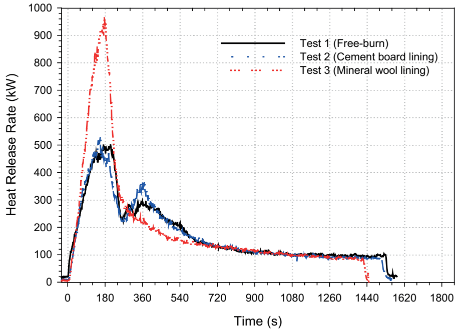

Figure 7. Graph of HRR vs. time.

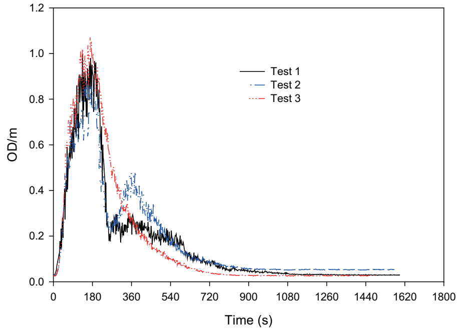

Figure 8. Measurements of smoke optical density in the exhaust duct.

Figures 9 to 14 show the results of temperature measurements at corresponding measurement locations in Tests 2 and 3 (presented side-by-side). Figures 9 and 11 show that peak temperature in the room during Test 2 was generally below 435 °C, although TC2 recorded a peak temperature of 659 °C, which was a localized effect since it was located directly above the burning specimen. In contrast, in Test 3, all peak temperatures in the upper smoke layer (up to 1.2 m below the ceiling) exceeded 600 °C (Figures 10 and 12), which is indicative of the attainment of flashover conditions. In Test 2 temperatures in the lower level (at 1.6 m below the ceiling) were less than 100 °C, which indicated that a two zone division of the room existed. In Test 3, the temperature at the same position had peak value of more than 300 °C, indicating that the smoke layer had likely descended to that level.

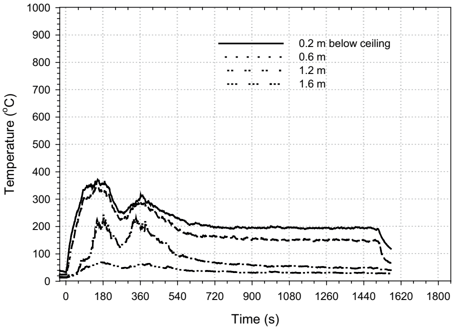

Figure 9. Test 2: Temperatures profiles from TC tree #1.

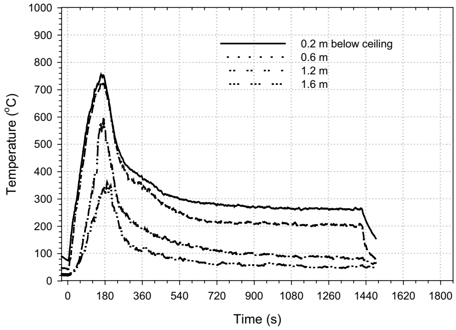

Figure 10. Test 3: Temperatures profiles from TC tree #1.

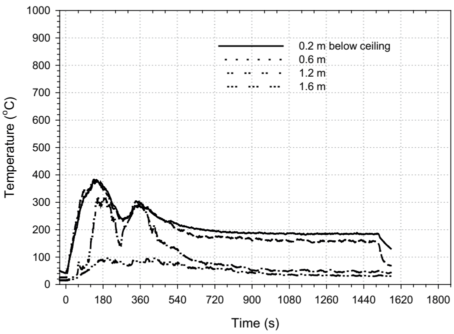

Figure 11. Test 2: Temperatures profiles from TC tree #2.

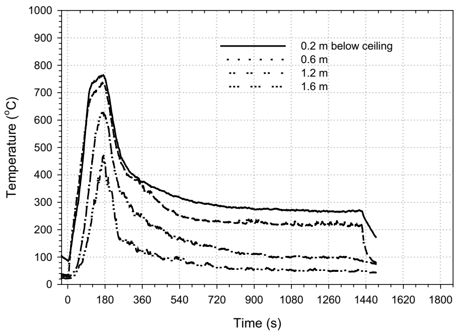

Figure 12. Test 3: Temperatures profiles from TC tree #2.

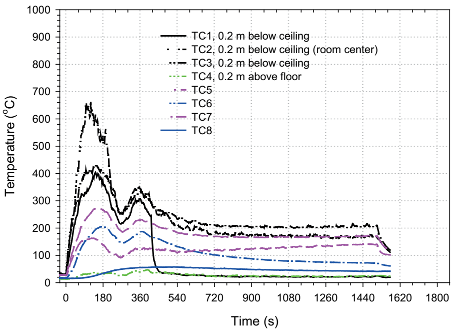

Figure 13. Test 2: Temperatures profiles from TCs 1 to 8.

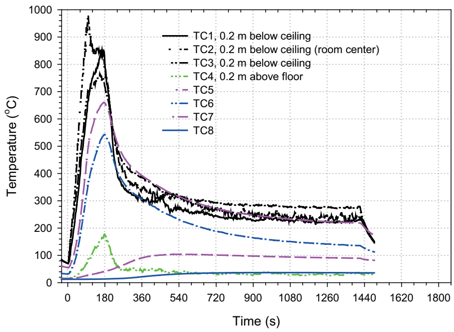

Figure 14. Test 3: Temperatures profiles from TCs 1 to 8.

Measurements of heat flux by gage HF#1 (located at 600 mm from the center of the pan) are given in Figure 15. Since the heat flux meter was facing the flame, the measurements followed the trend of the HRR. The difference between Tests 1 and 2 is more distinct than indicated by HRR measurements; the higher peak heat flux record in Test 2 is consistent with the peak HRR and temperature trends. Figure 16 shows the heat flux measured by gauge HF#2 located at the end of the pan (in a horizontal plane). The measurements give an indication of the background radiation from the room, although when flames were approaching the rear of the pan they likely influenced the measurements. Figure 16 also shows that the background radiation levels were comparable for Test 1 and Test 2 whereas Test 3 (mineral wool lining with low thermal inertia) had significantly higher background radiation due to higher room temperatures (and hotter smoke layer).

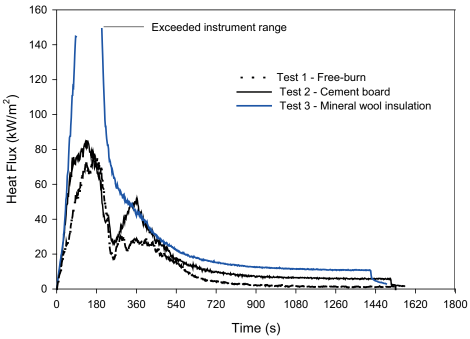

Figure 15. Graph of HF#1 vs. time.

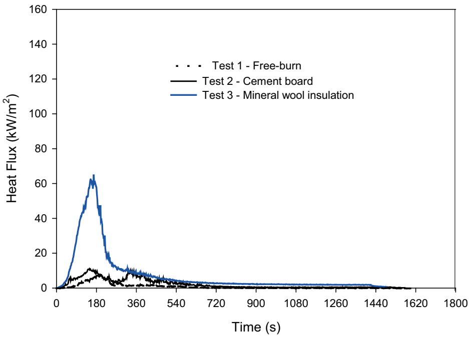

Figure 16. Graph of HF#2 vs. time.

The results of velocity measurements in the room opening are given in Figures 17 and 18 for Tests 2 and 3, respectively. The velocity profiles followed the HRR trend, as can be expected.

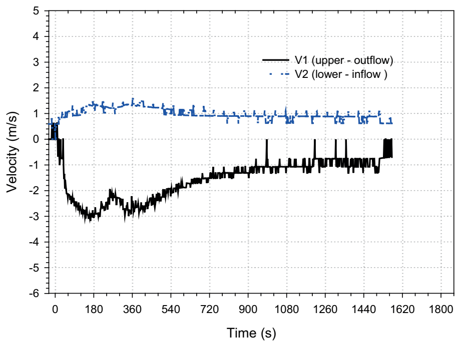

Figure 17. Test 2: Velocity profiles in the ventilation opening.

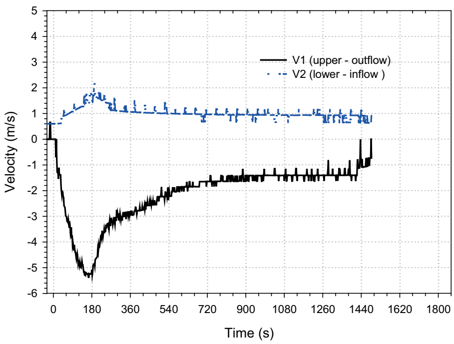

Figure 18. Test 3: Velocity profiles in the ventilation opening.

Figures 19 and 20 show the O_2, CO_2 and CO measured in the room for Tests 2 and 3, respectively. The results are consistent with the respective magnitudes of HRRs for the two Tests – lower O_2 (high depletion due to increased HRR) and consequently higher CO_2 and CO concentrations in Test 3.

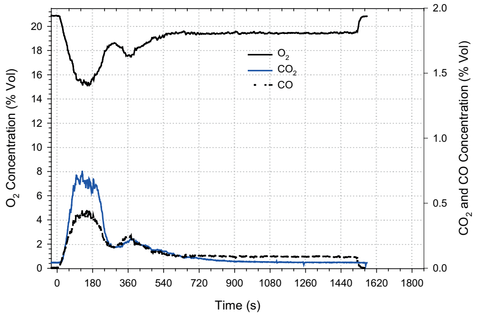

Figure 19. Test 2: O_2, CO_2 and CO measured in the room.

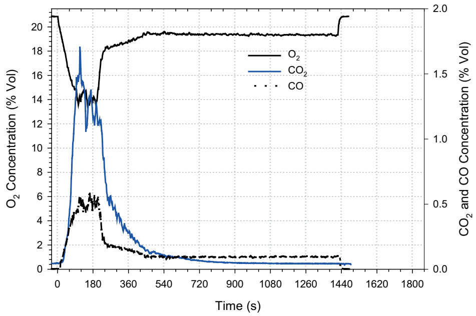

Figure 20. Test 3: O_2, CO_2 and CO measured in the room.

5.2 Mass Loss Measurements

Analysis of the results of mass loss measurements did not show meaningful trends after the peak HRR was reached. Contrary to expectations, there was an inexplicable period of significantly negative readings followed by a rebound to positive readings. Therefore, these measurements have been omitted from this report.

5.3 Observations from Thermal Images

All three experiments were recorded using an infrared camera. Figures 21 to 24 show examples of thermal images taken during Test 3.

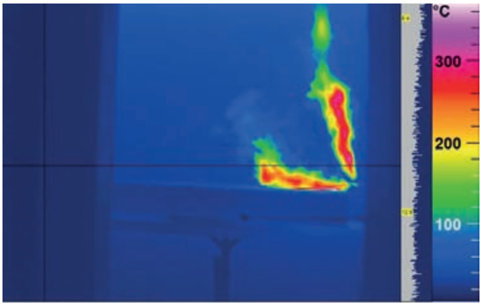

Figure 21. Thermograph at ignition.

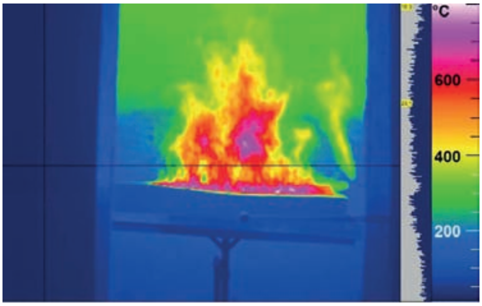

Figure 22. Thermograph showing flame spread at about 44 s after ignition.

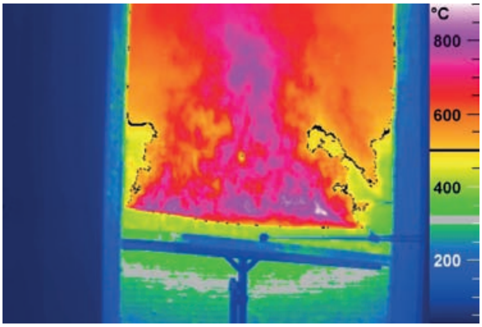

Figure 23. Thermograph at 100 s after ignition during Test 3,

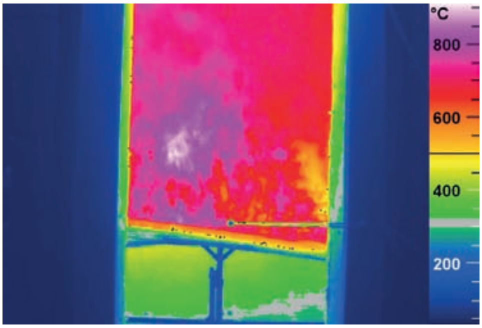

Figure 24. Thermograph at time for peak HRR during Test 3,

Table 5**Error! Not a valid bookmark self-reference.** lists the flame spread rate versus time as recorded by the infrared camera. To avoid influence of the burner, the flame spread rate was measured from the time the flame front reached the longitudinal center of the slab until the flames reached the end of the slab. The observations show that the two room burn tests had comparable flame spread rates, which were faster than the free-burn test. The average velocity of flame spread was found to be 8 mm/s for the free-burn test and 12 mm/s for both room tests.

Table 5. Flame spread rate recorded by infrared camera.

Distance[a] [mm]	**Time[a] [s]**		
	Test 1 (Free-burn)	Test 2 (Cement Board)	Test 3 (Mineral wool)
0	0	0	0
200	32	22	20
400	58	46	40
600	78	52	48

[a] Measurements of distance and time starts when the flames reaches the middle of the slab.

Table 6 summarizes the observations that were made by reviewing the thermal images. An interesting observation was that the pan was deflecting, in all three tests, by which two opposite corners bent down leaving the middle of the pan and the other two corners to form a ridge. This caused molten PUF to separate and flow towards opposite ends of the pan, see Figure 25. After flaming had ceased, it was observed that there was some char on the ridge which may also have contributed to the separation of the molten PUF.

Table 6. Observations from the recordings from the infrared camera.

Event	Test 1 [s]	Test 2 [s]	Test 3 [s]
Ignition	0	0	0
Flame spread to the center of the specimen	14	6	4
Flame spread to the end of the specimen	92	58	52
Full surface involvement,	96	58	54
Center of the specimen melt down	186	158[a]	120[a]
Burn out at the middle of the specimen	232	212[a]	228[a]
The pan starts to deflect	154	96[a]	70[a]
Max pan deflection	222	264[a]	122[a]

[a] Events occurring in the room were very difficult to see from the infrared recordings, which means that an even greater uncertainty is associated with these observations.

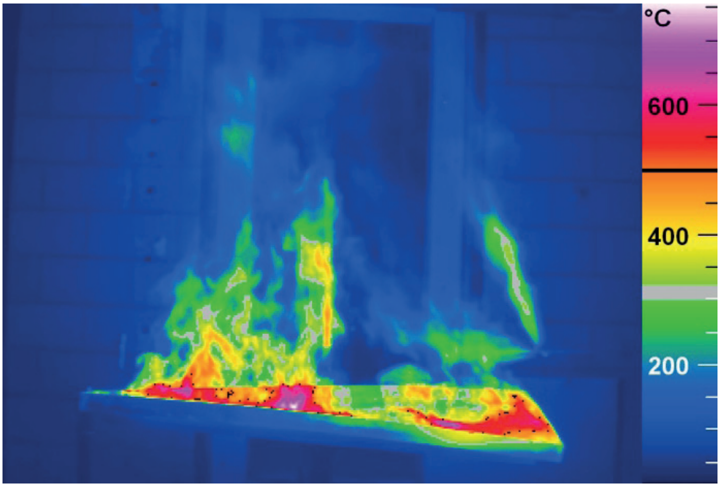

Figure 25. Test 1: Deflection of the pan and separation of molten PUF.

5.4 Test sequence

Table 7 lists the actual sequence and timing of the tests, including the duration of the test. All test durations were comparable.

Table 7. Actual sequence and timing of events.

Event	Test 1 (Free-burn)	Test 2 (Cement board)	Test 3 (Mineral wool)
Start data logger	0:00	0:00	0:00
Horizontal flame lit	2:00	0:32	1:08
Vertical flame lit (burner fully lit)	2:00	1:02	2:02
Switch-off burner	3:30	2:00	3:12
PUF block placed on load cell			
Burner re-lit (to ignite PUF)	6:00	4:23	5:30
PUF ceases to burn	30:30	28:30	28:00
Switch-off burner	31:30	29:30	29:10
Stop data logger	32:30	30:30	30:10
Test duration (from PUF ignition)	23:30	24:30	22:30

5.5 Summary of Test Results

Table 8 summarizes selected test results. The results show that flame spread rates are faster in the room than for free-burn conditions, regardless of the lining material used. The flames spread to the end of the block before the peak HRR occurred. When flames had covered the entire PUF surface, there were no significant differences in the magnitude of the HRRs. This indicates that the HRR may not be the only dominant factor in estimating the flame spread rate, as other phenomena such as air flow patterns (likely induced by the exhaust suction) and the specific different boundary conditions may influence the flame spread rate. Since peak HRRs occurred at more than double the time it took for the flames covered the entire surface, it suggests that peak HRRs may be dependent on other parameters than the ignited surface area alone. Since peak HRR appeared to occur after the center of the specimen had completely melted, pool formation and build up of room temperatures are likely to influence the time for peak HRRs as well.

It is noted that Test 3 had almost twice the peak HRR of Test 2, and the room temperatures were considerably higher in Test 3. This indicates that radiation feedback, due to higher room temperatures, was mainly responsible for the enhancement of burning rate (and consequently higher peak HRR) in Test 3.

Table 8. Summary of selected test results.

Test	Flame travel time [a] [s]	Peak HRR [kW]	Peak OD/m	Peak Heat Flux [kW/m^2]	Peak Room Temp[b] [°C]	Peak Lining Temp [°C]
Test 1 (Free-burn)	78	498 (172 s)	1.0	78(HF#1) 8 (HF#2)	-	-
Test 2 (Cement board)	52	526 (159 s)	0.9	85 (HF#1) 11 (HF#2)	435 (TC#1)	270
Test 3 (Mineral wool)	48	965 (176 s)	1.1	NA[c] (HF#1) 65 (HF#2)	850 (TC#1)	660

[a] Measured time it took for the flame front to travel from the center of the block to the end.
[b] As TC#2 is influenced by flame/plume this TC is not included in the finding the peak temperature.
[c] NR - Not recorded, instrument limit exceeded (maximum reading was 150 kW/m^2)

6 Conclusion

This report presented the results of three fire experiments (one free-burn and two room tests) that were carried out to investigate the influence of thermal radiation feedback on the rate of surface flame spread and heat release rate (HRR) of a horizontal block of furniture-grade non fire retarded polyurethane foam measuring 1200 x 600 x 200 mm and weighing approximately 4.8 kg.

The free-burn peak HRR was found to be 498 kW at 172 s from ignition, plateauing at this value for approximately 34s before it rapidly declined. The peak HRR for the test conducted with a cement board room lining was 526 kW at 159 s from ignition (with immediate decline), while that for a mineral wool insulation lining was 965 kW at 176 s (with immediate decline). The maximum room temperatures for the tests with cement board and mineral wool linings were 435 ℃ and 850 ℃, respectively. The results indicated that for the test with a cement board lining, there was no significant change in the rate of fire growth and peak HRR compared to the test conducted under free-burn conditions. Lowering the thermal inertia (with a mineral wool lining) resulted in a considerably greater (~ 90%) increase in peak HRR compared to the other two tests, which confirmed that radiation feedback from hot layer and walls was responsible for the dramatic increase in the peak HRR.

From the analysis of data record with an infrared camera, it was found that surface flame spread rates were higher (~ 12 mm/s) when the PUF was burning in the room than under free-burn conditions (~ 8 mm/s), regardless of the lining material used.

7 Acknowledgment

The authors are thankful to:

1) *Foreningen Østifterne, DK; Foreningen af kommunale beredskabschefer, DK; and Otto Mønsteds fond, DK* for providing financial support.
2) Bruce Taber, Josip Cingel and Sasa Muradori at the NRC-IRC Fire Research Program who conducted the experiments and provided valuable technical advice.

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Appendix A. Preliminary Experiments

Two preliminary free-burn tests were conducted to refine the test setup and procedures.

A1. Test 1P

The PUF was ignited with a 19 kW propane T-burner positioned at 10 mm from the short edge of the PUF, as shown in Figure A1. The burner was turned off after 80 seconds.

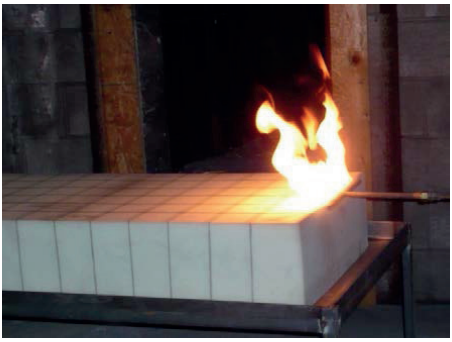


Figure A1. Ignition of PUF block with a 19 kW propane T-burner.

Figure A2. Fire progression at 40 s from ignition.

Test 1P had a peak HRR of 625 kW at 352 s from ignition, as shown in Figure A3. The results of heat flux measurements are shown in Figure A4. It was observed that this configuration resulted in the formation of a backward slope (Figure A2) and PUF material melted and flowed directly onto the pan (towards the burner end) and burnt in that position.

In Test 1P, the PUF block was placed on pan that was in turn placed directly onto a weighing scale for mass loss measurements. The weighing scale failed to measure mass loss and was replaced with a load cell apparatus in Test 2P.

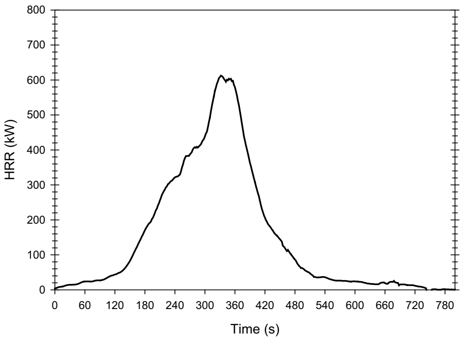


Figure A3. HRR vs. Time for Test 1P.

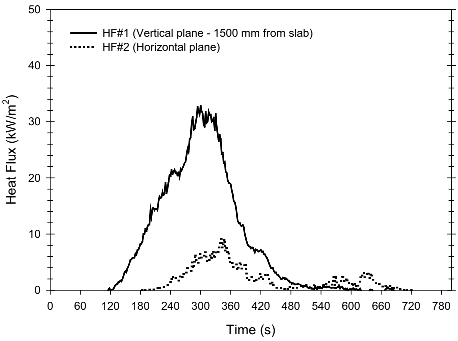


Figure A4. Heat flux measured by vs. Time for Test 1P.

Conclusion: The melt-flow behaviour during the test was undesirable for the purpose of the study. Therefore, in the interest of preventing early formation a PUF melt pool on the pan, a second test (Test 2P) was conducted with the burner moved forward so that it was positioned at 100 mm along the length of the PUF block (i.e. 100 mm from the edge). As well, the HRR of the propane T-burner was increased to 75 kW in order to augment the HRR and ensure that the total HRR in a room test exceeded the threshold value 500 kW required for room feedback effects to be significant. The 75 kW burner HRR was used in previous studies [7] to simulate an ignition source provided by a large waste paper basket.

A2. Test 2P

Figure A5 shows the position of the T-burner in Test 2P. The HRR of the T-burner ignition source was set to 75kW and was left on for the duration of the test. The fire had a peak HRR of 573 kW at 176 s after ignition (Figure A7). The graph was plotted without subtracting the HRR of the burner. The second HRR peak is due to the burning of unconsumed PUF material around the edges of the block after the material in the central area was consumed. In addition, it was observed that the pan began deflecting around the time that the peak HRR was reached, which caused the molten PUF to collect at the opposite ends of the pan. This likely contributed to the occurrence of the second peak. The results of heat flux measurements are shown in Figure A8. Due to the higher burner HRR, a larger area around the center of the PUF was ignited and the file plume was more centralized (Figure A6). This also resulted in a more rapid surface flame spread and rate of fire growth compared to Test 1P, as shown in Figure A9. One disadvantage of the burner arrangement used in Test 2P is that the initial ignition area was very large, which made it difficult to investigate flame spread.

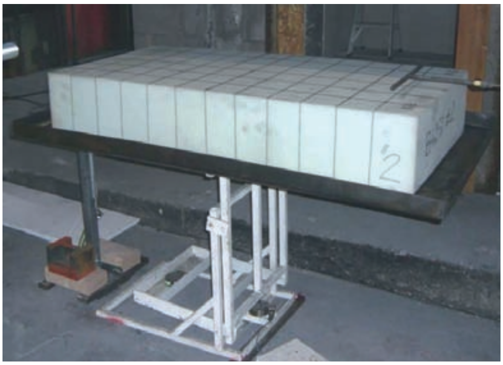
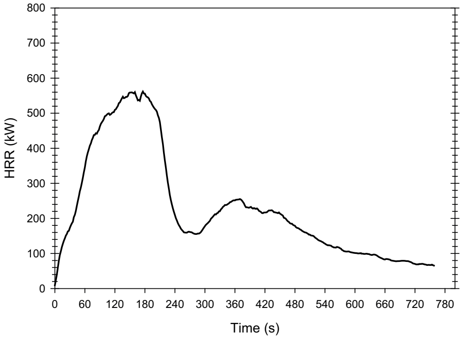


Figure A5. Ignition of PUF block with a 75 kW propane T-burner in Test 2P.

Figure A6. Fire progression at 40 s from ignition.



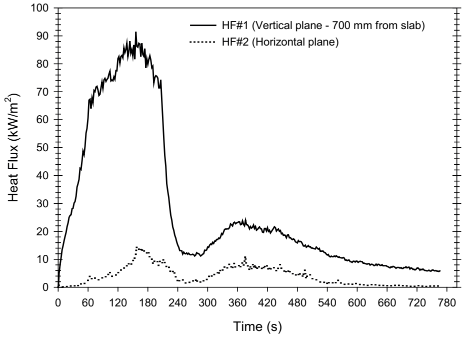


Figure A7. HRR vs. Time for Test 2P.

Figure A8. Heat flux measured by vs. Time for Test 2P.

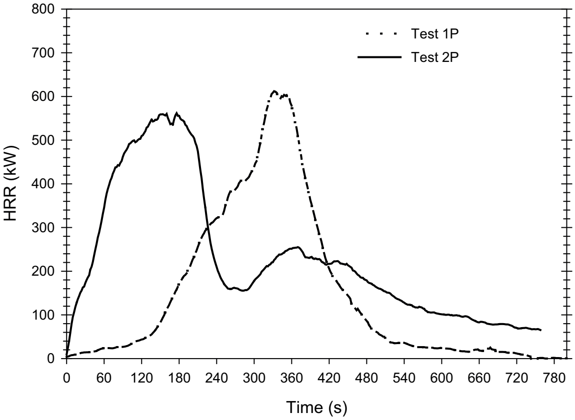


Figure A9. Comparison of HRR vs. time for Tests 1P and 2P.

Conclusion:

The burner configuration was not ideal as too large an area was ignited by the burner leaving an area too small for the investigation of flame spread rate. It was also observed that the gas flow, due to the relative high line pressure, may have influenced the flame spread. Therefore, the single-flame burner was replaced with a dual-flame burner and it was moved further away from the edge of the foam in the final experiments.

Conference poster

Experimental study on the role of thermal feedback from different wall linings in a room fire

Annemarie Poulsen and Grunde Jomaas

Presented at 10th IAFSS Symposium, University of Maryland, 2011

DTU Civil Engineering
Department of Civil Engineering

Experimental study on the role of thermal feedback from different wall linings in a room fire

A. Poulsen and G. Jomaas

Room scale experiments on round heptane pools showed that:

- **thermal feedback can lead to an increase of the heat release rate which may lead to thermal runaway**
- **before thermal runway the increase of the heat release rate correlates well with lining temperatures irrespectively of the type of lining material**
- **different thermal inertias of the linings are found to lead to different onset points for thermal runaway**
- **results of fire tests on pool fires may be affected by the room an type of lining**

Introduction

Thermal feedback induce an increased heat release rate and lead to thermal runaway, TR [1]

The objectives of this experimental program [2] was to investigate the influence of different linings on the increase of heat release rate and thermal runaway.

Circular heptane pools are tested under room burn conditions and free burn conditions.

The experimental setup

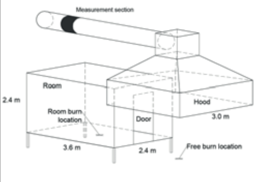
The ISO Room Corner Test facility was used.

The thermal feedback was changed by using two types of linings with substantially different thermal inertias.

- Lining 1 (mineral wool), kρc = 0.0036 kW^2s/m^4K^2
- Lining 2 (light weight concrete), kρc = 0.09 kW^2s/m^4K^2

Measurements included:

- heat release rate, mass loss rate,
- heat flux and
- temperatures (two thermocouple trees and back wall).



Free burn is tested under the hood

Room burn is tested in the center of the room

10 different tests were conducted for different pool sizes, burning conditions and linings comprising the following experimental matrix:

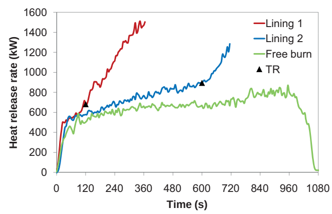
Test no.	Pan Diameter (m)	Amount of heptane (l)	Burning condition
1	0.70	25	Free burn
2	0.70	25	Lining 1
3	0.70	25	Lining 2
4	0.50	10	Free burn
5	0.50	10	Lining 1
6	0.50	10	Lining 2
7	0.50	15	Lining 2
8	0.35	4	Free burn
9	0.35	4.2	Lining 1
10	0.35	4.2	Lining 2

Results

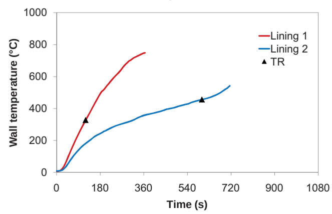
Only the tests with the large pools had a large enough energy to show a clear effect of thermal feedback.

Measurements of HRR and temperatures, in this case given as the wall temperature measured 2.0 m above the floor, showed that for both types of lining the HRR increased slightly in an incipient period followed by a rapid increase compared to free burn. The rapid increase is interpreted as a thermal runaway, which can be associated with flashover. Temperatures follows the trend of the development of the HRR.

Heat release rate



Wall temperature

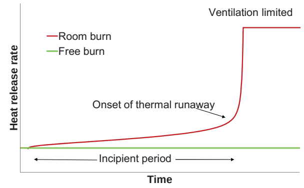


Effect of the thermal feedback

The effect of the thermal feedback on the development of the HRR can be found as [1]:

$$\dot{Q}_F = \dot{Q}_0 + A_F \cdot \Delta H_{eff} \cdot \left(\frac{\dot{q}''_{ext}}{L_g} \right)$$

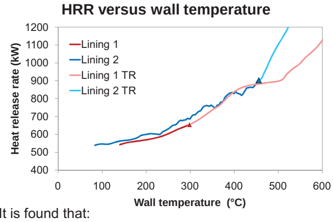
As the HRR increases initially compared to free burn this can be seen as an effect of the thermal feedback from the room before thermal runaway occurs. After the thermal runaway the HRR is theoretically only limited by ventilation. This is summarized in the figure below.



Effect of different linings

By comparing the HRRs and the wall temperatures, it can be seen that the different linings show similar results until the onset of thermal runaway, at which point the two materials yield drastically different results.

HRR versus wall temperature



It is found that:

- The HRRs are comparable for same temperatures before thermal runaway but not after.
- For lining 1 thermal runaway occurred at a wall temperature of 330 °C and for lining 2 thermal runaway occurred at 460 °C, showing that the onset temperature is higher for higher thermal inertia.

References

[1] Thomas PH, Bullen ML, Quintiere JG and McCaffrey B (1980) Flashover and instabilities in fire behavior. Combustion and Flame 38:159-171.

[2] Poulsen A and Jomaas G (2011) Experimental study on the burning behavior of pool fires in rooms with different wall linings. Fire Technology, DOI : 10.1007/s10694-011-0230-0

This project analyses experimentally how the thermal feedback from the room and smoke layer may affect the development of a pre-flashover fire compared to free burn fires. Two phenomena that relate well to theory were observed. In an incipient phase the HRR rose with the temperature of the smoke layer/room. A rapid increase of the HRR commenced after the incipient phase. This is seen as a thermal runaway. The onset of thermal runaway was found to depend on the thermal inertia of the linings and the flammability of the burning objects. In building design the effect of thermal feedback is commonly neglected. The project shows that this may be critical.

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