Industrial fires – An Overview

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Abstract

In this study, the results of an overview of industrial fires in manufacturing plants and warehouses are reported. The overview is based on data reported in international papers, technical reports, magazines and news media.

Flame heights and other information from real fires have been listed and analysed. Correlations for the calculation of flame heights, effects of cross-winds, heat fluxes and ignition of materials are discussed. This study has focused on an investigation of the risk for fire spread from burning industrial building or warehouse to the other activities in their surroundings. The survey shows that there is very limited information concerning flame heights and methods to calculate fire spread from buildings where the fire has broken through a large hole in the ceiling.

Key words: industrial fires, warehouse fires, flame height, radiation, fire spread

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Photo frontpage: Explosive warehouse fire ignited by fireworks

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Preface

This project has been financed by the Swedish Fire Research Board (BRANDFORSK). In connection to the project start, an advisory group was created. This advisory group consists of the following people from a variety of different fire disciplines:

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1 Introduction

Industrial fires, in particular warehouse fires, are often characterised by being very intensive due to high contents of fuel in a unit area to volume ratio. Depending of the type of storage and fuel, such fires are intense emitters of smoke and toxic products. Because fires of this kind are usually very large, they results in environmental pollution and the spreading of carcinogenic substances. Industry and warehouses connected to them are usually located in or nearby towns where the population is high. Hence, in the case of fire, they can potentially give rise to evacuation of people and fire spread to adjacent buildings.

The fire development, in particular industrial fire development, depends largely on the type of fuel, the size of storage, fire load and type of storage (i.e., height, how the gods are stacked, etc) and the type and size of building in which the material is stored. Weather conditions also play an important role once the fire has developed beyond an enclosure fire. Windy conditions may jeopardize the entire building and increase the risk for fire spread to neighbouring buildings. Fire growth can be classified from extremely fast (or explosions) to slow. As there are an unlimited number of different kinds of commodities and storage methods, industrial fire types can vary considerably. Indeed, commodities can be everything from chemical products, rubber, plastic, petroleum, wood, clothes, computer parts, furniture, etc or combinations of these and an industrial fire can develop in a daunting number of ways.

As industrial fires are usually large, they requires a large number of fire fighters to control, extinguish and prevent the fire from spreading to adjacent buildings. The fire can spread to adjacent building by flying brands, direct contact of flames, convective and radiative heat transfer from the fire plume or some combination of these mechanisms. Ignition due to radiation is the most common mode of fire spread between buildings and can occur at much greater distances than direct flame contact and convection. For fire spread by radiation to neighbouring buildings, the size of flames (visible from the neighbouring building) plays an important role. When the flames break through the building of origin, the risk of fire spread by radiation is increased significantly. At the time when the flames penetrate through the roof, the flame heights can become large, resulting the huge increase of thermal radiation to the surroundings.

The shape and height of the flames penetrating through the roof may vary considerably, and in windy conditions the risk for fire spread increases when the flames are projected towards the neighbouring buildings. If the width of the opening becomes very large, the flame height may decrease and at a certain ratio of diameter of the fire base and the flame height, there is a risk for a break up of the flame into many smaller fires. This phenomena has been investigated by Heskestad [1], but the tests in Heskestad's investigation were carried out to investigate "mass fires". Mass fires are not expected to generate high flames relative to their base dimension. This type of fires may be related to large industrial fires where large portions of the roof have collapsed. There is, however, very little information concerning flame heights and shapes of industrial fires, mainly because this type of information is usually not systematically registered. This information is, however, critical if one would like to calculate the risk for fire spread between buildings.

In the Swedish building regulations [2], there is a regulation concerning the risk for fire spread between adjacent buildings (paragraph 5:72). The requirement is as follows: the incident radiation should not exceed 15 kW/m^2 during a period of 30 minutes. This means that necessary calculations are performed when the building has flashed over or flames extend from windows or/and through the roof. This regulation is only applicable when the building is not sprinklered. Due to the performance based codes system applied in

Sweden and many other countries, the method for showing that the fire will not spread, is based on analytical fire safety engineering solutions. A way of getting around this problems is to show that the fire inside the building will not be large enough to create a flash over situation, and therefore reduce the risk of any type of break through the roof. If no flames penetrate the roof, or the windows, there is no risk for fire spread beyond the building of origin. If one shows that there is a risk for the fire to spread and for the building to flash over, one has to show calculations that credibly indicate that this risk is sufficiently low. This requires knowledge of view factors related to flame heights, radiative emittance of the flame volume, the effect of wind on flame tilting and the thermal response of receiving material and critical ignition conditions.

There are numerous engineering methods available to calculate flame heights and, using view factors or simpler methods, to calculate the risk of fire spread [3-6]. These correlations are based on tests in a laboratory environment, and work well for pool fires and wood crib fires. Fire spread in an industrial building, in particular with flames penetrating through the roof, may not give similar results using traditional fire engineering methods.

The design of the structure of the building can have a critical influence on the results. Calculation results may vary depending on how and when the flames penetrate through the roof. There may be many smaller flames, which burst through the window openings or a high flame, which occurs when all or part of the roof is collapsing. There is therefore a great need to examine and evaluate the tools used today to calculate the risk of fire spread between buildings. “What restrictions are there? What are the parameters that govern these restrictions? What parameters should be taken into account in making the relevant calculations?”, are all questions that need answering. In conversations with investigative authorities, and even fire consultants who carry out the work, it has become clear that there is a strong need for guidance on how to make necessary fire safety engineering calculations.

In Sweden, major concern has been raised about the new trend towards using sandwich constructions in industrial buildings. Many of these sandwich constructions contain light weight plastic foam insulation mounted between two stiff steel plates. The concern is related to the consequences of a fire in buildings using a sandwich construction with plastic insulation. The plastic insulation material may start to burn, which may allow the fire to spread rapidly inside the building and ultimately burn through the ceiling and increase the risk for fire spread to adjacent buildings. The entire building may also be at risk for collapse thereby threatening the lives of the fire fighters. Concerns have been raised by some fire services in Sweden that the building regulations and testing methods for these materials do not fully cope with the real threat generated by the fire load found in non-sprinklered industrial buildings and warehouses.

During the last 5 years, the use of sandwich constructions has rapidly increased in Sweden and the whole issue about new types of construction techniques that may generate new types of risks for fire spread inside and between buildings is very important from a fire safety point of view. Today, sandwich constructions are used in almost 90 % of all newly constructed buildings, and it is estimated that between 40 – 50 % of the industrial buildings in Sweden contain this type of material [7]. The risk for fire spread, both inside the building and to adjacent buildings, related to these new sandwich materials, is a concern that needs to be investigated.

In the following, an overview of large fires in industrial buildings and warehouses is presented as well as an analysis of flame heights and fire sizes from real cases. Methods to calculate flame heights and radiation are outlined and validated.

2 An overview of large industrial fires

Large fires in industries and warehouse are reported almost every day somewhere in the world. This overview covers examples of the largest industrial and warehouse fires that have occurred in modern history, worldwide. Based on experience of fires internationally, factories are considered to be a high fire risk in most cases.

Fires in a wide range of different kinds of industries have been selected in this survey from international papers, the scientific literature and technical reports. Many of the articles report information concerning the fire size, flame lengths, flame penetration of the roof, roof collapse, building collapse, etc. The most interesting cases found, concerning fire spread or risk of fire spread to the activities adjacent to the burning building, are considered in a deeper analysis.

There are several databases for fires available in most countries in the world. One large database that is probably the most detailed fire database of accidental fires is that contained in the Real Fire Library (RFL) collected by the London Fire Brigade [8] since 1996. It contains basic incident statistics such as type of the property, location and cause of the fire, source of ignition, details of the fire scene, fire development, fire detection and protection and building egress. The library contain on average about 4000 incidents per annum.

Statistic from fire damage in Sweden is collected in Swedish Rescue Service Association’s (SRSA) statistical database and SBF (Svenska Brandförsvarsföreningen) annual statistics on fires.

2.1 Related previous studies

2.1.1 Statistical analysis of typical industrial fires and their origin

A large investigation of typical fires in industry has been made previously by Johansson [9]. The main purpose of his work was to evaluate models that can be used when assessing industrial fire frequencies in Sweden and to calculate the expected economic losses due to fire in Sweden. The investigation was based on the study of a large number of international papers. In Johansson’s investigation two models for calculating the probability of fire have been described: Ramachandrans’ and Rutstein’s models.

The Ramachandrans model describes how statistical methods can be used to estimate a risk by calculation. The probability of origin of a fire in a building and distribution of fire events within industry are discussed. Types of industries with similar fire risks have been divided in separate sub-groups. The probability of a fire start is connected to the size of the building and the activity in the building. Within the same category of building, for example chemical industry, the fire probability is related to the area of the building. Size distribution of industry buildings in Sweden is given by a frequency function, which is the probability of drawing each particular value from a discrete distribution.

For a given category the probability of fire can be calculated based on knowledge of the number of buildings in this category related to number of fires occurring in the same activity. The probability of fire in the given building is then weighted to the area of the building.

The probability of fire in Rutstein's model is also based on the floor area of the building, but the probability is not linear as a function of area. The non-linearity depends on the actual activity in the building and is specified by two constants estimated by fire statistic from the fires to which the fire brigade has been called.

Johansson [9] has applied the statistical method and categorized the industrial fires in following groups:

- Industrial hotel
- Chemical industry
- Foodstuff industry
- Metal/Machine industry
- Textile/Clothing industry
- Timber industry
- Other manufacturing industry
- Repair/workshop
- Warehouse

Johansson's investigation also included a summary of fire starts in specific locations within those 9 categories during 1996 in Sweden. In total, 37 specific fire start locations were recognized within those 9 categories. Each category therefore includes the statistics of fire start in different (maximally 37) locations, depending on the type of activity in the specific category.

According to the statistics, most fires occur in manufacturing industry, more than 1000 (distributed nearly equally in Metal/Machine, Timber, and other); but fires in chemical industry (132 fires) and repair/workshops (118 fires) are also relatively common.

The most probable location for fire starts is where manufacturing occur. Similarly, in a warehouse locations connected to activity (if any) are those where most fire starts occur.

2.1.2 The Real Fire library

Two large analyses have been made by Särdqvist *et al.* [10] and Holborn *et al.* [11]. Both investigators used a large volume of fire data from real fire incidents recorded in the Real Fire Library (RFL) collected by London Fire Brigade.

Särdqvist *et al.* [10] investigated data from 307 non-residential premises, occurring in London 1994-1997. The investigators obtained Complimentary Cumulative Distribution Functions (CCFD) for the different time intervals and fire areas which made it possible to derive a correlation between the water flow and total water applied to a fire damage area.

Holborn *et al.* [11] analysis included fire sizes, fire growth rates and times between events. The investigation covered about 2500 fire of which more than 400 were non-residential fires. Many of the incidents produced very large losses. The analysis included an estimate of the reasons why such extremes occur in real fires.

2.1.3 Industrial fires in Sweden

Previous investigations of industrial fires have been performed in the 1970s by Thor and Sedin [12-13] . In their analysis, the large fires which occurred in 1975 were divided according to fire losses. A further subdivision was made according to fire size, industrial fires and fires in other sectors. The large industrial fires were further sub-divided into fires in different building categories and branches of industry.

Of the total fires the large fires dominated in 1975. About 70 % of fires were classified as large fires with total loss more than 200 000 SEK (1970 years value of money). Of these large fires about 70 % were industrial fires and the rest non-industrial. The percentage of industrial fires was approximately constant (70 %) during the ten years period 1966-1975.

Thor and Sedin's [13] analysis included a total of 69 large industrial fires and the results are summarized in form of one-page data sheets with information categorized as

- Branch of industry
- Building layout
- Structure of building
- Equipment
- Fire load of contents
- Fire fighting
- Fire spread
- Damage to building
- Damage to contents
- Cost of damage

The data sheet is formed so that comparison of fire cases with each other is easy. Some sheets are connected to one or two pictures of a damaged building or burning building. The result are also summarised in a single table for a rapid (brief) comparison of the cases. The fire spread to adjacent buildings and the surroundings is not reported in the survey, but many of the pictures and information concerning the fire size and fire area allow the risk of fire spread to the surroundings to be estimated.

Analysis of three special large fires occurred in Sweden in last decade has been made by Särdqvist [14]. The fires investigated were a library and office fire in Lindköping (1996), a factory fire in Stockholm (1997) and an industrial fire in Västerås (1991). The results of analysis are presented in the form of "flowcharts" and "event trees". The method makes it possible to graphically illustrate the comparison between heat release rate curves and extinction effect curves.

2.1.4 Industrial fires in the US

In the Industrial Fire Protection Engineering book by Zalosh [15], a summary of numerous large industrial fires in the US is given. Zalosh gives a list of more than 60 of the largest US industrial fires and explosion losses during the period of 1947 – 1999. He reports that seventeen of the largest losses (27%) occurred in warehouses, with about half of these being used primarily for paper, plastic, or general commodity storage. There are also several flammable liquid warehouses, and several other cold storage warehouses. One common aspect of these warehouse fires was the failure of the installed sprinkler system to adequately control the fire. Data from United Kingdom for the period 1985 – 1986 indicates that the types of industrial facilities with the largest number of large loss fires are general warehouses, textile mills and the combined category of wood, furniture, paper, and printing plants. The most costly industry fires are related to gas explosions and oil platforms. These types of accidents are not included in this report.

Electrical ignition sources are responsible for the greatest number (25%) of large loss manufacturing facility fires, whereas deliberately set open flame ignition sources are responsible for the greatest number (24%) of large loss storage facility fires. Other ignition sources playing significant roles in industrial fires include cutting/welding operations, hot objects, fuel fire equipment, and spontaneous ignition.

Zalosh [15] discussed some fire protection lessons learned from some major fires. The lessons learned were that there is a need for:

- fire walls and other possible barriers in large plants
- roof deck fire spread tests
- regularly test sprinkler flows
- upgrade warehouse sprinkler protection to accommodate storage of more combustible commodities
- smoke control in buildings with sensitive equipment
- fire resistant electrical cables
- adequate emergency egress provisions
- improved protection of flammable liquid warehouse
- containment of contaminated water runoff

Indeed, in this list there are lessons still going unheeded at many industrial facilities. These concern compartmentization, special hazard commodities, residues of flammable liquids, automatic detection, emergency egress and effective sprinkler protection.

2.2 Description of “worst case” fires

In rare cases a fire might become so large that it is not optimal to try to extinguish it but to focus on restriction of fire spread. A fire in some industrial building or warehouse with certain types of fuel is not possible to extinguish with water. One example is a fire in magnesium recycling plant in Ohio, 2003 [16], which was impossible to extinguish with water. Although much effort was made to protect the other buildings in the vicinity of the fire it did spread the other buildings.

2.2.1 Fire in seven whiskey warehouses

In November 1996 a fire occurred in seven large whiskey warehouses in Kentucky, Texas (see Figure 1). Because the fuel was alcohol the fire spread was very rapidly. It took less than 15 minutes before the first whiskey warehouse, floor area 2000 m^2 (each floor), was fully involved in the fire. The buildings were constructed from a heavy timber structure with metal siding and a tar roof. The flames rapidly extended to the next (similar) warehouse located at 125 m distance and ignited it. There were 44 warehouse in total in the vicinity, but “only” 7 were burned, i.e. 37 survived. The flame lengths from the burning warehouses were at least 100 m. The enormous radiation level created a very difficult situation for the fire fighters. Four of the fire fighters had helmets that distorted and melted while they were wearing them. This rescue operation was complicated by storm winds up to up to 35 m/s.

Totally 90 00 barrels, i.e. 15 million litres of high proof alcohol, were burned. As the warehouses collapsed, the alcohol poured out, spreading almost invisible flames across the roadways and cutting off access to much of the one square mile area involved. The fire spread across burning alcohol “rivers” after collapse of warehouses was so rapid that the firemen had run for their lives to avoid being engulfed by flames.

2.2.2 Fire in magnesium processing and recycling plant, Garfield Heights, Ohio

A fire in a magnesium storage facility may be the worst nightmare that a fireman can encounter, especially if it occurs near other buildings that need to be protected against the heat impact. This scenario was exactly what occurred in Garfield Heights, Ohio 2003.

The building was a 60 m long storage building with a wooden roof. Only a narrow one lane road separated that warehouse structure from the main building.

Burning magnesium reacts violently to water, producing great heat and a piercing white light. Flame temperatures reached near 3000 °C, which is sufficient to melt most metals. Indeed, this temperature is sufficient to break water down into its basic components, hydrogen and oxygen. This reaction, in turn, feeds the fire rather than extinguishes it.

When first responders arrived (a few minutes after alarm) the fire had already broken through the roof. Flame lengths were 20-30 m according to photos. The radiation from 3000 °C flames made it a very difficult working environment for the fire fighters. Precipitation (rain and snow) made it even worse, creating small explosions and “fire works” from burning magnesium.

The firemen had to concentrate their efforts on the protection of nearby buildings, rather than on extinguishing the fire. Several other buildings were threatened by the fire, including a storage building and another business building nearby, which were ultimately destroyed. A higher radiation level than that expected from “conventional” fires (flame temperatures near 3000 °C, instead of 1000 °C) demanded a much higher volume of cooling water to the building surfaces to be protected than in a traditional fire scenario. The firemen simply did not have sufficient water capacity to keep the building surfaces below their ignition temperature and the adjacent buildings were destroyed.

As the fire progressed, it became more and more difficult to keep water away from burning magnesium. Precipitation was part of the problem, but the water runoff from the protected exposure was also flowing towards the fires. When the water reached the burning magnesium explosions occurred. Large pieces of glowing steel could be seen flying hundreds of metres from the fire. The glowing metal falling off the wooden roofs onto the neighbouring building ignited and destroyed it.

3 Fire spread and flame heights

In the following, a summary of experimental and theoretical aspects concerning fire spread, heat fluxes, flame heights, ignition processes and flame projection is given. The chapter is, however, opened by a clarification of the basic nature of fire spread between buildings. Carlsson [17] presented an overview of different parameters affecting the fire spread between buildings which are partly recapitulated here.

3.1 Parameters affecting fire spread between buildings

The spread of fire from a burning building to an adjoining building can occur in a number of different ways. It has been found that some modes, or a combination of modes, are more common, and therefore more hazardous, than others.

3.1.1 Flying brands

Ignition of combustible materials may occur due to flying brands emitted from a building on fire [18],[19]. These brands may travel long distances and protection against this is possible by fitting external surfaces with appropriate fire resistant claddings. Flying brands do not represent a significant hazard by themselves with respect to ignition of buildings. They may, however, act as an igniting source together with radiation, where the pyrolysis species given off by the material exposed to radiation may ignite.

3.1.2 Flame contact

It is possible that projected flames from an opening may impinge onto an adjoining building and cause ignition. The projection distance, i.e. the horizontal extension of the flame from the facade, and the flame length, i.e. the vertical extension of the flame, are dependent on many factors including geometry and size of the opening as well as wind conditions and mass burning rate [18], [20].

3.1.3 Convective heat transfer

Convective heat transfer may also result in the ignition of an adjoining building, given that the stream of hot gases hitting the building can be several hundreds of degrees centigrade [21]. In order for ignition to occur by this phenomenon, the exposed building has to be very close to the fire source.

3.1.4 Radiative heat transfer

Ignition due to radiation is the most common way for fire to spread between buildings, and can occur at much greater distances than possible through direct flame contact and convection [21]. We will focus on this mode of ignition in the following reporting of different methods to calculate radiative heat transfer.

3.2 Large scale pool fire tests in Sweden

As mentioned previously, the main reason that fire spreads between adjacent buildings is through flame radiation (incident heat flux). There is not much data on measured heat fluxes from large scale fires. Actually, in 1990, four large scale pool fire tests were performed in Borås, Sweden, where the main focus was on testing different portable foam extinguishing systems [22]. Two tests with gasoline and two tests with an acetone/ethanol mixture were carried out in the open. A slight crosswind was experienced when the tests were performed. The open pool fire surface was 197 m^2, divided into a circular part of 141 m^2 and diameter of 13.4 m^2, and a rectangular part of 56 m^2. The effective diameter of the fuel surface area was estimated to 15.8 m. The measured average burning rate for the gasoline was 6.5 and 6.9 mm/min, respectively and 5.8 and 6.7 mm/min for the acetone/ethanol mixture (70/30%). The density for gasoline can be assumed to be 740 kg/m^3 [23] which means that the burning rate in average is 0.0826 kg/m^2 s.

If we assume that the heat of combustion is 43.7 MJ/kg, a combustion efficiency of 0.9, and an area of 197 m^2, we obtain the heat release rate for the gasoline test to be 640 MW. It is more difficult to estimate the heat release rate of the acetone/ethanol mixture. The density for acetone and ethanol is about the same, 790 kg/m^3, and the heats of combustion are 25.8 MJ/kg and 26.8 MJ/kg, respectively [23]. If we assume that the heat of combustion is the weighted average or 26.1 MJ/kg, we can calculate the average heat release rate for the both tests as 0.0823 kg/m^2 s. Using this value, and the heat of combustion for acetone/ethanol, we obtain a heat release rate of about 390 MW, assuming a combustion efficiency of 0.93. These heat release rates will be used in chapter 4.1 to estimate the flame heights.

Heat flux meters were located at different distances in the North West (NW) direction from the pool edge at distances 5m, 10m, 20m, 30m, and 50m. One heat flux meter was located 10 m from the pool edge in the North East (NE) direction and one at 27 m in the South West (SW) direction. The heat flux meters were of the type Schmidt-Boelter water cooled. In Figure 1 the measured heat fluxes at different distance from the edge of the pool fire (SW-direction) are shown. The level of heat flux towards the heat flux meters is considerably higher from the acetone/ethanol mixture compared to gasoline. One reason for the difference in heat flux is the smoke that covered the yellow flames in the gasoline tests. Mudan and Croce [24] have described this phenomena in the following way: “It has been observed that in large liquid hydrocarbon fuel fires with a carbon-to-hydrogen ratio greater than about 0.3, a substantial part of the fire is obscured by a thick black smoke on the outer periphery. This smoke layer absorbs a significant part of the radiation and results in very little emission to the surroundings. However, the smoke layer occasionally open up, exposing the hot flame, and a pulse of radiation is emitted to the surroundings.” This description fits very well into what has been observed in the Persson tests [22].

The flames from the acetone/ethanol tests were nearly free from smoke obstruction. Although the heat release rate is higher for gasoline, the heat flux at different distances is higher for the acetone/ethanol mixture due to the smoke production and higher flame temperatures. Thermographic images were taken from these tests which clearly show the difference, but these photos were presented on the back side of the report [22] and cannot be reproduced here. During the tests, the wind conditions varied considerably. Wind velocities of 2 – 11 m/s were from South to South West. This means that the heat flux meter at 10 m in the NE direction showed slightly higher values than a comparable heat flux meter at the NW direction. The flames leaned towards that heat flux meter in the NE direction. In Table 1, a summary of these values are given in order to show the influence of the leaning flames towards the heat flux meters. The angle of the leaning flames was estimated by the authors to be about 30 – 45° from the vertical axis.

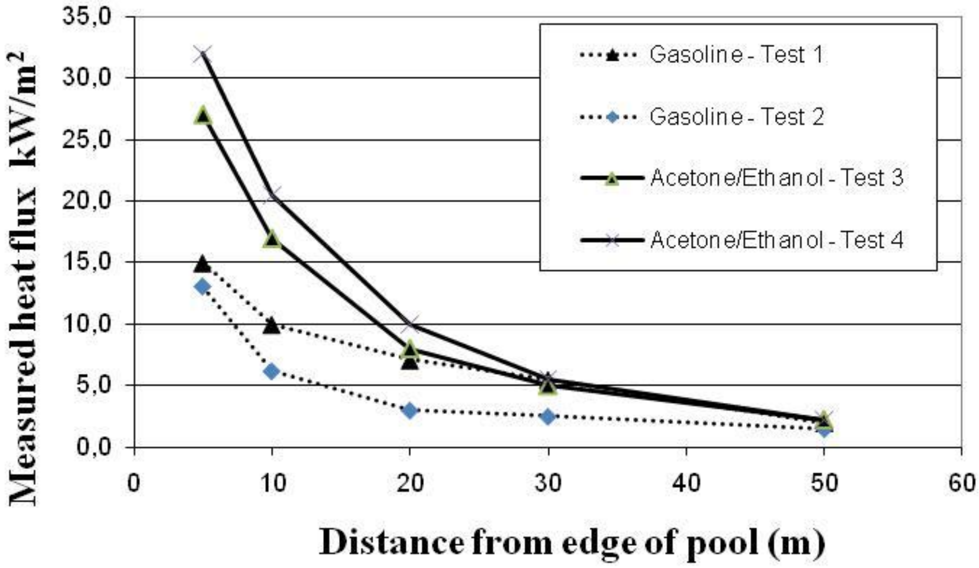


Figure 1 Measured heat flux from different pool fires given by Persson [22].

Table 1 Comparison of measured heat flux in two directions, NW and NE, where the flames leaned over the heat flux meter in the NE direction.

Test	Heat flux 10 m NW	Heat flux 10 m NE
Gasoline Test 1	10	13
Gasoline Test 2	6,2	NA
Acetone/Ethanol Test 3	17	25
Acetone/Ethanol Test 4	20,5	35

NA Not Available

The results in Table 1 show the effects on the wind on the heat flux measurements at the ground level. Persson [22] suspected that these values could be higher than reported as one could expect that the flame length is longer than the position of the heat flux meter, and that part of the total radiation radiated from the flame volume, were not “caught” by the heat flux meters.

3.3 The effects of wind on flame length and flame tilt

The effects of the wind on heat flux to neighboring objects are discussed by Mudan and Croce [24], where several correlations are presented from different authors, e.g., the effects of the wind on the flame tilt can be calculated using the correlation given by Thomas [25] or from the American Gas Association (AGA) [26]. The correlation by Thomas is as follows:

$$\frac{H_f}{D} = 55\left[\dot{m}"/\rho_a\sqrt{gD}\right]^{0.67} u^{*-0.21} \qquad (1)$$

where H_f is the flame height, D is the diameter of the fire source, $\dot{m}"$ is the mass burning rate per unit fuel area (kg/m^2 s), ρ_a is the ambient air density (kg/m^3) and $u*$ is the non-dimensional wind velocity given by

$$u^* = u_w / \left(\frac{g\dot{m}"D}{\rho_a}\right)^{1/3} \quad (2)$$

The corresponding equation from Thomas in ambient conditions is:

$$\frac{H_f}{D} = 42\left[\dot{m}"/\rho_a\sqrt{gD}\right]^{0.61} \quad (3)$$

Moorhouse [27] conducted several large scale tests of LNG pool fires. The crosswind and downwind motion picture data were analyzed to determine the exact flame length. The correlation given by Moorhouse is as follows:

$$\frac{H_f}{D} = 6.2\left[\dot{m}"/\rho_a\sqrt{gD}\right]^{0.254} {u_{10}^*}^{-0.21} \quad (4)$$

Where u_{10}^* is the nondimensional wind speed determined from equation (2) with measured wind speed at a height of 10 m. Assuming that $\dot{m}" = \dot{Q}/H_c$, we can use equations (1) to (4) to calculate the flame height easily if we know $\dot{Q}$ and H_c for the fuel. $\dot{Q}$ and H_c are the heat release (kW) rate and the heat combustion (kJ/kg) for the fuel, respectively. The use of equations (1) to (4) will be shown in discussion chapter 4.

Mudan and Croce [24] also present methods to take into account the tilting effects on the flame and the incident receiving element. These effects are mainly related to the view factor perspective of the flame volume and the receiver such as a heat flux meter. Thomas gave the following correlation for flame tilt based on the data from two-dimensional wood cribs:

$$\cos\theta = 0.7\left[\frac{u_w}{\left(g\,\dot{m}"\,D/\rho_a\right)^{1/3}}\right]^{-0.49} \quad (5)$$

where θ is the tilted angle from a vertical axis. Based on measured values, the American Gas Association (AGA) proposed the following correlation to determine the flame tilt:

$$\cos\theta = \begin{cases} 1 & for\ u^* \leq 1 \\ 1/\sqrt{u^*} & for\ u^* \geq 1 \end{cases} \quad (6)$$

where u^* is the non-dimensional wind speed determined from equation (2) with measured wind speed at a height of 1.6 m. According to Mudan and Croce [24], the correlation given by equation (6) yields more accurate results compared to Thomas equation (5).

Brzustowski *et al.* [28] and Gollahalli *et al.* [29] conducted a series of wind tunnel tests involving hydrogen and propane diffusion flames in a crosswind. It was observed that the initial effect of crosswind was to shorten the flame, after which increases in the cross flow velocity caused increases in the flame length. Shortly before blow-off conditions were reached, the flame length was observed to decrease with increased crosswind [24]. These types of cross flows are not relevant for large industrial fires but do indicate that the crosswind can influence the flame length.

3.4 Flame heights from large industrial fires

It is extremely difficult to obtain reliable flame height data from industrial buildings on fire. Therefore, an attempt has been made to estimate the flame heights from real large scale fires to provide methodological guidance. One difficulty methodologically is the fact that the heat release rate in a real fire is never measured and therefore not known.

A summary of values for flame heights, fire areas and heat release rates are presented in Table 2. The flame height is based on visual estimation from photos of the fire in question. A more detailed description of each case is given in Appendix A.

Table 2 Selected large industrial fires where the flame height and heat release rate has been estimated.

Fire, year	**Reference**	**Fire area [m²]**	**Flame length [m]**	**Estimated max HRR, $\dot{Q}$ [GW]**	**Effective diameter, D_{eff} [m] eq (7)**	**Main fuel type**
Warehouse fire, 1984	Fire Command, May 1984	> 10 000	20-25	8-9	>113	Furniture
Plastic warehouse fire, 1985	Fire command, January 1986	8500	15-20	6-7	104	PVC waste
Sherwin-Williams Warehouse fire, 1987	Fire Command, August 1987	17 000	30-50	16-21	147	Paints, and other liquids in plastic containers, aerosol cans, etc.
Seven whiskey warehouses, Bardstown, Kentucky, 1996	Industrial Fire World, Jan/Feb 1997	2 000 each house	100-150	11-22 (each warehouse)	50	High proof alcohol, ethanol 90 000 barrels (about 15 million liter = 15 000 m^3, Heavy wood structure
Magnesium recycling plant, Garfields Heights, Ohio, 2003	Industrial Fire World. Mar/Apr 2004	At least 5-10 000	30-50	5- 13	80-113	Magnesium storage, recycled magnesium.

In order to estimate the heat release rate, we assumed that the flame height correlation given by Heskestad [30] is a correct starting point. The flame height correlation by Heskestad states that:

$$H_f = -1.02D + 0.235\dot{Q}^{2/5} \qquad (7)$$

where H_f is the flame height in metre, D is the diameter of the fuel base in metre and $\dot{Q}$ is the heat release rate in kW. Equation (7) applies well for pool fires and has been validated for rack storages and other types of fuels [31] using an effective diameter of the fuel base. This equation has, however, not been applied to the estimation of flame heights in buildings with large openings in the ceiling. As we have an estimation of the base of the fire we can estimate the effective diameter, $D = D_{eff}$, from the following equation:

$$D_{eff} = \sqrt{\frac{4A}{\pi}} \qquad (8)$$

where A (m) is the area of the hole in the ceiling.

Consequently, we can estimate the heat release rate from equation (7):

$$\dot{Q} = \left(\frac{H_f + 1.02 D_{eff}}{0.235}\right)^{5/2} \tag{9}$$

The estimated heat release rate, $\dot{Q}$, is found in the sixth column in Table 2. The estimated heat release rate varies between 6 GW – 22 GWs. The corresponding flame heights vary from 15 m – 150 m. The reason for this wide gap in the flame height is that, in most cases, the effective diameter is rather large in relation to the flame height, except for the fire in the whiskey warehouse. The ratio H_f/D_{eff} varies between 0.1 – 0.4 in all cases except for the whiskey warehouse where it is between 2 – 3. The heat release rate per unit projected area (area of effective diameter) lies in the range of 0.5 MW/m^2 – 1.3 MW/m^2 except for the whiskey warehouse which lies in the range of 5.5 MW/m^2 – 11 MW/m^2. The whiskey warehouse case must be regarded as an extreme case. The heat release rates per unit exposed fuel area is usually in the range of 0.1 MW/^{2} – 0.5 MW/m^2 for most common solid materials [32]. In the calculations we have used a projected area instead of exposed fuel area, which means that the estimated numbers for heat release rates and fire areas in Table 2 are reasonable. This conclusion is based on the fact that exposed fuel area is, in most cases, higher than the projected area.

Heskestad [1] has discuss his flame height correlation in relation to the ratio H_f/D. According to Heskestad, low flame height data exhibits a transition from coherent flaming to distribute flamelets when the ration H_f/D becomes less than about 0.5. When this transition occurs, the air induced or entrained by combustion, if shared by all the fuel vapours, will dilute the vapours below their ability to burn. Based on this consideration, Heskestad speculates that mass fires in sufficiently large homogenous fuel beds may only be possible as distributed localized fires.

Experiments carried out by Heskestad [1] using wood fibreboard arranged to produce a square array measuring 7.32 m on each side, confirmed that luminous flames exhibited a first tendency to break up into distributed flamelets near H_f/D =0.52, being fully broken up near H_f/D = 0.34. Heskestad was able to go down to H_f/D = 0.04 in his experiments, where the entire burner surface showed flickering blue flamelets racing back and forth. These ratios are in the same range as the values obtained from Table 2 (0.1 – 0.4). Therefore, Heskestads observations from fires with low H_f/D values are of great interest for the study presented here, and indicate that equation (7) can be used for industrial buildings after the flames have penetrated through a large portion of the ceiling.

If we look at the other extreme, that is very large fires with a very small fire area the flame height becomes much higher than in the cases shown for industrial fires with large fire bases. This means that the H_f/D ratio is relatively high. An example of such fires can be found in the paper presented by Evans *et al.* [33]. During the Kuwait war in the early 90s, numerous jet fires were created as a consequence of the war. Evans *et al.* estimated the heat release rates and flame heights to vary between 0,9 GW – 2 GWs and 35 m – 50 m, respectively. The flame height correlation was found to be as follows:

$$H_f = 0.21 \cdot \dot{Q}^{2/5} \tag{10}$$

The diameter of the fuel source is not important here as the diameter of the oil wells is very small in relation to the flame height. With the exception of the diameter dependence of the fire source, this equation is very similar in form as the one given by Heskestad [30] for pool fires in the open. These equations will be used in the analysis of the experimental data presented later in this report.

There is a need to investigate the validity of Heskestad equation (7) further for industrial buildings, e.g. one should explore whether we should use the width of the building or the effective diameter as a base in industrial buildings that are very long but not very wide (close to a linear fire source).

3.5 Flame projection

Flames projected out of openings in a burning compartment may cause ignition either by emitting radiation to combustible objects or by direct flame contact with nearby objects. The effect of the radiation contributed by external flames during a fire with regard to the total amount of radiation received by an adjacent building is not totally understood in the fire engineering discipline today [17]. The projected flames can, e.g. be calculated according to work by Law *et al.* [20]. Equation (11) is given for the correlation between flame height above the compartment floor and the ratio between mass burning rate and width of the opening, which was obtained from test data for "no wall" conditions:

$$z_1 + H = 12.8\left[\frac{R}{W}\right]^{2/3} \qquad (11)$$

where:

z_1 = flame length above top of window [m]
H = height of window [m]
W = width of window [m]
R = rate of weight loss of fuel [kg/s]

Figure 2 shows the layout and dimensions of projected flames according to Law *et al.* [20].

The flame tip is defined to be located at the point where the flame temperature is 540 ^{o}C, which is where the luminous zone of the flame ends.

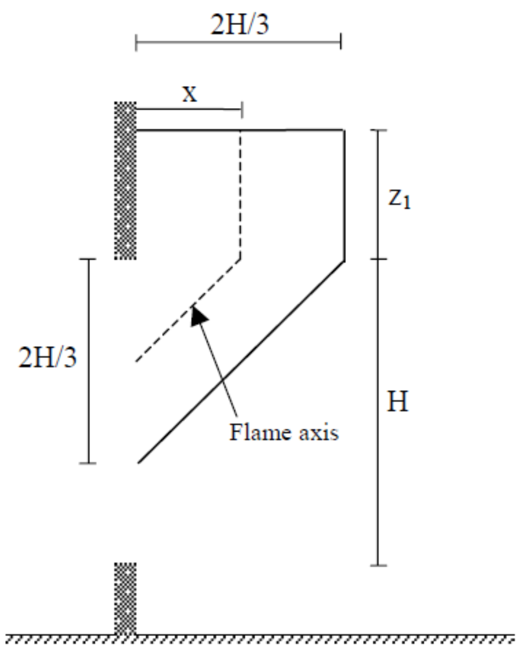
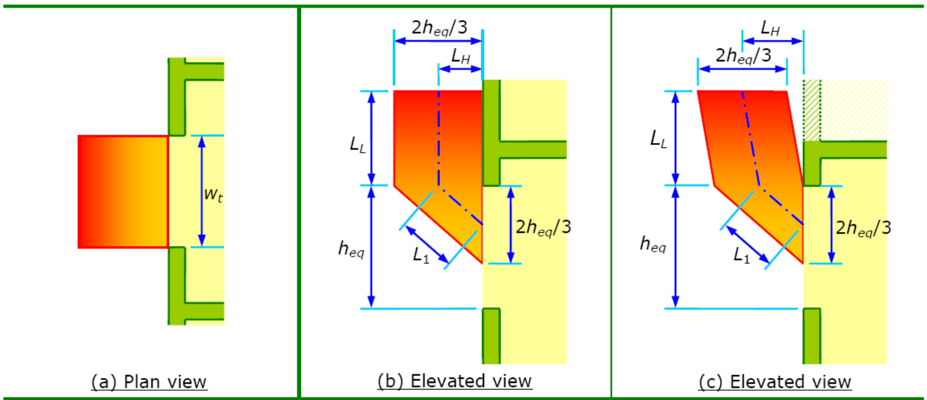


Figure 2 Flame shape for no through draught conditions according to method by Law *et al.* [20].

The work by Law *et al.* [20] has been extended and the latest summary of equations for the calculation of the flame length in windows is found on the webpage *One Stop Shop in Structural Fire Engineering* [34]. This webpage is shown in Figure 3.



Flame dimension [m]	Wall above	No wall above
Flame width and depth	Flame width = window width w_t ; flame depth = $2h_{eq}/3$	
Flame height L_L	$L_L = h_{eq}\left(2.37\left(\frac{Q}{A_v \rho_g \sqrt{h_{eq} g}}\right)^{2/3} - 1\right) > 0$ (36) $L_L = 1.9\,(Q/w_t)^{2/3} - h_{eq}$ for ρ_g = 0.45 kg/m^3 & g = 9.81 m/sec^2 (37)	
Flame horizontal projection L_H a) $h_{eq} \le 1.25w_t$ b) $h_{eq} > 1.25w_t$ and distance to any other window $> 4w_t$ c) In other cases	$L_H = h_{eq}/3$ $L_H = 0.3\,h_{eq}(h_{eq}/w_t)^{0.54}$ $L_H = 0.454\,h_{eq}(h_{eq}/2w_t)^{0.54}$	In all cases, $L_H = 0.6\,h_{eq}(L_L/h_{eq})^{1/3}$ (38)
	Wall above or $h_{eq} < 1.25w_t$	No wall above or $h_{eq} > 1.25w_t$
Flame axis length L_1	$L_1 = \sqrt{L_H^2 + h_{eq}^2/9} \cong h_{eq}/2$ (39)	
Flame length along axis L_f: (a) for $L_L > 0$ (b) for $L_L = 0$	$L_f = L_L + L_1$ $L_f = 0$	$L_f = \sqrt{L_L^2 + (L_H - h_{eq}/3)^2}$ $L_f = 0$ (40)
Heat Transfer Parameter	For both cases	
Flame temperature T_w at window and emissivity ε_f	$T_w = \frac{520}{1 - 0.4725(L_f\, w_t/Q)} + T_0$ and $\varepsilon_f = 1.0$ (41)	
Flame temperature T_z along the axis and emissivity ε_f	$T_z = (T_w - T_0)\cdot\left[1 - 0.4725\left(\frac{L_x w_t}{Q}\right)\right] + T_0$ and $\varepsilon_f = 1 - e^{-0.3d_f}$ (42)	
Convective heat transfer coefficient α_c	$\alpha_c = 4.67\left(\frac{1}{d_{eq}}\right)^{0.4}\left(\frac{Q}{A_v}\right)^{0.6}$ (43)	

with $L_f\, w_t/Q < 1.0$

where
- ρ_g is the initial gas density [kg/m^3];
- A_v is the total area of vertical openings on all walls [m^2];
- d_{eq} is the geometric characteristics of external member (diameter or side) [m];
- d_f is the flame thickness [m];
- g is the gravitational acceleration [= 9.81 m/sec^2];
- h_{eq} is the weighted average of window heights on all walls as given in Eq.(1) [m];
- L_x is the axis length from the window to the point where the calculation is made [m];
- O is the opening factor of the fire compartment as given in Eq.(1) [m$^{0.5}$];
- Q is the rate of heat release as given in Eq.(1) [MW].

Figure 3 Window flame properties under no forced draught conditions (published by permission of Professor Colin Bailey, University of Manchester).

3.6 Calculation of incident heat flux using view factor method

Mudan and Croce [24] present different methods for the calculation of the incident radiation to an adjacent object. They present two thermal radiation models. The first is the point source radiation model, and the other is the solid flame radiation model using view factors. Law [35] presented a similar radiation model in Part 2 of the BRE report.

The first model is a point source model, assuming that the flame can be represented by a small source of thermal energy, that the energy radiated from the flame is a specified fraction of the energy released during combustion and that the thermal radiation intensity varies proportionately with the inverse square of the distance from the source. Expressed mathematically, radiant intensity at any distance from the source is given by [24]:

$$\dot{Q}''_{rad,in} = \frac{\chi \dot{Q}_{comb}}{4\pi L^2} \tag{12}$$

where $\chi = \frac{\dot{Q}_{rad}}{\dot{Q}_{comb}}$ is the fraction of total heat release that is radiated away and L is the distance from the flame centre to the observer in metres. This means the distance L is dependent on the flame height. Mudan and Croce say that while the model is elegant in its simplicity, two important limitations should be recognized. The first limit involves the modelling of radiative output and the second is the description of the variation of the intensity as a function of the distance from the source. There is a considerable variation in the fraction of radiated energy from flames, everything from 0.2 – 0.4. A value that is often quoted is 30 % ($\chi = 0.3$) for many fuels [36].

The second model is a solid flame radiation model. The solid flame model is based on the postulation that the entire visible volume of the flame emits thermal radiation and the non-visible gases do not emit much radiation. The thermal radiation intensity, $\dot{Q}''_{rad,in}$, can be obtained using the following equation [24]:

$$\dot{Q}''_{rad,in} = \tau \cdot E_f \cdot \phi \tag{13}$$

where τ is the atmospheric transmissivity ($\tau = 1$ here), E_f is the average emissive power of the flame and ϕ is the geometric view factor which is a measure of the decrease of the radiation at different distances. Mudan and Croce give different correlations for the view factor. Siegel and Howel [37] give a very simple expression for the configuration factor of a rectangular radiator and a remote receiver, see equation (14):

$$\phi = \frac{1}{2\pi}\left[\frac{x}{\sqrt{1+x^2}}\tan^{-1}\left(\frac{y}{\sqrt{1+x^2}}\right) + \frac{y}{\sqrt{1+y^2}}\tan^{-1}\left(\frac{x}{\sqrt{1+y^2}}\right)\right] \tag{14}$$

where

$X = H_f / r$
$Y = W_f / r$
H_f=height of rectangular (m)

W_f=width of rectangular (m)
r=distance between radiating and receiving surface (m).

Equation (14) determines the configuration factor in one of the corners of a rectangle representing the flame volume. The distance r must be at right angles to the rectangle. Configuration factors are additive, given the configuration factors of each contributing part are calculated from the same receiver [38]. The total configuration factor ϕ is a sum of the configuration factors of each rectangle. The emissive power of a large turbulent fire may often be approximated by the following expression [24]:

$$E_f = E_b . \varepsilon \tag{15}$$

where E_b is the blackbody emissive power, kW/m^2, and ε is emissivity. The emissive power can vary considerably depending on the fuel type and the diameter of the flame volume. If the mean radiation temperature of the fire is known it can be converted to irradiance using the Planck's law of radiation. Thus, the blackbody emissive power, E_b is given by [24]

$$E_b = \sigma \left(T_f^4 - T_a^4 \right) \tag{16}$$

where
T_f=radiation temperature of flame, K
T_a=ambient temperature, K
σ =Stefan-Boltzmann constant, kW/m^{2}K^4

Mudan and Croce [24] report that for large fires, the numerical value of the emissivity of flames approaches unity. Therefore, the emissive power can be determined using the mean radiation temperature. There is, however, a lack of experimental data although they do report some, e.g. the emissive power E_f of gasoline is between 60 – 130 kW/m^2 (max) for pools varying between 1 m – 10 m, of JP-5 is 30 kW/m^2 – 50 kW/m^2 for pool fires varying between 1 m – 30 m and of ethylene 130 kW/m^2 for a 2.5 m pool fire.

Mudan and Croce report that most hydrocarbon fuel fires become optically thick when the diameter is about 3 m or larger. Substantial parts of hydrocarbon fires are obscured by a thick black smoke on the outer periphery. This smoke layer absorbs a significant part of the radiation and results in very little emission to the surroundings. In fact, the smoke layer occasionally opens up, exposing the hot flame, and a pulse of radiation is emitted to the surroundings. Although the thermal radiation from black soot is low, the hot spots appearing on the flame surface due to turbulent mixing have a higher emissive power. Large eddies within the flame bring fuel to the outer edges of the fire plume and a more efficient combustion takes place on the flame surface. These luminous spot have an emissive power of about 110 – 130 kW/m^2. It is not possible to calculate the radiation field surrounding a fire with intermittent luminous sport. For example Hägglund and Persson [39] observed that the emissive power of the black smoke for pool fires with 10 m diameter is 20 kW/m^2 when the temperate is about 800 K [24].

An interesting observation from Mudan and Croce [24] is that the measured heat fluxes appear to decrease for larger fires, indicating that the emissive power is decreasing with size of the fire. According to them, this is a counter intuitive result that has been reported numerous time in the literature.

3.7 Critical ignition

Carlsson [17] gives an overview of different ignition criteria for different materials. Already in 1963, Law [38] defined the process of ignition by radiation. According to Law, ignition of combustible material due to radiative exposure can occur either spontaneously or piloted, i.e. in presence of an ignition source such as a spark or a flame that can ignite combustible volatiles (pyrolysis gases) given off by the exposed surface. According to Law, much higher levels of radiation are required to cause spontaneous ignition compared to piloted ignition. This value can be as high as 33 kW/m^2 for spontaneous ignition of wood. However, since ignition sources will be present in a fire situation, the value for piloted ignition is usually used for building separation design. A value of 12.5 kW/m^2 is used in most Building Codes and calculation methods as the maximum tolerable level of radiation at the exposed facade, (NFPA 80A 1996). This value is used as the lowest value at which piloted ignition of dry wood can occur and has been derived by the Joint Fire Research Organization in the United Kingdom.

Clarke [40] reviewed a number of experiments considering ignition of solid materials due to radiant heating. He reports on work completed by Law and Simms in 1977 where they investigated the effect of moisture content in wood for piloted and spontaneous ignition. The conclusions from this work was that higher moisture content in wood resulted in increased minimum ignition radiation and time to ignition.

Clarke reported on work conducted by Janssens in 1991[41] where the critical radiant heat flux was established for different oven dried timber species. The critical radiation was found to vary between approximately 10 – 14 kW/m^2.

The minimum radiation intensity causing piloted ignition was determined in a series of tests conducted in Sweden and Finland in the 1970s (Nordiska industrigruppen-trähus/brandskydd, 1975), The minimum critical radiation was determined both in full scale fire tests and in laboratory tests for painted and unpainted wooden walls. In the large scale tests the minimum critical radiation were found to vary between 18 – 19 kW/m^2 for unpainted walls and 26 – 30 kW/m^2 for painted wooden walls. For the laboratory tests these number were much lower or in the range of 10 – 15 kW/m^2.

There are models available to calculate the time to ignition using critical heat flux. One of the best known is the one presented by Janssens [42] :

$$q" = q^{"}_{cr}\left[1 + 0.73\left(\frac{k\,\rho\,c}{h_{ig}^2 t_{ig}}\right)^{0.547}\right] \tag{17}$$

where $q"$ is exposing radiation (kW/m^2), $q^{"}_{cr}$ is critical radiation (kW/m^2), $k\rho c$ is thermal inertia (kW^{2}s/m^4 K^2), h_{ig} is the heat transfer coefficient (W/m^2 K) and t_{ig} is the time to ignition (s). Janssens obtained critical heat fluxes for different oven dry timbers. The values varied between 9.7 kW/m^2 to 14 kW/m^2. These values are in line with what is reported in this overview.

3.8 Methods to calculate fire spread

There exist many computer programs and mathematical models for fire spread calculations. However, most models deal with the calculation of single compartment or single multi-room buildings. There is very little work reported concerning the modelling of fire spread from one building to another. This section contains a summary of those methods which have been applied to such calculations.

3.8.1 Calculation models

The most common calculation models today are CFD models (Computational Fluid Dynamics) and so called Zone models, of which Zone models were those most commonly used in the 1980-90s, when the development of personal computers started began.

The Zone models are simple fire models based on empirical correlations to describe the fire plume and the ceiling jet. One disadvantage is that they are one-dimensional models, which means that at any given time one physical state prevails in the whole hot gas layer. Similarly, only one state prevails in the whole cold layer. The Zone models can be applied in a single or multiple rooms at the same time. The main advantages with the Zone models are that they require small (in modern terms insignificant) computer storage capacity and calculation time. As they model the flow magnitudes through the vents and openings quite well, they are particularly suitable as initial calculations in preparation for larger work, e.g. with CFD.

The use of CFD models has expanded during the latest decade. In contrast to Zone models they are three-dimensional. Since fires and turbulent flows are essentially three-dimensional, the use of CFD has resulted in large improvements in fire modelling. One disadvantage with CFD models is the need for large computer capacity, but rapid development in the computer technology during recent years has contributed to CFD models becoming invaluable tools in fire science. It is now possible to perform calculations on large fire scenarios involving large buildings in a portable PC, but it is still a quite time consuming process. Computer capacity is, however, drastically increased when fire spread from one building to another is to be modelled. Using multi-mesh CFD programs [43] which are specially coded for parallel calculation, i.e. possible to run across the network using several processors (a PC-cluster) and multiple memory banks at the same time, the calculation of huge scenarios, that include many buildings are possible and calculation time can be reduced drastically. One example of simulation of industrial outdoor fires has been reported by Howard and McGrattan [44]. Further application of CFD calculations to such scenarios will no doubt become more common in the future.

3.8.2 British method to calculate safety distances

When planning for the safety distance between buildings one should be aware of two important factors:

- The radiation level that can ignite material, both on the outside of the building and inside the building because of radiation passing through windows, and
- The radiation level from the burning building.

The UK has conducted studies that assume these basic parameters. They have produced both complex techniques and methods that are relatively simple to use. In the simplified method, safety margins have been introduced concerning the choice of a safe distance [6]. A short summary of the methodology is given below.

Fire spread between buildings has been modelled by Building Research Establishment (BRE) [35]. In Part 1 in the BRE report, two methods for determining the boundary distance are presented: Enclosing Rectangles (Geometric method) and Aggregate Notional Areas (Protractor method). The boundary distance is based on the assumption that the more openings or other unprotected areas in the external enclosure of the building, the further the building, or side of the building should be from the boundary. Firstly, consideration should be taken to determine what constitutes an ‘unprotected area’ in relation to space separation. This means that windows, doors and any parts of an external wall that can open up in the fire need to be considered relative to the emittance of radiation. The percentage of such openings becomes the key design parameter. Secondly, consideration should be taken of how much of the elevation of the building must be included in the calculations. For buildings with low fire load other methods apply. Based on permitted unprotected percentages in relation to enclosing rectangles and the width of enclosing rectangle, minimum boundary distances can be obtained from tabulated data.

When these two methods, i.e. the Geometric method or the Protractor method show a tendency to overestimate the distance, it is possible to use methods described in Part 2 of the BRE document. The Geometric and the Protractor methods are described in more detail below. Full details are given in the BRE report [35].

The Enclosing Rectangles (Geometric) method is sub-divided in five stages [35]:

1. Determine what parts of the building must be taken into account
2. Determine the plane of reference from which the boundary distance is measured
3. Determine the extent of the exposure hazard due to the unprotected areas in the side off the building
4. Determine a minimum boundary distance based on the assessment of the risk determined by Stage 3
5. Locate any special area of exposure hazard which may call for a greater or lesser boundary distance than has been obtained from Stage 4, and determine the final distance of the building from the 'relevant boundary'.

In the stage 2 the plane of reference is to be established. This plane should preferably be the side of the building, but other planes can be defined (see Figure 6).

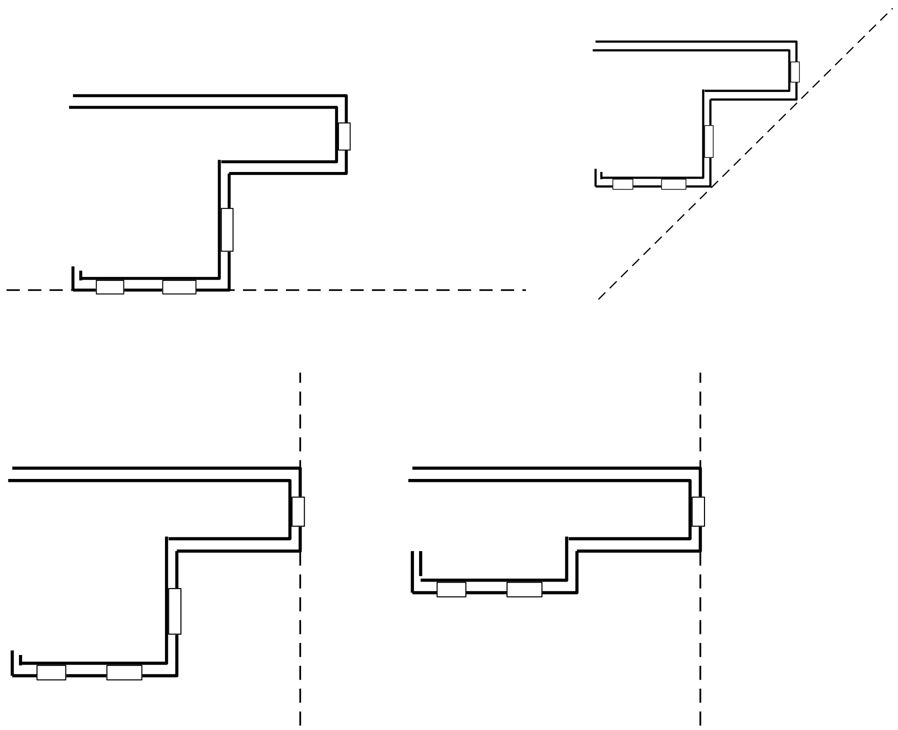


Figure 4 The reference plane for each object to be considered [35].

The Aggregate Notional Areas (Protractor) method is sub-divided in four stages [35]:

1. Determine what part(s) of the building must be taken into account

2. Determine the points on the ‘relevant boundary’ to be tested
3. Determine which unprotected areas need to be taken into account
4. Calculate the ‘aggregate notional area’ of these unprotected areas

In Part 2 in the BRE report [35] an alternative method is described. The method is called the ‘Heat Radiation from Fires and Building Separation’ (Radiation) method, written by Margaret Law. In the Radiation method the fire spread from the burning building to neighbouring property is calculated as if the radiation alone was responsible for heat transfer. The flying brands are a hazard, but the fire spread by them are assumed to be slow in comparison to radiation, because fires started by them would develop slowly. In determination of building separation not only the combustible materials outside of neighbouring (outer wall) are considered, but also the combustible contents inside the room due to radiation entering the windows.

3.8.3 Other national methods

There are also simplified methods to calculate the distance in U.S. standards, such as the National Fire Protection Association (NFPA 80A, 1980) and in an FM Global standard (FMDS 1-20, 1979). The basic parameters are the potential radiation, various view factors and critical ignition radiation for wood, i.e. 12.6 kW/m^2. In NFPA 80A, buildings are classified into three groups according to hazard: Severe, Moderate and Light, depending on fire load and flame spread classification. Depending on these parameters a safe distance can be calculated. The method FM Global has developed includes four different groups where the safe distance is determined based on the fire performance (Flammability classification) of the burning cargo and the type of exposed wall panels involved.

The New Zealand Building Code and Acceptable Solution uses a radiation intensity of 12.6 kW/m^2 as the critical value of when ignition may occur. The emitted radiation from a building during a fire is assumed to be either 84 or 168 kW/m^2, depending on the type of occupancy. Carlson outlined five methods for how to calculate minimum separation distance between building and maximum acceptable unprotected areas of external walls. He found that in general buildings should be separated from the relevant boundary by half the distance at which the total radian heat flux would be 12.6 kW/m^2. This principle is sometimes called the “mirror image” concept [17].

According to the building Code of Australia (BCA 1996), a building solution must satisfy the performance requirements. The BCA relies on two tables to verify that the performance requirements are met. A building should not be able to cause a radiant heat flux in excess of 80 kW/m^2 at the boundary and a building should be able to withstand a radiation varying between 10 – 80 kW/m^2, depending on the distance to the boundary or neighbouring building. The designer can use performance based engineering methods to show that the performance requirements are fulfilled [17].

In Sweden, buildings must be located at least 4 m from the boundary or at least 8 m from any buildings at the neighboring property. If a building is closer to the boundary it must be shown, with best engineering principles, that fire spread between the buildings will not occur. A building should be able to withstand a radiant heat flux of 15 kW/m^2 during a time period of 30 minutes [17].

3.8.4 Method by Zalosh to calculate safe distances

In the Industrial Fire Protection Engineering book by Zalosh [15], a method to calculate safe distances is presented. In this method one should:

- Assume a worst case scenario with regard to fire spread and fire extent
- Determine the heat release rate or effective flame temperature and emissivity (the ratio of the radiated energy of the material and radiated energy from a blackbody at the same temperature).
- Calculate the flame radiant potential (emissive power), *E*
- Calculate the flame height in the burning building
- Calculate the view factor between the burning building and the radiation exposed building, ϕ
- Calculate the incident radiation, q'', to the affected building as $q'' = \phi E \tau$ where ϕ is the view factor determined by the geometric relationships between the buildings, where *E* is the potential radiation and τ is the transmittance (transmissivity).
- Compare the expected value of q'' with the critical ignition value of the materials found in the affected building
- Repeat the calculation, taking into account the impact of wind on flame height and design (slope)
- If the calculated radiation is higher than the critical value, the distance should be increased if possible, otherwise one should ensure that critical parts are protected against radiation. Alternatively, one could select different material or protect the facility with water sprinklers.

It is not always the models themselves are the problem, but the fire size to be inserted into the model. Therefore, the first four points given above may be quite difficult to determine. Information concerning how to calculate flame heights, emissive power and other parameters may assist obtaining the correct values for these calculations.

4 Discussion

The goal of this project was to evaluate the tools used to calculate the fire spread risk from one building to nearby buildings. The overview given in chapter 3 covers the most important tools and methods that are available today. The main problem when calculating the risk for fire spread is to determine the input parameters to the models. These include heat release rates, effective fire diameter, flame heights, crosswind effects, emissive power of flames or flame temperatures and view factors. Estimates of all these parameters are necessary in order to obtain the critical heat flux towards a specific object.

An estimation of heat release rates per unit projected area of a flashed over industrial building is important as input to determine the flame heights. In our study, these values were found to vary between 0.5 MW/m^2 – 1.3 MW/m^2 for flame height ratios (H_f/D_{eff}) varying between 0.1 – 0.4. These values are based on a rather crude method where the flame heights and fire areas were determined from photos of real fires. If we have a building that is 100 m long and 30 m wide, we would expect a fully developed fire to be in the range of 1.5 GW – 3.9 GW using our values. Using equations (7) and (8) we can then estimate the flame heights to be in the range of 6 m – 38 m. This is a relatively large range but in order to improve the results one must perform a more accurate analysis of the potential heat release rate per unit projected area. This should be done for each part of the building that has a fire compartmented section. Using more accurate values for the heat release rate per unit projected area one could make these calculation more reliable. If we assume instead that this is a warehouse with furniture we would, based on the data found in Table 2, obtain a heat release rate that is 2.7 GW and a flame height of 25 m. Nevertheless, the numbers obtained here can always be used to explore if the calculated results are reasonable.

If we look at the effects of crosswind, we can use equation (1) to (6). These equations yield flame heights that are slightly different than presented by Heskestad [30], i.e. equation (7). If we assume the same example again using the furniture warehouse, the heat release rate is 2.7 GW. If we assume that H_c is 25 MJ/kg for furniture, this yields $\dot{m}''$ = 0.12 kg/s m^2. The effective diameter is 62 m, and through equation (4), we determine that the flame height during no wind conditions is 78 m, which is considerably higher than 25 m obtained by Heskestad equation. If we assume that there is a crosswind of 5 m/s, the corresponding flame height can be calculated by equation (1). The flame height becomes 80.5 m, which is even higher than that calculated by equation (4). The flame heights obtained by Heskestad appears to be more realistic than the ones obtained by equations (1) to (4). When concerning calculation of tilting effects, equation (6) gives more accurate results. A combination of flame height calculations using equation (7) and the tilting using equation (6) is probably the most appropriate. This is discussed in more details in section 4.1. Using equations (6) and (7), if we assume a flame height of 25 m, crosswind of 5 m/s, we obtain a tilt of the flame by 27 degree from the vertical axis.

Another interesting finding is that Heskestad [1] has explored the effect of the diameter of the flame on the final flame height. His experiments, using largely an extended fire source representing a “mass fire”, are quite useful for this study. They indicate that we should use his type of representation for calculating the flame height. The only uncertain parameter is whether we should use the width or the length of building as a diameter. He discussed his flame height correlation in relations to the ratio H_f/D thoroughly.

The methods presented to calculate fire spread vary considerably. The models themselves are not always the critical problem, but the fire size to be inserted into the model. A discussion of the input parameters needed and the difficulty in obtaining these input parameters is given in Chapter 3. Clearly, the better the quality of the input data the better the output from the model.

The overview shows that spontaneous ignition of wood occurs at approximately 33 kW/m^2, whereas critical radiant heat flux for piloted ignition of wood was found to vary between approximately 10 – 14 kW/m^2. The value of 15 kW/m^2 in the Swedish regulations is found to comply well with these findings. The emissive powers given in regulations for calculation of fire spread are found to vary between 80 – 168 kW/m^2.

In order to evaluate the formulas given in the literature, a comparison was carried out for the Swedish pool fire tests reported by Person [22]. These tests have not previously been used for such comparison. A more detailed discussion of this comparison is given below.

4.1 Comparison with Swedish pool fire tests

In order to investigate the validity of the models, a simple calculation was carried out for the Swedish pool fire tests presented by Persson [22]. The tests were briefly presented in chapter 3.1 and full details can be found in reference [22]. Firstly, a comparison with a point source method using equation (12) was carried out. The basic data for the calculations can be found in Table 3. The area of the pool was estimated to be 197 m^2 and the effective diameter 15.8 m.

Table 3 Calculated values for the Swedish pool fire tests.

Test	m" (kg/s m^2)	H_c (MJ/kg)	Combustion efficiency*	Q (MW)	H_f (m)	χ
Test 1 Gasoline	0,080	43,7	0,9	621	33	0,12
Test 2 Gasoline	0,085	43,7	0,9	659	34	0,12
Test 3 Aceton/Ethylene	0,076	26,1	0,93	365	23	0,37
Test 4 Aceton/Ethylene	0,088	26,1	0,93	422	26	0,37

*Assumed values

The calculated and measured heat fluxes at different distances for gasoline are shown in Figure 5. The only parameter that could be changed was the ratio χ , which is the fraction of combustion energy resulting in radiation. This value is much lower than the expected 0.3 as discussed previously. It has been observed in large hydrocarbon liquid fires that substantial parts of the fire are obstructed by thick black smoke on the outer periphery of the fire. This smoke layer absorbs a significant part of the radiation and results in very little emission to the surroundings. This was the case in Persson [22] experiments for the gasoline fire. One should note that test 2, was affected by the wind conditions, in such a way that the heat flux towards the NW direction was clearly reduced, as can be seen in Figure 5. The same experimental approach was used for the tests with acetone/ethylene and the results are shown in Figure 6. The value of χ that was found to fit the data best was 0.37.

In general, the agreement between the measured and calculated is reasonable when the values of χ have been determined. The chosen values appears also to be reasonable compared to values found in the literature, i.e. values varying between 0.2 – 0.4. A value of χ between 0.25 – 0.36 for ethylene is found in reference [24], whereas no corresponding value is given for gasoline. The gasoline fire was covered by black smoke, indicating that the amount of energy radiated away decreased compared to if it had not been covered by smoke. A value of $\chi = 0.12$ is, therefore, probably quite reasonable here. The calculated values for both fuels appear to follow the reduction with relation to the distance from the fire quite well. This show that the simple point source method is fairly accurate, if one can determine the value of χ for each case.

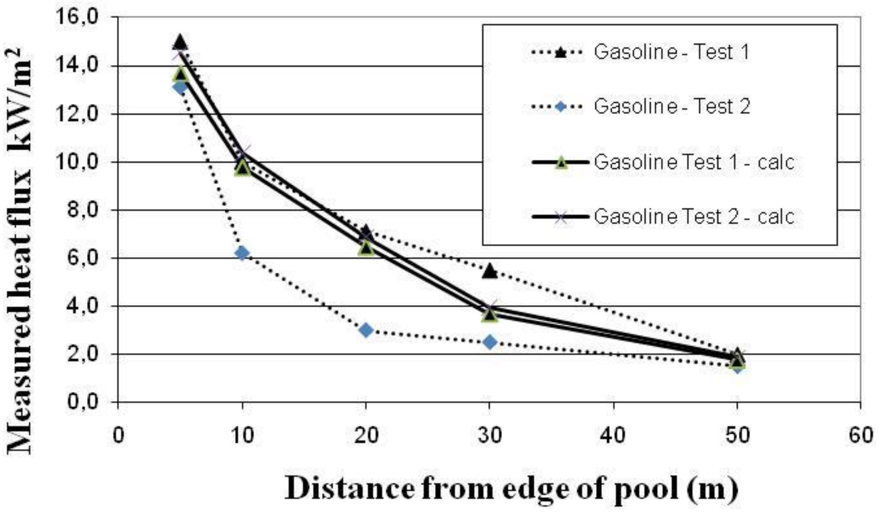


Figure 5 Comparison of measured and calculated heat flux for gasoline pool fire in the experiments presented by Persson [22].

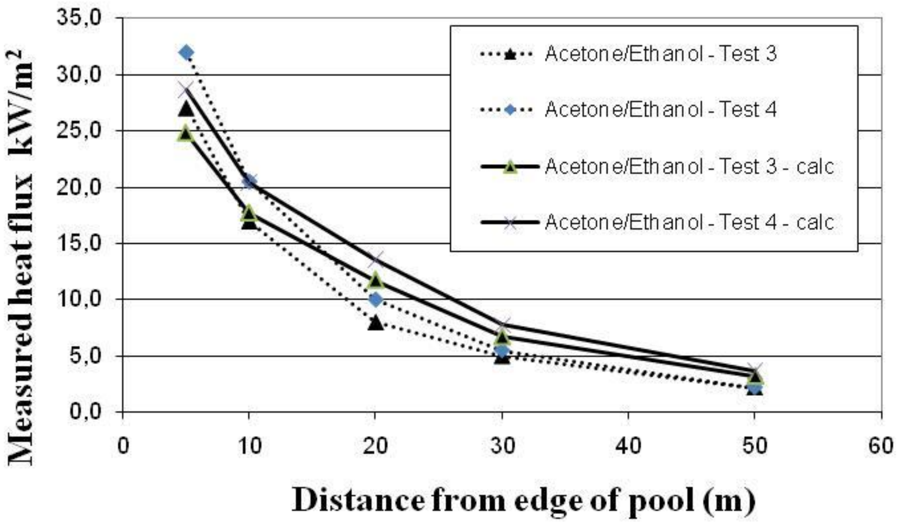


Figure 6 Comparison of measured and calculated heat flux for Acetone/Ethanol mixture in the experiments presented by Persson[22].

The second method tested to calculate the heat flux at different distances from the fire source was the solid flame model represented by equations (13) to (16). There are numerous parameters in these equations that are uncertain and difficult to determine. There are several assumptions that are valid for both fuels: the atmospheric transmissivity τ is set to one=1, the radiation temperature T_f = 800 °C and the ambient temperature T_a = 20 °C. Other parameters, i.e. E_b och , where determined in order to fit to the data. The flame heights are the same as found in Table 3. In Table 4, a summary of the values obtained is given, and in Figure 7 and Figure 8, a plot of the results are given for the both fuels.

Table 4 Values used to calculate the heat flux using the view factor method when comparing to the tests performed by Persson [22].

Test	ϵ	E_b (kW/m^2)	E_f (kW/m^2)
Test 1 Gasoline	0.47	74.7	35.1
Test 2 Gasoline	0.47	74.7	35.1
Test 3 Aceton/Ethylene	1.0	74.7	74.7
Test 4 Aceton/Ethylene	1.0	74.7	74.7

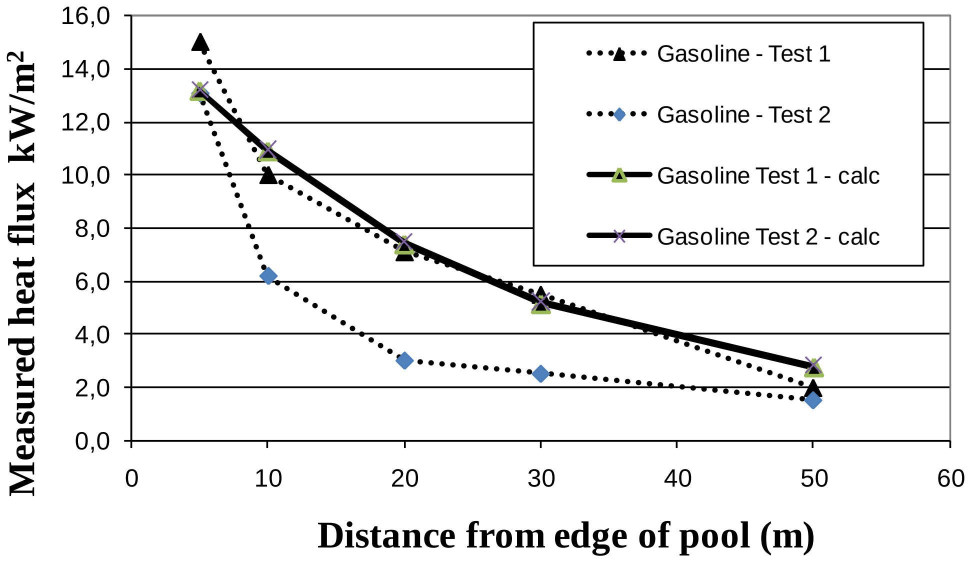


Figure 7 Comparison of measured and calculated heat flux for gasoline using the view factor method.

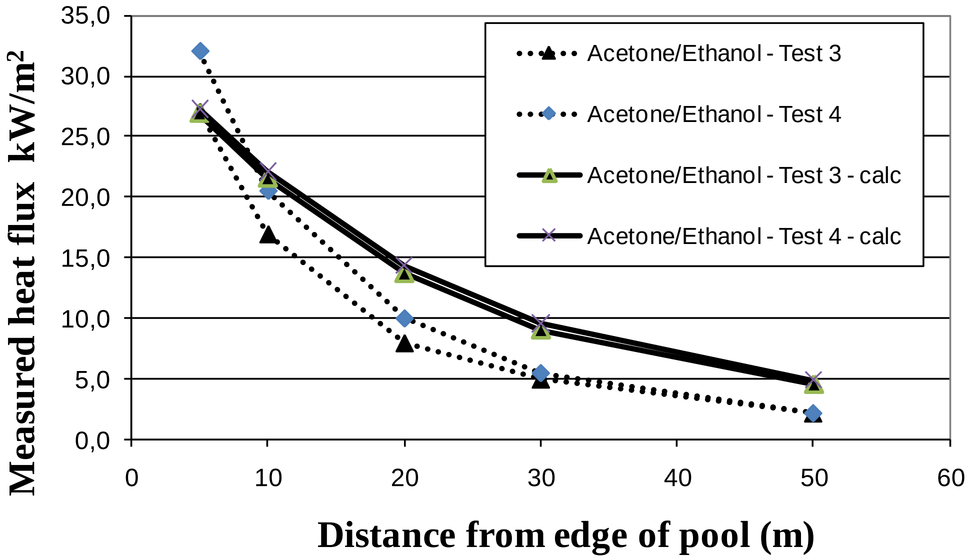


Figure 8 Comparison of measured and calculated heat flux for acetone/ethanol mixture using the view factor method.

As mentioned previously, Hägglund and Persson [39] found that for pool fires that are 10 m in diameter have emissive power, E_f= 20 kW/m^2 when the flames are covered by black smoke. The results given here indicates that the value of 35 kW/m^2, see Table 4, for gasoline is reasonable. It was reported by Persson [22] that the flames were surrounded by black smoke, but there were also some luminous spots appearing occasionally. Mudan and Croce gave an example of a hydrocarbon pool fire with 80% black smoke and 20% luminous spots, where they calculate the emissive power to be 42 kW/m^2. Such an estimate is said to be consistent with the wide-angle radiometer measurements conducted on JP-4, JP-5 and gasoline fires [24].

The emissive power of 74 kW/m^2 obtained for acetone/ethylene is difficult to assess. The calculated values for both fuels appear not to follow the reduction relative to the distance from the fire particularly well. In summary, we can say that the emissive power for the gasoline fuel appears to be reasonable but the reduction of the radiation using the view factor method does not yield as good compliance as for the point source method.

Finally, we have calculated the flame tilt according to equation (6). As reported previously we have estimated the flame tilt angle to be around 30 – 45^o from the vertical axis. The crosswind was reported to be 2 – 5 m/s in direction of S to SV for tests 1, 3 and 4 and for test 2 it was 3.5 – 11 m/s. In order to check the validity of equation (6) we used the data from Table 3, and for test 4. In test 4, the wind velocity was reported to be 4 – 5 m/s, in the S-SV direction. The mass burning rate was 0.088 kg/s m^2 and the effective diameter was 15.8 m. If we use 5 m/s, we obtain u^* =2.21 from equation (2), and from equation (6) we find $\cos\theta$ = 0.67. Consequently, the flame tilt angle θ from the vertical axis is 47^o. The corresponding value for 4 m/s is 41^o angle. This shows that these equations work quite well for the experimental data given by Persson [22].

In summary, we can say that the flame height model given by Heskestad works well for industrial buildings and that the point source model and the flame tilt model according to equation (6) gives very reasonable values. The view factor method gives satisfactory results but there are more parameters to determine, which introduces a certain uncertainty. The point source model gives a better description of the distance dependency of the radiation reduction compared to the view factor method.

5 Conclusions

An overview of numerous large industrial fires is given. A deeper analysis of some cases provided some data for the validation of some mathematical models to calculate fire spread between buildings. The main problem when estimating the risk for fire spread is to determine the input parameters to the models. The most important parameter is the heat release rate.

We estimated the heat release rates from some of these large fires and found them to be in the range of 6 GW – 22 GWs. The flame lengths were estimated to be in the range of 15 m – 150 m. The effects of cross winds were discussed and analysed. We also estimated the heat release rates per unit projected area of flashed over industrial buildings. We found them to vary between 0.5 MW/m^2 – 1.3 MW/m^2 for flame height ratios (H_f/D_{eff}) varying between 0.1 – 0.4. Calculation of tilting effects were discussed and equation (6) was deemed to give the most accurate results. Comparison with experimental data presented in the report confirm this. A combination of flame height calculation using equation (7) and the tilting using equation (6) is the most appropriate method.

Another interesting finding is that Heskestad [1] has explored the effects of the diameter of the flame on the final flame height. His experiments, using largely extended fire source representing a “mass fire”, were quite useful for this study. They indicate that we should use his type of representation for calculating the flame height. The only uncertain parameter is whether we should use the width or the length of building as a diameter.

The overview showed that spontaneous ignition of wood is 33 kW/m^2, whereas the critical radiant heat flux for piloted ignition of wood was found to vary between approximately 10 – 14 kW/m^2. Therefore the value of 15 kW/m^2 in the Swedish regulation is found to comply well with these findings. The emissive powers given in regulations for calculation of fire spread are found to vary between 80 – 168 kW/m^2.

In order to evaluate the formulas given in the literature, a comparison was carried out for the Swedish pool fire tests reported by Persson [22]. These tests have not previously been used for such comparison. Based on this comparison we can say that the flame height model given by Heskestad works well for industrial buildings and that the point source model and the flame tilt model according to equation (6) gives very reasonable values compared to Persson’s tests. The view factor method gave satisfactory results but as it requires the determination of a greater number of parameters, it is more cumbersome in its application and introduces a greater uncertainty. The point source model gives a better description of the distance dependence of the radiation reduction compared to the view factor method.

There is a need to investigate the validity of Heskestad equation (7) further for industrial buildings. For example one should explore whether we should use the width of the building or the effective diameter as a base in industrial buildings that are very long but not very wide (close to a linear fire source).

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Appendix A

The table has been constructed from articles describing fires in fire magazines, referenced in column Reference . Short description of fire development has extracted from the text.

Table A1. Selected industrial fires in USA.

Fire	Reference	Year	Fire area [m^2]	Fuel type	Building(s) involved in fire	Short description
Warehouse fire	Fire Command, May 1984	1984	> 10 000	Furniture	Four-story building	**Fire rages through the huge office furniture warehouse, threatening to claim nearby exposures. Fire alarm at 20:32, at 21:13 the warehouse was fully involved fire, flames out roof and window threatening other buildings nearby. Building size more 100 m length, 4 stores high (only part of the building is seen in the picture). Flames in whole side of the building.**
Fire in grain processing facility	Fire Command, March 1985	1985	9600		Four-story, heavy timber mill construction	**Fire started 9:51 a.m. At 9:52 heavy fire and smoke reported from one of the building (building A). At 9:58 a.m. building A fully involved in fire and fire had spread to neighbouring building B. Explosions heard inside. Flames extended 50 feet across the street and threatened on other factory building (west of the Building B). In employee parking lot east of Building A, automobile tyres and gasoline tanks began to explode. At 10:01 a.m. Building B was totally involved.** **The factory across the street became an extreme exposure hazard. Because large area of**

						neighbouring factory wall was glass the heat from the Building B was sufficient to activate sprinkler heads in the factory, which created a water curtain of sorts, which helped to keep windows intact and reduced the radiation. After one hour from the first alarm fire was spread to Monmec Building. At 1:30 p.m a 30 foot section of south wall of this building collapsed and by 3:00 p.m the north wall collapsed. Flames were 100 feet high at that time. **Another large storage warehouse of the north side of the Monmec building was threatened by intensive heat so that the sprinklers adjacent to the south wall did activate.** **An automobile repair shop nearby was totally destroyed. In the Hudson river (nearby) an abandoned barge docked at fourth and River streets caught fire. A roof of a church ignited.**
Plastic warehouse fire	Fire command, January 1987	1985	8500	PVC waste	85 000 m^3 warehouse	**Fire started at 12:14. The fire fighters arrived at 12:17, smoke at the west door, inside the building already large fire.** **Defensive attack was indicated. Immediate exposures facing the radiant heat from 40 foot high flames included two- and four-family wood frame dwellings and a masonry church.** **Incipient exterior fires occurred in four other wooden structures.** **Early collapse of roof occurred, which diminished the radiation, but changing wind created difficult**

						smoke conditions.
Sherwin-Williams Warehouse fire	Fire Command, August 1987	1987	17 000	Paints, and other liquids in plastic containers, aerosol cans,, etc		**Fire started 9:02. Fire fighters arrived 9:10. At that time fire was reported to be through the roof. Protection of exposures started. The fire breached the fire wall at 9:20-9:25. at 9:30 the entire warehouse in fire.**
Wood Products-Manufacturing Plant	Fire Journal 1979	1978				**Alarm 3:35 pm. At 4:00 fire had burned through the roof and by 4:30 pm major portions of the roof collapsed. After the roof collapse four of the six buildings were involved in fire. As a results of the fire, six buildings and their storage were damaged. Finished products in other portions of the complex were water damaged.**
Chemical-Manufacturing Plant	Fire Journal 1979	1978		Chemical household products	Factory, manufacturing household chemical products. The plant consisted of five interconnected buildings and several exterior storage tanks. In addition two railroad tank cars containing chlorine and one containing LP-G were parked on a railroad siding in close proximity of the plant. The buildings were of mixed construction,	**The fire was discovered at 9:05 pm (by an employee) in a stack of empty containers. The fire brigade received alarm 9:16 pm. Fire was broken through the roof at 9:25. The fire threatened the storage tanks nearby. The fire extended into all of the five buildings. All building and their contents were damaged.**

					with metal deck or gypsum form board on steel-joist roof systems.	
Warehouse, containing various plastics, acetones, glues and ketones	Fire Journal, 1979	1979			The structure was two stories high and had a ground floor area of approximately 32 000 square feet. The building was masonry construction, and no automatic fire protection or detection systems.	**The fire was reported to the fire department at 6:07 pm and first arriving units found approximately one-half of the building involved in fire. During the fire the entire roof system collapsed, as did portions of the exterior walls.**
Warehouse	Fire Journal 1979	1979		Merchandise in bins and cartons being stacked approximatel y 7 m high. Wooden pallets were stored in aisles.	The one-story structure, approximately 860 feet long by 356 feet wide and 27 feet high. It vas constructed of concrete masonry units, with a metal-deck-on-metal-bar-joist roof system supported by 8-inch-by-10-inch box columns. Automatic sprinkler protection was provided in the ceiling level. The interior of the building was divided into three major section, each separated by a concrete-block wall. The main portion of the building, approximately 560 feet by	**The fire was discovered at 12:25 in the rack storage area and the in-house fire brigade responded. The public fire department units reported heavy smoke showing from loading doors at the rear of the building. 12: 41 the roof of the major warehouse section collapsed.**

					356 feet, was used for rack storage of general merchandise. The storage arrangement resulted in merchandise in bins or cartons being stacked approximately 23 feet high. In addition, merchandise and wooden pallets were stored in aisles.	
Texas Plywood Manufacturing Plant	Fire Journal, April 1984	1984	22 000	Plywood	The building had three undivided sections. The manufacturing section 330 by 520 feet, a "green section" 110 by 200 feet and a 213 to 303-foot-by-75-foot addition was added to the south end of the manufacturing section. Together all sections area 236 000 square feet. The manufacturing section was build using heavy timber and laminated timber structural members and plywood walls and roof decking. The roof assembly was designed using 300-for-long	**The fire was discovered at 12:25 pm. At 12:27 pm fire department receives telephone massage of fire. At 12:29 pm first-in fire department units arrive at the plant site. 236 000-square-foot manufacturing building is heavily involved in fire. At the same time fire department dispatcher notifies the water department of the fire and the booster pump two miles east of the plant is remotely shut off.** **At 12:35 pm fire ground officers report that the 236 000-square-foot manufacturing building is fully involved in fire.** **At 12:35- 12:45 pm firebrands from the burning manufacturing plant ignite a fire at a building materials warehouse ¼ to ½ mile from the plant site.** **At 12:45 water company personnel place a third**

					laminated bow-string wood trusses placed on 20-foot centres, running east to west. The trusses were supported at the exterior walls by wood columns with approximate dimensions of 12 by 10 inches spaced 20 feet on centre. Side walls of the building were generally half-inch-thick plywood siding on wood framing	**1000-gpm pump at the city's No.2 Pumping station in operation.** **At 13:45 pm the wood truss roof assembly of the plant collapses, rupturing sprinkler and standpipe system piping.** **The decision is made to close the post indicator valves on the supply lines to the 12 sprinkler and 2 standpipe systems. Fire fighters are unable to close post indicator valves located 15 to 30 feet from the east side of the building.** **11.30 pm next day the fire is extinguished.**
Electrolux fire	Brandförsvar 6-7/75	1975 (or before)		Mostly plastic materials piled 14-15 m high		**Fire was spread rapidly vie roof, which consisted of mineral wool boards covered metal plates.**
Luxor fire	Brandförsvar 12/76	1976 (or before)		Plastic material		
Köln fire		1977		Plastic car steering wheels, plastic instrument		**About 10 minutes after alarm the occurred failure in electricity, and pumps went out of order** **Part of the roof collapsed about 1 hour after fire alarm**

				panels, windscreen wipers, carpets, engine oil in cans, at fire time 150 000 litre engine oil was storaged in cardboard boxes		
K-Mart fire				All kinds of articles, as food, car deals, plastic toys, foamed plastic, aerosol, butane lighters, bicycle and car tyres, etc	110 000 m^2 building, sectioned in four equal sections	**Extremely fast fire growth, which started in aerosol storage, about 4 -50 pallets of aerosol was involved in the initial fire.** **Fire penetrates the roof 20 min after ignition, 52 min after ignition whole warehouse in fire 110 000 m^2 area.**
Fire in SALK hall	Brand & Räddning 11 1993	1993			X	**Largest effort ever made in Stockholm. Roof collapse (no time to it given). A helicopter also took part in extinguishment work. Roof of a hotel and two rooms began to burn on the other side of the street .** **The whole building collapses and nothing can be saved.** **The layout of the building was bad which**

						contributed bad results in extinguishing effort. Difficult to get water, etc.
Lesjöfors fire	Brand & räddning 10, 1996	1996	Near 6000	The fuel cisited 50-60 000 threats, oils, and crease, wooden pallets.	6000 m^2 total building area, many buildings in connection with each others.	**Fire height about 10-20 m, very fast fire growth. After 6 min were the first firemen on the scene. The whole building were already in fire.**
Skultuna fire in aluminium rolling mill	Brand & Räddning 8, 2000	1999	4000 (roof area), fire possible as max near the same area	Oil in machines, plastic, details,etc.		**Flames out early through the roof which was made of aluminium plate. Whole building in fire, flame heights > 20 m (according to picture). The fire brigade had to concentrate to protection of rolling mill 2, (mill 1 was totally involved in fire) and 60 000-liter-storage of paraffin oil in the basement below the fire.**
Fire in seven whiskey warehouses, Bardstown, Kentucky	Industrial Fire World, Jam/Feb 1997	1996	2000 each house	High proof alcohol, ethanol 90 000 barrels (about 15 million liter = 15 000 m^3, Heavy wood structure	Seven large 7-store whiskey warehouse, each about 2000 m^2 floor area. Buildings made of heavy timber structure with metal siding and a tar roof.	**Very rapid fire growth, flame heights at least 100 m. Flame lengths downwind longer than separation between two adjacent warehouse (125 m). At the time of fire there was a storm in the area with wind gusts of 35 m/s . Total heat release was enormous.** **As the warehouses collapsed, the alcohol poured aout, spreading almost invisible flames across the roadways and cutting access to much more than a square mile area involved. There were totally 44 warehouses in the site, but 37 of them survived, seven were burned.**

Fire in magnesium recycling plant, Garfields Heights, Ohio	Industrial Fire World. Mar/Apr 2004	2003	At least 5-10000	Magnesium storage, recycled magnesium.	60 m long storage building with wooden roof. Only a narrow one lane road separated that structure from the main building	**When first responders arrived (a few minutes after alarm) the fire was broken through the roof. Flame temperatures near 3000 °C. The temperature is high enough the brake water down to its basic components, hydrogen and oxygen. That in turn, feeds the fire rather than extinguishing it. Flame lengths 20-30 m according to photo.** **The firemen had to concentrate to protect building nearby, rather than extinguish the fire.** **Several other buildings were threatened by fire. A storage building and other business building near by were totally destroyed.**
Ten-Story Rack system at Wisconsin plant	Industrial Fire World. Jan/Feb 2003	2002	2500	Paper, un finished magazines. 25 000 pallets off printed material.	34 m high storage building, 10 stores. Floor area about 6000 m2. Storage type ASRS (Automated Storage Retrieval Systems)	**The ASRS storage collapsed in fire. Not written much about the fire. Possible in the lower parts of the storage burned, and the storage collapsed due to heavy load above the fire.**

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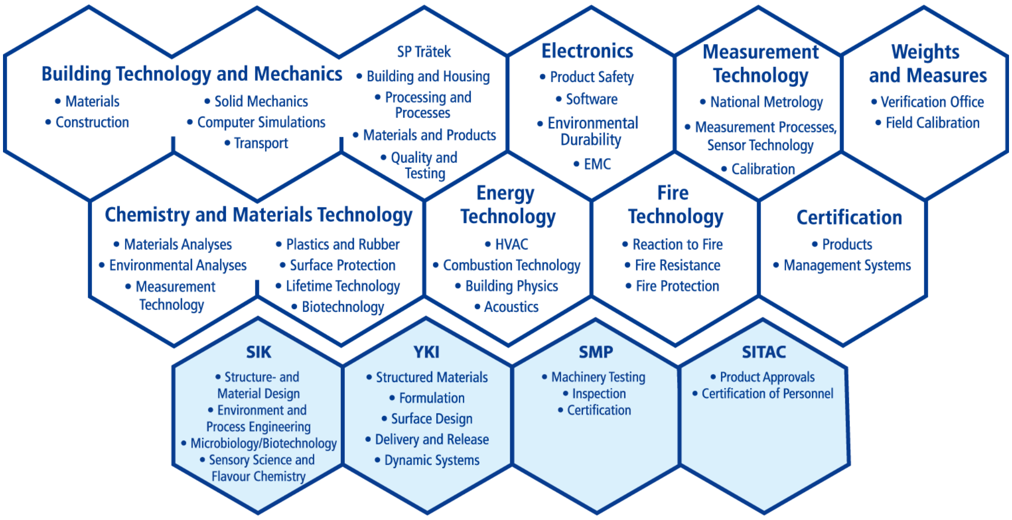

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