EXTERNAL FIRE SPREAD TO ADJOINING BUILDINGS

- A review of fire safety design guidance and related research

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Utvändig brandspridning till intilliggande byggnader – En utvärdering av riktlinjer för brandteknisk dimensionering samt relevant forskning

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Abstract: This report discusses different parameters that affect external fire spread between buildings. A comparison between different methods and regulations of determining safe separation distances between buildings is made. The importance of external flames projected from openings is investigated with regards to the amount of emitted and received radiation. Finally, areas of further research are suggested. (English)

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17th December, 1999

EXECUTIVE SUMMARY

At the present, there is no internationally accepted method to design buildings against external fire spread between buildings. National Building Codes are generally based on more or less prescriptive provisions and usually no background is given on how the provisions have been obtained. Where engineering methods can be used, i.e. in a performance based Building Code environment, the guidance is not globally consistent.

This project was initiated in order to clarify what parameters that should be considered when designing buildings against external fire spread and what factors that are not necessary to take into account. Additionally, the report should also try to make indications of what methods that should be used to determine the safe separation distances between buildings.

THE OBJECTIVE of this report is to summarise and review research with regards to external fire spread between buildings. Furthermore, available fire engineering guidance literature, calculation methods and Building Regulations addressing safe separation distances between buildings will be investigated.

The report will also investigate whether the levels of radiation emitted from projected flames are large enough for it to be necessary to account for when determining safe separation distances between buildings. The alternative is to use the openings as the only radiators with an appropriately determined temperature.

THE METHOD used to achieve the results in this report was a combination of an extensive literature study and assessments of different calculation methods. The regulations set out in different Building Codes have been compared to each other. A number of calculations of separation distances between buildings and acceptable unprotected areas have been performed for three different building types, using calculation methods referred to by different Building Codes and other methods set out in the literature.

The importance from externally projected flames was investigated in two ways. A method derived in Sweden of how to determine the total amount of received radiation by an adjoining building, was compared with the radiation received if only the window was assumed to radiate at an appropriate determined temperature. This radiation from the window was also compared with calculations performed with equations for flame projections and flame temperatures that are commonly used in the fire engineering discipline.

THE CONCLUSIONS that have been made based on the findings in this report are listed below.

- ❑ Since the radiation intensity is dependent on the temperature to the power of four, the fire temperature is a very important factor when determining the emitted radiation from a burning building. The fire temperature is dependent on several factor such as compartment dimensions, opening factors, size and distribution of the fire load and type of interior linings.

- The value of 12.5 kW/m^2 for piloted ignition of an adjoining facade may be slightly low and thus too conservative. Ignition due to exposure from full scale fires may occur at higher levels of radiation, i.e. 15-18 kW/m^2.

- The prescriptive Building Regulations studied in this report use values of 84 and 168 kW/m^2 (2 and 4 cal/cm^{2}s) as the maximum values of radiation that can be estimated in a fire.

- The Building Regulations in Australia, England and Wales, New Zealand and Sweden are performance based, which gives greater flexibility to the fire engineer in the design process of buildings.

- The calculation methods studied in this report predicted approximately the same separation/boundary distance for simple building shapes. The differing factor was that various flame projection distances are used in the methods. Complicated building shapes, e.g. irregular shaped facades, generated a larger distribution of separation distances, which is believed to be due to the variation in applicability of the different methods.

- The calculations performed with a method by Fredlund et al. (1976) as well as with a method set up by the author indicated that the percentage of radiation contributed by externally projected flames to the total emitted and received radiation was in the order of 12-18 %. This contribution is not very large, which implies that the simpler approach of assuming that the openings, with an appropriate determined temperature, are the only radiators, is a method that can be used for design purposes.

- Areas that need further research are; radiation from projected flames, ignition criteria of materials exposed to full scale fires, temperatures in fires in modern buildings and wind effects on the levels of emitted radiation. Another area that should be investigated more thoroughly is whether the whole or only a portion of the facade should be counted as radiating when determining separation distances for large warehouses.

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1 INTRODUCTION

This introduction will present the reason for the initiation of this project and what the objectives of the report are. A brief description of the used methods and what limitations that has been necessary to make for the fulfilment of the report is also given.

This report was conducted by Emil Carlsson as the final requirement for a degree of Bachelor of Science in Fire Protection Engineering at the Department of Fire Safety Engineering, Lund University, Sweden.

1.1 Background

At the present, there is no internationally accepted method to design against external fire spread between buildings. National Building Codes are generally based on more or less prescriptive provisions and generally no background is given on how the provisions have been obtained. Where engineering methods can be used, i.e. in a performance based Building Code environment, the guidance is not globally consistent.

Very little published reviews regarding external fire spread between buildings have been presented during the latest 15 years at conferences or in the literature. This is a concern given the development in the performance based fire engineering codes during the last decade.

This project was initiated in order to clarify what parameters that should be considered when designing buildings against external fire spread and what factors that are not necessary to take into account. Additionally, the report will also try to make indications of what methods that should be used to determine the safe separation distances between buildings.

1.2 Objectives

The objectives of this report are to summarise and review research performed during the latest 50 years with regards to external fire spread between buildings. Furthermore, available fire engineering guidance literature and calculation methods addressing safe separation distances between buildings will be investigated.

The report shall also study the Building Regulations and acceptable solutions of a few countries. Some of the regulations allow for a performance based design while others are strictly prescriptive. Differences and similarities between the different regulations will be compared and discussed.

The report shall also investigate the importance of radiation from projected flames with regards to determining safe separation distances between buildings. Will a flame projected from an opening during a fire, contribute with high enough levels of radiation for it to be necessary to take into account, or is it safe to assume that the openings or windows are the only radiators?

A very important purpose with this report is to identify areas, regarding external fire spread between buildings that need further research.

1.3 Method

A combination of an extensive literature study and assessments of different calculation methods have achieved the results presented in this report. The regulations set out in different Building Codes have been compared to each other and the scope discussed. A number of calculations of separation distances between buildings and acceptable unprotected areas have been performed for three different building types, using calculation methods referred to by different Building Codes and other methods set out in the literature.

The importance from externally projected flames was investigated in two ways. A method derived in Sweden of how to determine the total amount of received radiation by an adjoining building, was compared with the radiation received if only the window was assumed to radiate at an appropriate determined temperature. This radiation from the window is also compared with calculations performed with equations for flame projections and flame temperatures that are commonly used in the fire engineering discipline.

Based on findings and ideas that have arisen during the progress of the report, a number of suggestions were made of areas of further research.

1.4 Limitations

The report will only discuss horizontal fire spread between buildings due to thermal radiation, i.e. other aspects such as ignition due to convective heat transfer and flying brands will only be mentioned and not discussed in detail. The different countries' Building Codes that will be compared and investigated are; Australia, Canada, England and Wales, New Zealand, Sweden and the United States of America. Furthermore, the building types that will be used in the study are warehouses, office buildings and residential buildings.

2 PARAMETERS AFFECTING FIRE SPREAD BETWEEN BUILDINGS

This chapter aims to point out the most important parameters that influence fire spread between buildings. A brief description will first be made about how fire may spread from building to building. Secondly, a more detailed explanation will be made concerning the factors that affect fire spread due to radiation. The detailed explanation is divided into three sub-chapters, which addresses the following parameters; emitted radiation, radiative heat transfer and critical received radiation.

2.1 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 ways, or a combination of ways, are more common and often more hazardous than others.

2.1.1 Flying brands

Ignition of combustible materials may occur due to flying brands emitted from a building on fire, (Barnett 1988, Jönsson et al. 1994). These brands may travel far distances and protection against this is possible by fitting external surfaces with appropriate fire resistant claddings, (McGuire 1965). Flying brands do not represent a significant hazard by itself with respect to ignition of buildings. They may though act as an igniting source together with radiation, where the volatiles given off by the radiation exposed material may ignite.

2.1.2 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, (Barnett 1988, Law et al. 1981).

2.1.3 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, (McGuire 1965). In order for ignition to occur by this phenomenon, the exposed building has to be very close to the fire source.

2.1.4 Radiative heat transfer

Ignition due to radiation is the most common way for fire to spread between buildings, (Jönsson et al. 1994), and can happen at much greater distances than by direct flame contact and convection, (McGuire 1965). Typical values of radiation where ignition of wood may occur is 33.5 kW/m^2 for spontaneous ignition, i.e. ignition in absence of an ignition source, and 12.5 kW/m^2 for piloted ignition, i.e. ignition in presence of an ignition source such as a spark or a brand, (Barnett 1988). These values are widely used throughout the world.

Since ignition by radiative heat transfer is the most common and hazardous way of fire to spread between buildings, the other means of fire spread explained above will not be further discussed in this report.

2.2 Emitted radiation

A body with a certain temperature, T, emits energy, P, to the surroundings at all times, (Jönsson et al. 1994). This transfer of energy can be described by Equation 2.1 below. The emitted energy is expresses in terms of energy emitted per second an area unit, i.e. J/sm^2 or W/m^2.

$$P = \varepsilon \sigma T^4 \qquad [2.1]$$

where: P = emitted radiation [W/m^2]
ε = emissivity of the radiating surface
σ = Stefan-Boltzmann constant = 5.67×10^{-12} W/m^2K^4
T = temperature of object [K]

How this equation is used for fire situations, where flames and a hot gaseous mass are assumed to be an object, and the importance of the different variables are discussed later in this report. However, since the temperature is taken to the fourth power, it is obvious that the temperature was the greatest impact on the total amount of emitted radiation.

2.2.1 Fire temperature

There are several methods available on how to predict the temperature of a fire in a compartment. This report will not discuss these methods in detail but will give a brief summary of some of the methods and factors influencing the temperature. However, since the emitted radiation from a burning building and hence the building separation distance is dependent on the fire temperature to the power of four, this factor should be investigated thoroughly in a performance based design.

A compartment fire can be either fuel controlled or ventilation controlled, (Law 1963). A fuel controlled fire has an excess of oxygen and not sufficient fuel, while a ventilation controlled fire has an excess of fuel and the limiting factor is oxygen. Law found that in ventilation controlled fires, the rate of heat release rate and hence the fire temperature is dependent on the area of the opening multiplied by the square root of the opening height, i.e. $A\sqrt{h}$. This factor is often referred to as the ventilation factor. The maximum compartment temperature found in the tests reviewed by Law (1963) was 1100 °C, which represents a maximum radiation intensity of 168 kW/m^2 (4 cal/cm^2s). In the tests where the ventilation factor was a non-limiting factor, i.e. where the window area is comparable to the floor area, approximately the same temperatures and levels of radiation were found. For fires with a relatively low fire load, i.e. less than 25 kg/m^2 (the amount of combustible material per unit floor area), temperatures of 800 °C were found in the compartments. This temperature represents a radiation of 84 kW/m^2 (2 cal/cm^2s). These values have been and are still used in several prescriptive Building Regulations as the maximum levels of radiation that can be expected in a fire.

Drysdale (1985) reports on a method to predict fire temperatures in compartments developed in Sweden by Pettersson et al. (1976). The results of the method are often referred to as the Swedish fire curves. The method uses heat balance equations for the fully developed compartment fire to predict the temperature.

The following assumptions has been made in order to simplify the method:

- *combustion is complete and takes place entirely within the confines of the compartment;*
- *the temperature is uniform within the compartment at all times;*
- *a single surface heat transfer coefficient may be used for the entire inner surface of the compartment; and*
- *the heat flow to and through the compartment boundaries is unidimensional, i.e. corners and edges are ignored and the boundaries are assumed to be "infinite slabs".*

The full derivation of the Swedish fire curves will not be presented here. The interested reader is referred to Drysdale (1985) or the original document by Pettersson et al. (1976). The result is an equation that can be solved by numerical integration to give a time-temperature relationship for various values of the opening factor $A\sqrt{h}/A_{tot}$, where A is the area of the opening, h is the height of the opening and A_{tot} is the total area of all interior surfaces in the enclosure. A number of time-temperature relationships have been established for different compartments, window configurations and fire loads. Figure 2.1 below is an example of Swedish fire curves. Each curve represents a specific fire load.

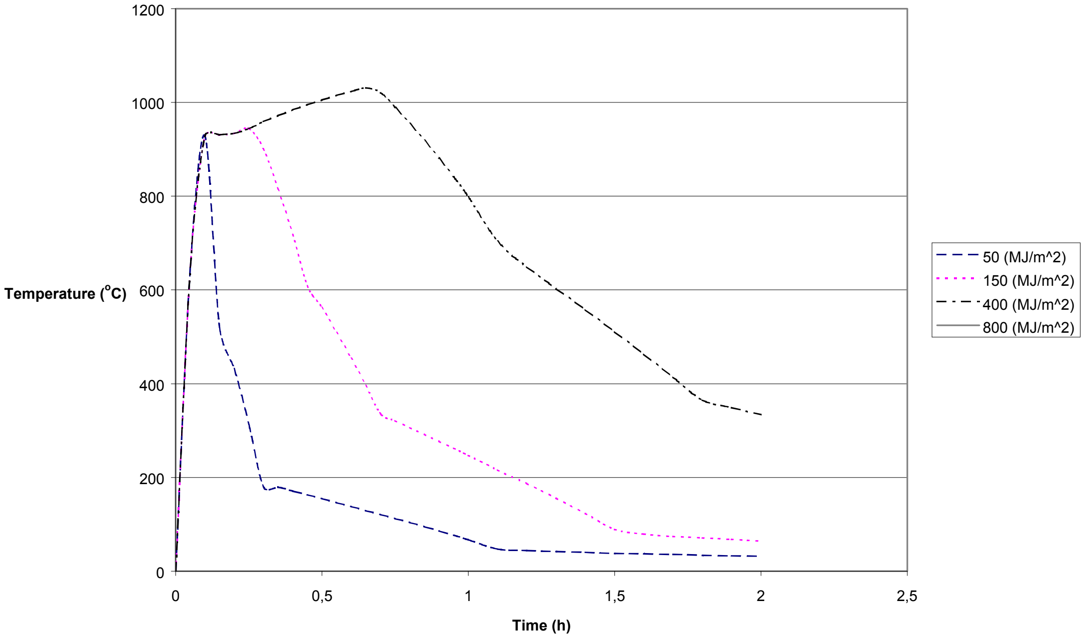

Figure 2.1 *Example of the Swedish fire curves for fire loads between 50 and 800 MJ/m^2. The above example is for $A\sqrt{h}/A_{tot}$ =0.08$m^{1/2}$, wall thickness = 0.2 m, k = 0.8 W/mK and ρc = 1700 kJ/m^3K and is derived from data in Drysdale (1985).*

This theoretical model has been compared with full scale fire tests, (Drysdale 1985). The comparison showed that the model can be used with satisfactory result to estimate the fire temperature in a compartment.

Another method that is used to determine the fire temperature is with the use of standard time-temperature curves. Building elements are tested against fire exposures in large furnaces that can be programmed to produce certain temperatures, (Clarke 1998). In order to make tests conducted in different places and in different furnaces comparable, time-temperature curves have been developed that the furnaces should obey. The two most common tests are ASTM E119 and ISO 834 and expressions for the temperature, T, determined by these tests are given in Equation 2.2a-b and presented graphically in Figure 2.2.

ASTM E119: $$T = 750\left(1 - e^{-3.79553\sqrt{t}}\right) + 170.41\sqrt{t} + T_o \qquad [2.2a]$$

ISO 834: $$T = 345\log(8t + 1) + T_o \qquad [2.2b]$$

where: T_o = temperature of ambient air [°C]
t = time in hours for ASTM E119 and time in minutes for ISO 834

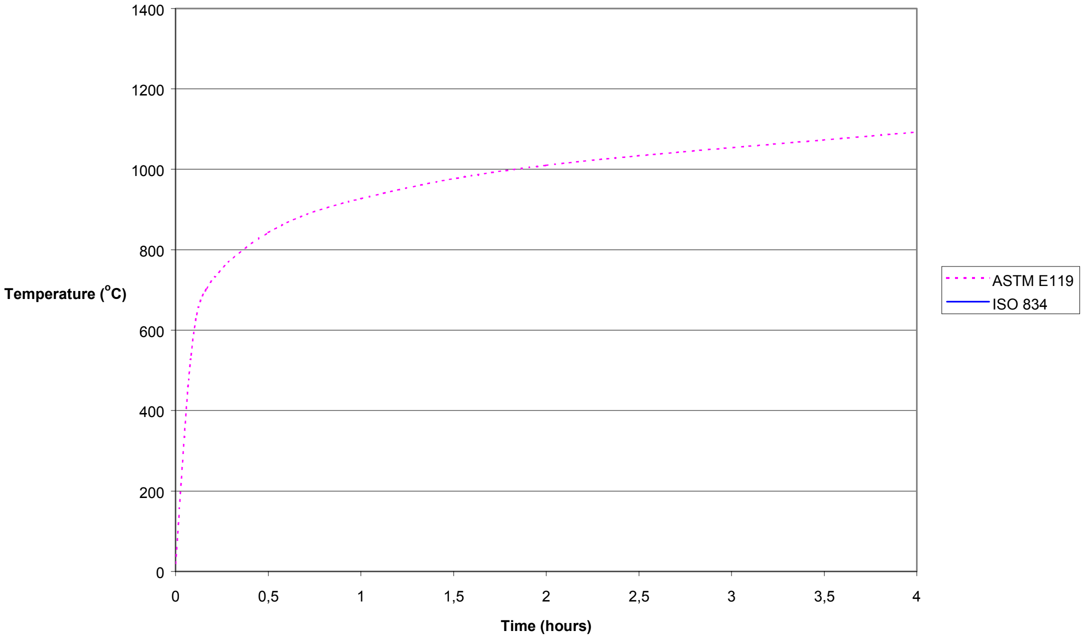

Figure 2.2 Time-temperature curves for ASTM E119 and ISO 834 standard furnace tests

It should be noted that the time-temperature curve of the furnace tests is different from those resulting from a real fire. The growth phases are more rapid and the furnace tests lack any decay phases. Barnett (1988) proposes that the ISO 834 standard furnace time-temperature curve can be used for the purpose of building separation. Exposure to the ISO 834 fire for a duration of 30 and 120 minutes would result in the same levels of emitted radiation as is used in the British and New Zealand Building Regulations, (Clarke 1998). Drysdale (1985) quotes work on Ingberg (1928), who proposed that if the areas under two time-temperature curves were equal, the fires could be assumed to have equal fire severity. The standard furnace relationship could therefore be used if the fire severity was equal to the severity from an expected real fire. Ingberg also derived tables for fire loads with belonging values of fire resistance requirements that could be used for building design. Drysdale was doubtful to this method mainly due to three reasons;

1. the fire load in the building has to stay the same during the entire lifetime of the building,
2. the data on which the method was based, was conducted in old buildings, and
3. the equal area concept is not totally true, e.g. the effect of a 10 minutes exposure to 900 °C will differ from that of a 20 minutes exposure to 600 °C.

Drysdale (1985) concludes that the method by Ingberg (1928) may not be applicable in the present day.

Law et al. (1981) give an expression, see Equation 2.3, for determining the fire temperature T_f in a compartment. The equation was derived from experiments and uses fire load, ventilation configuration and compartment dimensions as inputs.

$$T_f - T_a = 6000\frac{\left(1-e^{-0.10\eta}\right)}{\eta^{1/2}}\left(1-e^{-0.05\psi}\right) \qquad [2.3]$$

where:

η = $\frac{A_T}{A_w h^{1/2}}$ [$m^{-1/2}$]

ψ = $\frac{L}{(A_w A_T)^{1/2}}$ [kg/m^2]

T_a = temperature of ambient air [K]

A_T = total area of floor, ceiling and walls minus total window area [m^2]

A_w = sum of window areas on all walls [m^2]

h = window height or weighted average of window heights on all walls [m]

L = fire load [kg]

This method will however not give a complete time-temperature relationship for the fire. The output will be an average temperature of the fully developed fire that can be expected for the specific compartment, fire load and window configuration.

In 1958, the Division of Building Research, National Research Council (Canada) carried out a series of full scale fire tests that are commonly known as the St. Lawrence Burns (McGuire 1965). The main findings from the tests are summarised below.

- The type of exterior cladding did not influence the levels of emitted and received radiation.
- The maximum levels of received radiation at some distance from the buildings was found to be comparable to those that would result if the

window openings were assumed to be the only radiators radiating with an appropriate temperature.
- The maximum levels of radiation were twice as high for buildings with highly flammable linings as for buildings with non-combustible linings.
- The levels of radiation were found to be higher on the leeward side of the building than on the windward side.

Another finding from the tests was that the levels of radiation measured after 16 minutes and onwards were much greater than expected and what would be practical for the purpose of building separation design. However, since fire fighting activities generally is in progress well before that time, the extraordinary high levels of radiation were neglected when configuration factors for building separation design were established. The findings from the St. Lawrence Burns has been incorporated in the National Building Code of Canada, where it also is regulated that if Fire Service intervention cannot be guaranteed within ten minutes, the building separation distance should be doubled.

2.2.2 Fuel

The temperature in a compartment during a fire is also dependent on the type of fuel that is burning. Plastics and other synthetic materials generally have a higher calorific value than for example wood, which can cause a higher fire temperature (Buchanan 1994). Examples on calorific values are 16.7 MJ/kg for wood and 39.9 MJ/kg for polystyrene. Table 2.1 below sets out calorific values and heat release rates per square metre of some liquids, plastics and different shapes of wood.

Table 2.1 Net calorific value and heat release rates for different material. Adapted from Buchanan (1994).

Material	**Net calorific value (MJ/kg)**	**Heat release rate (MW/m^2)**
Liquids		
Petrol	43.5	3.27
Light oil	41.9	1.75
Wood		
Flat wood	16.7	0.10
1 m cube	16.7	0.61
Furniture	16.7	6.63
25 mm in crib	16.7	15.3
Plastics		
PMMA	24.9	1.34
Polyethylene	43.8	1.36
Polystyrene	39.9	1.40

The distribution of the fuel within the compartment is also an important factor. An example can be made for wooden pallets, which will cause a higher maximum heat release rate than the same amount (in weight) of solid cubical shaped wood would do. This is due to the greater surface area of the wood pallets. The wood pallets will therefore achieve a higher maximum heat release rate but it will at the same time not burn for as long time as the solid wood will do.

The type of fuel can also have an impact on the amount of emitted radiation from flames projected from an opening. Plastics tend to cause a higher emissivity and hence higher levels of emitted radiation than wood, (Karlsson et al. 1999). The emissivity of projected flames is discussed in chapter 2.3.2.

2.2.3 Properties of compartment

In chapter 2.2.1 it was shown that there are a number of factors that affect the fire temperature in a compartment and hence the emitted radiation. The thermal properties of walls, ceilings and floors have an impact on the heat transfer through the boundaries of the compartment. The geometry, i.e. width, depth and height, of the compartment as well as the number and dimensions of windows have a great influence on the fire temperature. The opening factor does also influence the temperature since it can be a limiting factor with regards to combustion efficiency and supplying the fire with oxygen. Furthermore, large openings can allow hot gases to escape from the compartment, which thereby can result in lower temperatures within the compartment. The opposite is valid for small openings, i.e. they can result in higher temperatures in the compartment. It will also be shown later in this report that the size of the windows influence the temperature and size of flames projected from the window, which in some cases can result in higher levels of emitted radiation.

2.3 Radiation transfer

Parameters that influence the transfer of radiation between a burning building and a receiving surface are for example; projections of flames from openings, the emissivity of the flame, the configuration factor and the Fire Service intervention. These parameters will be discussed below.

2.3.1 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 regards to the total amount of radiation received by an adjacent building is not totally agreed on in the fire engineering discipline today. The National Building Code of Canada uses a flame projection distance of 1.2 m for unprotected openings (Clarke 1998), while the other Building Codes reviewed in this report disregard the effect of flame projection. The effect of flame projection will be investigated in a separate chapter in this report and it is not the purpose of this section to further discuss the matter. This section will only discuss methods of determining the properties of projected flames.

Law et al. (1974) have reviewed work done by Webster (1959, 1961, 1964), Yokoi (1960) and Seigel (1969) on flame projections from buildings on fire. Equation 2.4 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.

$$z_1 + H = 18.6\left(\frac{R}{W}\right)^{2/3} \qquad [2.4]$$

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 2.3 shows the layout and dimensions of projected flames according to Law et al. (1981). Note that the method is for no through draught conditions.

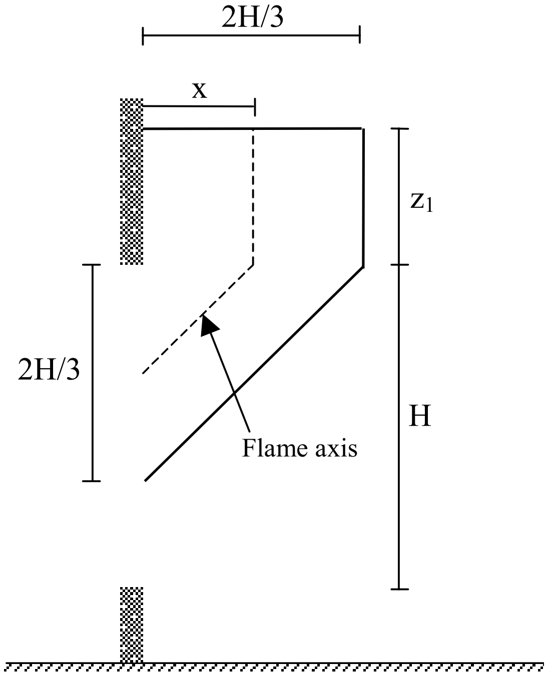

Figure 2.3 Flame shape for no through draught conditions according to method by Law et al. (1981)

The flame tip is defined to be located at the point where the flame temperature is 540 °C, which is where the illuminous zone of the flame ends. The rate of burning, R (in kg/min), can be estimated by the well known expression presented in Equation 2.5, which was originally derived by Kawagoe, (Drysdale 1985). The correlation below was derived from a series of both full and small scale tests with wood cribs as fuel and compartments with different ventilation openings.

$$R = 5.5 A_o \sqrt{H} \qquad [2.5]$$

where: A_o = area of opening [m^2]
H = height of opening [m]

The report (Law et al. 1981) also states that flames projected from narrow windows tend to be longer and not lie against the facade, while flames projected from wide windows will be shorter and cling to the wall above the window, which is also described in Jönsson et al. (1994). Extra long flames can emerge where there is;

- flammable linings in the fire compartment,
- fires on floors below the window from where flames are projected, resulting in a chimney effect and,
- there is a wind across the fire.

Equation 2.4 for the flame height has later been changed to Equation 2.6 (Law et al. 1981), which is used in several documents, e.g. (Buchanan 1994, Jönsson et al. 1994, Drysdale 1985).

$$z_1 + H = 12.8\left(\frac{R}{W}\right)^{2/3} \qquad [2.6]$$

Law et al. (1981) presents a method of how to estimate flame shapes and determine emitted radiation from projected flames. The method was derived in order to design external steel members. The horizontal flame projection of the flame axis away from the building facade can be determined with Equations 2.7a-b.

Wall above window: $$x = 0.312H^{1.54}W^{-0.54} \qquad [2.7a]$$

No wall above window: $$x = 0.60H^{2/3}z_1^{1/3} \qquad [2.7b]$$

The dimensions are the same as explained above. The flame is stated to have a thickness of $\mathrm{d} = 2\mathrm{H}/3$, which means that the flame front is located at distance 2H/3 from the facade.

Fredlund et al. (1976) has conducted a series of full and small scale fire tests with small houses made in light-weight concrete. In those tests, air was blown into the fire compartment in order to simulate natural wind conditions. The projected flames observed in these tests had a slightly different shape than those reported by Law et al. (1981). The flame shape was triangular and projecting from the upper two thirds of the window. These tests and the method of approximating the flame shape will be further discussed in Chapter 6, where also a picture of the flame shape is shown.

In full scale tests performed in Sweden by Ondrus et al. (1986), the temperature in projected flames was measured. The aim of the tests was to investigate the effect of externally applied additional thermal insulation. The tests were conducted in a three storey building and the fuel consisted of 184 kg of wood cribs. The maximum recorded temperature recorded just outside the window was approximately 900-950 °C. The flame temperature then decreased with both horizontal and vertical distance away from the window. Drysdale (1985) presents results from three small scale tests performed by Bullen and Thomas (1979). The maximal temperature recorded in the external flames was in the same order and distribution as found by Ondrus et al. (1986).

Law et al. 1981 gives a theoretical expression of the temperature distribution along the axis of a projected flame, see Equation 2.8.

$$\frac{T_z - T_a}{T_o - T_a} = 1 - 0.027\frac{lw}{R} \qquad [2.8]$$

where: T_z = temperature at distance l along flame axis [K]
T_a = temperature of ambient air [K]

T_o = temperature at the window [K]
l = distance along flame axis [m]
w = window width [m]
R = rate of burning [kg/s]

The temperature just outside the window may be found to be higher than the fire temperature. This is due to unburned gases that are being combusted outside the compartment.

2.3.2 Emissivity

The emissivity can be said to express how efficient a surface or an object is as a radiator, (Jönsson et al. 1994). The emissivity is dependent on factors such as temperature and properties of the object. An ideal black body is assumed to have an emissivity of 1.

When it comes to flames, the emissivity is dependent on the thickness of the flame and contents of soot particles. An emissivity of 0.3-0.7 is often used for ordinary flames, while it can be as low as 0.066 for flames of burning alcohol, (Jönsson et al. 1994). Equation 2.9 below is often used to determine the emissivity ε of a flame projected out from an opening in a burning compartment, (Law et al. 1981, Jönsson et al. 1994, Drysdale 1985).

$$\varepsilon = 1 - e^{-a\lambda} \qquad [2.9]$$

where:
a = absorption coefficient
λ = flame thickness [m]

The absorption coefficient is dependent on the type of burning material and Table 2.2 sets out values for flames of various fuels. According to Law et al. 1981 and the CEN document “Eurocode 3, Design of Steel Structures, Part 1.2 Structural Fire Design”, a value of a = 0.3 is appropriate for design purposes of external structural steel.

Table 2.2 Absorption coefficient for flames from different materials. Adapted from Drysdale (1985).

Material	Coefficient a
Diesel oil	0.43
PMMA	0.50
Polystyrene	1.20
Wood	0.50-0.80
Furniture	1.13

An emissivity of 1 is often used for window radiation from compartments, (Barnett 1988, Law 1968), which is a conservative approach.

2.3.3 Configuration factor

The intensity of emitted radiation from a hot surface will decrease when the distance from the surface increases. A measure of this decrease is the so called configuration factor, ϕ. Buchanan (1994) gives an expression for the configuration factor of a rectangular radiator and a remote receiver, see Equation 2.10 below.

$$\phi = \frac{1}{360}\left[\frac{x}{\sqrt{1+x^2}}\tan^{-1}\left(\frac{y}{\sqrt{1+x^2}}\right)+\frac{y}{\sqrt{1+y^2}}\tan^{-1}\left(\frac{x}{\sqrt{1+y^2}}\right)\right] \qquad [2.10]$$

where:
x = H_f/r
y = W_f/r
H_f = height of rectangle [m]
W_f = width of rectangle [m]
r = distance between radiating and receiving surface [m]

The above equation determines the configuration factor in one of the corners of the rectangle. Several documents, e.g. (Drysdale 1985, Jönsson et al. 1994), give the configuration factor in tables or graphs where different combinations of height, width and distance has been used to calculate the configuration factor. Note that when determining the configuration factor with this method, r must be at right angles to the rectangle. Configuration factors are additive given that the configuration factors of each contributory part are calculated from the same receiver, P, (Law 1963). Figure 2.4a-b shows the orientations of the variables used to determine the configuration factor.

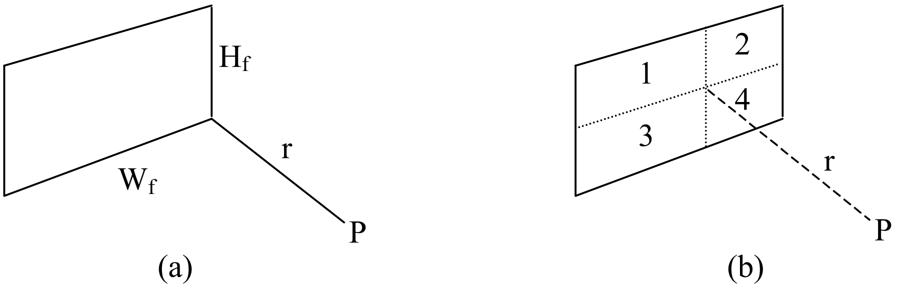

Figure 2.4 Determination of configuration factors

In Figure 2.4b, the total configuration factor ϕ_{tot} is the sum of the configuration factors of each rectangle as shown in Equation 2.11.

$$\phi_{tot} = \phi_1 + \phi_2 + \phi_3 + \phi_4 \qquad [2.11]$$

The same method can also be applied when any of the rectangles should not be included. In this case the configuration factor of this part should be subtracted from the total configuration factor, which is shown in Law (1963) and Jönsson et al. (1994).

When it comes to determining separation distances between buildings, critical values of configuration factors that are widely used in Building Regulations and other calculation methods are 0.15 for buildings where a low intensity fire can be expected and 0.075 for higher intensity fires, (Law 1963). McGuire (1965) and NFPA 80A (1996) use 0.035 for severe hazard levels (buildings with highly flammable linings according to McGuire 1965), 0.07 for moderate hazard levels and 0.14 for light hazard levels. As explained above, the configuration factor expresses the decrease in radiation transfer between the radiator and receiver. Therefore, the critical configuration factor for different building occupancies can be determined by dividing the critical radiation intensity that would cause ignition of the receiving surface by the maximum radiation intensity predicted in a fire in the relevant building. The configuration factor then achieved is the maximum allowable in order for ignition not to occur.

2.3.4 Fire Service Intervention

As reported earlier in chapter 2.2.2, the St. Lawrence Burns generated very high radiation intensities after 16 minutes, i.e. much higher than what would be practical for the purpose of determining separation distances. However, since the Fire Service generally will respond within in this time, only the lower values measured before that time were adopted in regulations. It is required by both the Canadian and English and Welsh regulations that where Fire Service intervention cannot be guaranteed within reasonable time, the separation distance should be increased.

2.4 Critical received radiation

Whether ignition of a building facade exposed to radiation will occur depends on the ignition criteria and physical properties of the facade material and how long time it will take for the material to ignite at that specific exposing radiation.

2.4.1 Ignition criteria

Ignition of combustible material due to radiative exposure can occur either spontaneously or piloted, i.e. in presence of an igniting source such as a spark or a flame that can ignite combustible volatiles given off by the exposed surface, (Law 1963). Much higher levels of radiation is required to cause spontaneous ignition and Law (1963) states a value of approximately 33 kW/m^2 (0.8 cal/cm^{2}s) for spontaneous ignition of wood. However, since igniting sources will be present in a fire situation, the value for piloted ignition must be used for the purpose of building separation design. A value of 12.5 kW/m^2 (0.3 cal/cm^{2}s) 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. According to McGuire (1965), unfinished and untreated fibre board can ignite at lower radiation intensities, but no account needs to be taken to this since such material is unlikely to be a material located in an area where it would be exposed to radiation from a fire in an adjoining building.

Clarke (1998) has reviewed a number of experiments regarding 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 conclusion from the work was that higher moisture content in wood resulted in increased minimum ignition radiation and time to ignition, which is also shown in Law (1968). Clarke (1998) also reports on work done by Janssens in 1991 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.

In a series of tests conducted in Sweden and Finland in the 1970's (Nordiska industrigruppen, 1975), the minimum radiation intensity causing piloted ignition was determined. The critical radiation was determined both in full scale fire tests and in laboratory tests for painted and unpainted wooden walls. One conclusion that was made based on the results from these tests was that higher levels of radiation was required in order to cause ignition in the full scale tests than in the smaller laboratory tests. Table 2.3 sets out the minimum radiation intensity that caused piloted ignition for the different tests and exposed surfaces.

Table 2.3 Critical levels of radiation from full scale and laboratory tests causing piloted ignition of painted and unpainted wooden walls. Adapted from Nordiska industrigruppen (1975).

Levels of radiation causing piloted ignition (kW/m^2)	**Unpainted surface**	**Painted surface**
Full scale test	18-19	26-30
Laboratory test	10	15

The small scale laboratory tests were based on 15 minutes continuous radiation exposure.

The Swedish Building Regulation (Boverket 1995) uses a value of 15 kW/m^2 at where piloted ignition can occur.

2.4.2 Time to ignition

A surface will not ignite immediately when being exposed to the critical levels of radiation presented in the previous section. The time to ignition depends on factors such as moisture content and thermal inertia (kρc) of the exposed material, (Drysdale 1985). Law (1968) states that it would take approximately ten minutes for oven dried wood (ρ = 500 kg/m^3) to ignite when exposed to a radiation of 15.8 kW/m^2, while it would take approximately 65 minutes for wood (ρ = 800 kg/m^3) with a moisture content of 15 % (by weight of dry wood) to ignite when exposed to the same levels of radiation.

In the same review by Clarke (1998) as was mentioned above, a model by Janssens (1991) to predict time to ignition for piloted ignition of timber is presented. Equation 2.12 explains the model.

$$q = q_{cr}\left[1 + 0.73\left(\frac{k\rho c}{h_{ig}^2 t_{ig}}\right)^{0.547}\right] \qquad [2.12]$$

where: q = exposing radiation [kW/m^2]
q_{cr} = critical radiation [kW/m^2]
$k\rho c$ = thermal inertia [kW^{2}s/m^{4}K^2]
h_{ig}^2 = heat transfer coefficient [W/m^{2}K]
t_{ig} = time to ignition [s]

Janssens has also obtained values of these properties for different oven dry timbers which is shown in Table 2.4.

Table 2.4 Properties of various timber species obtained with Janssens model. Adapted from Clarke (1998).

Species	**T_{ig} [°C]**	**q_{cr} [kW/m^2]**	**h_{ig} [W/m^{2}K]**	**kρc [kJ^{2}s/m^{4}K^2]**
Western Red Cedar	354	13.3	34.9	0.087
Redwood	364	14.0	35.9	0.141
Radiata Pine	349	12.9	34.6	0.156
Douglas Fir	350	13.0	34.6	0.158
Victorian Ash	311	10.4	31.5	0.260
Blackbutt	300	9.7	30.6	0.393

The report "Standard Test Method for Determining Material Ignition and Flame Spread Properties" (ASTM 1990) sets out a method of how to theoretically determine the time to ignition of a surface exposed to radiation. The surface is assumed to be a semi-infinite slab. The outcome of the method is explained in Equation 2.13.

$$\frac{\dot{q}''_{o,ig}}{\dot{q}''_e} = \left[1 - \exp(\tau)erfc\left(\sqrt{\tau}\right)\right] \qquad [2.13]$$

where: τ = $\frac{h^2 t_{ig}}{k\rho c}$

$\dot{q}''_{o,ig}$ = critical flux for ignition [kW/m^2]

$\dot{q}''_e$ = measured incident flux [kW/m^2]

h = heat loss coefficient [kW/m^{2}K]

t_{ig} = ignition time under incident flux [s]

$k\rho c$ = thermal heating property (thermal inertia) [kW^{2}s/m^{4}K^2]

3 BUILDING CODES

This chapter will describe and discuss what is regulated in the Building Codes of a number of countries with regards to external fire spread between buildings. The countries that will be discussed are; Australia, Canada, England and Wales, New Zealand, Sweden and the United States of America. A brief comparison between the different codes will also be made in chapter 7.

3.1 Australia

In order to comply with the Building Code of Australia (BCA 1996), a building solution must satisfy the performance requirements. Satisfaction of the performance requirements can be achieved in either of three ways;

1. *complying with the Deemed-to-Satisfy Provisions; or*
2. *formulating an alternative solution which-*
    - *(i) complies with the Performance Requirements; or*
    - *(ii) is shown to be at least equivalent to the Deemed-to-Satisfy Provisions; or*
3. *a combination of (1) and (2).*

3.1.1 Deemed-to-Satisfy Provisions

If a building design fulfils the Deemed-to-Satisfy Provisions, it complies with the Performance Requirements.

3.1.2 Alternative Solution

An Alternative Solution has to be judged in accordance with at least one of the Assessment Methods described below. The Assessment Method used must show that compliance with the Performance Requirements has been achieved and thus also compliance with the BCA.

One or more Assessment Methods can be used to determine whether a building design agrees with the Performance Requirements or not. The Assessment Methods that can be used are briefly described below.

1. Prove that the design, type of construction and the materials used comply with the Performance Requirements or Deemed-to-Satisfy Provisions.
2. Verification Methods either set out in the BCA or accepted by the appropriate authority.
3. Comparison with the deemed-to-satisfy provision.
4. Expert judgement.

3.1.3 Objective

The objective of the BCA with regards to fire safety and fire resistance is to protect occupants from injuries which may arise due to a fire within a building and while the occupants are evacuating the building. Fire fighting and rescuing activities should also be allowed for. Furthermore, fire spread between adjoining buildings must be prevented and other properties protected from structural damage caused by structural failure due to a fire in a neighbouring building.

3.1.4 Performance Requirements

A building must be constructed in a way that guarantees a maintained structural stability while exposed to a fire. Spread of fire must also be avoided, both within the building and to adjoining buildings. In order to comply with these performance requirements, several factors have to be taken into account. Examples are:

- use and layout of building,
- fire load,
- estimated extent and severity of fire,
- fire safety measures,
- evacuation time, and
- intervention of rescue personnel.

3.1.5 Verification Methods

To comply with the performance requirement regarding prevention of fire spread between buildings, the BCA sets out two tables with distances between buildings or to the boundary and the maximum radiation allowed at that location.

Table 3.1 (adapted from Table CV1 in the BCA) should be used when determining the distance between buildings located on different properties. The table should be read as; a building will not cause a heat flux greater than what is stated by in Table 3.1 at the belonging distances inside the boundary of an adjoining property. The table can also be reversed and be read as; a building located at distances within the property boundary set out in the table will be able to withstand the stated radiation levels.

Table 3.1 Required distances and maximum radiative heat flux between buildings on different properties. Adapted from the BCA (1996)

Location	**Allowable radiation (kW/m^2)**
On boundary	80
1 m from boundary	40
3 m from boundary	20
6 m from boundary	10

Table 3.2 (adapted from Table CV2 in the BCA) should be used for buildings located on the same property. Fire spread between buildings will be prevented if the building will not cause a greater radiant heat flux onto the other building than given by Table 3.2 for belonging values of the distance between the buildings. It can also be expressed as; when the distance set out in the table separates the buildings, the buildings are able to withstand the belonging heat flux set out in the table.

Table 3.2 Required distances and maximum radiative heat flux between buildings on the same allotment. Adapted from the BCA (1996).

Distance between buildings	**Allowable radiation (kW/m^2)**
0 m	80
2 m	40
6 m	20
12 m	10

Table 3.2 is equivalent to Table 3.1 if it is assumed that the boundary is located in the middle of the separating distance.

As explained previously in this chapter, the designer can chose to use Table 3.1 and 3.2 to make sure that the design complies with the performance requirements. The deemed-to-satisfy provisions can also be used, as well as other methods of verifying that performance requirements with regards to building separation are satisfied.

The BCA does not give an absolute figure of at which radiant heat flux ignition will occur. The values set out in the BCA ranges between 10-35 kW/m^2, depending on type of material and whether piloted ignition is likely to occur or not. However, no background information is provided from where these values and how Tables 3.1 and 3.2 were obtained.

3.1.6 Summary

The BCA relies on two tables to verify that the performance requirements are met. In general, 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 distance to the boundary or neighbouring building. The designer can use performance based engineering methods to show that the performance requirements are fulfilled. The objective of the BCA with regards to external fire spread is to prevent fire spread between buildings, i.e. to protect both buildings independent of which is the fire source.

3.2 Canada

Unfortunately, a current version the National Building Code of Canada has not been available to the author. This description will therefore be based on what is written in other reports about the National Building Code of Canada and only point out the most relevant knowledge with regards to building separation.

The National Building Code of Canada sets out tables of building separation that are based on the same criteria of critical received radiation, i.e. 12.5 kW/m^2, as the Approved Document B (1991), which is the document used in England and Wales, (Clarke 1998). Canada uses higher values of emitted radiation and a flame projection distance from openings of 1.2 m.

The used values of emitted radiation was obtained from the St. Lawrence Burns reported on in chapter 2.2.1. The Canadian code uses configuration factors of 0.07 for normal buildings and 0.035 for buildings with combustible linings, which is expected to burn extra vigorously. These configuration factors are the same as those set out by McGuire (1965) and results in expected levels of radiation of 180 and 360 kW/m^2 respectively. The St. Lawrence Burns showed extraordinary high levels of radiation after 16 minutes, much higher than would practical to use when determining building separation. The National Building Code of Canada therefore requires that the separation distance should be doubled in areas where Fire Service intervention cannot be guaranteed within 10 minutes.

3.3 England & Wales

3.3.1 Requirement

The requirements in England and Wales regarding external fire spread are set out in the Building Regulations 1991, Part B of Schedule 1. The requirements are given in the Approved Document B and are set out below.

> *(1) The external walls of the building shall resist the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building.*
> *(2) The roof of the building shall resist the spread of fire over the roof and from one building to another, having regard to the use and position of the building.*

3.3.2 Performance

In order to meet with the B4 requirements and to prevent a fire from spreading between buildings on different sides of the relevant boundary, the Approved Document B requires that the following measures have to be taken:

1) The risk of ignition of external walls caused by an external fire source and fire spread over the wall surfaces must be limited. This is achieved by making provisions for the external walls to be built of material with low heat release rates.
2) The amount of radiant heat flux that is able to pass through an external wall must be limited. This is achieved by limiting the amount of unprotected openings in the wall and by taking into account for the distance to the relevant boundary.
3) The risk of flame spread over and/or penetration of the roof, caused by an external fire source, must be limited. This is achieved with an appropriate roof construction.

The extents to which these measures have to be taken are dependent on factors such as use of building, distance to the relevant boundary and height of building.

According to the Approved Document B, fire spread between buildings and the expected consequences if it does occur, are dependent on the fire severity, distance between buildings, fire resistance of external walls and the risk that occupants in the adjoining building are exposed to.

3.3.3 Space separation

The provisions in the Approved Document B4 regarding space separation are based on six main assumptions. The assumptions are listed below.

(a) The fire size is dependent on the fire compartmentation in the building.
(b) The fire intensity is dependent on the use of the building, i.e. purpose groups. An automatic sprinkler system can also decrease the fire intensity.
(c) Residential, Assembly and Recreation purpose groups are associated by a greater risk to life than other purpose groups.

(d) Fire spread between buildings located on the same property do not represent a great risk to life and can be disregarded, unless the building contains Residential, Assembly or Recreation purpose groups.
(e) Another building with a similar height to the building of concern is located on the other side of the relevant boundary. The buildings are located at equal distance from the common boundary.
(f) The radiant heat flux that passes through a fire resistant wall is negligible and can be disregarded.

Smaller fire compartments are recommended when a shorter separation distance or an increased amount of unprotected wall area is wanted.

Boundaries

The Approved Document B4 sets out the distance to the relevant boundary, i.e. actual boundary or an assumed boundary located in the middle in the space between two buildings, should be used when determining the separation distance. This enable the designer to calculate the total amount of unprotected area in the external wall without having to take into account to any building located on the other side of the boundary. An external wall is counted as facing the relevant boundary if any of the three cases shown in Figure 3.1 is fulfilled. In order to be considered as a relevant boundary, the boundary should:

1. coincide with,
2. be parallel to, or
3. not form an angle of more than 80° with the external wall of the building.

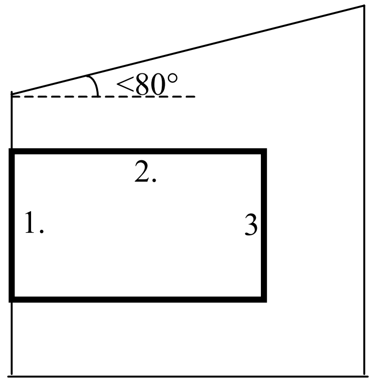

Figure 3.1 External walls facing the relevant boundary

The separation distance between buildings located on the same site is often decreased, unless the buildings of concern are the Residential, Assembly and recreation purpose groups. If the building is classified in any of these purpose groups, a notional boundary positioned in the space between the buildings should be assumed. The notional boundary should be located in a position that complies with the provisions for space separation for one of the buildings. The other building can then be used to certify that its location also complies with the provisions.

The relevant boundary is the boundary that a wall faces and can be either a notional boundary or the actual property boundary.

Unprotected areas

An area in the external wall with less fire resistance than what is required for the wall shall be regarded as an unprotected area. A fire resistant wall that is covered with combustible material with a thickness greater than 1 mm shall also be treated as an unprotected area with a total area of half the actual area of the combustible material. Small unprotected areas, i.e. < 1.0 m^2, can be neglected when determining the separation distance since the risk of fire spread caused by these small areas are very small. This assumption is valid when the separation distances of the unprotected areas in an external wall are;

- unprotected areas forming an area not more than 1 m^2 – a minimum distance of 4.0 m to other unprotected areas of the same size is required,
- unprotected areas not greater than 0.1 m^2 – a minimum distance of 1.5 m to other unprotected areas is required,
- unprotected areas positioned in different fire compartments – no restrictions, and
- unprotected external areas of a stairway forming a protected shaft – no restrictions.

The unprotected areas of an uncompartmented building that are more than 30 m above ground level may be neglected with regards to separation distance. External walls located within 1.0 m of the relevant boundary must not have unprotected areas in excess of what is described above and the walls must be fire resistant on both sides.

3.3.4 Calculation methods

The Approved Document B4 sets out two methods of calculating the acceptable unprotected area in an external wall. The methods are obtained from the Fire Research Technical Paper No. 5, 1963 and are useable for buildings located more than 1.0 m from the relevant boundary. The objective of the calculation methods is to make sure that the building is separated from the relevant boundary by at least half the distance at which the total radiant heat flux received from all unprotected areas in the external wall would be 12.6 kW/m^2. This is based on the assumption that the emitted radiation from the unprotected areas in the wall is as set out below.

1. 84 kW/m^2 for buildings in the Residential, Office, Assembly and Recreation purpose groups.
2. 168 kW/m^2 for buildings in the Commercial, Industrial, Storage or Other non-residential purpose groups.

The method is also called the “mirror image” concept. The concept of the mirror image is shown in Figure 3.2.

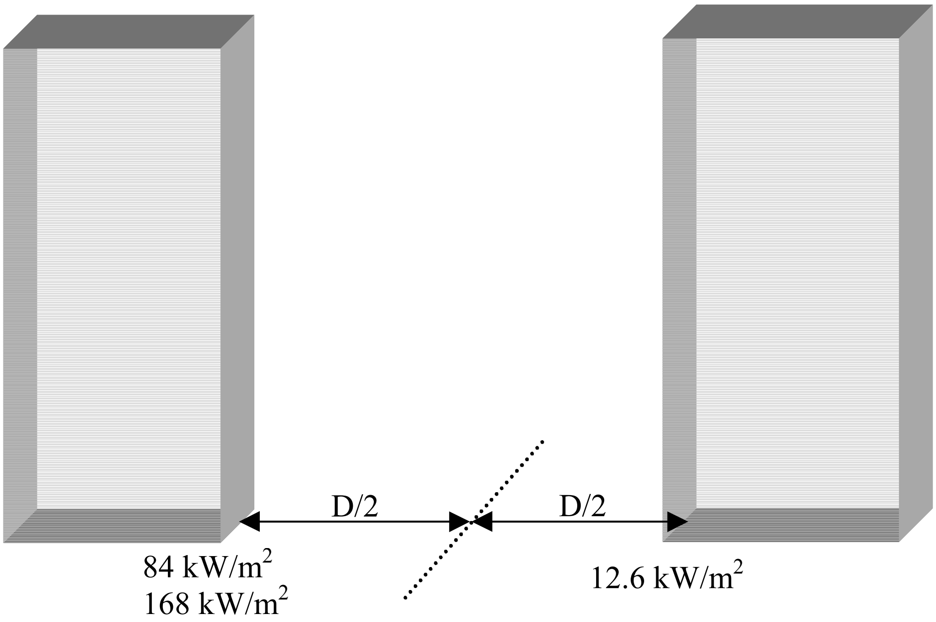

Figure 3.2 The "mirror image" concept

With a properly designed sprinkler system installed in the building, the separation distance D/2 from the relevant boundary may be halved. However, the distance to the boundary is not allowed to be less than 1.0 m. Other calculation methods may be used instead of the two methods set out above. The alternative methods are explained in *External Fire Spread: Building separation and boundary distances*, (Fire Research Station 1991).

Method 1

Method 1 should be used for dwelling houses, flats and other residential buildings. Furthermore, the external walls should not be longer than 24 m and the building height no more than three levels. The minimum distance from the relevant boundary to the sides of the building and the maximum acceptable unprotected areas are shown in Table 3.3. Figure 3.3 shows the principles of Method 1 and the distance to the relevant boundary. Areas of the external wall that are in excess of the values given by Table 3.3 should be fire resisting.

Table 3.3 Separation distances and maximum unprotected areas. Adapted from Approved Document B, (1992).

Minimum distance X between external wall and relevant boundary (m)	**Maximum acceptable unprotected area (m^2)**
1	5.6
2	12
3	18
4	24
5	30
6	No limit

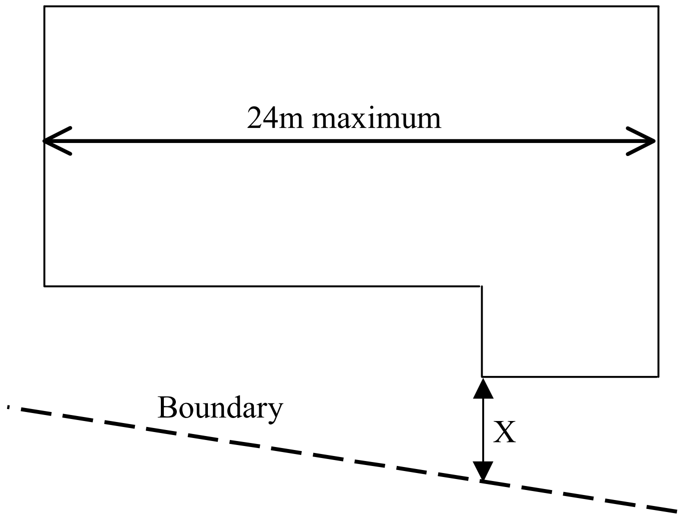

Figure 3.3 Principles of Method 1. Adapted from Approved Document B.

Method 2

Method 2 can be used for any building, regardless of the purpose group of the building. However, buildings should not be higher than 10 m, except for open-sided car parks. The distance from the relevant boundary to the side of the building and the amount of acceptable unprotected areas are set out in Table 3.4. Areas of the external wall that are in excess of the values given by Table 3.4 should be fire resisting.

Table 3.4 Separation distance and maximum acceptable unprotected areas. Adapted from Approved Document B

Separation distance between external wall and relevant boundary (m)		**Maximum unprotected area as a percentage of total wall area (%)**
Purpose groups		
Residential, Office, Assembly and Recreation	Shop & Commercial, Industrial, storage & other non-residential	
-	1	4
1.0	2	8
2.5	5	20
5.0	10	40
7.5	15	60
10.0	20	80
12.5	25	100

If an automatic sprinkler system is installed in the building, the separation distance may be halved, provided that the distance does not become less than 1.0 m. For buildings with a height in excess of 10 m, the calculation methods described in *External Fire Spread: Building separation and boundary distances*, (Fire Research station 1991) can be used.

External walls
The necessary degree of fire resistance of the external walls is dependent on usage, height and size of the building. A wall located more than 1.0 m from the relevant boundary is allowed to have a lower level of fire resistance. In order to limit an external wall's ability to ignite when exposed to an external fire source and to prevent fire from spreading upwards the external wall, provisions are made in the Approved Document B4 to limit the combustibility of the external wall. These provisions concern buildings located closer to the relevant boundary than 1.0 m, and buildings in the Assembly and Recreation purpose groups.

3.3.5 Summary

Approved Document B 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 building purpose group, so it is not necessary to look at the actual fire load. Two methods are presented of how to determine the amount of acceptable unprotected areas of external walls. The building separation distances are based on the "mirror image" concept, which means that another building is located on the other side of the relevant boundary. The building of concern should be separated from the relevant boundary by at least half the distance at which the total radiant heat flux would be 12.6 kW/m^2.

3.4 New Zealand

The New Zealand Building Code, has been performance based since 1992, i.e. the clauses say what has to be achieved but not the exact way of how the objectives should be fulfilled. As a complement to the Building Code, sets of Acceptable Solutions have been developed. The Acceptable Solutions provide one mean of how to meet with the performance requirements of the Building Code, (Building Industry Authority 1995).

3.4.1 Objective

The objective of the New Zealand Building Code with respect to spread of fire can be divided into four major areas. The objectives are summarised below.

1. Protect occupants from injuries during evacuating a building on fire.
2. Allow a safe enough environment for fire fighting and rescuing activities within a building during fire.
3. Prevent adjoining properties and neighbouring household units from being affected by a fire.
4. Protect noxious effects to the environment due to fire in a building.

3.4.2 Functional Requirements

The functional requirements regulate that buildings shall be constructed with fire safety measures that counteract the spread of fire. A building shall in a fire situation provide:

1) enough time for occupants to evacuate the building without being injured,

2) an environment that enables fire fighters to perform rescuing operations and protecting of property,
3) damage protection of adjoining properties and neighbouring household units, and
4) means of limiting the amount of hazardous substances released into the environment.

3.4.3 Performance

The performance provisions set out how the functional requirements shall be fulfilled and the objectives achieved. In order to prevent spread of fire and smoke to adjacent buildings, a building shall be provided with fire compartmentation within the building. The estimated fire load within a building and the spatial distance to other buildings shall determine the fire resistance of external walls and roofs.

According to the Acceptable Solution, external walls and roofs must be constructed in a way to prevent horizontal fire spread due to radiation and building collapse to other properties, neighbouring buildings with sleeping occupancies and to external safe paths. Measures achieving the required protection are by providing enough separation between buildings, fire resisting ratings of building elements and using less combustible finishes. Other measures are limiting the amount of unprotected areas in external walls and installing a sprinkler system. The requirements of external walls and roofs are adapted from the Building Regulations 1985 (England and Wales) and the Approved Document B4 “External Fire Spread” 1990.

3.4.4 Building Separation

According to Appendix A of the Acceptable Solution, buildings can be divided into purpose groups with a specific fire hazard category. Appropriate purpose groups can be determined based on the types of activities carried out within in the building. The fire hazard categories set out a range of values of fire load energy densities (FLED) and a fixed value that can be used for design purposes. Table 3.5 below shows fire hazard categories and fire load energy densities.

Table 3.5 Fire hazard categories and fire load energy densities of buildings. Adapted from Approved Document C3: Spread of Fire

Fire Hazard Category	**Fire Load Energy Density (MJ/m^2)**	**Design value of Fire Load Energy Density (MJ/m^2)**
1	0-500	400
2	501-1000	800
3	1001-1500	1200
4	>1500	-

Appendix C of the Acceptable Solution sets out five methods of determining the separation between buildings. They will be discussed in detail in Chapter 4. The separation is dependent on factors such as unprotected areas in external walls, purpose groups in the building of concern as well as in adjoining buildings, size of fire compartments and whether the building is sprinkler protected or not. The methods can also be reversed and used to determine the maximum allowed unprotected areas in an external wall, given that the separation distance is known from the beginning.

In order to prevent fire spread between buildings, buildings should be separated from the relevant boundary by at least half the distance at which the total radiant heat flux would be 12.6 kW/m^2. It is assumed that the emitted heat flux from a building during a fire will be:

a) 84 kW/m^2 for crowd or office purpose groups, or
b) 168 kW/m^2 for sleeping, commercial and industrial purpose groups.

It is further assumed that the emitted radiation can be reduced if the building is fitted with an automatic sprinkler system. In this case, the unprotected areas may be doubled or the separation distance halved but still not less than 1.0 m.

As said above, the five methods of calculating the separation distance and the amount of acceptable unprotected areas will be reviewed later in this report. They are obtained from BRE report “External fire spread: Building separation and boundary distances” (Fire Research Station 1991), which is based on Fire Research Technical Paper No. 5 “Heat radiation from fires and building separation” (Law 1963). A brief summary of the methods is presented below.

1) **Walls closer to the relevant boundary than 1.0 m.**
   External walls must have a fire resisting rating according to the Acceptable Solution and unprotected areas can range between 0.1-1 m^2. Unprotected areas in the walls of the same fire compartment have to be separated from each other by 1.5 or 4.0 m depending on the area. Furthermore, the unprotected areas must have a fire resistance rating for integrity of at least 30 minutes.

2) **Walls located more than 1.0 m from the relevant boundary.**
   This method is valid for occupancies containing attached and multi-unit residential dwellings and buildings with temporary accommodation (purpose groups SA and SR). The external walls must not be longer than 24 m and the building height not exceed 7.0 m. Table 3.6 (Table C1 in Appendix C of the Acceptable Solution) below sets out distances to the boundary and the maximum accepted unprotected area.

Table 3.6 Building separation and maximum unprotected areas for unsprinklered multi-unit residential dwellings and buildings with temporary accommodation. Adapted from Appendix C, Acceptable Solution.

Minimum distance between external wall and relevant boundary (m)	**Maximum acceptable unprotected area (m^2)**
1	5.6
2	12
3	18
4	24
5	30
6	No limit

3) **External walls more than 1.0 m from the boundary.** This method is valid for buildings no higher than 7.0 m and with fire hazard category of 1.

Minimum separation distances and acceptable unprotected areas are shown in Table 3.7 (Table C2 in Appendix C of the Acceptable Solution).

Table 3.7 Building separation and maximum unprotected areas as a percentage of total wall area for unsprinklered buildings with a fire hazard category of 1. Adapted from Appendix C, Acceptable Solution

Separation distance between external wall and relevant boundary (m)		**Maximum unprotected area as a percentage of total wall area (%)**
Purpose groups		
Other	Sleeping activities	
-	1	4
1.0	2	8
2.5	5	20
5.0	10	40
7.5	15	60
10.0	20	80
12.5	25	100

4) **Enclosing rectangles.** This method provides means of calculating the maximum unprotected area allowed as a percentage of the external wall of a fire compartment. The calculated value is then used together with the purpose group of the building to determine the minimum required distance to the relevant boundary, which is set out in a number of different tables (Tables C3 in Appendix C of the Acceptable Solution).

5) **Aggregate notional areas.** This method is used to calculate the effect on the relevant boundary of unprotected areas in external walls. Different assumed reference points on the boundary are to be investigated and the one resulting in the worst case scenario to be chosen for design purposes. For each of these reference points, the distance to and the size of unprotected openings are determined. The unprotected area is then multiplied by a factor, which is dependent on the horizontal distance and is set out in Table 3.8 (Table C4 in Appendix C of the Acceptable Solution). The notional areas of all unprotected areas facing the relevant boundary in the fire compartment are summarised and compared with the given criteria. In order to comply with the criteria, the aggregate notional area for each fire compartment must not exceed either 100 or 200 m^2 depending on purpose group and extent of the fire compartment. The procedure has to be redone until a separation distance resulting in a satisfactory aggregate notional area.

Table 3.8 Multiplication factor for various distances between unprotected areas and reference points on the relevant boundary. Adapted from Appendix C, Acceptable Solution.

Horizontal distance between unprotected area and reference point, (m)	Multiplication factor
1.0 - 1.2	80.0
1.2 - 1.8	40.0
1.8 - 2.7	20.0
2.7 - 4.3	10.0
4.3 - 6.0	4.0
6.0 - 8.5	2.0
8.5 - 12.0	1.0
12.0 - 18.5	0.5
18.5 - 27.5	0.25
27.5 - 50.0	0.1
>50	0.0

3.4.5 Summary

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. Five methods are presented of how to calculate minimum separation distances between buildings and maximum acceptable unprotected areas of external walls. In general, buildings should be separated from the relevant boundary by half the distance at which the total radiant heat flux would be 12.6 kW/m^2. This principle is sometimes called the “mirror image” concept. The objective of the New Zealand Building Code with regards to external fire spread is to protect adjacent buildings and other properties from being affected by a fire in the own building. Nothing is said about preventing the owner’s building from being affected by a fire in an adjoining building.

3.5 Sweden

The Swedish design guide contains regulations and general advice of how compliance with the Building Code and other essential directions that has to be followed in the building process is achieved (Boverket 1995).

3.5.1 Regulation

The regulation is applicable in either of the following cases:

- construction of new buildings,
- renovation and addition of existing buildings,
- ground and demolishing work, and
- properties that are claimed to be built on.

3.5.2 Advice

The regulations are complemented with a set of general guidelines on how the requirements of the regulation can be achieved. The advice states how a designer should or could act in order to make sure that the regulations are followed. However, each designer can chose to use other methods and solutions than suggested by the advice, as long as it is done in accordance with the regulations.

3.5.3 Objective

According to the Swedish design guide, fire spread between buildings should be prevented by limiting the radiant heat flux either emitted by a burning building or received by an adjacent building. This can be achieved in a number of ways.

- Providing a large enough distance between buildings.
- Limiting the size of unprotected building sections.
- Limiting the heat content of facade materials.
- Limiting the extent of the fire and thereby limit the radiant heat flux emitted from a fire. This can be done by e.g. smoke ventilation or an automatic sprinkler system.

3.5.4 Requirements

The main requirement with regards to separation between buildings is that a building should not be closer to the boundary than 4.0 m. If the building is located closer to the boundary than 4.0 m, the neighbouring building has to be located at a position that ensures a minimum separation of 8.0 m. In cases where a total separation distance of 8.0 m is not achieved, the building has to be constructed in a way that limits the risk of fire spread to adjacent buildings.

It is also said that fire spread should be made more difficult by limiting the radiant heat flux and preventing flames from affecting neighbouring buildings. This is achieved by providing a safe distance between the buildings, by a fire partition or a combination of both methods. Buildings located at the boundary must have a firewall, e.g. fire partition, facing the neighbouring property. The class of the firewall is dependent on the building classification.

The advice says that radiation received by neighbouring buildings should not exceed 15 kW/m^2 during a period of 30 minutes. Buildings with more than two levels are preferable constructed with a firewall facing the boundary. No background is given for where these figures are obtained from or what they are based on.

Extraordinary fire safety measures could be demanded by the Fire Service where evacuation and prevention of fire spread are dependent on Fire Service intervention and where fire fighting activities can not be guaranteed to begin within reasonable time.

3.5.5 Performance based design

The fire safety design may be performed in a different way than what is regulated by the code, provided that an investigation based on performance based engineering methods proves that the design is as good as if all demands in the regulation are fulfilled.

Residential dwellings in small houses should be separated to prevent fire spread for at least 60 minutes. Large buildings should be divided into compartments of appropriate sizes by firewalls. This would enable intervention by the fire service and thereby preventing or make it more difficult for the fire to spread to adjoining buildings. Factors that have to be considered are e.g. spatial distance, fire load, smoke ventilation, automatic fire alarm and automatic extinguishing system.

A firewall should contain a fire without any intervention of the fire service for a certain period of time. The wall should also be provided with enough stability to withstand any mechanical influences caused by a fire. The construction of a firewall is dependent on building type and estimated fire load in the building. Table 3.9 outlines the performance requirements of firewalls.

Table 3.9 Performance requirements of firewalls. Adapted from Boverket (1995).

Building class	**Fire class of wall at different fire load, f (MJ/m^2)**		
	f ≤ 200	F ≤ 400	f > 400
1. Br1	REI-M90	REI-M120	REI-M240
2. Br2 and Br3	REI-M60	REI-M90	REI-M120

REI-M90 means that the wall has load bearing capacity (R), integrity (E), isolation (I) and can withstand mechanical impact (M) in a fire for 90 minutes. Buildings can be divided into classes according to the following rules:

Br1- Buildings associated with a large risk of injuries to occupants in a fire situation, e.g. buildings with

- three or more levels,
- sleeping occupants without good knowledge of the building,
- occupants without ability to evacuate on their own, and
- an assembly on the second level.

Br2- Building with moderate risk for injuries to occupants in a fire situation, e.g. buildings with

- more than two dwellings and where living area or working room is located in the attic,
- an assembly on the ground level, and
- compartments larger than 200m^2.

Br3- Other buildings than listed above.

3.5.6 Summary

In Sweden, buildings have to be located at least 4.0 m from the boundary or at least 8.0 m from any building at the neighbouring property. If a building is closer to the boundary or another building than stated above, it has to 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.

3.6 The United States of America

There is no single Building Code that is valid for the whole country and different Building Codes can be used in different states. The three most commonly used Building Codes are; the National Building Code (BOCA 1996), the Uniform Building Code (1994) and the Standard Building Code (1997). They are strictly prescriptive codes with no allowance for performance based design.

One document that is used in the US to determine separation distances between buildings is the *NFPA 80A Recommended Practice for Protection of Buildings from Exterior Fire Exposures*. This method will be further discussed in chapter 4.

4 CALCULATION METHODS

This chapter will describe six methods of determining separation distances between buildings and the maximum allowable amount of unprotected areas. Some of them are referred to by Building Regulations, and others are set out in the fire engineering literature. The description of the methods presented in this report should not be used as a complete design guide. If anyone wants to use the methods, the original reports should be consulted.

4.1 Enclosing rectangles

This method called the Enclosing rectangle method is set out in the BRE report "External fire spread: building separation and boundary distance" (Fire Research Station 1991). The method is derived from work performed by Law (1963) and is incorporated in the Approved Document B2/3/4 (HMSO, 1985). The method determine the boundary distance based on rectangles that enclose unprotected areas in the facade, see Figure 4.1. Tables of boundary distances for different types of buildings and for different dimensions of the buildings are set out, which enable a person not familiar with the fire engineering knowledge to perform the design.

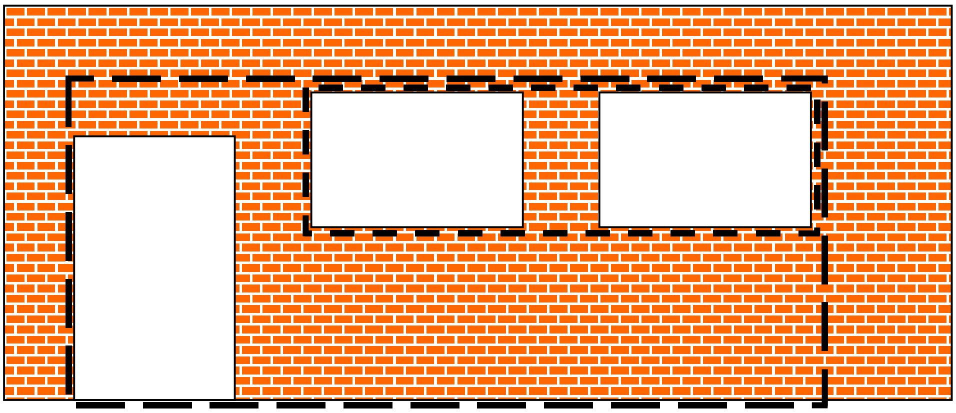

Figure 4.1 Enclosing rectangles

Step 1. **Identification of unprotected areas**
The Building Regulations of the country of concern should be consulted with regards to which areas in the facade that should be regarded as unprotected. This may vary between different countries and different regulations.

Step 2. **Establishing of a plane of reference**
A plane of reference should be established so that the plane complies with or touches the side of the building. Furthermore, it should not pass through any parts of the building (except for balconies and coping), nor the relevant boundary. If any part of the facade is set back no more than 1.5 m, this area may be disregarded and the plane of reference determined as explained above. Those unprotected areas that are at an angle of 80° or less to the plane of reference should be regarded in the design process.

Step 3. **Determination of the enclosing rectangle**

The enclosing rectangle should be chosen as the smallest rectangle with dimensions as set out in Table 1 in the original document, (Fire Research Station 1991) that encloses all unprotected areas projected onto the plane of reference. The extent of the enclosing rectangle depends on factors such as the horizontal and vertical dimensions of the fire compartmentation, type of cladding fitted on the exterior wall and if the wall has an approved fire resistance rating. The unprotected areas should be expressed as a percentage of the area of the enclosing rectangle.

Step 4. **Determination of the boundary distance or maximum unprotected areas**

Once the width, height and percentage of unprotected areas of the enclosing rectangle are known, Table 1 in the original document may be used to determine the minimum required distance between the plane of reference and the relevant boundary. The separation distance is also dependent on the fire load density within the building. The fire load density in Table 1 either classed as ‘normal’ or ‘low’ depending on for what purpose(s) the building is used. If the separation distance already is given, Table 1 can also be used to determine the maximum allowed unprotected areas. This latter process may require extraordinary work in order to determine an appropriate enclosing rectangle.

It may be needed to investigate more than one enclosing rectangle and the largest separation distance of these rectangles should be chosen. The process should be repeated for all sides of the building.

Step 5. **Consideration of areas of special exposure**

In some situations, unprotected areas may be concentrated to certain parts of the building, thereby representing a greater local hazard than if they were evenly distributed throughout the building. This area should be considered separately and it may be found that a greater separation distance is required.

The method explained above may also be used where groups of unprotected areas are widely spaced from each other. If the groups of unprotected areas are spaced from each other by more than four times the boundary distance determined by Step 1-4, they should the be treated separately since the amount of received radiation from the other group may be neglected.

Where a part of the building is set back more than 1.5 m, a reduction of the boundary distance is allowed. This is accomplished by creating an “equivalent radiator” positioned between the further most opening of the set back and the edge of the original facade and then determining the boundary distance in relation to this “equivalent radiator”.

In a recess with unprotected areas on all three sides, the total area, i.e. even the unprotected areas in the side of the recess, should be expressed as a percentage of the enclosing rectangle. If the recess only contains unprotected areas in the rear wall, it may in some cases be possible to reduce the boundary distance. A further description of how this is done is explained in detail in the original report.

4.2 Aggregate notional areas

This method is also set out in the BRE report “External fire spread: building separation and boundary distance” (Fire Research Station 1991). The method is derived from work performed by Law (1963) and is incorporated in the Approved Document B2/3/4 (HMSO, 1985).

In this method, a number of points on the relevant boundary are chosen and the amount of unprotected areas that are visible from the point is calculated. These areas are called effective or notional areas and are calculated by multiplying the actual unprotected area by a distance dependent factor. The aggregate notional areas must be less or equal to certain predetermined values in order to fulfil safe separation requirements. This method, which also is called the Protractor method, may be favourable for complicated building shapes and in combination with the Enclosing rectangle method. In this method, a protractor in the same scale as the building and with arcs representing fixed distances from the datum point of the protractor are made. A datum line perpendicular to the base line of the protractor is also established. The area between each arc represents a specific factor, which later is used to calculate the aggregate notional areas.

Step 1. **Identification of unprotected areas**
The Building Regulations of the country of concern should be consulted with regards to which areas in the facade that should be regarded as unprotected. This may vary between different countries and different regulations.

Step 2. **Determination of points on the boundary to be tested**
Points to be tested should be chosen along the relevant boundary at 3-m intervals. If a boundary distance has been determined with the Enclosing rectangle method, the only points on the relevant boundary that need to be tested are those that are inside the boundary set by the Enclosing rectangle method.

Step 3. **Determination of which unprotected areas that may be ignored**
A vertical datum of unlimited height should be set at the point to be tested and a datum line drawn between this point and the nearest point on the building. The protractor should be placed so that its datum point and datum line coincide with the datum and datum line of the point on the boundary to be tested. Unprotected areas that could be ignored are those that cannot be seen from the vertical datum. These are areas:

- positioned beyond the base line or the 50 m arc of the protractor,
- facing another direction (i.e. away from) than towards the vertical datum,

- shielded by other parts of the building, and
- making an angle of 10° or less with a line between the vertical datum and the unprotected area of consideration.

Step 4. **Calculation of aggregate notional areas**

To find the aggregate notional area, the actual unprotected area should be multiplied by a factor for the particular zone in which the area falls. The factor is given by the protractor as explained above. The multiplication factor of the different arcs is given in Table 4.1. This procedure should be made for all relevant unprotected areas for each point and vertical datum of concern. The sum of all notional areas will make the aggregate notional area. The aggregate notional area should not exceed 210 m^2 for Residential, Office and Assembly recreation use, or 90 m^2 for Shop and commercial, Industrial, Storage and Other non-residential recreation use.

Table 4.1 Multiplication factor for various distances between unprotected areas and reference points on the relevant boundary. Adapted from Fire Research Station (1991).

Horizontal distance between unprotected area and reference point, (m)	Multiplication factor
1.0 - 1.2	80.0
1.2 - 1.8	40.0
1.8 - 2.7	20.0
2.7 - 4.3	10.0
4.3 - 6.0	4.0
6.0 - 8.5	2.0
8.5 - 12.0	1.0
12.0 - 18.5	0.5
18.5 - 27.5	0.25
27.5 - 50.0	0.1
>50	0.0

4.3 Peter Collier

This method is presented in Collier (1996) and allows the user to specify the fire intensity depending on the actual building and its properties. The method can mainly be used for five situations.

(A) Calculate the required separation distance between buildings in order to prevent fire spread.
(B) Calculate the required distance to a boundary in situations where neighbouring buildings do not exist.
(C) Calculate the incident radiation received by neighbouring buildings.
(D) Calculate the maximum allowed area of unprotected openings in the facade of the owner's building.
(E) Check if fire spread can occur in an existing building situation.

The method is aimed to prevent fire spread between both the adjoining buildings; i.e. it is necessary to calculate the radiation in both directions.

The method is very user-friendly and allows the user to specify or calculate the temperature in the fire compartment. Furthermore, the critical radiant flux for ignition may be varied depending on the external cladding of the neighbouring building.

In situations where neighbouring buildings are not parallel to each other, the facades of the buildings can be assumed to be parallel which will thereby create a conservative separation distance. If a neighbouring building does not exist, the required distance to the boundary should be taken as half the distance of what would be required if the neighbouring building was a mirror image of the owner's building. It may be necessary to consider one or several openings separately if the openings are not distributed evenly throughout the facade.

The calculation procedure of how to determine the required separation distance between buildings is set out below. If the separation distance already is given, the methodology can be reversed to determine the incident radiant flux or maximum allowed unprotected openings.

Step 1. Set up enclosing rectangles.
This should be based on the extent of the fire compartment and the amount of unprotected openings. With irregular shaped facades the unprotected areas are projected onto a plane of reference, which is assumed to touch the outer parts of the building see Figure 4.2.

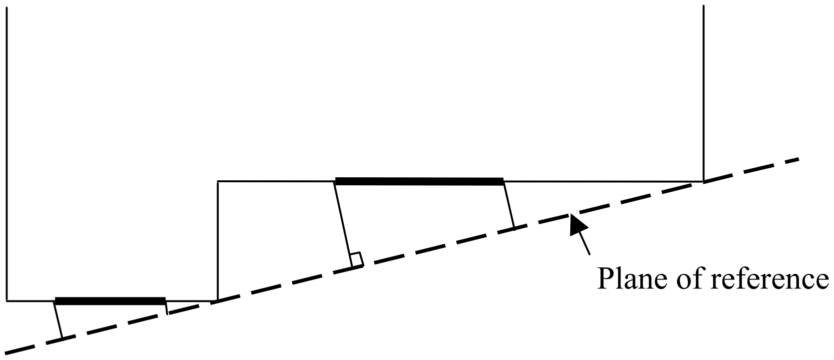

Figure 4.2 Projection of openings onto a plane of reference

Step 2. Calculate the area of the enclosing rectangle, A_e.

$$A_e = H \times W \quad [m^2]$$

where:
H = height of enclosing rectangle [m]
W = width of enclosing rectangle [m]

Step 3. Calculate the width-to-height or height-to-width ratio, AR, of the enclosing rectangle.

$$AR = H/W \text{ (or W/H)} \qquad AR \leq 1$$

Step 4. Determine the radiation intensity, I_s, in the fire compartment.

A fire temperature of 1000°C, which represents a radiation intensity of 149 kW/m^2, can be used for most cases. If a lower or higher temperature and radiation intensity can be expected, appropriate chosen or calculated values may be used instead.

The radiation intensity can be calculated with the following equation:

$$I_s = 5.67\times10^{-11} \times T^4 \quad [kW/m^2]$$

where: T = fire temperature [K]

The fire temperature can be determined by using the ISO 834 standard fire curve and the fire resistance rating of the fire compartment.

$$T = 345 \log_{10} (8t+1) \quad [°C]$$

where: t = fire resistance time [min]

Step 5. The whole facade of the owner's building should be counted as the radiating source if the external wall is not fire resistance rated. Where the wall is fire resistance rated the radiation intensity may be reduced by a reduction factor, Rf.

$$Rf = A_o / A_e$$

where: A_o = unprotected areas [m^2]
A_e = area of enclosing rectangle [m^2]

Step 6. Calculate the emitted radiant flux, I_e. If fire resistance glazing are fitted in the unprotected openings of the owner's building, the emitted radiation may be reduced by an additional 50%.

$$I_e = I_s \times Rf \quad [kW/m^2]$$

Step 7. Determine at which received radiant flux the neighbouring building will ignite. This value may vary depending on external cladding and if the openings are fitted with fire resistant glazing. In the latter situation the incident radiation that passes through windows may be reduced by 50%. Non fire-rated glazing is assumed to break when exposed to high levels of radiation. Examples on values of critical incident radiation, I_{cr}, received by the neighbouring building are set out in Table 4.2.

Table 4.2 Maximum permitted radiation at the facade of the neighbouring building. Adapted from Collier (1996).

Critical incident radiation, I_{cr} [kW/m^2]			
External cladding	No openings	Usage of non fire-rated glazing	Usage of fire rated glazing
EIFS(1)	9.0	9.0	9.0
Timber	12.5	12.5	12.5
Fibre-cement board	25.0	12.5	25.0
Non-combustible(2)	No limit	12.5	50.0

(1) Exterior insulation and finishing system.

(2) Concrete, brick, steel or aluminium.

Step 8. Calculate the acceptable configuration factor, ϕ.

$$\phi = I_{cr} / I_e$$

Step 9. Calculate the separation distance, S, between the buildings.

$$S = R + P \qquad [m]$$

Where: R = radiation distance obtained from Figure 4.3 [m]
P = projection distance [m]

The projection distance can be set to 2 m if the windows in the owner's building are fitted with non fire-rated glazing and 0 m if fire-rated glazing is used. Values other than 2 m may be used if it is proven by adequate calculations.

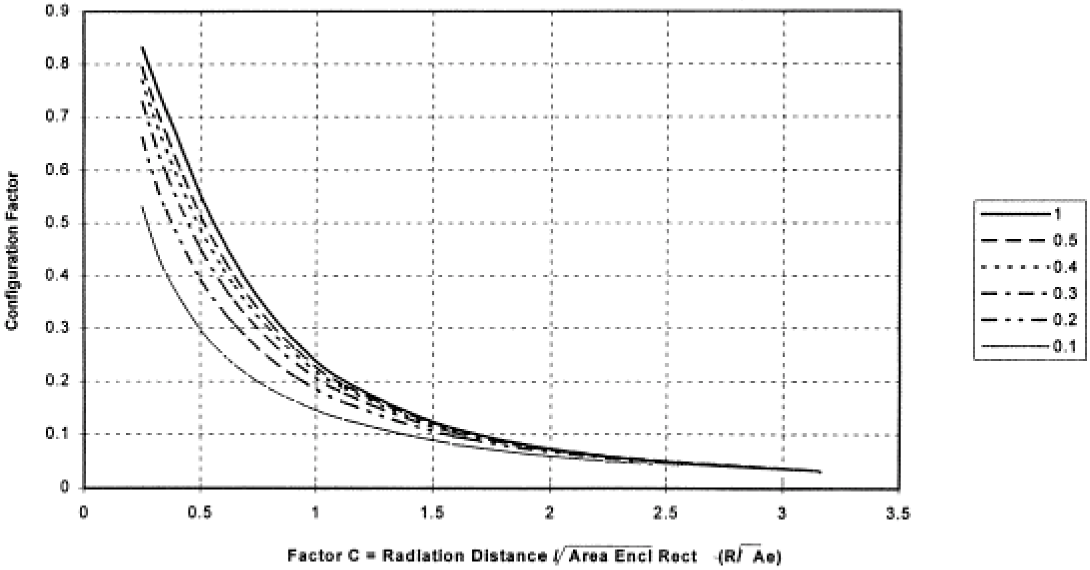

Figure 4.3 Configuration factor and radiation distance (Collier, 1996)

4.4 C.R. Barnett

This method by Barnett (1988) can be used in the design process of new buildings and to check critical situations for existing buildings. The method does not rely on the use of water or the intervention by the fire brigade and can be linked to the fire resistance rating of the building.

The method can be used in two ways. Either to calculate the maximum allowed unprotected permissible openings or the incident radiation intensity onto the neighbouring building.

Maximum allowed permissible openings

The area of the maximum allowed permissible openings can be determined with Equation 4.1.

$$A_V = \frac{A_E I_{RC}}{\phi_n I_{EC}} \qquad [4.1]$$

where:

A_E = area of enclosing rectangle [m^2].
A number of different rectangles that enclose a combination of openings (both big and small) in the facade should be chosen.

I_{RC} = critical value of received radiation [kW/m^2].
For design purposes this value should be chosen 12.5 kW/m^2. However, if the neighbouring building is fitted with non-combustible cladding and fire resistance glazing, the received radiation can be 25 kW/m^2 since no ignition source (e.g. spark) is present inside the window and the presumed ignition therefore has to be spontaneous. A fire window that remains in place for the whole duration of the fire is assumed to decrease the passing radiation intensity by 50 %, i.e. the radiation outside the fire window can be 50 kW/m^2 if the external walls are made of non-combustible material.

ϕ_n = configuration factor of the enclosing rectangle.
The enclosing rectangle can be divided into four minor rectangles of equal size and the configuration factor calculated as the sum of the configuration factors of each of these rectangles see Equation 4.2.

$$\phi_n = \phi_A + \phi_B + \phi_C + \phi_D = 4\phi_A \qquad [4.2]$$

The configuration of the smaller rectangles can be calculated with Equation 4.3.

$$\phi_A = \frac{1}{360}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right] \qquad [4.3]$$

where: X = H/2R

Y = W/2R
R = radiating distance [m]
H = height of enclosing rectangle [m]
W = width of enclosing rectangle [m]

In situations where flame projection out of the opening is expected, an extra two metres (or other appropriate distance if it is shown by adequate calculations) should be added to the radiating distance.

I_{EC} = critical value of emitted radiation [kW/m^2].
The emitted radiation can be calculated with the Equation 4.4.

$$I_{EC} = \varepsilon\sigma\left(T_2^{\,4} - T_1^{\,4}\right) \qquad [4.4]$$

where:
ε = emissivity of radiator, generally 1.0
σ = Stefan-Boltzmann constant = 56.7×10^{-12} [kW/m^{2}K^4]
T_2 = temperature in fire compartment [K]
T_1 = ambient temperature [K]

The temperature in the fire compartment can be determined by using the ISO 834 time-temperature curve as follows (Equation 4.5):

$$T_2 = 345\log_{10}\left(8t_m + 1\right) + T_1 \qquad [4.5]$$

where:
t_m = time [min]
T_1 and T_2 are expressed in degrees Centigrade.

If fire resistance glazing is fitted in the fire compartment, the radiation intensity that passes through the window can be reduced by 50 %.

Level of received radiation by the neighbouring building
The level of received radiation by the neighbouring building must not exceed the critical design value of received radiation I_{RC}. The level of received radiation intensity can be determined with Equation 4.6.

$$I_R = k_V \phi_n I_{EC} \quad \leq I_{RC} \qquad [4.6]$$

where:
k_V = ratio between the area of vertical openings and the area of enclosing rectangle, A_V/A_E.
ϕ_n = configuration factor of enclosing rectangle, see explanation above.
I_{EC} = critical value of emitted radiation [kW/m^2], see explanation above.

This latter method can be used to check whether an existing building situation is critical or not.

4.5 Williams-Leir

This method by Williams-Leir presents a way to determine safe separation distances between buildings where the results always are conservative. The method takes into account for a flame projection of 3 ft (1 m) out from the windows. Two different configuration factors are incorporated in the equations. They are 0.035 for high hazard occupancies and 0.070 for moderate hazard occupancies.

The derivation of the methodology will not be presented in this report. The interested reader are referred to the original report *Another Approximation for Spatial Separation* by Williams-Leir (1970).

Before the determination method is presented, a number of expressions and equations must be defined. They are:

EBF	Exposing Building Face The section of the facade that is situated within the boundaries of a fire compartment.
L	Limiting distance [ft] The closest distance between the exposing building face (EBF) and the boundary/lot line.
K	Floating-square distance [ft] $K = 3.54(L-3)$
J	Floating-zone distance [ft] $J = 3.14(L-3)$
BAUO	Basic Allowance of Unprotected Openings [ft^2] $BAUO = 0.44(L-3)^2$ for high hazard occupancies $BAUO = 0.88(L-3)^2$ for moderate hazard occupancies

The implication of these expressions and equations is determined by a set of rules. Rule 1 is valid where it is needed to determine the separation distance or maximum allowed unprotected areas for as much as 90 % of all cases. Rule 2 may be used for facades with a low amount of unprotected areas (approximately less than 15 % of the total area of the facade). Rule 3 is applicable for elongated facades where one of the dimensions is eight times longer than the other.

Rule 1: Every exposing building face (EBF) may include one or more basic allowance of unprotected openings (BAUO). The openings may be distributed in whatever way that is most suitable to the owner, given that the EBF includes a maximum of one BAUO.

Rule 2: Where one of the sides of the EBF is greater than K, a floating square of side K that is parallel to and placed on the EBF can only contain a maximum of one BAUO. The openings shall be distributed to fulfil this demand.

Rule 3: Where one of the sides of the EBF is greater than J, a suitable direction, generally perpendicular to the longest side of the EBF shall be chosen. A floating zone of side J, unlimited length and that is parallel to the chosen direction can only contain a maximum of one BAUO. The openings shall be distributed to fulfil this demand.

4.6 J.H. McGuire

This method by McGuire (1965) can briefly be described by the following three steps:

1. Determine the height and width of the relevant fire compartment.
2. Determine the percentage of window openings in the facade of the fire compartment. All parts of the wall that are not provided with sufficient integrity to meet with the performance requirements should be treated as a window opening.
3. McGuire sets out two tables, one for hazardous conditions and one for normal conditions, with values in feet of required building separations. Once the terms in steps 1. and 2. are determined, the distance can be easily read from the tables.

The two tables can be found in the original report "Fire and the Spatial Separation of Buildings" by McGuire (1965). In this method, piloted ignition of facade material is said to occur at an incident radiation level of 12.5 kW/m^2.

McGuire (1965) defines the configuration factor as;

> *The ratio of the radiant intensity at the receiving surface to that at the (one or more) radiating surfaces.*

For design purposes, configuration factors of 0.035 for hazardous cases, i.e. buildings with highly flammable linings, and 0.07 for normal cases, i.e. buildings with non-combustible linings, are used. These values are derived by dividing the value for piloted ignition by the maximum value of radiation measured in a series of tests in 1958 called the St. Lawrence Burns. However, much higher values of radiation was measured during the tests than what is used to derive the above configuration factors. The configuration factors are still justified since it was noted that much lower radiation intensities, approximately one fifth of the maximum radiation intensities, was measured during the first 16 minutes of the tests. After this time it can be assumed that the fire brigade has responded and has thereby prevented fire spread to adjoining the buildings.

The tables also take into account horizontal flame projection out of windows. 7 ft is added to the separation distance for hazardous cases and 5 ft is added for normal cases. The projections are justified by the St. Lawrence Burns tests.

Since the method uses a percentage of openings, the openings need to be distributed evenly throughout the facade in reality. If most of the windows are accumulated in one end of the building, a greater separation distance would be required for that part of the building. This is also valid where some of the windows are much larger than the other windows. When determining the separation distance for irregular shaped buildings, a line should be drawn between the farthest points of the facade. If all parts of the building are contained behind the line, the facade and openings can be projected onto the line and the separation distance determined based on this new imaginary facade. If any part of the building extends beyond this line, this part should be considered separately.

A dangerous situation may occur where neighbouring buildings are of different shape and size. Generally, the smaller building will be exposed to the greatest hazard. The reason for this is that the separation distance is often determined in relation to the property boundary rather than to the other building. Then a smaller building could be situated closer to the boundary than a larger building would be and thereby be exposed to too high levels of radiation from a fire in a larger building.

4.7 NFPA 80A

The scope of the "NFPA 80A Recommended Practice for Protection of Buildings from Exterior Fire Exposures" (NFPA 80A 1996) is to protect combustible material on the outside as well as the inside of a building exposed to an external fire source. The document is intended as a guide for assurance of property protection of buildings exposed to an external fire. Below is a description of how to determine the separation distance for buildings of greater or equal height as well as for building of lesser height.

Buildings of greater or equal height
The thermal radiation is the only means of exposure that needs to be considered when a building is exposed by a fire in a building of at least the same height. The separation distance between the buildings should be determined in a way to protect the exposed building and its contents from igniting due to piloted ignition. Determination of separation distances should be based on the assumption that neither of the buildings is fitted with means of protection against fire by, for example sprinklers and fire resistant glazing.

The width of the exposing wall that needs to be considered is the width between existing fire separations within the building. If no separations exist within the building, the width between the external walls should be used. The height of the exposing wall is dependent on factors such as number of stories involved in the fire, type of construction, vertical openings in the wall and fire resistance of floors.

Openings
Openings in an external and exposing wall that have to be considered are doors, windows and other openings that may contribute to the emitted thermal radiation. Other openings that should be considered are:

- Walls with less resistance against fire penetration than 20 minutes should be treated as being a 100% opening.
- Walls that can withstand fire penetration for more than 20 minutes but not longer than the estimated fire duration should be treated as being a 75% opening.

Severity
The severity of a fire will influence the amount of thermal radiation emitted from an exposing building. The fire severity is highly dependent on two factors; the average fire load per unit floor area within the building and the characteristics of interior finishes. Based on these factors, the fire severity can be divided into three major groups, namely light, moderate and severe. Table 4.3 (Table 2-2.4(a)-(b) in NFPA 80

A, 1996) shows the fire severity groups and the criteria after which they should be determined.

Table 4.3 Classification of fire severity. Adapted from the NFPA 80A.

Fire severity group	**Fire load per unit floor area (kg/m^2)**	**Average flame spread rating of interior wall and ceiling finish**
Light	0-34	0-25
Moderate	35-73	26-75
Severe	≥74	≥76

The factor resulting in the highest fire severity group should be used for design purposes. Consideration should be taken if the whole building or only a portion of the building is fitted with combustible interior finishes. The flame spread ratings are explained in the "NFPA 255 Standard Method of Test of Surface Burning Characteristics of Building Materials".

According to the explanatory part of the NFPA 80A, exposure fire severity can be defined as; *the intensity of the exposing fire*. Hence, the fire severity is the amount of thermal radiation passing through openings or from flames projected outside the building. The fire severity is dependent on several factors such as the ventilation conditions of the compartment in concern, fire load, characteristics of the fuel, geometry of the room and properties of the interior finishes.

Separation distances

It is assumed that the facade is made of cellulosic materials, with the ability to withstand ignition when exposed to a maximum radiation level, I_{crit}, of 12.5 kW/m^2. Table 4.4 (Table 2-3 in NFPA 80A, 1996) below, sets out guide numbers that should be used when determining the separation distances between buildings. To be able to determine a guide number from the table, the fire severity, percentage of openings in the wall and the ratio of the width-to-height or height-to-width of the compartment or the enclosing rectangle must be known. To calculate the required separation distance, D, the guide number, g, should be multiplied with the lesser dimension of the width, w, and height, h, of the exposing fire and then added by 1.52, which is given by Equation 4.7. The extra 1.52 m is added in order to take into account for flame projections out of openings and prevent ignition due to flame impingement on the exposed building.

$$D = gZ + 1.52 \qquad [4.7]$$

where: g = guide number from Table 4.4
Z = lesser dimension of w and h [m]

Table 4.4 Guide numbers for the determination of separation distances. Adapted from NFPA 80A (1996).

Fire severity			**Guide number**																
Percent openings			Ratio Width-to-Height or Height-to-Width																
Light	Moderate	Severe	**1.0**	**1.3**	**1.6**	**2.0**	**2.5**	**3.2**	**4**	**5**	**6**	**8**	**10**	**13**	**16**	**20**	**25**	**32**	**40**
20	10	5	0.36	0.40	0.44	0.46	0.48	0.49	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
30	15	7.5	0.60	0.66	0.73	0.79	0.84	0.88	0.90	0.92	0.93	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95
40	20	10	0.76	0.85	0.94	1.02	1.10	1.17	1.23	1.27	1.30	1.32	1.33	1.33	1.34	1.34	1.34	1.34	1.34
50	25	12.5	0.90	1.00	1.11	1.22	1.33	1.42	1.51	1.58	1.63	1.66	1.69	1.70	1.71	1.71	1.71	1.71	1.71
60	30	15	1.02	1.14	1.26	1.39	1.52	1.64	1.76	1.85	1.93	1.99	2.03	2.05	2.07	2.08	2.08	2.08	2.08
80	40	20	1.22	1.37	1.52	1.68	1.85	2.02	2.18	2.34	2.48	2.59	2.67	2.73	2.77	2.79	2.80	2.81	2.81
100	50	5	1.39	1.56	1.74	1.93	2.13	2.34	2.55	2.76	2.95	3.12	3.26	3.36	3.43	3.48	3.51	3.52	3.53
-	60	30	1.55	1.73	1.94	2.15	2.38	2.63	2.88	3.13	3.37	3.60	3.79	3.95	4.07	4.15	4.20	4.22	4.24
-	80	40	1.82	2.04	2.28	2.54	2.82	3.12	3.44	3.77	4.11	4.43	4.74	5.01	5.24	5.41	5.52	5.60	5.64
-	100	50	2.05	2.30	2.57	2.87	3.20	3.55	3.93	4.33	4.74	5.16	5.56	5.95	6.29	6.56	6.77	6.92	7.01
-	-	60	2.26	2.54	2.84	3.17	3.54	3.93	4.36	4.82	5.30	5.80	6.30	6.78	7.23	7.63	7.94	8.18	8.34
-	-	80	2.63	2.95	3.31	3.70	4.13	4.61	5.12	5.68	6.28	6.91	7.57	8.24	8.89	9.51	10.05	10.50	10.84
-	-	100	2.96	3.32	3.72	4.16	4.65	5.19	5.78	6.43	7.13	7.88	8.67	9.50	10.33	11.15	11.91	12.59	13.15

In cases where the facade consists of material with a different critical radiant heat flux, i.e. $I_{crit} \neq 12.5$ kW/m^2, and where no openings exist in the external wall of the exposed building, the percentage of openings in the exposing building should be adjusted. The new percentage of openings, O_{new}, should be obtained by multiplying the old percentage openings of the external wall, O_{old}, with the ratio between 12.5 kW/m^2 and the critical radiant heat flux for the particular facade material. This procedure is explained in Equation 4.8.

$$O_{new} = O_{old} \times \frac{12.5}{I_{crit}} \qquad [4.8]$$

It is very important to note that the method of determining separation distances contemplates Fire Brigade intervention. At locations where Fire Brigade intervention can not be guaranteed within reasonable time, the separation distance should be extended by multiplying by a factor of up to three. The values of emitted radiation used are obtained from a series of full-scale tests called the “St. Lawrence Burns”. These tests indicated much higher levels of radiation for fire duration of more than 20 minutes. Other findings from the “St. Lawrence Burns” were that the amount of emitted radiation was affected by the percentage of openings in the external walls. Furthermore, high amount of combustible interior finishes resulted in very high levels of emitted radiation outside the building. The external covering of the wall did not contribute to significantly higher levels of radiation.

Table 4.4 has been derived by using the methodology presented in “Fire and the Spatial Separation of Buildings” by McGuire (1965). NFPA specifically states that no consideration has been taken to the risk of ignition by convective heat transfer and flying brands. The critical level of thermal radiation, i.e. 12.5 kW/m^2, where piloted ignition of cellulosic material may occur has been obtained from work done in the UK by the Joint Fire Research Station.

The amount of thermal radiation received by the exposed building can be determined with Equation 4.9 below.

$$I = I_0 \phi \qquad [4.9]$$

where: I = received radiation at the surface of the exposed building [kW/m^2]
I_0 = emitted radiation from the exposing building [kW/m^2]
ϕ = configuration factor

The configuration factor is dependent on the size of the radiating surface and the separation distance. The configuration factor can be determined by using Equation 4.10, assuming the radiation surface being of rectangular shape.

$$\phi = \frac{2}{\pi}\left[\frac{X}{\sqrt{X^2+Y^2}}\arctan\left(\frac{Z}{\sqrt{X^2+Y^2}}\right)+\frac{Z}{\sqrt{Y^2+Z^2}}\arctan\left(\frac{X}{\sqrt{Y^2+Z^2}}\right)\right] \qquad [4.10]$$

where: X = half of the width of the radiating surface [m]
Y = half of the height of the radiating surface [m]
Z = distance between the radiating surface and the exposed surface [m]

Table 4.4 has been developed based on evenly distributed openings, which are not separated from each other by more than one third of the total separation between the buildings. Where this is not the case, additional calculations are required. The following methods should be considered:

1. A calculation should be made for the smallest area including all openings, which in some cases may be a single window. The largest calculated separation distance for this area should be used.
2. A calculation should be made for a single opening in cases where the openings are separated from each other by more than one third of the total separation distance between the buildings.

According to the NFPA 80A (1996), the amount of received radiation at a specific point opposite the exposing building is barely influenced by radiation from openings separated from the point by more than twice the total separation distance between the buildings, as shown in Figure 4.4. Then calculations for a single window should be made and considered valid.

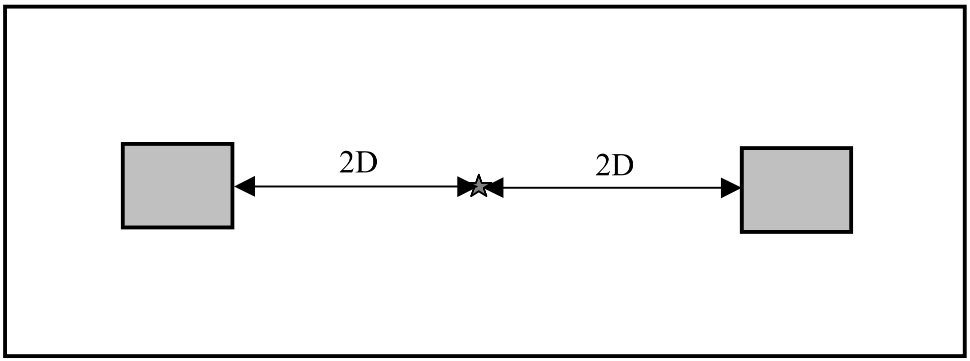

Figure 4.4 Separation of openings from a specific point at the exposed building

Buildings of lesser height

The separation distance for an exposing building of lesser height than the building that are being exposed should first be determined with the same method as explained above for buildings of the same height or higher. In cases where the roof of the exposing building consists of combustible material without a fire resistance rating, Table 4.5 (Table 2-4 in NFPA 80A, 1996) should be used in order to determine the required separation distance and means of protection necessary above roof level.

Table 4.5 Required separation distance or height of protection for buildings with combustible and roof with no fire resistance rating. Adapted from NFPA 80A (1996).

Number of stories likely to contribute to flaming through the roof	**Horizontal separation distance or height of protection above exposing fire (m)**
1	7.6
2	9.8
3	12.2
4	14.3

When the distances determined from Table 4.5 are greater than those determined from Table 4.4, the exposed building should be fitted with means of protection. The protection should have a height above roof level of the exposing building that is equal to the required separation distance. Where the roof of the building is not provided with enough fire resistance to contain a fire, Table 4.5 should be applied. The top storey and those stories directly underneath that are not fire separated from each other, should be counted as the number of stories likely to contribute to flaming through the roof.

Means of protection

According to the NFPA 80A (1996), several means of protection of a building from an external fire source can be applied. The means of protection are listed below.

- Spatial separation between buildings
- An automatic sprinkler system
- External walls of non-combustible material
- Extended external masonry walls to form protective wings
- Automatic external water curtains
- Removal of openings
- Openings fitted with:
  - glass block panels
  - wired glass in steel sash
  - automatic or deluge sprinklers
  - fire shutters
  - fire doors
  - fire dampers

If means of protection are installed, the separation distances can be decreased in accordance to Chapter 4 in NFPA 80A (1996). Appropriate standards should be followed and the means of protection installed in a building should be approved for its particular application.

No exposure hazard is assumed to exist if the exposing building is fitted throughout with a properly installed and maintained automatic sprinkler system. The exposure hazard to the exposed building is assumed to be greatly reduced if the exposed building is fitted throughout with an automatic sprinkler system.

5 COMPARISON OF BOUNDARY REQUIREMENTS

In this chapter a comparison of the different calculation methods presented in chapter 4 will be made by applying the methods on fictitious buildings. Three different types of buildings will be investigated; a warehouse, an office building and a residential building. Conclusions with regards to the applicability of the methods will be made based on the findings from the comparison.

5.1 Warehouse

A fictitious warehouse has been used for the comparison between different methods of determining separation distances between buildings. The building is assumed to be 50 m wide and 50 m long and have a height of eight metres. Furthermore, the external walls are not provided with enough fire resistance to contain a fire for its whole duration, i.e. the whole facade is considered to be an opening. The interior finishes are non-combustible. The fire load within the building is assumed to be of the same size as is generally found in warehouses and storage facilities. It is estimated that the duration of the fire will be 120 minutes. This estimation is made for comparison purposes. A fire will according to the ISO 834 time-temperature curve have then reached a temperature of about 1050 °C. This fire temperature represents a radiation intensity of 173 kW/m^2, which is approximately the same levels of radiation used in those methods with fixed radiation values, (Law 1963).

In the comparison, the distance to the relevant boundary will be determined. It is assumed that an identical building is positioned at the same distance from, but on the other side the boundary, i.e. the buildings are mirror images of each other. The critical received radiation is in all cases set to be 12.5 kW/m^2.

The boundary distance that is required by the different determination methods is shown below in Table 5.1. The calculations that have been performed in order to achieve the results below are presented in detail in Appendix 1.

Table 5.1 Comparison of required boundary distance for the warehouse used in the study

Method	**Required boundary distance (m)**
Peter Collier	19.4
C.R. Barnett	20.4
J.H. McGuire	19.2
G. Williams-Leir	22.2
NFPA 80A	19.9
Enclosing rectangle	18.3

As can be seen from the table, the methods predict approximately the same boundary distance. If the enclosing rectangle method, which does not take into account for flame projections, is used as a basis for the comparison, it can be seen that the methods will compare even better if the flame projection of each method is subtracted from the overall boundary distance. Therefore, the methods predict approximately the same boundary distance for relatively simple building shapes and opening configurations. One exception is the method by Williams-Leir, which predicts a boundary distance slightly higher than the other methods.

The methods by Collier and Barnett are almost similar and the difference in boundary distance is most probably due to the lack in precision when obtaining values from the graph of configuration factors, aspect ratios and constants used in Collier's method. Another factor that may have a small impact is that Collier's method does not take into account for the temperature of the receiving surface and ambient air when determining the levels of emitted radiation. The radiation intensity is therefore slightly lower than what is used in Barnett's method.

5.2 Office building

A fictitious office building has been used in this comparison and Figure 5.1 shows the building layout and relevant measurements. The building is 40 m wide and consists of five storeys, each with an individual height of 3.8 m. Each storey is a separate fire compartment, i.e. the floors will resist a fire for its whole duration. Seven windows, two metres high and three metres wide, are distributed evenly along each storey. A distance of three metres separates the windows from each other. The external wall is fitted with non-combustible cladding.

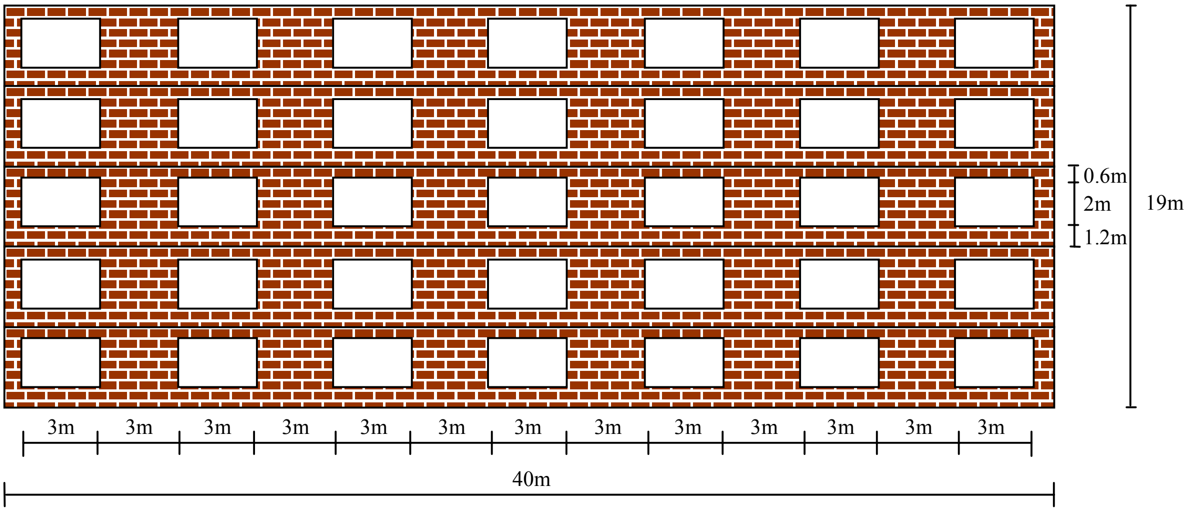

Figure 5.1 Office building used in the comparison

The fire is assumed to last for a period of 0.5 h (30 min), resulting in a fire temperature of 842 °C according to the ISO 834 time-temperature curve. This temperature will cause a radiation intensity inside the fire compartment of 87 kW/m^2, which is approximately the same level of radiation used for an office building in the methods by Read and NFPA 80A and will therefore make the calculations more comparable. The critical incident radiation is set to be 12.5 kW/m^2.

In the comparison, the distance to the relevant boundary was determined. It is assumed that an identical building is positioned at the same distance from, but on the other side the boundary, i.e. the buildings are mirror images of each other.

The boundary distance required by the different calculation methods is shown below in Table 4.2. The calculations that have been performed in order to achieve the results below are presented in detail in Appendix 2.

Table 5.2 Comparison of required boundary distance for the office building used in the study

Method	Required boundary distance (m)
Peter Collier	2.9
C.R. Barnett	3.0
J.H. McGuire	4.9
NFPA 80A	2.7
Enclosing rectangle	2.0

The enclosing rectangle method by Fire Research Station (1991) is the method predicting the shortest boundary distance, but it should be noted that this is the only method that does not take into account for flame projection. The method by McGuire (1965) is not totally comparable with the others since the table for normal cases uses a configuration factor of 0.07 while the other methods use a configuration factor for office buildings of 0.14 or 0.15. This is the reason why the method by McGuire (1965) predicts a boundary distance that is about two metres higher than predicted by the other methods.

Once again, the methods predict similar boundary distances for a building with rather simple layout. A difference can be noted between methods that use flame projection and methods that do not.

The complete results of each method presented in Appendix 2 shows that the enclosing rectangles that cause the largest boundary distance is the rectangles that enclose two, three or four of the windows in the storey. If a fire duration of 120 minutes and hence a higher radiation intensity had been chosen for the methods by Collier (1996) and Barnett (1988), the predicted boundary distance would be approximately 1.7 m longer. The distance would in that case be caused by the rectangle that encloses all seven windows in the storey.

5.3 Residential building

The fictitious residential building that has been used in this comparison is two storeys high which equates to a total height of seven metres. No fire compartmentation exists within the building or between the storeys, i.e. a fire is assumed to involve the whole building. The building is 20 m wide and has a recess located in the right corner of the building. The recess is 1.5 m deep and five metres wide. Figure 5.2 shows a simplified layout of the building.

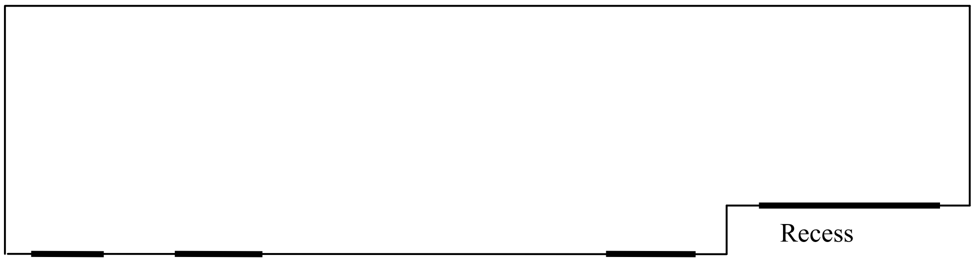

Figure 5.2 Simplified layout of the residential building

There are seven openings in the facade and they are distributed according to Figure 5.3. The openings consist of five windows, one door and one carport. The carport and one large window are positioned in the recess while the other openings are positioned in the other part of the facade. The external wall is fitted with non-combustible cladding.

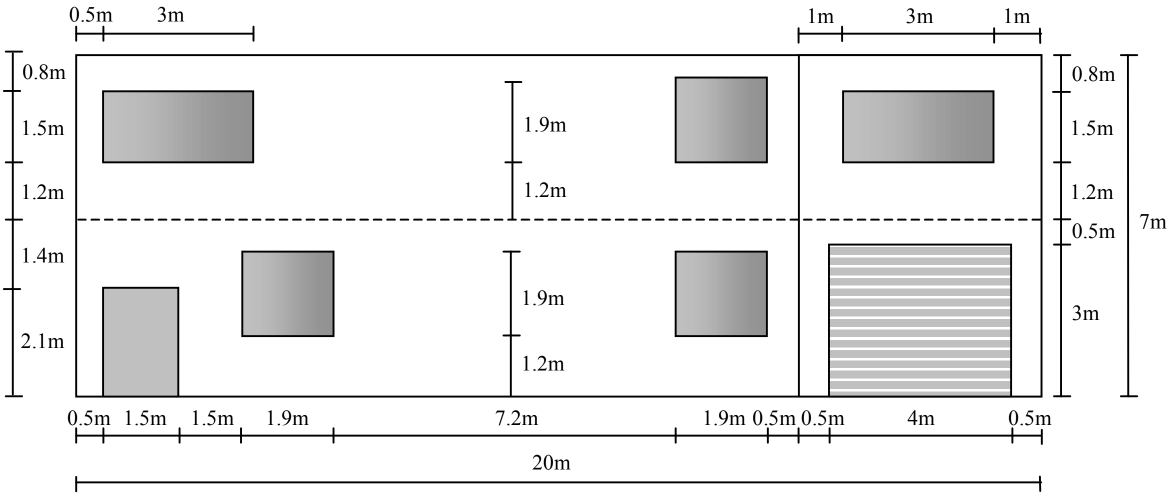

Figure 5.3 Residential building used in the comparison

The fire is assumed to last for a period of 0.5 h (30 min), resulting in a fire temperature of 842 °C according to the ISO 834 time-temperature curve. This temperature will cause a radiation intensity inside the fire compartment of 87 kW/m^2, which is approximately the same level of radiation used for an office building in the methods by Read and NFPA 80A and will therefore make the calculations more comparable. The critical incident radiation is set to be 12.5 kW/m^2.

In the comparison, the distance to the relevant boundary will be determined. It is assumed that an identical building is positioned at the same distance from, but on the other side the boundary, i.e. the buildings are mirror images of each other.

The boundary distance required by the different determination methods is shown below in Table 5.3. The calculations that have been performed in order to achieve the results below are presented in detail in Appendix 3.

Table 5.3 Comparison of required boundary distance for the residential building used in the study

Method	**Required boundary distance (m)**	
	With recess	**Without recess**
Peter Collier	3.5*	3.4
C.R. Barnett	3.0	3.6
J.H. McGuire	5.8*	n.a.
NFPA 80A	2.7	3.3
Enclosing rectangle	2.2	2.2

* Boundary distance counted from the plane of reference.
n.a. = not applicable

With this more complex building shape, the boundary distance required by the different calculation methods varies more and are harder to compare. Table 5.3 is divided into two columns. The column labelled "With recess" is for the actual building layout and the methods are applied exactly according what is described in each method, e.g. where nothing is said about a recess, no plane of reference is established that touches the outer parts of the building and makes an angle to the facade. The column labelled "Without recess" sets out the boundary distances when the recess is assumed not to exist.

The method by The Fire Research Station (1991) once again predicts the shortest boundary distance. One reason is that no account is taken to flame projection, but another contributing factor may be that the enclosing rectangles have to have dimensions according to the tables. This will make the area of the enclosing rectangle larger than the smallest rectangle that encloses the same openings in the other calculation methods. Since the area of unprotected openings is the same but the area is larger, the unprotected percentage will be smaller.

The other methods vary more in relation to each other for this building. It should be noted that the distance predicted from the methods by Collier and McGuire is counted from the plane of reference.

The method by McGuire (1965) is not totally comparable with the others for this building either. The reasons for this are that a higher configuration factor is used and that the method is made for evenly distributed openings.

Where the recess is assumed not to exist, approximately the same boundary distance is predicted by the different methods. Once again the method that does not take into account for flame projection predicts the shortest distance.

5.4 Discussion of results

The performed comparison has drawn the attention to some interesting and important matters when it comes to determining boundary distances with different methods. There is no consistency with regards to if account for flame projections should be taken and in that case, which distance that should be used.

As has been seen in the comparison, the methods predict approximately the same boundary distance for simple building shapes. However, for more complex building shapes there are greater differences between the different methods. Since some methods do not cover all situations, differences will occur due to variation in judgements of the user.

The methods by McGuire (1965), Williams-Leir (1970), Fire Research Station (1991) and NFPA 80A (1996) use predetermined values of radiation, configuration factor and flame projections (where such are used), and no performance-based design is possible. In the methods by Barnett and Collier, there is a greater flexibility with regards to determining the radiation intensity, flame projections and hence the boundary distances. This is a great advantage today with all new building materials, furnishings and more complex building shapes. One disadvantage is that it requires an experienced engineer in the field of fire protection to perform a design according to these methods. An advantage with the methods using predetermined values is that they can be used and applied by persons without any particular knowledge in fire protection engineering.

McGuire’s (1965) method is restricted in the way that it does not have a table for buildings with low fire load density such as office and residential buildings. It is though stated that such tables can be available on request. Furthermore, the method is only applicable for buildings with evenly distributed openings or windows.

The enclosing rectangle method presented by the Fire Research Station (1991) gives a good and systematic description of how to determine the boundary distance. Detailed explanations are given of how complicated building shapes should be treated. The aggregate notional area method that is presented in the same document can be used as a complement to the enclosing rectangle method, which may be especially favourable for complicated building shapes. An example is buildings with recesses where a plane of reference is used to determine the boundary distance. The distance may then be overestimated at some locations and the aggregate notional area method can be used to find the proper boundary distance at those specific locations.

It has been shown that for higher intensity fires, more openings and openings separated further apart will contribute with radiation and thus increase the boundary distance. For very wide buildings such as the warehouse used in this study, this will lead to very large separation distances. One question that arises from the above discussion is whether it is reasonable to assume that the whole facade of a warehouse will radiate at the same time? It may well be a reasonable assumption for smaller facades, but since it takes time for the fire to spread horizontally within the building it may lead to an overestimation of the boundary distance for wider buildings.

6 IMPORTANCE OF RADIATION FROM PROJECTED FLAMES

In the comparison of the different calculation methods it was found that one difference between the methods was whether account should be taken for flame projection or not. This chapter will investigate if a projected flame from an opening contributes with enough radiation for it to be necessary to take into account when determining safe separation distances between buildings.

6.1 Full scale fire tests

Law (1968) reports on a series of full scale fire tests that were conducted to investigate the levels of radiation from fires in compartments. The compartments used were brick-walled with dimensions 7.7×3.7×3 m (width×depth×height). Two different window areas, 5.6 and 11.2 m^2, were used and the total fire load, fire load distribution and wall linings were varied. The fuel used in the tests was 45 mm thick wood cribs. In order to measure the radiation contributed by the projected flames, two radiometers were placed adjacent to the burning building and facing the midpoint of the windows. One of the radiometers was shielded from the flames above the windows, i.e. one radiometer only measured the radiation from the windows while the other radiometer measured the total radiation from both the window and the projected flames.

From these tests, Law (1968) concluded that the fire was cooler and hence the radiation less for the larger windows, independent of the fire load. The window area and fire load had a significant effect on the window radiation. The tests also showed that the radiation from flames was not significant for the larger windows and significant only at the 20 percent level for the smaller windows. Law (1968) therefore came with the conclusion that:

> *Thus the analysis of these eleven tests indicates that there is a small but not highly significant increase in intensity due to flames from the smaller window; it can therefore be neglected.*

and that this small increase in intensity from the smaller windows does not justify an increase in building separation recommendations.

Law (1968) also reports on another full scale test carried out by Webster and Smith (1964) and, where one side of the 2.4 m cubical compartment was totally opened. In this test it was estimated that the radiation contributed by the flames above the opening was only two percent of the total amount of received radiation.

6.2 Swedish method

Fredlund et al. (1976) have developed a method of determining separation distances between buildings which is based on both full scale and small scale fire tests, as well as theoretical derivation. The method uses fire load density, opening factor, dimension of opening areas and the area of the compartment's interior surfaces as inputs. The method has been approved by the Swedish building authorities to be used in the design process of small houses.

6.2.1 Tests

Calculation of time-temperature curves for the fire compartment was performed with heat and mass balance equations according to methods by Magnusson and Thelandersson (1970, 1971, 1974). This is the same method that has been used to derive the so-called Swedish fire curves. Note that the time-temperature curves used in this model were derived for the specific test configuration and therefore differ from the original Swedish curves. The validity of the results calculated with the theoretical model has been checked with the time-temperature curves obtained in the tests. The fire compartments used in the tests were made of light-weight concrete with a density of 500 kg/m^3.

A number of assumptions have been necessary in deriving the curves.

- *combustion is complete and takes place entirely within the confines of the compartment;*
- *the temperature is uniform within the compartment at all times;*
- *a single surface heat transfer coefficient may be used for the entire inner surface of the compartment; and*
- *the heat flow to and through the compartment boundaries is unidimensional, i.e. corners and edges are ignored and the boundaries are assumed to be "infinite slabs".*

In the same tests by Fredlund et al. (1976), the radiation received at different points on the facade of an adjoining house was measured. These measures have been the basis behind this method to predict incident radiation and separation distances. A strength with the model is that it takes into account for both the radiation from the fire compartment through openings as well as the radiation from externally projected flames. The calculated levels of radiation can also be combined with ignition characteristics of the receiving surface to predict time to ignition. Three sets of tables are set out for design purposes; one that gives the time-temperature curve of the fire compartment, one that gives the time-radiation curve at various distances and locations on the neighbouring building and finally the sidewise radiation from external flames. All these tables are given for different fire loads and different opening factors. In the tables of received radiation at various distances and locations on the receiving surface, expressions for emissivity and configuration factors are already incorporated. The tables also set out a correlation between time of the burning period and received radiation. The radiation is expressed as a fraction of the total received radiation and allows the user to establish a time-radiation curve for the receiving point. Below is a brief description of which equations and assumptions that has been used to obtain the tabulated values.

6.2.2 Limitations

The method is derived for one-storey buildings with walls and supporting members made of light-weight concrete. The roof should be constructed in a way that has little ability to ignite and thereby starting a secondary fire, i.e. the roof could extend a distance no greater than 0.5 m from the facade. If the roof extends further than this, the extra distance should be added to the building separation distance. Ceilings and internal walls should be constructed so that they are difficult to ignite. The method is derived for houses made of light-weight concrete but can also be used for houses made of concrete, with a slightly conservative separation distance as a result.

Another restriction in the model is that the width of the opening, from which radiation is to be calculated, must not be greater than the separation distance. In this case, the opening should be divided into smaller parts so that the above requirement is fulfilled and the radiation from each part summarised.

6.2.3 Theory

The radiative contribution from the fire, i.e. the flame neglected, has been calculated with Equation 6.1 and 6.2. Equation 6.1 gives the radiative heat exchange dQ_{12} between two surfaces and Equation 6.2 gives an expression for the radiation dP_{12} received by a certain point at a distance, r, from the radiator.

$$dQ_{12} = \varepsilon_r \sigma T_a^4 dA_1 dA_2 \frac{\cos\beta_1 \cos\beta_2}{\pi r^2} \qquad [6.1]$$

where:

ε_r = resulting emissivity of both elements
σ = Stefan-Boltzmanns constant = 1.37×10^{-12} cal/cm^{2}sK^4
T_a = temperature of radiating surface dA_1, [K]
r = distance between surfaces [m]
β_1 = angle between r and the normal to surface dA_1
β_2 = angle between r and the normal to surface dA_2

$$dP_{12} = \frac{dQ_{12}}{dA_2} \qquad [6.2]$$

The orientations used in the equations above are explained in Figure 6.1.

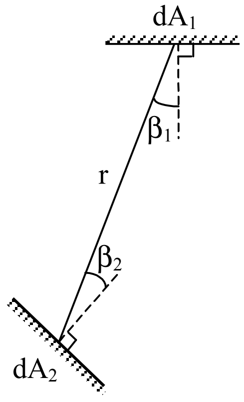

Figure 6.1 Orientations used when calculating the received radiation

In the tests, air with a velocity of 10 m/s was blown into the fire compartment, which is claimed by Thuresson (1973) to represent natural wind conditions with a velocity of 20 m/s. The projected flames were noticed to have a triangular shape, see Figure 6.2 below.

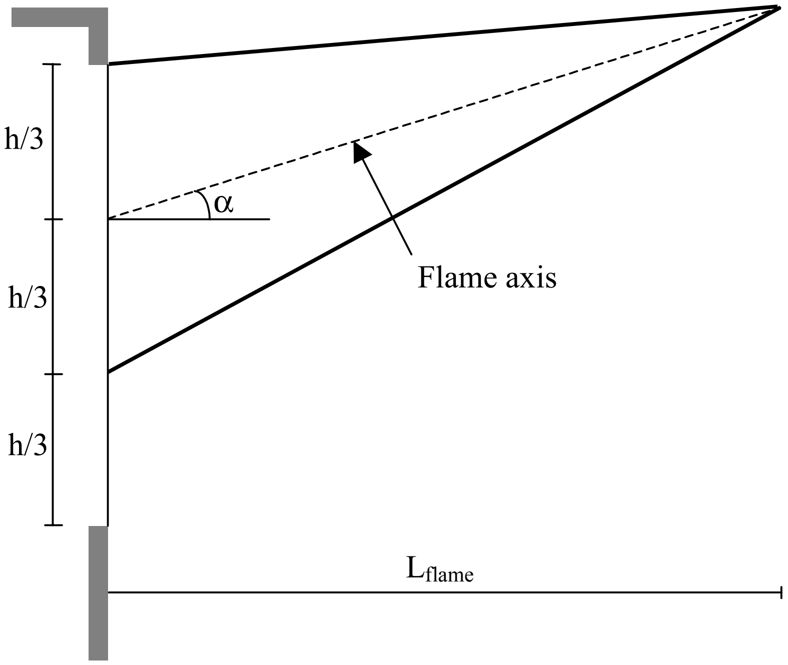

Figure 6.2 Simplified layout of exterior projected flame used in the model by Fredlund et al. (1976)

The angle, α, between the flame axis and the horizontal plane was estimated to be 30°, which also can be used for design purposes. The maximum flame length was determined with Equation 6.3.

$$L_{flame,\max} = CR_{80-30}^{1/3} \qquad [6.3]$$

where:

R_{80-30} = average burning rate for period when the fuel loses its weight from 80% to 30% of its initial value, [kg/min]

C = coefficient obtained from full scale fire tests, [$\text{min}^{1/3}\text{m/kg}^{1/3}$], see Figure 6.3,

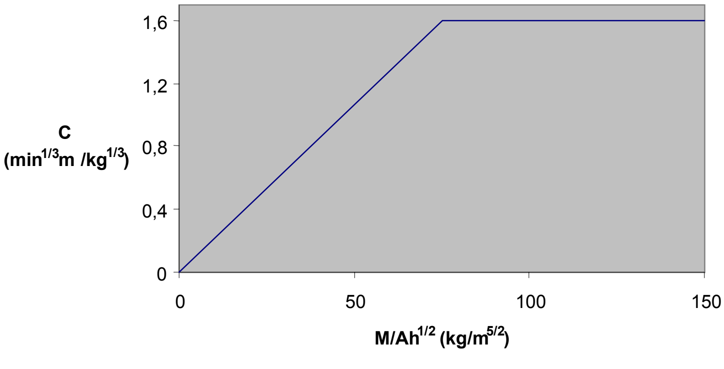

Figure 6.3 The coefficient C's dependence on amount of mass, M, in fire compartment, area, A, of window and height, h, of window.

The total radiation from the flame to a remote receiver has been calculated by dividing the flame into several smaller units and then adding the radiative contribution from each unit.

The resulting emissivity, ε_r, for the radiation from the window was calculated with Equation 6.4.

$$\frac{1}{\varepsilon_r} = \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_m} - 1 \qquad [6.4]$$

where: ε_w = emissivity of the window opening, 0.55 is used in the model for the entire burning

ε_m = emissivity of the receiving surface, 1.0 is used in the model

The emissivity of the flame is dependent on flame thickness and type of burnt fuel. Figure 6.4 gives the correlation used in the model.

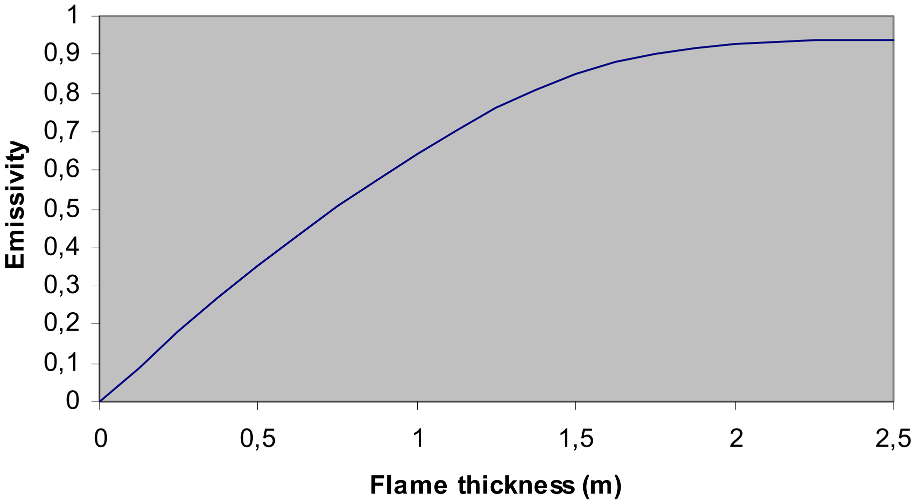

Figure 6.4 Flame emissivity as a function of flame thickness for wood based fuel

Fredlund et al. (1976) shows in a number of examples how well the time-temperature curves of the theoretical derived method compares with the full scale tests. The comparison in Figure 6.5 below is for an opening factor $A\sqrt{h}/A_{tot} = 0.04$. The upper two curves are for a fire load f = 30 Mcal/m^2 and a separation distance c = 4 m, while the lower two curves are for a fire load f = 20 Mcal/m^2 and a separation distance c = 6 m.

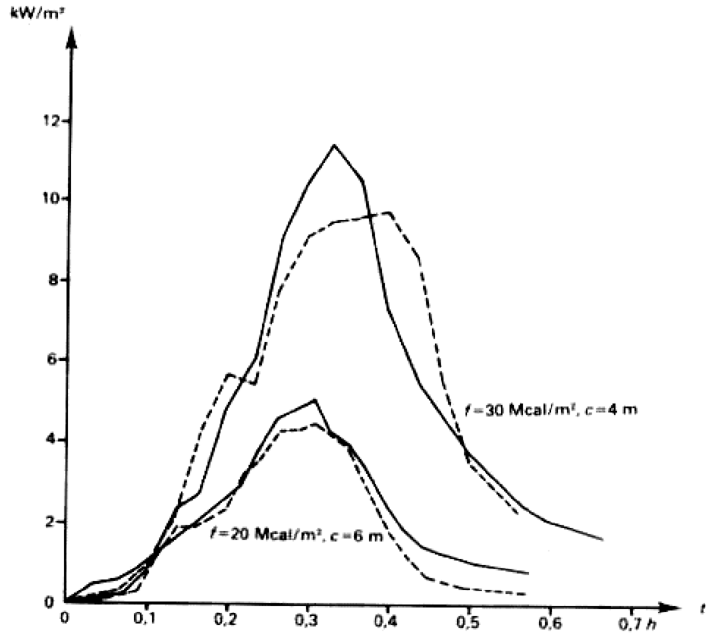

Figure 6.5 Comparison between theoretical derived calculation model and full scale fire tests. The dashed curve is for the theoretical derived time-radiation relationship and the solid curve is for full scale fire tests.

6.2.4 Calculation methodology

Calculations of separation distances or received radiation at various locations can be divided into five main steps, which are briefly explained below.

1. Determination of the total fire load f within the fire compartment.
   The fire load should be expressed as energy content (Mcal/m^2 or MJ/m^2) per unit of total interior surface area (openings included and internal walls excluded). Note that the fire load in this method is not, like in many other methods, expressed as energy content per unit floor area.

2. Determination of the opening factor $A\sqrt{h}/A_{tot}$ of the fire compartment.
   where:
   A = area of all vertical openings in the fire compartment [m^2]
   h = average height of all openings [m]
   A_{tot} = total area of the fire compartment's interior surfaces (openings included and internal walls excluded) [m^2]

3. The opening factor and fire load is then used to find the appropriate table for received levels of radiation.

4. Equation 6.5 explains the correlation between the maximum received radiation at the point of concern. The radiation set out in the tables. This procedure is necessary since the tables are derived for A_{tot} = 85 m^2.

$$P_{\max,p} = \gamma_p \varepsilon_{mp} \frac{A_{tot,p}}{85} P_{\max,t} \qquad [6.5]$$

where:
$P_{max,p}$ = maximum radiation intensity at the relevant point [kW/m^2]
γ_p = ratio between area A_a of the opening of concern and the total area A of all openings
ε_{mp} = emissivity of receiving surface = 1
$A_{tot,p}$ = total area of the fire compartment's interior surfaces (openings included and internal walls excluded) [m^2]
$P_{max,t}$ = maximum radiation intensity set out in the tables [kW/m^2]

5. Establishing of a time-radiation curve
   When the maximum received radiation has been determined, the correlation between time and fraction of total radiation can be used to establish a time-radiation curve for the receiving point. Together with ignition characteristics, which also is set out in the report by Fredlund et al., of the receiving surface, the time-radiation curve can be used to predict whether ignition will occur and also the time to ignition.

6.3 Projected flame or notional radiator

As has been shown in previous chapters, there is no consistency in the calculation methods with regards to whether one should account for flame projection when determining the separation distance between buildings. Most of the Building Regulations studied in this report use the openings or unprotected areas as radiators and neglect flame projection and radiation contributed from external flames. One exception is Canada where a flame projection of 1.2 m is used , (Barnett, 1988). The studied calculation methods use various projection distances. For example, Collier (1996) and Barnett (1988) uses a distance of 2 m, NFPA 80A (1996) uses 1.5 m, Williams-Leir (1970) uses 0.9 m and McGuire (1965) uses 1.5 m for normal cases and 2.1 m for hazardous cases.

6.3.1 Swedish method

It is the aim of the following chapter to check whether it is necessary to take into account for flame projections when determining safe separation distances, or if the assumption that the openings (with emissivity $\varepsilon = 1$) are the only areas contributing with radiation is acceptable. This will be done by applying the method by Fredlund et al. (1976), on a number of representative houses with different dimensions, window configurations and fire loads. No definite conclusions can be made from the study, but it can act as an indication to see if the above assumption is safe or if account for the flame projection needs to be taken.

Six cases were investigated with the model by Fredlund et al. (1976). The basic inputs and results of the calculations will be presented here and all main steps of the calculations will be presented in Appendix 4. The emissivity of all receiving surfaces is assumed to be $\varepsilon_{mp} = 1$ and the point that receives the highest levels of radiation are studied. The results from these calculations were compared with the radiation achieved when only the window is assumed to radiate with emissivity $\varepsilon = 1$ and compartment temperature estimated by the time-temperature curves given in Fredlund et al. (1976).

Calculations were made for notional radiators, i.e. the window is assumed to be the only radiator, especially at a projection distance of 0 m but also for distances 1.2, 1.52 and 2 m away from the opening. In case 1-5 comparisons were made at distances where the received levels of radiation are significant for building separation purposes while case 6 was investigated to show how the radiation varies with the distance. The radiation, P, received from the notional radiators was calculated with Equation 6.6.

$$P = \varepsilon\sigma\phi\left(T_f^{\,4} - T_a^{\,4}\right) \qquad [6.6]$$

where:
ε = emissivity of radiator = 1
σ = Stefan-Boltzmanns constant = 56.7×10^{-12} kW/m^{2}K^4
ϕ = configuration factor of a notional radiator
T_f = temperature in the fire compartment [K]
T_a = temperature of the receiving surface [K]

Case 1a
Compartment: 5×4.5×2.4 m (width×depth×height)
1 window: 3×1.5 m (width×height)
Fire load: 30 Mcal/m^2 (125 MJ/m^2)
Distance: 5 m

Figure 6.6 below shows the results of all projection distances for case 1a and Figure 6.7 shows only the results from the method by Fredlund et al (1976) and a notional radiator with no projection distance, i.e. 0 m. It can be seen from Figure 6.6, that the received radiation from the notional radiators with projection distances of 1.2, 1.52 and 2 m was much higher than the levels of radiation resulted from the method by Fredlund et al. (1976) and a notional radiator without any projection distance at all. This was also the situation for all the other cases studied in this chapter. Therefore, presentation of all radiation distances will only be made in Appendix 4.

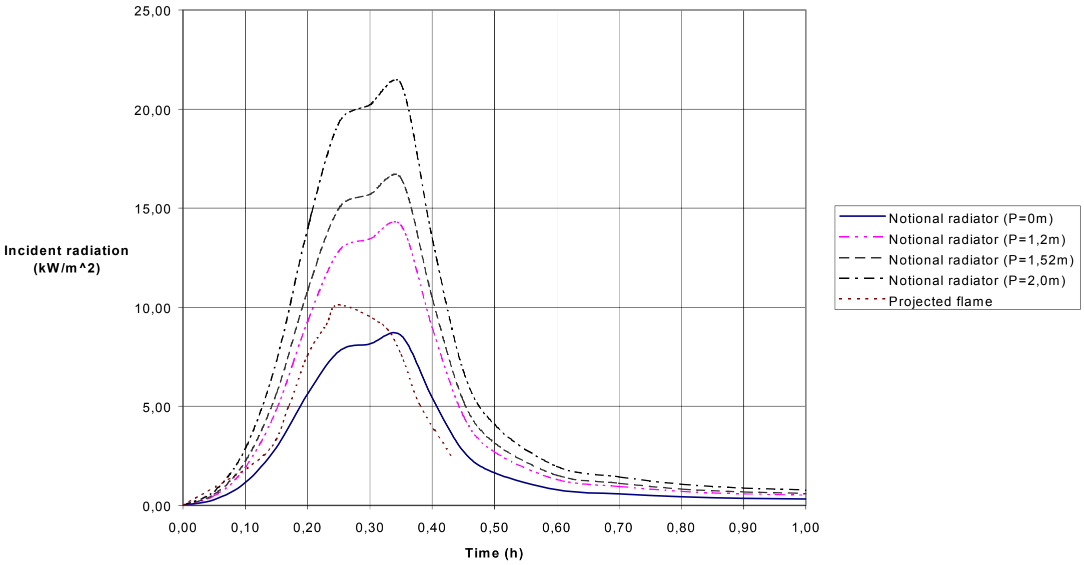

Figure 6.6 Comparison of received radiation for all projection distances for case 1

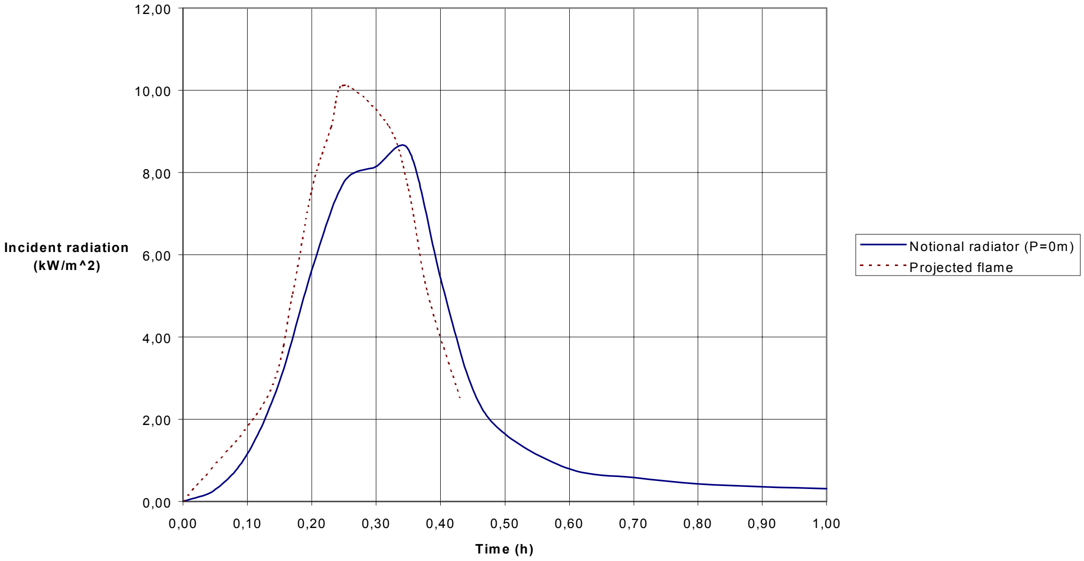

Figure 6.7 Comparison of received radiation for method by Fredlund et al.(1976) and a notional radiator with projection distance 0 m for case 1

The peak levels of radiation predicted by the method by Fredlund et al. (1976) and the notional radiator are 10.1 and 8.6 kW/m^2 respectively, which makes a difference of 1.5 kW/m^2.

To check how higher fire load affects the radiation at the same distance, an extra calculation was made for a compartment with the same dimensions as above but where the fire load was higher.

Case 1b

Compartment:	5×4.5×2.4 m (width×depth×height)
1 window:	3×1.5 m (width×height)
Fire load:	50 Mcal/m^2 (209 MJ/m^2)
Distance:	5 m

Figure 6.8 shows a comparison for case 1b between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

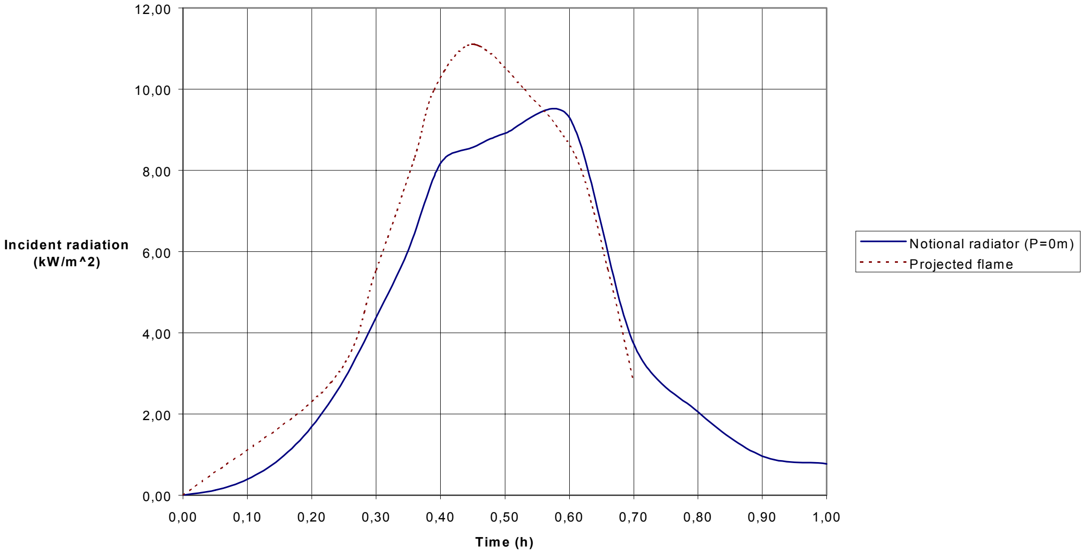

Figure 6.8 Received radiation for case 1b

The peak levels of radiation predicted by the method by Fredlund et al. (1976) and the notional radiator are 11.1 and 9.3 kW/m^2 respectively, which makes a difference of 1.8 kW/m^2. The higher fire load resulted in increased levels of radiation for both methods.

Case 2

Compartment:	8×10×2.5 m (width×depth×height)
3 windows:	2×1.3 m (width×height) each
1 window:	4.2×1.3 m (width×height)
Fire load:	50 Mcal/m^2 (209 MJ/m^2)
Distance:	5 m

Figure 6.9 shows a comparison for case 2 between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

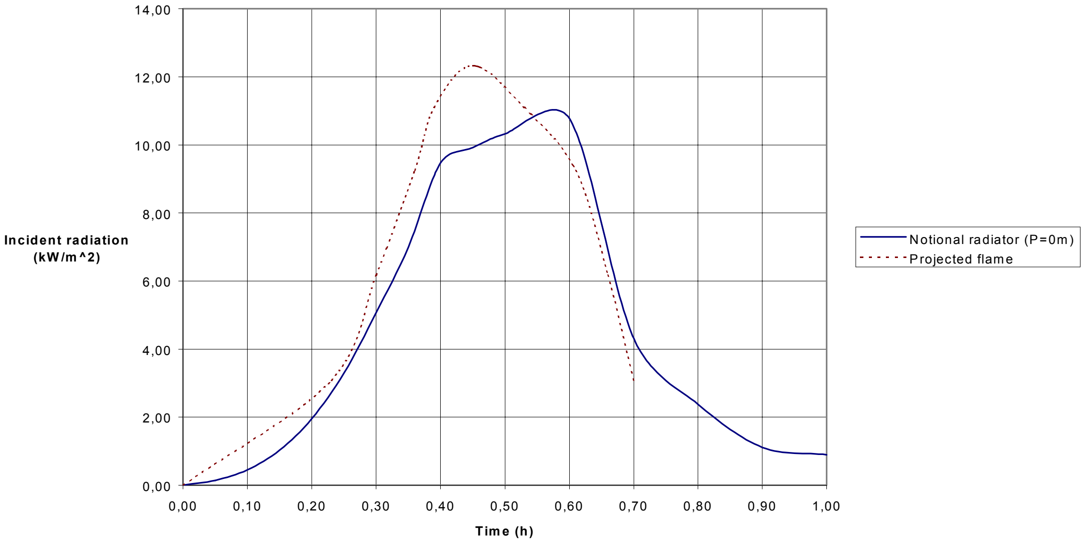

Figure 6.9 Received radiation for case 2

The peak levels of radiation predicted by the method by Fredlund et al. (1976) and the notional radiator are 12.3 and 10.8 kW/m^2 respectively, which makes a difference of 1.5 kW/m^2.

Case 3

Compartment: 10×5×2.5 m (width×depth×height)
6 windows: 2×1.3 m (width×height) each
Fire load: 40 Mcal/m^2 (167 MJ/m^2)
Distance: 3 m

Figure 6.10 shows a comparison for case 3 between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

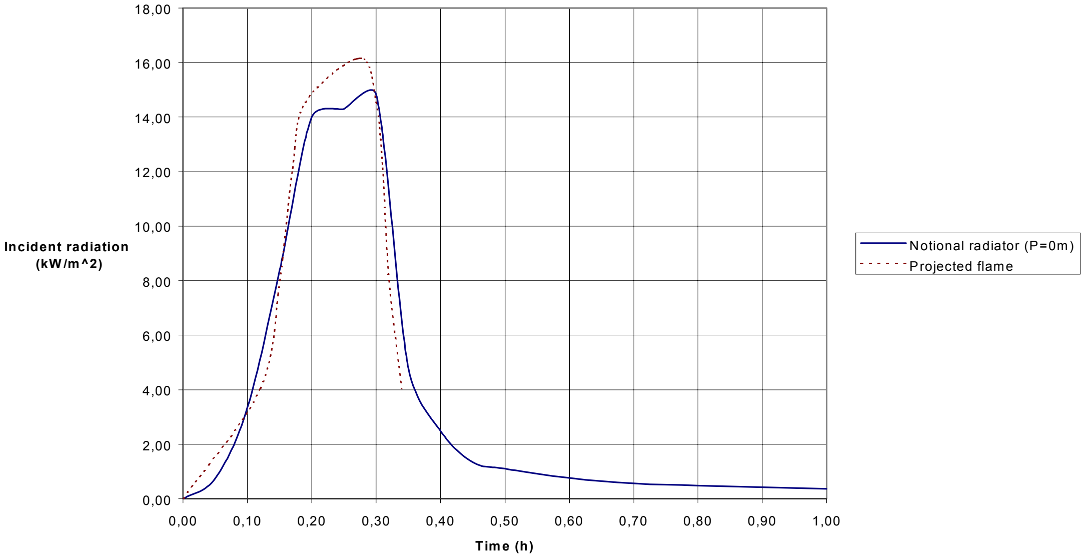

Figure 6.10 Received radiation for case 3

The peak levels of radiation predicted by the two methods are 16.2 and 14.8 kW/m^2 respectively, which makes a difference of 1.4 kW/m^2.

Case 4 – This case has been investigated since narrow window tend to produce long flames that are projected a relatively great distance away from the facade.

Compartment: 6.3×5.5×3.0 m (width×depth×height)
2 windows: 1×2 m (width×height) each
Fire load: 30 Mcal/m^2 (125 MJ/m^2)
Distance: 3

Figure 6.11 shows a comparison for case 4 between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

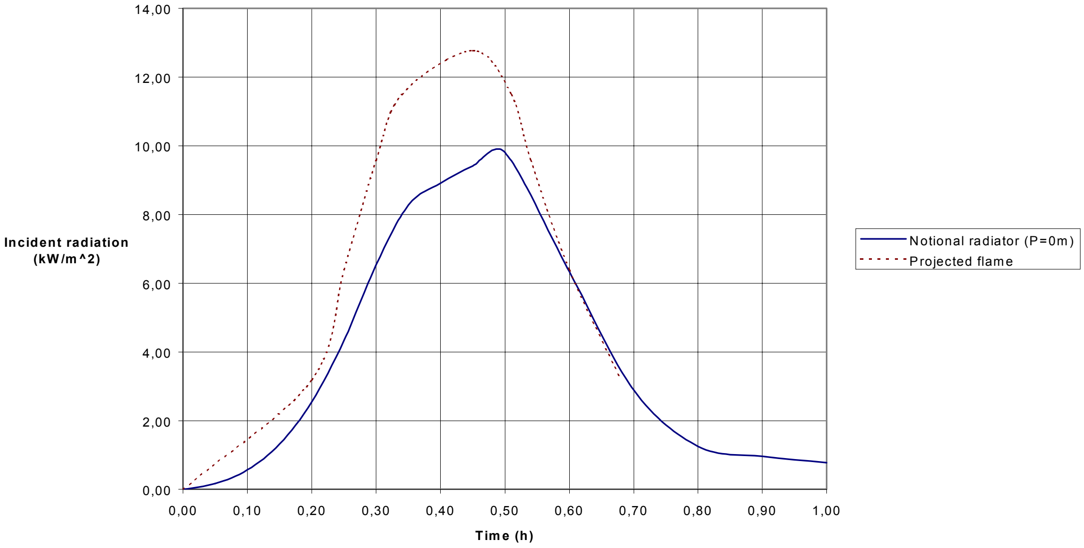

Figure 6.11 Received radiation for case 4

The peak levels of radiation predicted by the method by Fredlund et al. (1976) and the notional radiator are 12.8 and 9.8 kW/m^2 respectively, which makes a difference of 2.0 kW/m^2.

Case 5 – This case has been investigated since windows with equal sides also tend to produce flames that are projected far away from the facade, (Barnett 1988).

Compartment: 10×8×2.5 m (width×depth×height)
4 windows: 1.45×1.45 m (width×height) each
Fire load: 50 Mcal/m^2 (125 MJ/m^2)
Distance: 3 m

Figure 6.12 shows a comparison for case 5 between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

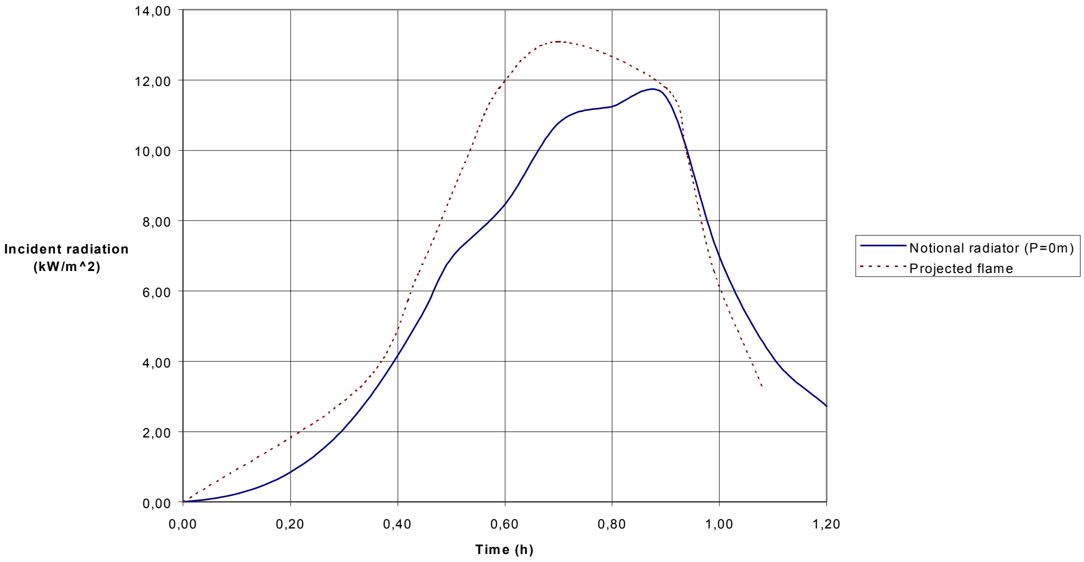

Figure 6.12 Received radiation for case 5

The peak levels of radiation predicted by the method by Fredlund et al. (1976) and the notional radiator are 13.1 and 11.5 kW/m^2 respectively, which makes a difference of 1.4 kW/m^2.

<u>Case 6</u> – This case was investigated in order to check how well the method by Fredlund et al. (1976) compares with the radiation from the window (with no flame projection) only, when the distance to the receiving point increases.

Compartment:	4×4×2.5 m (width×depth×height)
1 window:	1.52×1.52 m (width×height)
Fire load:	30 Mcal/m^2 (125 MJ/m^2)
Distance:	3, 4, 5, 6 and 8 m

Figure 6.13 shows a comparison for case 6 between the levels of radiation predicted by Fredlund et al. (1976) and a notional radiator with a projection distance of 0 m.

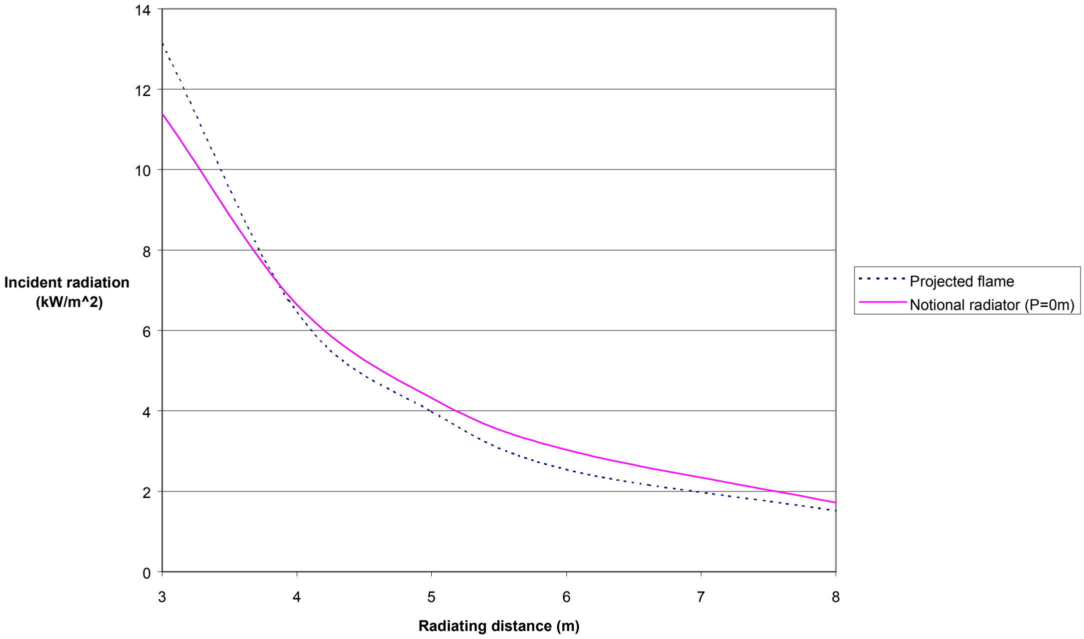

Figure 6.13 Received radiation for case 6

The biggest difference for this case occurs at a radiation distance of 3 m, where the levels of radiation are 13.1 and 11.3 kW/m^2 respectively. However, when the distance increased, the radiation resulting from the notional radiator became larger in relation to the method with flame projection. This is due to the shape of the flame. As the distance becomes larger, the angle between a line connecting the receiver and the flame front becomes smaller and the effective area of the flame seen from the receiver will therefore be less. Accordingly, the fraction of received radiation resulting from the flame was less as the distance increased.

6.3.2 Hand calculation model

The method investigated above can only be applied with accuracy for specific cases. It would be interesting to check if equations that are more commonly used in the fire engineering discipline will predict that the projected flame contributes with the same percentage of radiation as observed in chapter 6.3.1. To do this a calculation procedure has been established by the author of this report and sample calculations performed on relatively simple cases. The method is presented for a compartment with only one opening, but can also be extended to be valid for compartments with several openings of various dimensions. The procedure is mainly based on Law et al. (1981), but has been modified in certain ways to giver higher accuracy.

For no-wind conditions Law et al. (1981) uses a flame shape and dimensions according to Figure 6.14.

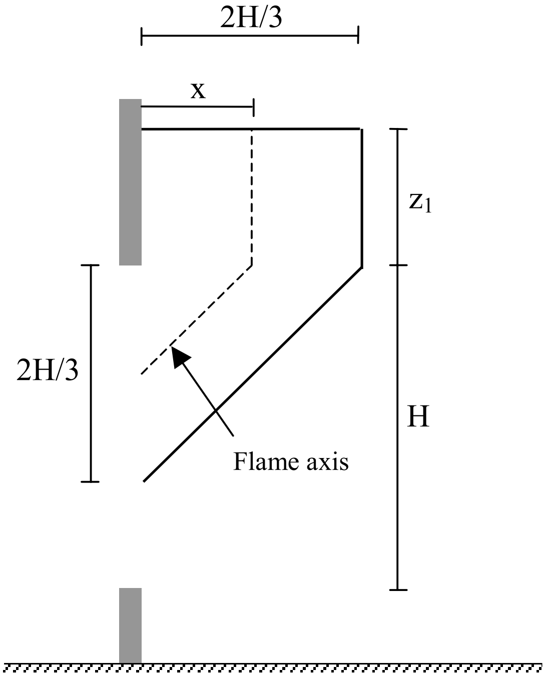

Figure 6.14 Flame shape and dimensions used in the calculation procedure,(Law et al. 1981)

The opening is assumed to radiate with the temperature found inside the fire compartment and with an emissivity ε =1. One further assumption is that the leaning part of the flame is assumed not to exist, i.e. the window will radiate with its total area and is not shielded by any flame. This has been agreed on in correspondence with Law. One argument against this assumption may be that the radiating distance will be longer and accordingly the configuration factor smaller. However, the temperature in the compartment is generally higher than the average flame temperature and the emissivity in the compartment is much greater than the emissivity of the flame. Two radiators will therefore be used in the calculations; the window with height, H, and width, W, and the part of the projected flame that is above the soffit with height, z_1, and width, W. In the sample calculations, the received radiation is calculated in a point located in the centre of the window at a distance, r, away from the facade. The maximum received radiation may be found in point located slightly higher up but this is assumed to have a negligible effect.

Radiation from the window

The radiation from the window is calculated in ordinary way with Equation 6.5.

$$P_{window} = \varepsilon\sigma\phi\left(T_f^{\,4} - T_a^{\,4}\right) \qquad [6.5]$$

where:
ε = emissivity of radiator = 1
σ = Stefan-Boltzmanns constant = 56.7×10^{-12} kW/m^{2}K^4
ϕ = configuration factor of window
T_f = temperature in fire compartment [K]
T_a = temperature of receiving surface [K]

The temperature T_f in the fire compartment is determined with Equation 6.6 (Equation 3 in Law et al. 1981) or with any other appropriate method.

$$T_f - T_a = 6000\frac{\left(1-e^{-0.10\eta}\right)}{\eta^{1/2}}\left(1-e^{-0.05\psi}\right) \qquad [6.6]$$

where:
η = $\dfrac{A_T}{A_w h^{1/2}}$ [$m^{-1/2}$]
ψ = $\dfrac{L}{\left(A_w A_T\right)^{1/2}}$ [kg/m^2]
T_a = temperature of ambient air [K]
A_T = total area of floor, ceiling and walls minus total window area(s) [m^2]
A_w = sum of window area(s) on all walls [m^2]
h = window height or weighted average of window heights on all walls [m]
L = fire load [kg]

Radiation from the projected flame

The temperature of a flame projected from a window is not constant through the full extent of the flame. An average flame temperature could be used, but in order to achieve as precise results as possible, the temperature is varied along the flame axis and the flame is divided into strips with a height Δh. The total received radiation P_{flame} is calculated with Equation 6.7 as a sum of the radiation $P_{flame,p}$ from each strip.

$$P_{flame} = \sum P_{flame,p} \qquad [6.7]$$

The radiation from each strip is calculated with Equation 6.8.

$$P_{flame,p} = \varepsilon\sigma\phi_p\left(T_{flame,p}{}^4 - T_a{}^4\right) \qquad [6.8]$$

where:
ε = emissivity of radiator
σ = Stefan-Boltzmanns constant = 56.7×10^{-12} kW/m^2K^4
ϕ_p = configuration factor of relevant flame strip
$T_{flame,p}$ = average temperature of flame strip [K]
T_a = temperature of receiving surface [K]

The height, z_1, of the flame tip is calculated with Equation 6.9 (Equation 4 in Law et al. 1981).

$$z_1 + H = 12.8\left(\frac{R}{W}\right)^{2/3} \qquad [6.9]$$

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]

The emissivity of the flame is calculated with Equation 6.10 (Equation 12 in Law et al. 1981).

$$\varepsilon = 1 - e^{0.30\lambda} \qquad [6.10]$$

where: λ = flame thickness, i.e. 2H/3 [m]

The configuration factor $\phi_{tot,p}$ of each flame strip can be determined with Equation 6.11. In order for configuration factors to be additive, they have to be calculated from the same reference point, O, which is shown in Figure 6.15.

$$\phi_{tot,p} = 2\phi_p - 2\phi_{p-1} \qquad [6.11]$$

where: ϕ_p = configuration factor of the rectangle with height = H+p×Δh and width = W/2
ϕ_{p-1} = configuration factor of the rectangle with height = H+(p-1) ×Δh and width = W/2
p = number of the relevant flame strip counted from the soffit

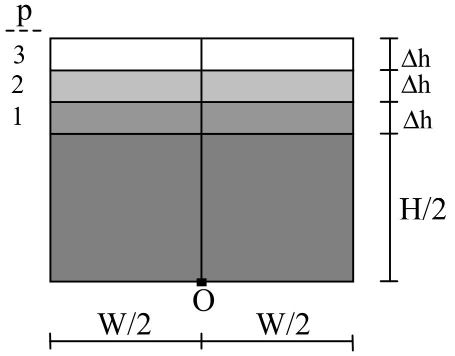

Figure 6.15 Rectangles used when determining the configuration factor of each flame strip

The configuration factor ϕ_p should be calculated to the corner of the rectangle with width W/2 and height depending on the flame strip in concern. This is done with Equation 6.12.

$$\phi_p = \frac{1}{360}\left[\frac{x}{\sqrt{1+x^2}}\tan^{-1}\left(\frac{y}{\sqrt{1+x^2}}\right) + \frac{y}{\sqrt{1+y^2}}\tan^{-1}\left(\frac{x}{\sqrt{1+y^2}}\right)\right] \qquad [6.12]$$

Where: x = (H+p×Δh)/2r
y = W/2r
H = height of rectangle [m]
W = width of rectangle [m]
r = distance between radiating and receiving surface [m]
p = number of the relevant flame strip counted from the soffit

The distance between the radiator and receiver is equal to the distance between the facade and receiver, minus the thickness of the flame, i.e. 2H/3.

The flame temperature varies along the flame axis. The temperature is assumed to be constant through the full width and thickness of the flame, which is a conservative approach. The temperature in the beginning and end of each flame strip can be determined to give the average temperature in the strip. The temperature varies along the flame according to Equation 6.13 (Equation 10 in Law et al. 1981).

$$\frac{T_z - T_a}{T_o - T_a} = 1 - 0.027\frac{lw}{R} \qquad [6.13]$$

where:
T_z = temperature at distance l along flame axis [°C]
T_a = temperature of ambient air = 20 °C
T_o = temperature at the window [°C]
l = distance along flame axis [m]
w = window width [m]
R = rate of burning [kg/s]

The rate of burning R (in kg/min) is calculated with Equation 6.14, which was originally derived by Kawagoe, (Drysdale 1985). Other appropriate methods of determining the burning rate may also be used.

$$R = 5.5A_o\sqrt{H} \qquad [6.14]$$

where:
A_o = area of opening [m^2]
H = height of opening [m]

The temperature at the window can be found since it is known that the temperature at the flame tip is 540 °C and that the total length of the flame axis is approximately $H/2+z_1$.

Total level of received radiation
The total level of received radiation ,P_{tot}, can be calculated by adding the radiative parts of the window and the projected flame , see Equation 6.15.

$$P_{tot} = P_{window} + P_{flame} \qquad [6.15]$$

Applications
The model presented above has been applied on four relatively simple cases. Calculations have been made for case 1a-b that was used in chapter 6.3.1. An extra calculation has been made for case 1a where the window is smaller, i.e. 1.5×1.5 m instead of 3×1.5 m. One calculation has also been made for case 4 but where only one of the original two windows exists. Table 6.1 below sets out the inputs that have been used and the calculated values of temperatures and radiation intensities. The same fire loads, which were given as energy contents per square metre, have been used for each case as was done in the previous study. The fire load needs to be expressed in

kilograms when determining the compartment temperature according Equation 6.6, and therefore has the total area of the enclosure and a calorific value of 18 MJ/kg (wood) been used to convert the fire load into the right unit. The portion of the total radiation that is contributed by the projected flame is also given.

Table 6.1 Properties and results from the sample calculations

	Case 1a	**Case 1b**	**Case 1c**	**Case 4**
Compartment (m)	5×4.5×2.4	5×4.5×2.4	5×4.5×2.4	6.3×5.5×3
Window (m)	3×1.5	3×1.5	1.5×1.5	1×2
Fire load (kg)	629	1052	629	972.9
η ($m^{-1/2}$)	15.62	15.62	32.06	48.83
ψ (kg/m^2)	31.96	53.44	44.60	98.45
T_f (°C)	977	1137	927	865
T_o (°C)	1072	1072	1072	957
Flame thickness (m)	1	1	1	1.3
Flame height* (m)	2.4	2.4	2.4	3.2
Radiating distance (m)	5	5	3	3
P_{window} (kW/m^2)	7.4	11.9	8.6	6.1
P_{flame} (kW/m^2)	1.6	1.6	1.9	1.2
P_{total} (kW/m^2)	9.0	13.6	10.5	7.3
P_{flame}/ P_{total}	**0.18**	**0.12**	**0.18**	**0.16**

*The flame height is counted from the soffit.

It can be seen in the table above that the difference between the total levels of received radiation and the radiation from the window was found to be in the range 1.2-1.9 kW/m^2. The radiative portion from the projected flame was in the order of 12-18 %. In increase in fire load resulted in higher temperature in the compartment and hence an increased level of received radiation. It was also found that the radiative portion from the flame decreased as the fire load was increased.

6.3.3 Discussion of results

The difference in received radiation predicted by the method by Fredlund et al. (1976) and a notional radiator with projection distance 0 m for the studied cases varies between 1.4-2.0 kW/m^2. Note that this difference occurred around the area of interest for building separation and ignition purposes, i.e. the distance where the level of radiation is approximately 12.5 kW/m^2. In this area it was always the method with projected flames that predicted the highest radiation intensities. The largest difference in levels of received radiation, i.e. 2.0 kW/m^2, occurred for high and narrow windows.

The received radiation from the projected flame decreased with distance and become less than the radiation for a non-projected notional radiator. This is due to that the effective flame area viewed from the receiver also decreases with distance, but it also gives an indication that the flame shields some of the radiation emitted from inside the compartment.

The assumption of notional radiators at distances 1.2, 1.52 and 2.0 m appears to overly estimate the levels of received radiation.

An increase in fire load caused a slightly higher fire temperature with both the method by Fredlund et al. (1976) and the hand calculation method presented, and accordingly higher levels of emitted and received radiation. However, this is only valid to a certain extent since the fire will become ventilation controlled with a high enough increase in fire load. The hand calculations predicted that the percentage of radiation from the projected flame decreased when the fire load increased.

The calculations performed using the method by Fredlund et al. (1976) and the presented hand calculation method, show only a small difference between taking into account for flame projections and using non-projected notional radiators with the compartment temperature and an emissivity of $\varepsilon = 1$. The contribution from the flame to the total emitted radiation in the area of interest appears to be in the order of 12-18 %.

The use of the notional radiator is an acceptable assumption that can be used for building separation purposes with reasonable accuracy, which also has been concluded by Law (1968) as presented in Chapter 6.1. It should be noted that all possible compartment configurations, window dimensions and fire loads have not been tested and a higher percentage of radiation from projected flames may occur for a case not identified by the author.

7 DISCUSSION AND CONCLUSIONS

The purpose of this chapter is to discuss findings made in this report and to make conclusion based on the work performed for the fulfilment of this report. Some recommendations will be made with regards to how different parameters and methods should be used.

7.1 Radiation

Ignition due to radiation is the most common and thus hazardous way for a fire to spread between adjoining buildings. There are other ways for fire spread to occur, such as flying brands and convective heat transfer, but they are often disregarded in the design process of spatial separations of buildings.

Two very important parameters with regards to determining safe separation distances between buildings are;

a) the predicted fire temperature in the compartment, and
b) the levels of emitted radiation from the building.

Generally used values of the expected emitted radiation are 84 and 168 kW/m^2 (2 and 4 cal/cm^{2}s) depending on the type of facility. These values have been derived from several full scale fire tests.

There are a numbers of methods to determine the fire temperature in a burning compartment. It is up to the designer to determine which method that is best applicable for the specific building in concern. The fire temperature is highly dependent on the following factors;

- the dimensions of the compartment,
- the opening factor,
- the size and distribution of the fuel, and
- interior linings.

Flames will project out of openings in a compartment during a severe fire. The height, z_1, of the external flame above the top of the window is generally determined by the use of Equation 9.1, where the flame tip is defined as the point where the flame temperature is 540 °C.

$$z_1 + H = 12.8\left(\frac{R}{W}\right)^{2/3} \qquad [9.1]$$

H is the height of the opening, W is the width of the opening and R is the mass burning rate in the compartment.

The transfer of radiation between a building on fire and an adjoining building depends on several factors. Some parameters that have an influence are the dimensions and shape of the radiating source, emissivity of radiating and receiving surfaces, as well as the distance between the buildings.

Ignition of a radiation-exposed building can occur either spontaneously or piloted, depending on whether an ignition source is present or not. Piloted ignition should be considered in fire situations since ignition sources, such as sparks and flames, most certainly are present. The level of received radiation that is commonly used as ignition criteria for piloted ignition is 12.5 kW/m^2. However, this value is adopted from laboratory tests and findings presented in this report have indicated that the value of critical received radiation that will cause ignition in full scale fire tests conducted in an outdoor environment, may be in the range 15-18 kW/m^2.

7.2 Comparison of Building Codes

The comparison of different Building Regulations and acceptable solutions showed that performance based design solutions can be used in Australia, England and Wales, New Zealand and Sweden. Canada and the United States of America still use strictly prescriptive regulations with regards to spatial separation of buildings.

In general, the separation requirements are based on findings from the so-called St. Lawrence Burns or work conducted by Law (1963). Values used for the maximum levels of radiation that can be expected in a fire are 84 and 168 kW/m^2 (2 and 4 cal/cm^{2}s). In opposite to the other Building Codes studied in this report, the National Building Code of Canada does not have a table with separation values for buildings classed as having a light fire severity, i.e. a configuration factor of 0.14-0.15.

A widely used method in the regulations is to determine the distance to the relevant boundary rather than to an adjoining building. Then it is assumed that an identical building will be located at equal distance from, but on the other side of the relevant boundary. This method is often referred to as the “mirror image concept”. However, a hazardous situation can occur where “the mirror image concept” has been applied, but where one of the buildings is greater or classed in a different purpose group.

The National Building Code of Canada and the NFPA 80A (1996) are the only codes requiring that account should be taken to flames projected from openings. The flame projection is not only incorporated in these codes with respect to the emitted radiation from the flames, but also in order to guard against direct flame impingement.

7.3 Comparison of calculation methods

Three of the calculation methods studied in this report are incorporated or referred to by Building Codes. The Enclosing rectangle method and the Aggregate notional area method (Fire research Station 1991) are set out in the English and Welsh Approved Document B (1991) and the New Zealand Approved Document C3 (BIA 1995), while the method by McGuire (1965) is used in the NFPA 80A (1996) and the National Building Code of Canada.

Most of the calculation methods studied in this report were developed in order to be applicable to people without any particular knowledge in fire engineering. However, the methods by Collier (1996) and Barnett (1988) require some extent of expert judgement when it comes to determining the fire temperature and the flame projection. Furthermore, these methods do not specify exactly how every possible case should be treated, which enables the designer to treat the building in the most appropriate way.

Even though the Enclosing rectangle method and the Aggregate notional area method (Fire Research Station 1991) do not allow the user much flexibility when determining the separation distance, the methods can be combined and used with great benefit for complicated building shapes. One disadvantage may be that the Aggregate notional area method is very time demanding to use.

The method by Williams-Leir (1970) does not require any expert judgement by a fire engineer in order to perform the design. However, the rules set out are hard to understand and very difficult and time demanding to apply on complex building shapes.

The method by McGuire (1965) is easy to use when determining separation distances for simple building shapes with evenly distribution of openings. One disadvantage is that no table with separation distances is given for buildings classed as having a light exposure hazard.

The NFPA 80A is a user-friendly method that can be used for most cases. However, nothing is said of how buildings with recesses and set backs should be treated. The method has a great flexibility and account can be taken for many influencing factors, such as sprinklers and other fire safety measures, Fire Service intervention and actual fire load in the building.

All the methods use rectangles that enclose unprotected areas when determining the separation distance between buildings. It was noticed when the methods were applied on different building types, that the methods predict approximately the same separation/boundary distance for simple building shapes. The observed differences could be referred to the various flame projection distances used in the methods. A more complicated building shape generated larger differences in the separation distances. This is as well caused by the flame projection distances, but also by the limitations in applicability in the different methods.

7.4 Projected flame or notional radiator

The comparison between different calculation methods for determining safe separation distances between buildings showed that there is an inconsistency in whether to account for flame projections out of openings in a fire compartment or not. This report has shown, both with performed calculations and in reviews of work conducted earlier by others, that the levels of radiation contributed by the flames can be neglected compared to the total amount of radiation received by an adjoining building.

The calculations were performed with two different methods, which both showed similar results, i.e. 12-18 % of the total received radiation were contributed by the flames. Note that this value only is valid in the area of concern for piloted ignition, i.e. 12.5 kW/m^2. The increase in total received radiation due to projected flames is not large enough for it to be necessary to take into account. For the purpose of building separation design, it is therefore only needed to consider the openings as radiators with an appropriate chosen temperature or radiation.

The use of notional radiators located at various distances from the facade tends to overestimate the levels of received radiation and will thereby cause a separation distance that is too conservative. However, in the design process it may be necessary to use flame projection equations to make sure that flame impingement and flame contact with the adjoining building will not occur.

The hand calculation method presented in this report of how to calculate the emitted radiation from the fire compartment and the externally projected flames can be used with a reasonable result. Note that the method is valid for no-wind conditions.

8 FURTHER RESEARCH

As this project has progressed, a number of parameters have been identified that influence horizontal fire spread to adjoining buildings. The importance of and the significance of some these parameters are however not thoroughly investigated and further research is needed in certain areas in order to achieve reliable methods of determining safe separation distances. Below is listed a number of suggested areas to further investigate in the future.

- Even though this and other reports has shown that no account needs to be taken to projected flames with regards to radiative heat transfer, it should be investigated more thoroughly. It may well be so, that a situation, e.g. small and narrow windows, not studied in detail may cause extraordinary high levels of radiation.

- Most of the research on which the Building Regulations and calculation methods of today are based, has been derived from old fire tests. The building materials and interior furnishings used in those days are very different from the material used today. Today, the materials are more complex and generally contain more energy and it is therefore essential to investigate what levels of radiation and temperatures that can be expected in a fire in a modern building.

- The sample calculations performed in this report for a warehouse, indicated that separation distances predicted for large warehouses will be very large and may be too conservative. It should be investigated how much of the facade that can be expected to radiate at the same time.

- Full scale fire tests reported on in this project have shown that the levels of radiation required to cause ignition of a neighbouring building actually was higher than the commonly used value of 12.5 kW/m^2. The ignition criteria should therefore be reinvestigated in full scale fire tests conducted in an outdoor environment.

- Wind effects have not been addressed in this report. An interesting research project in the future would be to investigate the influences of external wind on the total amount of emitted and received radiation.

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APPENDICES

APPENDIX 1 – COMPARISON OF BOUNDARY REQUIREMENTS FOR WAREHOUSE

The calculation methods and all used equations and terms are presented earlier in this report. The following chapter only shows how the methods are used and what separation distances that is predicted by each method.

C.R. Barnett (1988)

By calculating the configuration factor of the enclosing rectangle, the separation distance between the buildings can be determined. At first, the fire temperature has to be determined. The ISO 834 time-temperature curve gives for duration of 120 minutes the following temperature:

$T_2 = 345\log_{10}(8\times120+1)+20 = 1049\ °C$

The configuration factor can then be calculated with equation A1.1:

$$\phi_n = \frac{A_E I_{RC}}{A_V I_{EC}} \qquad [A1.1]$$

where:

$A_E =$ $5\times80\ m^2 = 400\ m^2$
$A_V =$ $5\times80\ m^2 = 400\ m^2$
$I_{RC} =$ $12.5\ kW/m^2$
$I_{EC} =$ $1\times56,7\times10^{-12}[(1049+273)^4 - 293^4] = 172.79\ kW/m^2$

Which gives:

$\phi_n = 0.07234$

The radiation distance can be found by iteration of Equation 4.3, which is described in the summary of this method by Barnett (Chapter 4.4). The width of the enclosing rectangle is 50 m and the height is 8 m, which result in a radiation distance of 36.7 m. Since the external walls are not fire resistance rated, another two metres should be added to take into account for flame projection giving a total radiation distance of 38.7 m. The distance to the relevant boundary is half the total radiating distance and the required boundary distance will in this case be **19.4 m**.

J.H. McGuire (1965)

This calculation will follow the three main steps that are explained in the summary of J.H. McGuire's method (Chapter 4.6).

1. Height and width of fire compartment.
   H = 8 m (26 ft)
   W = 50 m (164 ft)

2. Percent of window openings in the building facade.
   The external walls are not fire resistance rated ➔ 100 % opening

3. Since the interior walls are fitted with non-combustible linings and the building therefore is considered as "normal", Table 3 in McGuire, 1965, can be applied. Interpolation gives a radiating distance of 38.5 m (126.2 ft). Thus, the distance to the relevant boundary is **19.2 m** (63.1 ft). Note that a horizontal flame projection distance of 1.52 m (5 ft) already is incorporated in the tables.

Peter Collier (1996)

Step 1: Determination of the enclosing rectangle.
The enclosing rectangle equals the whole building facade.

Step 2: Area of enclosing rectangle
$H = 8$ m
$W = 50$ m
$A_e = 8 \times 50 \text{ m}^2 = 400 \text{ m}^2$

Step 3: Aspect ratio, AR.
$AR = H/W$
$AR = 8/50 = 0.16$

Step 4: Radiation intensity of the fire source, I_s.
$T = 345\log_{10}(8t+1)$
$T(120) = 345\log_{10}(8\times120+1) = 1029$ °C
$I_s = 5.67\times10^{-11}T^4$
$I_s = 5.67\times10^{-11}\times (1029+273)^4 = 163.0 \text{ kW/m}^2$

Step 5: Reduction factor, Rf.
$Rf = A_o/A_e$
$Rf = 400/400 = 1$

Step 6: Determination of the emitted radiation, I_e.
$I_e = I_s\times Rf$
$I_e = 163.0\times1 = 163.0 \text{ kW/m}^2$

Step 7: Critical incident radiation, I_{cr}.
$I_{cr} = 12.5 \text{ kW/m}^2$

Step 8: Determination of the permissible configuration factor, ϕ.
$\phi = I_{cr}/I_e$
$\phi = 12.5/ 163.0 = 0.07669$

Step 9: Determination of the separation distance, S.
$S = R+P$
$P = 2$ m (projection distance of flames)
$R = C\sqrt{A_e}$
$C = 1,94$ (obtained from Figure 3)

$R = 1.94\sqrt{400} = 38.75$ m
$S = 38.75+2 = 40.75$ m

Accordingly, the required distance to the relevant boundary with this method is **20.4 m**.

G. Williams-Leir (1970)
The dimensions of the exposing building face (EBF) are:
Width = 164.04 ft
Height = 25.25 ft
$A_{EBF} = 164.04\times 26.25 = 4306.05$ ft^2

Applying Rule 1 gives:
$2\times 0.44(L-3)^2 = A_{EBF}$
$2\times 0.44(L-3)^2 = 4306.05$ ft
$L = 72.95$ ft

Check Rule 2:
$K = 3.54(L-3)$
$K = 3.54(72.95-3) = 247{,}62$ ft $> 164{,}04$ ft ➔ Rule 2 does not apply

Check Rule 3:
$J = 3.14(L-3)$
$J = 3.14(72.95-3) = 219.64$ ft $> 164{,}04$ ft ➔ Rule 3 does not apply

The limiting distance or the distance to the relevant boundary is **22.2 m** (73.0 ft).

Enclosing rectangle (Fire Research Station 1991)
Step 1: Determination of unprotected areas.
The whole building facade should be considered as an unprotected area.

Step 2: Establishing a plane of reference
The plane of reference should be located so that it touches all parts of the building facade.

Step 3: Determination of the area of exposure.
The whole facade of the building should be considered as the area of exposure, i.e. the enclosing rectangle.
Width = 50 m
Height = 9 m
Unprotected area = $50\times 8 = 400$ m^2
Area of enclosing rectangle = $50\times 9 = 450$ m^2
Unprotected percentage = $100\times 400/450 = 88.89$ %

Step 4: Determination of boundary distance.
Table 1 in Fire Research Station (1991), gives for Storage purposes a minimum distance to the relevant boundary of **18.3 m**.

NFPA 80 A (1996)
The width and height of the exposing fire are the same as the facade dimensions, i.e. 164.04 and 26.25 ft respectively. The fire is assumed to penetrate the exterior walls within 20 minutes, giving 100 % openings in the exposing wall. Warehouses and storage facilities can be assumed to have a moderate fire severity, which equals the same configuration factor as used by the other methods for warehouses. In order to find the appropriate guide number g, from Table 4.4, the ratio between the height and width of the exposing fire needs to be calculated.

$W/H = 164.04/26.25 = 6.25$

Interpolation in Table 4.4 gives the guide number g, as follows:

$g = 4.7925$

Note that Table 4.4 already is based on a critical incident radiation of 12.5 kW/m^2 and therefore, no further modifications needs to be done with regards to ignition criteria. The separation distance between the buildings can now be determined as explained below:

$D = g \times Z + 5$
$D = 4.79 \times 26.26 + 5 = 130.80$ ft (39.87 m)

Hence, the required distance to the relevant boundary is **19.9 m** (65.4 ft) and in this distance, account is taken for horizontal flame projection of 1.52 m.

APPENDIX 2 – COMPARISON OF BOUNDARY REQUIREMENTS FOR OFFICE BUILDING

In the comparison, the distance to the relevant boundary will be determined. It is assumed that an identical building is positioned at the same distance from, but on the other side the boundary, i.e. the buildings are mirror images of each other.

The calculation methods and all used equations and terms are presented earlier in this report. The following chapter only shows how the methods are used and what separation distances and boundary distances that are predicted by each method.

In those methods that use enclosing rectangles, the rectangles have been named according to the following:

Rectangle 1:	The rectangle that encloses only one window
Rectangle 2:	The rectangle that encloses two windows
Rectangle 3:	The rectangle that encloses three windows
Rectangle 4:	The rectangle that encloses four windows
Rectangle 5:	The rectangle that encloses five windows
Rectangle 6:	The rectangle that encloses six windows
Rectangle 7:	The rectangle that encloses all seven windows

C.R. Barnett (1988)

The ISO 834 time-temperature curve is used to determine the temperature in the fire compartment.

$T_2 = 345\log_{10}(8\times t_m+1)+T_1$
$T_2(30) = 345\log_{10}(8\times 30+1)+20 = 842\ °C$

Knowing the fire temperature allows the radiant heat flux inside the compartment to be determined.

$I_{EC} = \varepsilon\sigma(T_2^4 - T_1^4)$
$I_{EC} = 1\times 56{,}7\times 10^{-12}[(842+273)^4 - 293^4] = 87.15\ \mathrm{kW/m^2}$

Seven different enclosing rectangles are of interest with regards to determining the minimum required boundary distance. The rectangle resulting in the largest distance should be chosen. Table A2.1 below sets out relevant properties of the enclosing rectangles, configuration factors and eventually the boundary distance. The configuration factors are determined with equation A2.1.

$$\phi_n = \frac{A_E I_{RC}}{A_V I_{EC}} \qquad [A2.1]$$

The radiating distance, i.e. the distance to where the received radiation is 12.5 kW/m^2, has been found by iteration of Equation 4.3. Equation 4.3 is described in the summary of this method by Barnett (Chapter 4.4).

Table A2.1 Relevant measures and boundary distances for the enclosing rectangles

Properties	**Enclosing rectangle**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Width (m)	3	9	15	21	27	33	39
Height (m)	2	2	2	2	2	2	2
Area of openings, A_v (m^2)	6	12	18	24	30	36	42
Area of enclosing rectangle, A_e (m^2)	6	18	30	42	54	66	78
Configuration factor, ϕ	0.1434	0.2151	0.2391	0.2510	0.2582	0.2630	0.2664
Radiating distance, R (m)	3.4	3.9	3.9	3.8	3.7	3.7	3.6
Flame projection, P (m)	2	2	2	2	2	2	2
Boundary distance, B (m)	2.7	3.0	3.0	2.9	2.9	2.9	2.8

The largest and thus the minimum required boundary distance is **3.0 m**. This distance is caused by the rectangles that enclose two and three windows in the storey.

If the designer had chosen a fire duration time of 120 minutes, like what was done for the warehouse, rather than 30 minutes, the required boundary distance would have been 4.7 m. The rectangle that encloses all seven windows in the storey would be the rectangle resulting in the largest boundary distance.

J.H. McGuire (1965)

1. Determination of height and width of fire compartment
   H = 12.47 ft (3.8 m)
   W = 131.23 ft (40 m)

2. Percentage of openings in the facade
   $$\frac{A_v}{A_e}100 = \frac{7*3*2}{3.8*40}100 = 26.18\,\%$$

3. The office is assumed to be fitted with non-combustible linings and therefore, the building is classed as a “normal case” building and has a configuration factor of 0.07. Interpolation of Table 3 in McGuire (1965), sets the building separation to 32.06 ft (9.77 m) and accordingly the boundary distance to **4.9 m** (16 ft). Note that a five feet horizontal flame projection distance is included in the boundary distance.

Peter Collier (1996)

With this method it is interesting to investigate the same seven enclosing rectangles as in the method by Barnett (1988). The plane of reference is located so that it touches the whole length of the building facade. Table A2.2 sets out Step 2-9 for the seven rectangles.

Note that in this method by Collier (1996) and in difference to the method by Barnett (1988), the temperature of ambient air is neglected in the calculations of the fire temperature and radiation intensity.

Table A2.2 Determination of boundary distance

Step	**Properties**	**Enclosing rectangle**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
	Width (m)	3	9	15	21	27	33	39
	Height (m)	2	2	2	2	2	2	2
2	Area of enclosing rectangle, A_e (m^2)	6	18	30	42	54	66	78
3	Aspect ratio, AR	0.667	0.222	0.133	0.095	0.074	0.061	0.051
4	Fire temperature, T (°C)	822	822	822	822	822	822	822
	Radiation intensity, I_s (kW/m^2)	81.45	81.45	81.45	81.45	81.45	81.45	81.45
5	Reduction factor, Rf	1	0.667	0.600	0.571	0.556	0.545	0.538
6	Emitted radiation, I_e (kW/m^2)	81.45	54.33	48.87	46.51	45.29	44.39	43.82
7	Critical incident radiation, I_{CR} (kW/m^2)	12.5	12.5	12.5	12.5	12.5	12.5	12.5
8	Configuration factor, ϕ	0.153	0.230	0.256	0.269	0.276	0.282	0.285
9	Projection distance, P (m)	2	2	2	2	2	2	2
	Factor from Figure 4.3, C	1.34	0.83	0.68	0.53	0.46	0.40	0.35
	Radiating distance, R (m)	3.28	3.52	3.72	3.43	3.38	3.25	3.09
	Separation distance, S (m)	5.28	5.52	5.72	5.43	5.82	5.25	5.09
	Boundary distance, B (m)	2.6	2.8	2.9	2.7	2.7	2.6	2.5

The minimum required boundary distance is **2.9 m**. The largest distance is caused by the rectangle that encloses three windows in the storey.

If the designer had chosen a fire duration time of 120 minutes, like what was done for the warehouse, rather than 30 minutes, the required boundary distance would have been 4.7 m. The rectangle that encloses all seven windows in the storey would be the rectangle resulting in the largest boundary distance in that case.

Enclosing rectangle (Fire Research Station 1991)

The same enclosing rectangles will be investigated with this method as has been done with previous methods. Table A2.3 below gives the necessary properties of Step 3-4 and eventually the boundary distance from Table 1 in Fire Research Station (1991). Note that the enclosing rectangles must have dimensions according to Table 1 in Fire Research Station (1991). Since the building is an office building, it belongs to the Office purpose group, which is considered to have a low fire load density.

Table A2.3 Determination of boundary distances for residential building

Step	**Properties**	**Enclosing rectangle**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
3	Width, W (m)	3	9	15	21	27	40	40
	Height, H (m)	3	3	3	3	3	3	3
	Unprotected area, A_v (m^2)	6	12	18	24	30	36	42
	Area of enclosing rectangle, A_e (m^2)	9	27	45	63	81	120	120
	Unprotected percentage	66.7	44.4	40	38.1	37.0	30	35
4	Boundary distance, B (m)	1.5	1.72	2.0	1.90	1.85	1.5	1.75

With this method, the required boundary distance is **2.0 m** and is caused by the rectangle that encloses three windows.

NFPA 80A (1996)

Once again, five enclosing rectangles have been investigated and the calculation procedure can be followed in Table A2.4. An extra calculation has also been made for the whole extent of the fire compartment, i.e. not only the smallest rectangle that encloses all openings. This extra rectangle is labelled Rectangle 8. All windows are considered to be 100-percents openings. An office building does not generally contain 35 kg of combustible material per metre square or more and the building is therefore classed as having a light exposure severity and the building will then have the same configuration factor as is used in the other methods for office buildings. The guide number g, is obtained from Table 4.4. Since the critical incident radiation already is set to 12.5 kW/m^2, no further compensation needs to be done with regards to this.

Table A2.4 Boundary distances determined with NFPA 80A (1996)

Properties	**Enclosing rectangle**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Width of exposing fire, W (m)	3	9	15	21	27	33	39	40
Height of exposing fire, H (m)	2	2	2	2	2	2	2	3.8
Area of openings, A_v (m^2)	6	12	18	24	30	36	42	42
Area of enclosing rectangle, A_e (m^2)	6	18	30	42	54	66	78	152
Percent of openings	100	66.7	60	57.1	55.6	54.5	53.8	27.6
Width-height ratio, W/H	1.5	4.5	7.5	10.5	13.5	16.5	19.5	10.53
Lesser dimension, L (m)	2	2	2	2	2	2	2	3.8
Guide number, g	1.68	1.96	1.98	1.93	1.90	1.87	1.85	0.838
Separation distance, S (m)	4.88	5.43	5.47	5.39	5.32	5.27	5.22	4.70
Boundary distance, B (m)	2.4	2.7	2.7	2.7	2.7	2.6	2.6	2.4

The largest and hence the required boundary distance predicted by this method is **2.7 m** and is caused by the rectangle that encloses three widows in the storey.

APPENDIX 3 – COMPARISON OF BOUNDARY REQUIREMENTS FOR RESIDENTIAL BUILDING

In the comparison, the distance to the relevant boundary will be determined. It is assumed that an identical building is positioned at the same distance from, but on the other side the boundary, i.e. the buildings are mirror images of each other.

The calculation methods and all used equations and terms are presented earlier in this report. The following chapter only shows how the methods are used and what separation distances and boundary distances that are predicted by each method.

In those methods that use enclosing rectangles, the rectangles have been named according to the following:

Rectangle 1:	The smallest rectangle that encloses all openings
Rectangle 2:	The rectangle that encloses both openings in the recess
Rectangle 3:	The rectangle that encloses the carport in the recess
Rectangle 4:	The rectangle that encloses the door and the two windows closest to it
Rectangle 5:	The smallest rectangle that encloses all openings in the front facade, i.e. the recess not included
Rectangle 6:	The rectangle that encloses the two windows to the left of the recess
Rectangle 7:	The rectangle that encloses the largest window in the front facade, i.e. the recess not included

C.R. Barnett (1988)

The ISO 834 time-temperature curve is used to determine the temperature in the fire compartment.

$T_2 = 345\log_{10}(8\times t_m+1)+T_1$
$T_2(120) = 345\log_{10}(8\times 120+1)+20 = 842$ °C

Knowing the fire temperature allows the radiant heat flux inside the compartment to be determined.

$I_{EC} = \varepsilon\sigma(T_2^4 - T_1^4)$
$I_{EC} = 1\times 56{,}7\times 10^{-12}[(1049+273)^4 - 293^4] = 87.15\ \mathrm{kW/m^2}$

Seven different enclosing rectangles are of interest with regards to determining the minimum required boundary distance. The rectangle resulting in the largest distance should be chosen. Table A3.1 below sets out relevant properties of the enclosing rectangles, configuration factors and eventually the boundary distance. The configuration factors are determined by Equation A3.1.

$$\phi_n = \frac{A_E I_{RC}}{A_V I_{EC}} \qquad [A3.1]$$

The radiating distance, i.e. the distance to where the received radiation is 12.5 kW/m^2, has been found by iteration of Equation 4.3. Equation 4.3 is described in the summary of this method by Barnett (Chapter 4.4).

Table A3.1 Relevant measures and boundary distances for enclosing rectangles used for the residential building

Properties	**Enclosing rectangle**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Width (m)	19	4	4	4.9	14	1.9	3
Height (m)	6.6	6.2	3	6.2	6.6	5.4	1.5
Area of openings, A_v (m^2)	34.98	16.5	12	11.26	18.48	7.22	4.5
Area of enclosing rectangle, A_e (m^2)	125.4	24.8	12	30.38	92.4	10.26	4.5
Configuration factor, ϕ	0.5142	0.2156	0.1434	0.3870	0.7171	0.2038	0.1434
Radiating distance, R (m)	5.1	5.3	4.8	3.9	3.0	3.3	2.9
Flame projection, P (m)	2	2	2	2	2	2	2
Boundary distance, B (m)	3.6	3.7	3.4	3.0	2.5	2.7	2.5

The largest distance is **3.7 m** and is caused by the rectangle that encloses both openings in the recess. However, since the recess is set back 1.5 m, the distance between the relevant boundary and the front facade is instead **3.0 m** resulting from the rectangle that encloses the door and the two windows closest to it. If the recess is assumed not to exist, the rectangle that encloses all openings would call for a boundary distance if **3.6 m**.

If fire duration of two hours had been used instead, the required boundary distance would be 5.9 m. This distance is caused by the rectangle that encloses all unprotected openings in the facade.

J.H. McGuire (1996)

This method is derived for building facades with even distribution of openings. Therefore, reliable results cannot be obtained when this method is applied to the building used in the comparison. A sample calculation has even though been made strictly for comparison purposes. Step 1-3 outlines the calculation procedure. Since the building is irregular shaped, all openings are assumed to be projected onto a plane of reference. The plane of reference joins the extremities of the facade.

1. Determination of height and width of fire compartment
   H = 22.97 ft (7 m)
   W = 65.62 ft (20 m)

2. Percentage of openings in the facade

$$\frac{A_v}{A_e}100 = \frac{3*1.9^2 + 4*3 + 2*3*1.5 + 1.5*2.1}{7*20}100 = 25.0\,\%$$

3. The office is assumed to be fitted with non-combustible linings and therefore, the building is classed as a "normal case" building and has a configuration factor of 0.07. Interpolation of Table 3 in McGuire (1965), sets the building separation to 38.26 ft (11.66 m) and accordingly the boundary distance to **5.8 m** (19 ft). Note that a five feet horizontal flame projection distance is included in the boundary distance and that the boundary distance should be counted from the plane of reference.

Since some parts of the facade are located in front of the plane of reference, extra calculations should be made for this section. However, the percentage of openings within in this section is less than 25 %, which is the lowest value set out in the table. Hence, no separate distance can be found for this section.

Peter Collier (1996)

This method allows for unprotected areas to be projected onto a plane of reference for buildings with irregular shaped facades. In this case, the plane of reference is located so that it touches but not passes through both corners of the recess. The smallest rectangle that encloses all projected unprotected areas in the plane of reference is called Rectangle 8. The plane of reference makes an angle of 17° to the building facade. The recess is dealt with according to methods outlined by Law (1963), which means that calculations should be made for both Rectangle 1 and 8, and the boundary distance be a combination of the two as shown in Figure A3.1. When determining the boundary distance caused by Rectangle 1, the recess is assumed not to exist. To make sure that no single opening or combination of openings call for a greater boundary distance, calculations has also been made for the other six rectangles mentioned above. Table A3.2 sets out Step 2-9 for the eight rectangles.

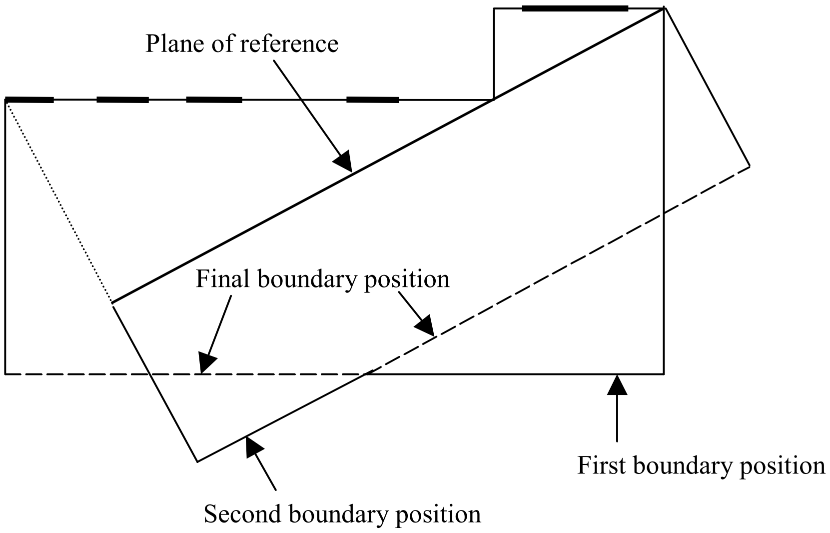


Figure A3.1 Boundary distance for a recess according to Law (1963)

Note that in this method by Collier (1996) and in difference to the method by Barnett (1988), the temperature of ambient air is neglected in the calculations of the fire temperature and radiation intensity.

Table A3.2 Determination of boundary distance

Step	**Properties**	**Enclosing rectangle**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	Width (m)	19	4	4	4.9	14	1.9	3	18.6
	Height (m)	6.6	6.2	3	6.2	6.6	5.4	1.5	6.6
2	Area of enclosing rectangle, A_e (m^2)	125.4	24.8	12	30.4	92.4	10.3	4.5	122.8
3	Aspect ratio, AR	0.347	0.645	0.750	0.790	0.471	0.352	0.500	0.355
4	Fire temperature, T (°C)	822	822	822	822	822	822	822	822
	Radiation intensity, I_s (kW/m^2)	81.45	81.45	81.45	81.45	81.45	81.45	81.45	81.45
5	Reduction factor, Rf	0.279	0.665	1	0.371	0.200	0.704	1	0.285
6	Emitted radiation, I_e (kW/m^2)	22.72	54.14	81.45	30.21	16.28	57.32	81.45	23.21
7	Critical incident radiation, I_{CR} (kW/m^2)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
8	Configuration factor, ϕ	0.550	0.231	0.154	0.414	0.768	0.218	0.154	0.539
9	Projection distance, P (m)	2	2	2	2	2	2	2	2
	Factor from Figure 4.3, C	0.43	0.98	1.38	0.65	0.25	0.98	1.35	0.45
	Radiating distance, R (m)	4.82	4.88	4.78	3.58	2.40	3.15	2.86	4.99
	Separation distance, S (m)	6.82	6.88	6.78	5.58	4.40	5.15	4.86	6.99
	Boundary distance, B (m)	3.4	3.4	3.4	2.8	2.2	2.6	2.4	3.5

The minimum required boundary distance is **3.5 m** and the shape of and distances to the boundary is shown in Figure A3.1 above. No single opening or combination of openings call for a greater separation distance. If the recess were assumed not to exist the required boundary distance would be **3.4 m**

If fire duration of two hours had been used instead, the required boundary distance would be 5.3 m. This distance is caused by the rectangle that encloses all unprotected openings in the facade and is also counted from the plane of reference.

Enclosing rectangle (Fire Research Station, 1996)

The same enclosing rectangles will be investigated with this method as has been done with previous methods. Since the recess is only 1.5 m wide, the recess can be assumed not to exist and the plane of reference positioned in a way that it touches the whole front part of the facade. This method outlines that any parts of the facade that are set back not greater than 1.5m is assumed not to be a set back at all. Table A3.3 below gives the necessary measures of Step 3-4 and eventually the boundary distance from Table 1 in Read, 1991. Note that the enclosing rectangles must have dimensions according to Table 1 in Fire Research Station (1991). Since the building is a residential building, it belongs to the Residential purpose group, which is considered to have a low fire load density.

Table A3.3 Determination of boundary distance

Step	***Properties***	**Enclosing rectangle**						
		1	**2**	**3**	**4**	**5**	**6**	**7**
3	Width, W (m)	21	6	6	6	6	3	3
	Height, H (m)	9	9	3	9	9	6	3
	Unprotected area, A_v (m^2)	34.98	16.5	12	11.26	18.48	7.22	4.5
	Area of enclosing rectangle, A_e (m^2)	189	54	18	54	54	18	9
	Unprotected percentage	18.51	30.56	66.67	20.85	34.22	40.11	50
4	Boundary distance, B (m)	2.0	2.0	2.0	1.1	2.2	1.5	1.5

With this method, the required boundary distance is **2.2 m** and is caused by the rectangle that encloses all windows in the front facade.

NFPA 80A

Once again, seven enclosing rectangles have been investigated and the calculation procedure can be followed in Table A3.4. An extra calculation has also been made for the whole extent of the facade and the enclosing rectangle used for this is named Rectangle 8. All windows are considered to be 100-percents openings. The building is classed as having a light exposure severity in order to make the results from the different calculation methods better comparable. The guide number g, is obtained from Table 2-3 in NFPA 80A, 1996. Since the critical incident radiation already is set to 12.5 kW/m^2, no further compensation needs to be done with regards to this.

Table A3.4 Boundary distances for residential building determined with NFPA 80A (1996

Properties	**Enclosing rectangle**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Width of exposing fire, W (m)	19	4	4	4.9	14	1.9	3	20
Height of exposing fire, H (m)	6.6	6.2	3	6.2	6.6	5.4	1.5	7
Area of openings, A_v (m^2)	34.98	16.5	12	11.26	18.48	7.22	4.5	34.98
Area of enclosing rectangle, A_e (m^2)	125.4	24.8	12	30.38	92.4	10.26	4.6	140
Percent of openings	27.89	66.53	100	37.06	20	70.37	100	24.99
Width-height ratio, W/H	2.879	1.550	1.333	1.267	2.121	2.844	2	2.857
Lesser dimension, L (m)	6.6	4	3	4.9	6.6	1.9	1.5	7
Guide number, G	0.782	1.323	1.58	0.785	0.465	1.768	1.93	0.672
Separation distance, S (m)	6.68	6.81	6.26	5.37	4.59	4.88	4.42	6.22
Boundary distance, B (m)	3.3	3.4	3.1	2.7	2.3	2.4	2.2	3.1

The largest distance predicted by this method is **3.4 m** and arises from the rectangle that encloses all the openings in the recess. However, since this rectangle is set back 1.5 m, the largest boundary distance resulting from the front facade is **2.7 m**. If the recess is assumed not to exist, the required boundary distance would be **3.3 m**.

A boundary distance of **5.9 m** would be required if the building was classed as having a moderate exposure severity.

APPENDIX 4 – IMPORTANCE OF RADIATION FROM PROJECTED FLAMES

This chapter contains the performed calculations for the comparison of radiation from a compartment with projected flames according to Fredlund et al. (1976) and notional radiators at various distances. The radiation from the notional radiators has been calculated with the method discussed in Chapter 6 and the used temperatures are obtained from Fredlund et al. (1976) for the specific compartment configuration. The results are presented directly in the figures presented below.

Case 1a

Compartment: 5×4.5×2.4 m (width×depth×height)
1 window: 3×1.5 m (width×height)
Fire load: 30 Mcal/m^2 (125 MJ/m^2)
Distance: 5 m

Calculation procedure

1. Fire load f = 30 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot} = (3\times1.5\sqrt{1.5})/(5\times4.5\times2+5\times2.4\times2+4.5\times2.4\times2) = 0.060\ \mathrm{m}^{1/2}$
3. f = 30 Mcal/m^2 and $A\sqrt{h}/A_{tot} = 0.060\ \mathrm{m}^{1/2}$ → Table 20a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p} = 92.5\ \mathrm{m}^2$
   $\varepsilon_{mp} = 1$
   $\gamma_p = 4.5/4.5 = 1$
   $P_{max,p} = 1\times1\times(92.5/85)\times P_{max,t} = 1.088\ P_{max,t}$
   c = 5 m → $P_{max,t} = 9.3\ \mathrm{kW/m^2}$ → $P_{max,p} = 1.088\times9.3 =$ **10.1 kW/m^2**
5. Figure A4.1 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

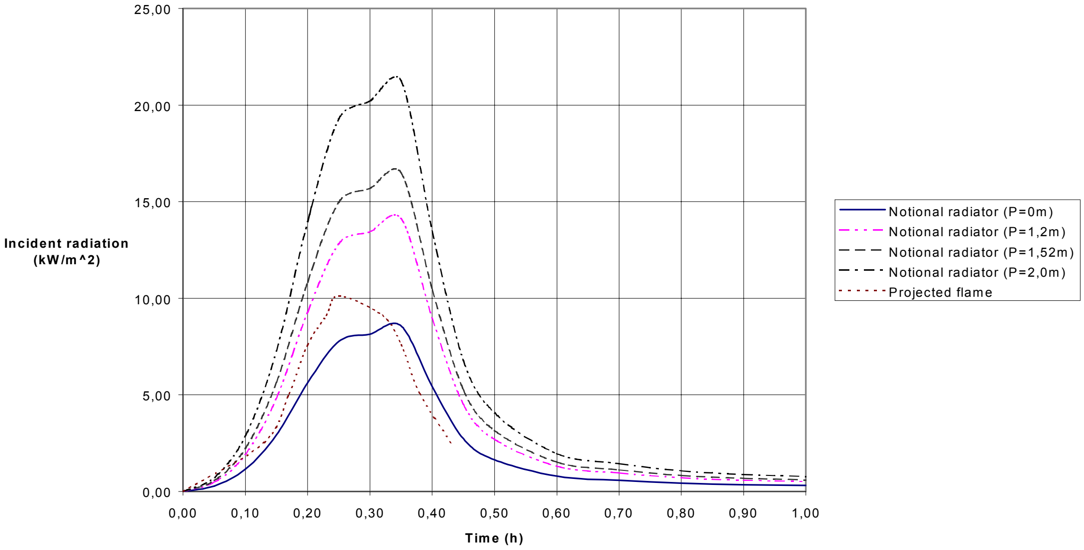


Figure A4.1 Received radiation for case 1a

Case 1b

Compartment: 5×4.5×2.4 m (width×depth×height)
1 window: 3×1.5 m (width×height)

Fire load: 50 Mcal/m^2 (125 MJ/m^2)
Distance: 5 m

Calculation procedure

1. Fire load f = 50 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = (3×1.5 $\sqrt{1.5}$)/(5×4.5×2+5×2.4×2+4.5×2.4×2) = 0.060 m$^{1/2}$
3. f = 50 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.060 m$^{1/2}$ → Table 22a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p} = 92.5$ m^2
   $\varepsilon_{mp} = 1$
   $\gamma_p = 4.5/4.5 = 1$
   $P_{max,p} = 1\times1\times (92.5/85) \times P_{max,t} = 1.088\ P_{max,t}$
   c = 5 m → $P_{max,t}$ = 10.2 kW/m^2 → $P_{max,p}$ = 1.088×10.2 = **11.1 kW/m^2**
5. Figure A4.2 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

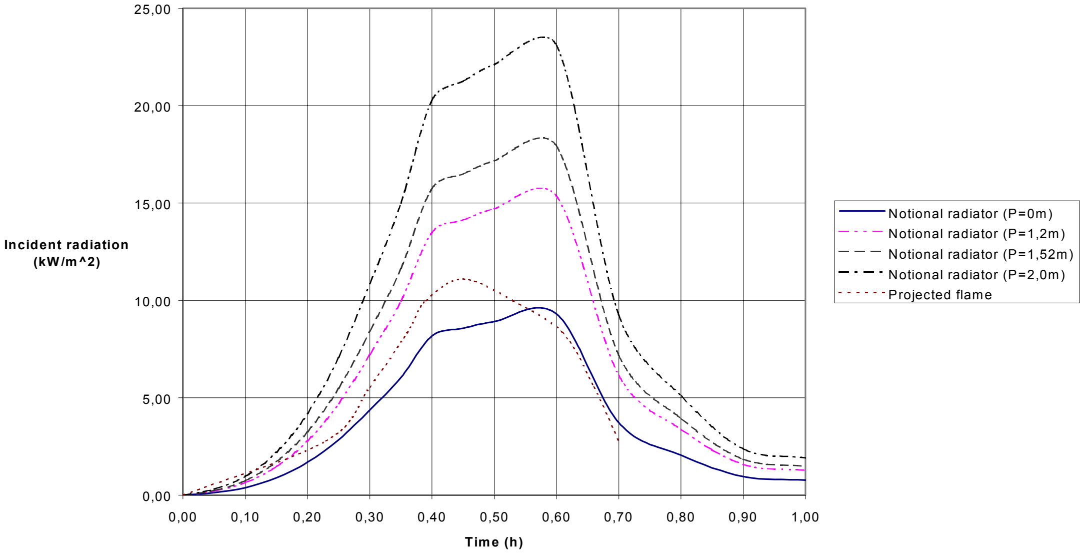


Figure A4.2 Received radiation for case 1b

Case 2

Compartment: 8×10×2.5 m (width×depth×height)
3 windows: 2×1.3 m (width×height) each
1 window: 4.2×1.3 m (width×height)
Fire load: 50 Mcal/m^2 (209 MJ/m^2)
Distance: 5 m

Calculation procedure

1. Fire load f = 50 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = ([3×2×1.3+4.2×1.3] $\sqrt{1.3}$)/(8×10×2+8×2.5×2+10×2.5×2) = 0.040 m$^{1/2}$
3. f = 50 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.040 m$^{1/2}$ → Table 14a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p} = 250$ m^2

$\varepsilon_{mp} = 1$
$\gamma_p = (4.2\times1.3)/(3\times2\times1.3+4.2\times1.3) = 0.411$
$P_{max,p} = 1\times0.411\times(250/85)\times P_{max,t} = 1.209\ P_{max,t}$
c = 5 m → $P_{max,t} = 10.2$ kW/m^2 → $P_{max,p} = 1.209\times10.2 =$ **12.3 kW/m^2**

5. Figure A4.3 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

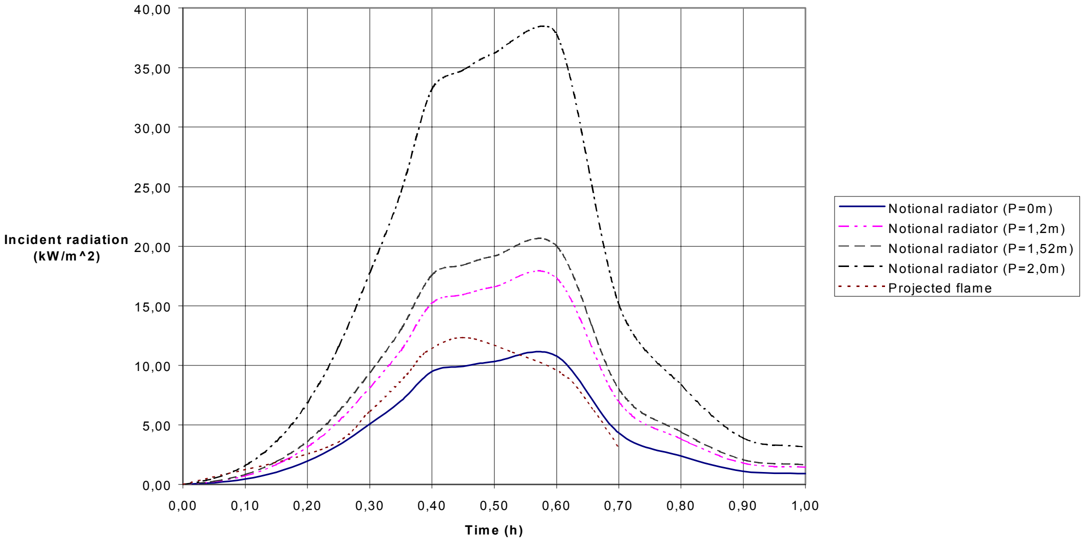


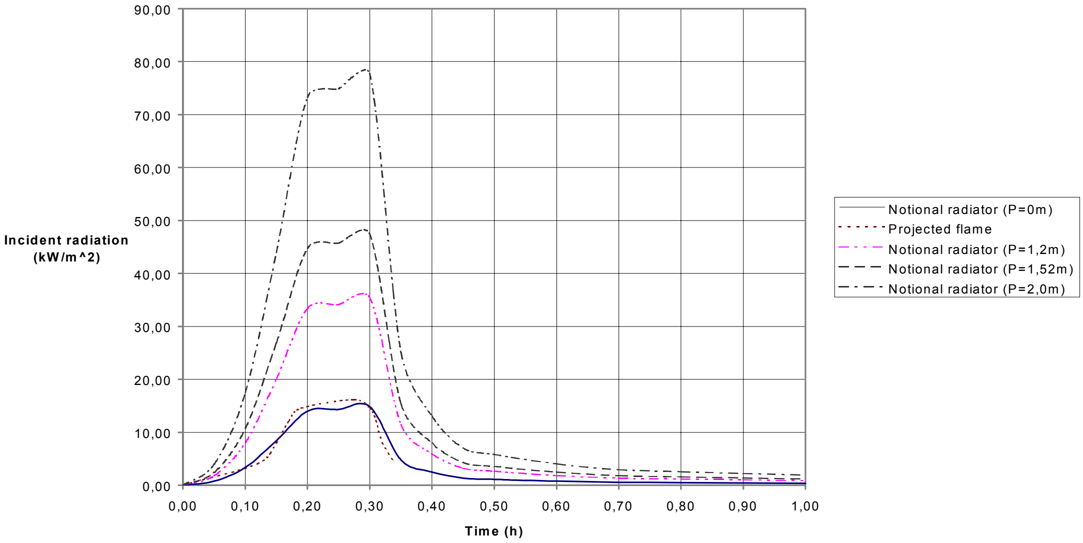
Figure A4.3 Received radiation for case 2

Case 3

Compartment: 10×5×2.5 m (width×depth×height)
6 windows: 2×1.3 m (width×height) each
Fire load: 40 Mcal/m^2 (167 MJ/m^2)
Distance: 3 m

Calculation procedure

1. Fire load f = 40 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = $(6\times2\times1.3\sqrt{1.3})/(5\times10\times2+5\times2.5\times2+10\times2.5\times2) = 0.10$ m$^{1/2}$
3. f = 40 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.010 m$^{1/2}$ → Table 37a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p} = 175$ m^2
   $\varepsilon_{mp} = 1$
   $\gamma_p = 1/6 = 0.167$
   $P_{max,p} = 1\times0.167\times(175/85)\times P_{max,t} = 0.343\ P_{max,t}$
   c = 5 m → $P_{max,t} = 47.1$ kW/m^2 → $P_{max,p} = 0.343\times47.1 =$ **16.2 kW/m^2**
5. Figure A4.4 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.



A4.4 Received radiation for case 3

Case 4

Compartment: 6.3×5.5×3.0 m (width×depth×height)
2 windows: 1×2 m (width×height) each
Fire load: 30 Mcal/m^2 (125 MJ/m^2)
Distance: 3 m

Calculation procedure

1. Fire load f = 30 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = (2×2×1 $\sqrt{2}$)/(6.3×5.5×2+6.3×3×2+5.5×3×2) = 0.040 m$^{1/2}$
3. f = 30 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.040 m$^{1/2}$ → Table 12a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p} = 140.1$ m^2
   $\varepsilon_{mp} = 1$
   $\gamma_p = 1/2 = 0.5$
   $P_{max,p} = 1 \times 0.5 \times (140.1/85) \times P_{max,t} = 0.824\ P_{max,t}$
   c = 3 m → $P_{max,t}$ = 15.5 kW/m^2 → $P_{max,p}$ = 0.824×15.5 **= 12.8 kW/m^2**
5. Figure A4.5 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

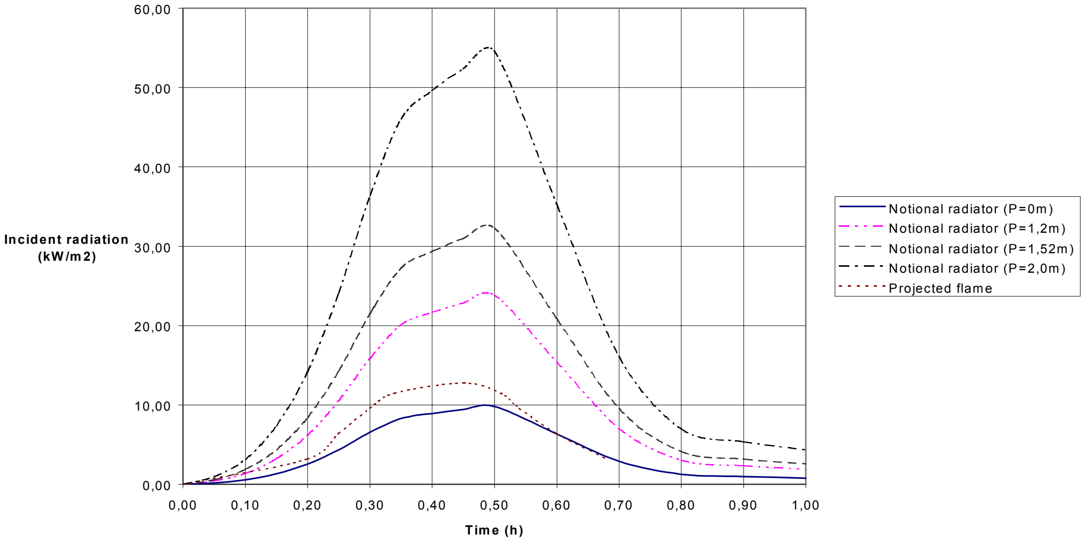


Figure A4.5 Received radiation for case 4

Case 5

Compartment: 10×8×2.5 m (width×depth×height)
4 windows: 1.45×1.45 m (width×height) each
Fire load: 50 Mcal/m^2 (125 MJ/m^2)
Distance: 3 m

Calculation procedure

1. Fire load f = 50 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = (4×1.45×1.45 $\sqrt{1.45}$)/(10×8×2+10×2.5×2+8×2.5×2) = 0.040 m$^{1/2}$
3. f = 50 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.040 m$^{1/2}$ → Table 14a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p}$ = 250 m^2
   $\varepsilon_{mp} = 1$
   $\gamma_p = 1/4 = 0.25$
   $P_{max,p} = 1\times0.25\times(250/85)\times P_{max,t} = 0.735\ P_{max,t}$
   c = 3 m → $P_{max,t}$ = 17.8 kW/m^2 → $P_{max,p}$ = 0.735×17.8 **= 13.1 kW/m^2**
5. Figure A4.6 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

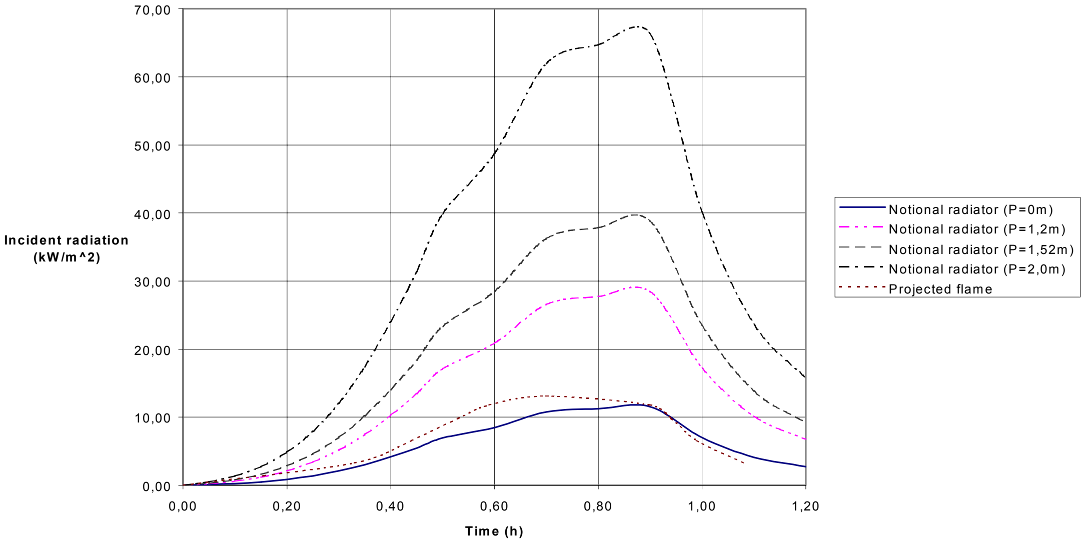


Figure A4.6 Received radiation for case 5

Case 6

Compartment: 4×4×2.5 m (width×depth×height)
1 window: 1.52×1.52 m (width×height)
Fire load: 30 Mcal/m^2 (125 MJ/m^2)
Distance: 3, 4, 5, 6 and 8 m

<u>Calculation procedure</u>

1. Fire load f = 30 Mcal/m^2 (125 MJ/m^2)
2. $A\sqrt{h}/A_{tot}$ = (1.52×1.52 $\sqrt{1.52}$)/(4×4×2+4×2.5×2+4×2.5×2) = 0.040 m$^{1/2}$
3. f = 30 Mcal/m^2 and $A\sqrt{h}/A_{tot}$ = 0.040 m$^{1/2}$ → Table 12a-b Appendix 2 and time-temperature curve from Appendix 1 in Fredlund et al. (1976)
4. $A_{tot,p}$ = 72 m^2
   $\varepsilon_{mp} = 1$
   $\gamma_p = 1$
   $P_{max,p} = 1\times1\times(72/85)\times P_{max,t} = 0.847\ P_{max,t}$
   c = 3 m → $P_{max,t}$ = 15.5 kW/m^2 → $P_{max,p}$ = 0.847×15.5 **= 13.1 kW/m^2**
   c = 4 m → $P_{max,t}$ = 7.6 kW/m^2 → $P_{max,p}$ = 0.847×7.6 **= 6.4 kW/m^2**
   c = 5 m → $P_{max,t}$ = 4.7 kW/m^2 → $P_{max,p}$ = 0.847×4.7 **= 4.0 kW/m^2**
   c = 6 m → $P_{max,t}$ = 3.2 kW/m^2 → $P_{max,p}$ = 0.847×3.2 **= 2.7 kW/m^2**
   c = 8 m → $P_{max,t}$ = 1.8 kW/m^2 → $P_{max,p}$ = 0.847×1.8 **= 1.5 kW/m^2**
5. Figure A4.7 shows the time-radiation relationship at the receiving point for the method by Fredlund et al. (1976) and notional radiators at various projection distances.

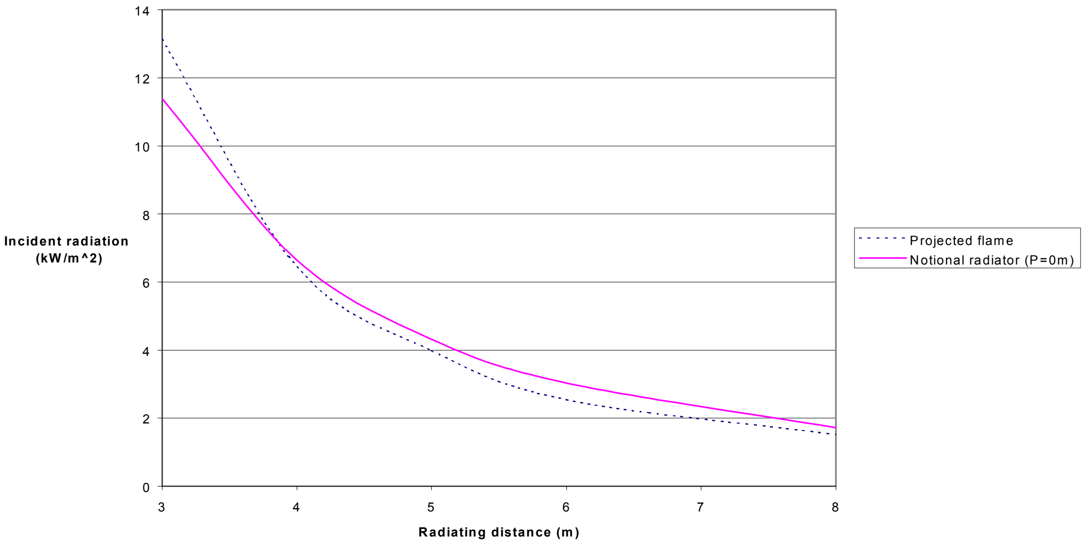


Figure A4.7 Received radiation for case 6