Fire Separation between External Walls of Buildings

C. R. BARNETT
Macdonald Barnett Partners, Ltd.
P.O. Box 37-077
Auckland, New Zealand

ABSTRACT

Most fire codes use only one or two radiation flux values when considering the external walls of buildings. If it is satisfactory to assume fire compartment temperatures are proportional to time, then it should be equally satisfactory to assume radiation flux levels are proportional to time. On this premise and using the standard time-temperature curve, a wider than usual range of design radiation values can be derived which are in step with standard FRR ratings. The method allows building designers more flexibility in the choice of ordinary or fire windows, both in "mirror-image" or "non mirror-image" situations.

INTRODUCTION

The paper focuses attention on the protection of "neighbour's property". Sub-divided into five categories, the hazards likely to cause a neighbour's property to be ignited by a burning building are:- external wall collapse; flying brands; flame contact; emitted heat radiation; received heat radiation. For the protection of the neighbour's property, certain steps need to be taken by the owners and different steps by the neighbours. The only way to provide mutual protection is to ensure that all buildings are built on the basis that during their lifetime they could be both an owner's (burning) building and a neighbour's (non-burning) building.

In a fire sense, an "external" wall is a special kind of wall that is different from ordinary internal walls, and may be different from fire walls and fire partitions. Within flame contact range, the external wall needs to function like a fire wall and cope with fire from both sides. Beyond flame contact range, but within radiation danger range, the external wall needs to cope with fire from inside and radiation on the outside.

It has long been recognised that the risk of fire spreading from one building to another reduces as the distance between them increases. Once the limiting radiation danger distance is exceeded no measures need to be taken for neighbour's property safety. Spreading risk can be eliminated if the buildings are far enough apart. In areas where no stored or running water may be available, such as rural areas, remote islands, or the Antarctic; this may be the only economic solution to fire spreading risks.

The aim of this paper is to provide a guide for building designers by setting out the principles for a "fire engineering design method for sepa-

ration between buildings" which can be used in step with a "fire engineering design method for fire compartment areas" (to be published). Both design methods will encourage smaller fire compartments to be constructed, which can in turn reduce the cost of property lost by fire.

MEANING OF "DISTANCE"

Because either building can catch fire, the positions of owner and neighbour can be reversed and all wall criteria apply equally to both parties. That is, each building situation should be regarded as the "mirror-image" of the other as illustrated in Fig. 1. Where the owner has no control over the neighbour's construction, "mirror-imaging" or equal limiting distances may not occur but safety is not necessarily impaired as illustrated in Fig. 2. "Mirror-imaging" does not necessarily err on the side of safety for unequal limiting distances as illustrated in Fig. 3. The meaning of distance is important in Fire Code applications and needs to be clearly understood. For the purpose of this paper, the following definitions shall be used:-

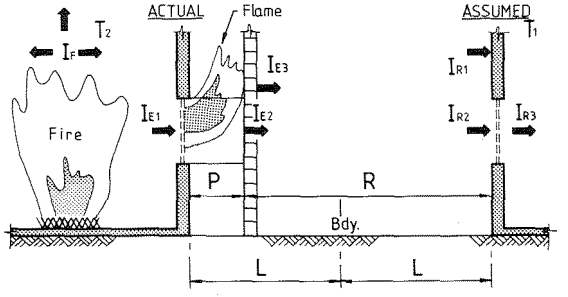
a) radiation distance (R) shall be the distance between the flame front of a burning building and the face of any exposed building.
b) separation distance (S) shall be the distance between the wall face of the burning building and the wall face of any exposed building.
c) limiting distance (L) shall be half the separation distance between the face of a burning building and the face of any exposed building.
d) protected limiting distance (L_x) shall be a value of the limiting distance specified by the writers of the Fire Code in which fire resistance closures shall be mandatory.
e) flame projecting distance (P) shall be either 2 metres (or less if calculated in an approved manner under full wind conditions), or zero if suitable fire windows are installed.

EXTERNAL WALL COLLAPSE

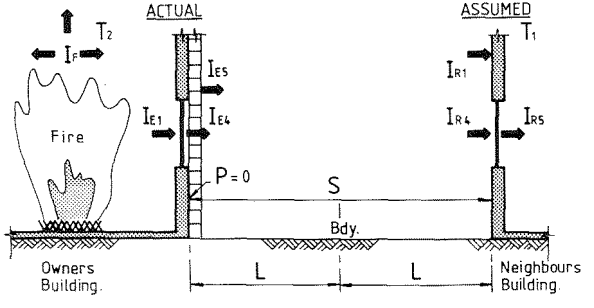
In designing the owner's building, ignition of the neighbour's property by the owner's wall collapse can be controlled by ensuring that any external wall of the owner's building within falling danger range (assumed as the height of the owner's wall), should remain standing for the duration of the fire to act as a heat barrier to prevent spread of fire to a neighbour's building. If any parts of the external wall collapse too soon, projecting flame sizes may be increased and emitted radiation areas will certainly be increased. Both effects may cause an ignition of the neighbour's property which otherwise may not have occurred.

FLYING BRANDS

Combustible materials on or inside neighbouring buildings can be ignited from a fire by any of three forms of ignition termed "spontaneous", "pilot" and "contact" ignition respectively. The most common combustible material found on the exterior of buildings is wood and its ignition behaviour when pre-heated by radiation is representative of a large variety of combustible building materials. Law (1963) quotes typical values of radiation intensities for pilot and spontaneous ignition of wood as 12.5 kW/m^2 (0.3 $cal/cm^2.s$) and 33.5 kW/m^2 (0.8 $cal/cm^2.s$) respectively. Where a neighbouring building exterior does not have any combustible material on the exterior and has fire windows installed, neither contact ignition nor pilot ignition will apply and flying brands can be ignored. Where a neighbouring building has ordinary glazing in its windows liable to crack under radiant



(a) ORDINARY WINDOWS - MIRROR IMAGED



(b) FIRE WINDOWS - MIRROR IMAGED

FIG.1: DIAGRAMS ILLUSTRATING SEPARATION DISTANCE S, FLAME PROJECTION DISTANCE P AND LIMITING DISTANCE L FOR ORDINARY WINDOWS AND FIRE WINDOWS RADIATION DISTANCE IS R

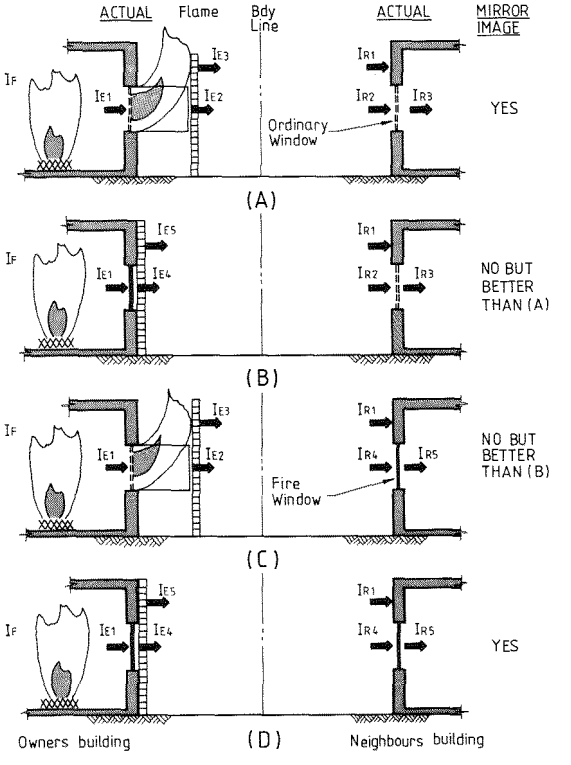


FIG.2 DIAGRAM ILLUSTRATING DIFFERENCES BETWEEN ORDINARY & FIRE WINDOWS AT EQUAL LIMITING DISTANCE WHEN BASED ON "MIRROR IMAGING."

heat; then through any broken opening of the window, flying brands may cause pilot ignition of combustibles just inside the window such as curtaining, wood panelling or stored goods.

FLAME CONTACT

The danger range for flame contact depends on the dimensions of the projecting flame. Law and O'Brien's (1983) steel building design guide provides a detailed method of calculating flame size, height, horizontal projection distance and temperature with and without wind conditions. Butcher and Parnell (1983) give examples of horizontal flame projections. In general, it can be said that under no wind conditions, flames will project a distance varying from half the window height for long windows to 1½ times the window height for square windows.

The control of ignition between buildings depends on the selected design values of the flame projection distance P and the specified protected limiting distance L_X. The values of P and L_X vary between different codes and are not always easy to determine from the codes themselves. For example, the British system seems to work from face-to-face of buildings, that is P = 0 m and L_X = 0 m. The Canadian system seems to work from flame front to building face using P = 1.5 m and L_X = 1.2 m.

4 x 4 matrix diagrams can be drawn up to illustrate the effect of varying values of P and L_X. For example, where P = 2 m, L_X = 0 m and ordinary glazing is used, it can be shown that flame contact will occur in 6 out of the 16 situations. If "approved" closures are used in the external walls of the O-buildings and the N-buildings, flames will both be prevented from gaining exit via the owner's openings and gaining entry via the neighbour's openings. The probability of remaining flame contacts then depends on the value of the protected limiting distance L_X as set by the Fire Code writers. For example, for P = 2 m and L_X = 1 m, Fig. 3 shows that the number of flame contacts reduces to 1 in 16 cases and then only against a fire window (case 2/0). Mirror-imaging only occurs in 4 cases, namely the 0/0, 1/1, 2/2 and 3/3 situations. Some of the non-mirror situations are unsafe. For example, situations 0/1 when reversed introduces a radiation hazard in that the area of openings for the N-building are set for R = 2 m, whereas in fact R = 1 m, thereby increasing the received radiation levels inside the O-building. Similarly in situation 2/3, the N-building "thinks" R = 4 m, when in fact R = 3 m. Where P = 2 m and L_X = 2 m, flame contact occurs in none of the 16 situations listed, 0/1 remains unsafe as in Fig. 3, but 2/3 improves.

PROJECTING FLAME TEMPERATURES

A flame projecting outside a window can radiate heat back onto the wall directly behind the rising flame, to adjacent external structural members, and to a neighbouring building. Law and O'Brien's (1983) design method is derived from the expression $t_f = L/(A_W A_T)^{\frac{1}{2}}$, where t_f = effective fire resistance time in minutes; L = total fire load in kg; A_W = ventilation (window) area in square metres; and A_T = area of fire compartment surfaces, but excluding A_W in square metres (Law (1971)). The design method suggests that if the levels of flame and compartment temperature reached are proportional to time, then the compartment radiation level is also proportional to time.

Butcher and Parnell (1983) give examples of flame temperatures for six window sizes, ranging from 300°C to 600°C or averaging 450°C for a compartment temperature of 1100°C. Keough (1963) suggests flame temperatures of 850, 1000 and 1250°C should be used for design purposes corresponding to

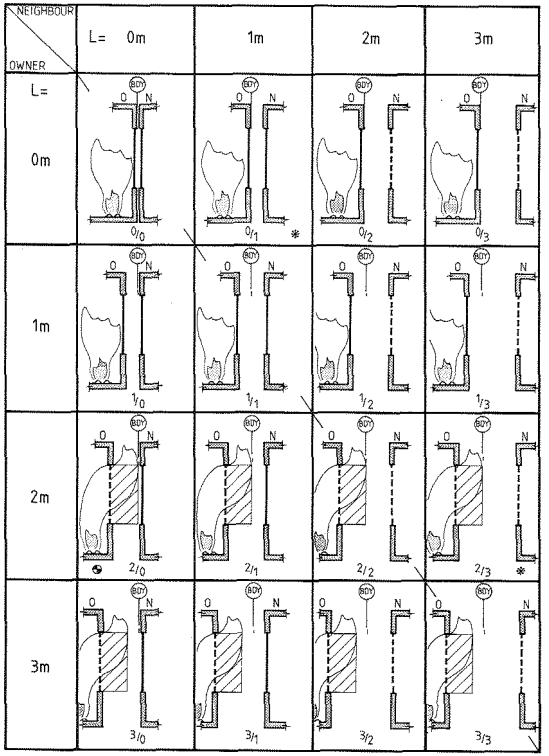


FIG.3 ILLUSTRATING FLAME CONTACT FOR P=2m & Lx=1m
FLAME CONTACT REDUCES TO 1 OUT OF 16 CASES (MARKED ⚽)
2 CASES ARE ALSO UNSAFE FROM RADIATION HAZARD
WHEN O & N ARE REVERSED (MARKED *)

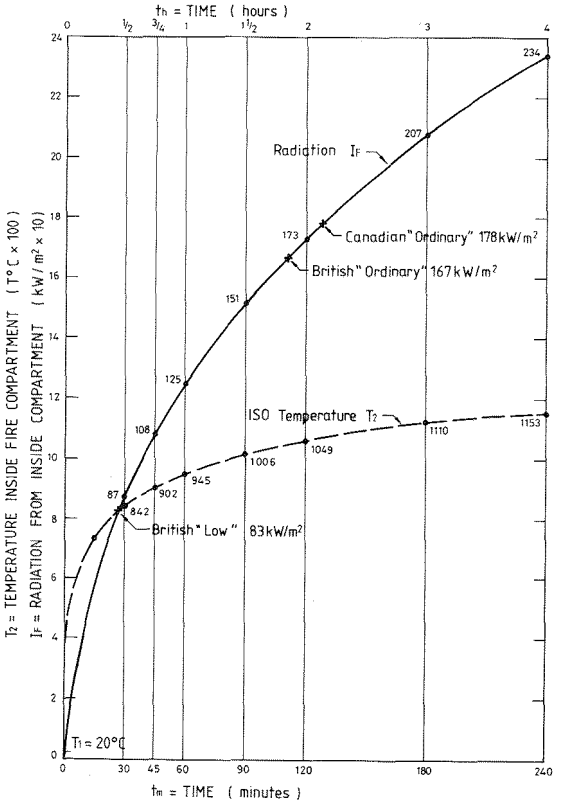


FIG.4 VALUES FOR ISO TEMPERATURE T_2 AND CORRESPONDING
RADIATION I_F VERSUS TIME t FOR A FIRE COMPARTMENT

effective radiation levels of 83.6, 150 and 300 kW/m^2. For the purpose of fire separation distance an average projecting flame temperature of 600^{o}C could be assumed as reasonable for all compartments where temperatures range from 842^{o}C (for ½ hour FRR) to 1153^{o}C (for 4 hour FRR).

EMISSIVITY

The intensity of radiant heat energy given off by a heated object depends on its emissivity ε. The perfect emitter is a "black" body and has an emissivity of unity. A fire compartment when heated acts as a cavity radiator with holes in it and thus approximates a "black" body with an emissivity of 1.00. On the other hand, the emissivity of flames emerging from openings depends on the type of fuel, the type and size of particles burning within the flame, and the thickness of the flames. For building fires, Law and O'Brien (1983) in their design Table 9 list a range of emissivities for flame thickness. When required for the purpose of fire separation design, compartment emissivity could be assumed as 1.00 and flame emissivity as 0.45 for 2 m flame thickness.

CONFIGURATION FACTORS

The intensity of radiant energy I_R falling on a surface remote from the emitter can be found by using an appropriate "configuration" factor ϕ_n which takes into account the geometrical relationship between the emitter and receiver. For external building facades a rectangular radiator F is assumed of height H and width W, which in turn is divided into four equal rectangles A, B, C and D. The configuration ϕ_A for rectangle A is taken perpendicular to the central corner of rectangle A. Similarly for B, C and D. This method of presentation allows advantage to be taken of the fact that configuration factors are additive. The value of ϕ_A would vary from 0 to 0.25, and the value of ϕ_n from 0 to 1.0. The total configuration factor ϕ_n for the whole rectangle is made up of the individual configuration factors for rectangles A, B, C and D thus:-

$$\phi_n = \phi_A + \phi_B + \phi_C + \phi_D = 4\phi_A \qquad (1)$$

Drysdale (1983 and 1985) illustrates graphical methods of determining ϕ_A. Law and O'Brien (1983) use the following formula for a receiver parallel to the radiator:-

$$\phi_A \quad \frac{1}{360}\left[\frac{x}{(1+x^2)^{\frac{1}{2}}}.\tan^{-1}\frac{y}{(1+x^2)^{\frac{1}{2}}} + \frac{y}{(1+y^2)^{\frac{1}{2}}}.\tan^{-1}\frac{x}{(1+y^2)^{\frac{1}{2}}}\right] \qquad (2)$$

where $x = H_A/R = H/2R$; $y = W_A/R = W/2R$; H_A = height of quarter rectangle A = H/2; W_A = width of quarter rectangle A = W/2; R = radiation distance between emitter and receiver; and $\tan^{-1}$ = degree mode. Eqs. (1) and (2) do not depend on the use of water and hence can be safely applied in non-water regions such as rural areas, small islands and frozen climates.

EMITTED HEAT RADIATION

Increasing the separation distance between buildings reduces the radiation hazard, but for a given separation distance the intensity of received radiation I_R on the non-burning building depends on the intensity of emitted radiation I_E from the burning building. The maximum fire compartment temperature T_2 in degrees Centigrade can be determined in a number of ways from a standard time-temperature formula such as BS 476 or ISO 834 as follows:-

$$T_2 = 345 \log_{10} (8 t_m + 1) + T_1 \quad {}^{o}C \qquad (3)$$

The radiant energy flux I_F present inside a fire compartment can be considered to be proportional to the difference in temperature of the fire compartment T_2 and its surrounding T_1 in degrees Kelvin thus:-

$$I_F = \varepsilon \sigma (T_2^4 - T_1^4) \quad kW/m^2 \qquad (4)$$

I_F can be considered as radiating in all directions inside the fire compartment at once and can therefore be expected to be the same value I_{E1} just inside any opening as illustrated in Fig. 1, thus $I_{E1} = I_F$. By using Eqs. (3) and (4), values of I_{E1} corresponding to standard fire resistance rating times can be determined as shown in Fig. 4.

Arising from the emitted radiation just inside the opening I_{E1}, the question arises as to what critical value of emitted radiation I_{EC} should be used outside the building. This will depend on whether the glazing remains in position or not. Fig. 1 illustrates I_{E2} as the critical value for ordinary windows and I_{E4} for fire windows. Grubits (1985) reports that when the glass remains in position, the radiation is reduced to a value between 7% and 46% of the impressed radiant heat. Thus a radiation reduction factor k_1 of 0.50 through wired glass would appear to be a reasonable design assumption. Providing the glass remains in position, this reduced radiation effect can be utilised in building separation calculations.

When ordinary glazing cracks and falls out of the openings, flames commence to project outside the building. The flame area greater than the openings are ignored and the radiating openings are assumed to be acting, not at the face of the building wall, but at a distance out from the building face equal to the flame projecting distance P. Law (1971) sets out the reasons why radiation from projecting flames are usually neglected in fire separation calculations. This is considered to be a conservative adjustment which greatly simplifies the design procedure for radiation distance calculations.

For ordinary glazing, $k_1 = 1.0$ and thus $I_{EC} = I_{E2} = I_{E1} = I_F$. For fire resistant glazing $k_1 = 0.50$ and thus $I_{EC} = I_{E4} = 0.5\ I_{E1} = 0.5\ I_F$. The above values for I_{EC} refer to the unit radiation from one opening. Most external walls have a number of openings, but the problem can be reduced to that of a single radiator, termed the "enclosing rectangle" which is considered as emitting radiation over its whole area at a reduced intensity I_{E3} (or I_{E5}) (refer Figs. 1 and 2). The "enclosing rectangle" should be taken for a number of selected large and small cases as shown on Fig. 5, the worst

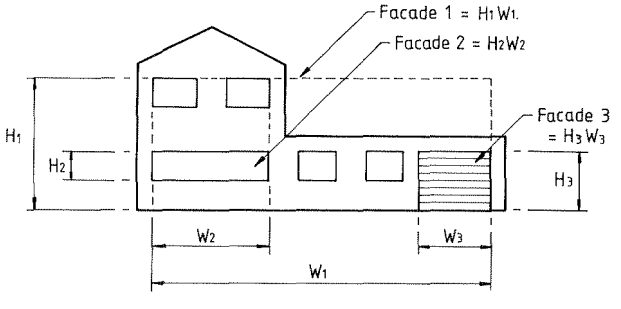


FIG. 5 ILLUSTRATION OF VARIOUS TYPES OF FACADES FROM WHICH SEPARATION DISTANCES ARE CALCULATED

case applying. The reduction factor k_v is taken as the ratio of the sum of the areas of all the vertical openings in the wall A_v to the total area of the enclosing rectangle A_E = H x W. k_v is also equal to the ratio between I_{E3} (or I_{E5}) and I_{EC} thus:-

$$k_v = \frac{A_v}{A_E} = \frac{I_{E3}}{I_{EC}} \text{ or } \frac{I_{E5}}{I_{EC}} \qquad (5)$$

RECEIVED HEAT RADIATION

When a neighbour's building receives heat radiation I_R, there is not only the hazard to any combustible material on the outside of the building I_{R1}, but also to the combustible contents in any rooms likely to receive radiation through glazed or unglazed openings I_{R3}, or fire windows I_{R5}. Refer to Figs. 1 and 2 which also show the received radiation just outside the openings as I_{R2} for ordinary windows and I_{R4} for fire windows. For design purposes the critical design value of received radiation I_{RC} will be the least value of I_{R1}, I_{R2} and I_{R4}. In order to avoid ignition by received radiation, limits have to be set on the values of I_{RC} depending on whether the situation is likely to be exposed to pilot ignition or spontaneous ignition. The critical design value I_{RC} can be compared with the radiant energy I_R received by a surface remote from a heated emitter as follows:-

$$I_R = \phi_n . I_{E3} \leq I_{RC} \qquad (6)$$

If the neighbour's building has a combustible material on the exterior walls, pilot ignition of 12.5 kW/m^2 is the likely criteria. Thus for design purposes $I_{RC} = I_{R1}$ = 12.5 kW/m^2. Ordinary glazing is likely to crack and fall out. This means the radiation reduction effect through ordinary glass cannot be relied on and pilot ignition of combustible materials just inside the openings must be used. The recommended radiant flux value based on pilot ignition should be 12.5 kW/m^2. Thus for design purposes $I_{RC} = I_{R2} = I_{R3}$ = 12.5 kW/m^2. For fire resistant glazing likely to remain in position for the design duration period of the burning building fire, then a spontaneous ignition value such as 25 kW/m^2 or other selected value will apply for I_{R5} inside the window. And if k_2 = 0.50 resulting in 50% radiation reduction through the fire window, the design value for I_{R4} outside the window can be twice I_{R5}, that is 50 kW/m^2. Thus for design purposes $I_{RC} = I_{R4} = I_{R5}/k_2$ = 50 kW/m^2.

The reason for selecting different reduction coefficients k_1 and k_2, is that while they may be the same for cases (a) and (d) as illustrated on Fig. 2, they will be different when cases (c) and (c) are being applied.

DESIGN METHODS

There are two methods available for the fire engineering design of separation between buildings depending on whether the required answer is to be in terms of the maximum permissible openings in the owner's building or the level of received radiation on the neighbour's building for a given set of owner's openings. In the first design method, the calculations are entered with FRR, k_1, k_2, T_1, I_{R1}, I_{R3}, I_{R5}, L or S, P, H and W. I_{EC} is calculated through Eqs. (3) and (4). I_{RC} is taken as the least value of I_{R1}, I_{R2} or I_{R4}. ϕ_n is determined from Eqs. (1) and (2) after ascertaining the appropriate R. A_E is determined from H and W. By combining Eqs. (5) and (6), the maximum permissible area of openings A_v can then be calculated as:-

$$A_v = \frac{A_E . I_{RC}}{\phi_n . I_{EC}} \quad m^2 \qquad (7)$$

In the second design method, the calculations are entered with FRR, k_1, T_1, L or S, P, H, W and A_v. I_{EC}, ϕ_n, A_E and k_v are calculated as above. The value of I_R is determined and compared with I_{RC} as follows:-

$$I_R = k_v.\phi_n.I_{EC} \leq I_{RC} \qquad kW/m^2 \qquad (8)$$

Eqs. (7) and (8) can be used to check existing fire codes providing the correct entry values can be identified. For instance, British Building Regulations (1985) appear to work from face-to-face of buildings with no allowances for flame projection or fire windows, i.e. P = 0 m, L_X = 0 m and FRR input values of ½ and 2 hours respectively. The National Building Code of Canada (1985) appears to work from flame front to face of building using P = 1.5 m, L_X = 1.2 m, and FRR input values of 2 and 7 hours respectively.

CONCLUSIONS

Five meanings for "distance" are defined for use in fire engineering design methods for separation between buildings. By making fire windows mandatory within a protected limiting distance L_X from the boundary, flame contact danger through openings can be virtually eliminated. "Mirror-imaging" does not always produce safe solutions for radiation hazard, but critical situations can be readily checked. "Non mirror-image" situations including mixtures of fire windows on one building and ordinary windows on the other building can also be readily checked. Where fire windows are used and external cladding is non-combustible, spontaneous ignition values can be used in the design process. At least 50% reduction in radiation can occur through fire windows. Combined, these two facts can lead to considerable increases in traditional opening areas in external walls, not only where fire windows are compulsory, but also where they are voluntarily used beyond the protected limiting distance L_X.

The design method described herein not only offers more than the usual choice in the fire engineering design of external walls, but can also be linked directly to the standard fire resistance ratings ranging from ½ to 4 hours and also directly to fire compartment area design methods. The design method is also readily adaptable to tables, graphs, and hand-held programmable calculators. It can be used not only to design new buildings, but also to check critical situations between existing buildings for both "mirror-image" and "non mirror-image" situations. The design methods do not rely on the use of water and are suitable for areas having little or no stored or running water such as rural areas, remote islands or frozen climates. Where running water is readily available for extinguishing or wetting down purposes, nominal concessions to design values would be reasonable.

NOMENCLATURE

A_E	= area of enclosing rectangle = H x W (refer Fig. 5)	m^2
A_v	= permissible area of openings	m^2
H	= height of enclosing rectangle	m
H_A	= height of quarter rectangle A = H/2	m
I_E	= emitted radiation energy flux	kW/m^2
I_{EC}	= critical design value of I_E	kW/m^2
I_{E1}	= I_E value just inside owner's glazing	kW/m^2
I_{E2}	= assumed I_E value at flame front distance P	kW/m^2
I_{E3}	= I_{E2} value spread over enclosing rectangle	kW/m^2
I_{E4}	= I_E value just outside owner's fire window	kW/m^2
I_{E5}	= I_{E4} value spread over enclosing rectangle	kW/m^2
I_F	= radiation inside compartment at relevant FRR time	kW/m^2

I_R	= received radiation energy flux	kW/m^2
I_{RC}	= critical design value of I_R	kW/m^2
I_{R1}	= pilot ignition I_R for neighbour's cladding	kW/m^2
I_{R2}	= pilot ignition I_R outside neighbour's ordinary glazing	kW/m^2
I_{R3}	= pilot ignition I_R inside neighbour's ordinary glazing	kW/m^2
I_{R4}	= increased value of I_{R5} due to reduction factor k_2	kW/m^2
I_{R5}	= spontaneous ignition I_R inside neighbour's fire window	kW/m^2
k_v	= ratio between areas = A_V/A_E or emitted radiations = I_{E3}/I_{EC}	-
k_1	= radiation reduction factor through owner's glazing	-
k_2	= radiation reduction factor through neighbour's glazing	-
L	= limiting distance (Fig. 1) = ½ S = ½ (R + P)	m
L_x	= protected limiting distance specified by Fire Code	m
P	= flame projection distance (Fig. 1)	m
R	= radiation distance (Fig. 1)	m
S	= separation distance (Fig. 1) = (R + P)	m
T_1	= ambient temperature, generally 20°C or 293°K	°C, °K
T_2	= fire compartment temperature as per Eq. (3)	°C, °K
t_m	= time	min
W	= width of enclosing rectangle	m
W_A	= width of quarter rectangle A = W/2	m
ε	= emissivity, generally 1.0	-
ϕ	= Stefan-Boltzmann constant = 56.7×10^{-12}	kW/m^2K^4
ϕ_A	= configuration factor for quarter rectangle A	-
ϕ_n	= configuration factor for enclosing rectangle	-

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(The foregoing is a condensed paper. Copies of the full paper, tables, other matrix diagrams, or HP-41-CV programmes are available from the author on request.)