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Predicting Time of Flashover

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ABSTRACT

The present methods for predicting the occurrence of flashover are reviewed. These methods are based on a closed-form estimate of the upper layer gas temperature which corresponds to the occurrence of flashover using correlations derived from a wide range of test data. It was found that these methods gave reasonable predictions of flashover for enclosures within the range of test data from which the correlations were derived. However, the predictions were found to be not suitable for predicting rapid burning or conditions of flameover due to fire plumes and not the hot gas layer. It was also found to be not suitable for use in high ceilings because cooling of the upper gas layer from plume entrainment was not considered. None of the methods appropriately addressed the time for occurrence of flashover which is an important determinant for assessing life safety. In this paper, a more general methodology for determining both the conditions for flashover to occur and an estimate of the time at which it could occur is outlined. The proposed method is more fundamentally based and can therefore be extended to predict conditions of flashover (and flameover) beyond the limits of the existing methods. Application of the proposed method is presented for predicting the occurrence and time of flameover from a burning storage rack to an adjacent exposed rack based on a developing fire plume. The use of the method in determining the likelihood of occurrence of flashover in high ceiling enclosures is also presented.

KEYWORDS

flashover, flameover, t-squared fire, zone model, fire plume, ignition time, fire growth rate

INTRODUCTION

From the time ignition occurs, a fire will grow if flammable vapours are released sufficiently to sustain combustion. As the fire grows and provided there is adequate ventilation, sufficient heat may be released such that all combustibles within the enclosure are involved. This transition is normally called *flashover* although various definitions for it exist. The definition used in the international standards organisations describes flashover as the sudden transition from a localised fire to combustion of all *exposed* fuel surfaces within an enclosure. The implication is that flashover only occurs within the bounds of an enclosure and therefore the assumption that *all* fuel surfaces which are exposed to the high temperatures are involved may be valid, provided the temperatures are high enough to initiate ignition. As the floor area increases, the time lag for the hot gases to spread outwards may result in non-uniform heating over the entire floor area.

The time of occurrence of flashover is undoubtedly an important event in the course of a fire. Besides representing a relatively quick transition from a small to a vigorously burning fire, the occurrence of flashover also represents the transition to being uncontrollable within the means of occupants. It is therefore strongly associated with the occurrence of flame spread beyond the room of fire origin. It has been found in USA retail fires that casualty and property loss rates increase by factors of 5.9 and 12 for fire fighter fatalities and injuries respectively, 10 and 2.0 for civilian fatalities and injuries respectively and 12 for property losses between fires with extent of flame damage not confined and those confined within the room of origin [1].

The models which are available for predicting the occurrence of flashover generally relate to the conditions in which flashover will occur, expressed as a minimum heat release rate as a function of available ventilation to the enclosure. However, the time to flashover is not explicitly expressed and this is because the time history of a fire is inherently too random to be able to predict deterministically. In the mean time engineering judgements are called upon to make realistic estimates of time to ignition and time to reac flashover. This paper discusses the variability in the determination of the time for flashover and propose a more fundamental procedure for estimating the occurrence and time of flashover. The method i appropriate for design applications whilst extending the application beyond the limits of present method c prediction.

CRITERIA FOR FLASHOVER

Because flashover is a state of transition usually expressed qualitatively and is not a precise event, number of definitions or 'descriptions' for flashover exists. These descriptions have a common theme i that the fire undergoes very rapid growth, usually covering the entire enclosure space, and occurrir within a relatively short time period. In order to objectively quantify this phenomenon, conditions und which flashover can occur can been prescribed by various researchers. The conditions which infer t occurrence of flashover include:

- a minimum heat flux at floor level (20 kW/m^2)
- a minimum burning rate (40-80 g/s)
- a critical ceiling temperature (600 °C)
- emergence of flames from opening
- thermal instability (between rate of heat release and heat losses)

However, the time at which these conditions are reached cannot be precisely defined because the tir history of the fire growth at the preflashover stage is affected by a large number of factors. These include

- proximity of adjacent combustible items
- orientation of burning surfaces
- orientation of exposed surfaces
- surface area to mass ratio
- size and thickness of items
- thermo-physical composition
- cross-radiation (eg burning between two closely spaced items)
- behaviour of thermoplastics (melting and creating pool fires, involving other combustibles)
- ventilation and oxygen concentration in the enclosure
- effect of fire location on fire growth

Hence the criteria for flashover is strongly associated with the likelihood of ignition of the expos combustibles.

TIME TO FLASHOVER

Although it has been recognised that flashover is an important and distinctive event in the course of t fire, the impact of the event in terms of designing for fire safety is less well described. Generall flashover marks the transition beyond the point at which control of the fire by occupants is not likely a control by the fire brigade services may be demanding, particularly if spread has occurred. The followi situations may be associated with the time of occurrence of flashover:

- Occupants within the fire enclosure are not likely to survive.
- Occupants outside the fire enclosure are not likely to control the fire.
- Occupants are likely to perceive the fire to be a threat.
- Fire is likely to spread beyond the fire enclosure through existing openings.
- Any glazing which has not broken is likely to break and fall off, thereby increasing the severity of the fire and its potential to spread.
- Impact of the fire on the structure becomes significant.

The time to flashover is normally taken from the time of ignition. Hence the longer the time to flashover, he more opportunity there is for detection and suppression of the fire to occur, and for the occupants to vacuate safely. The time to flashover therefore has an important impact on the safety of occupants and he likelihood of extensive damage to property [1]. Although the events and the conditions for the events an be distinguished and defined, the time to flashover remains highly variable because the period from the time of ignition to the occurrence of flashover occurs over a relatively unstable period of fire growth.

EXISTING METHODS OF PREDICTING FLASHOVER

The general basis of existing methods for predicting flashover is to apply an energy balance to the upper gas layer,

$$\dot{Q} = \dot{m}_g c_p \left(T_g - T_\infty\right) + q_{loss} \qquad (1)$$

where $\dot{Q}$ is the heat release rate of the fire (kW), $\dot{m}_g$ is the mass flow rate out of the opening (kg/s), c_p is he specific heat of gas (kJ/kg·K), T_g is the temperature of the upper layer gas (K), T_∞ is the ambient emperature (K) and q_{loss} is the net convective and radiative heat transfer from the upper gas layer (kW) hrough the boundaries. The limiting value of $\dot{Q}$ is determined on the basis of a critical rise in the upper ayer temperature to cause flashover, usually in the range of 500°C to 600°C.

A summary of the existing methods of predicting flashover is briefly outlined.

BABRAUSKAS [2]

Babrauskas approximates the gas flow rate through openings as $\dot{m}_g \approx 0.5 A_o \sqrt{H_o}$ where A_o is the opening area (m²) and H_o is the opening height (m). The boundary heat loss, assumed as radiation to 40 percent of he boundary surface area A_T (m²), is estimated as $q_{loss} = \varepsilon\sigma\left(T_g^4 - T_\infty^4\right)0.40 A_T$. The emissivity ε is assumed to be 0.5 and σ is the Stefan-Boltzmann constant (5.67×10^{-11} kW/m^2·K^4). From test data, a correlation between the boundary and opening areas is estimated as $A_T / A_o \cdot \sqrt{H_o} \approx 50$ and a best fit suggests the minimum Q for flashover is approximately 0.5 $\dot{Q}_{stoich}$. Flashover is considered to occur when he gas temperature reach 873 K (or 500 °C). The limiting heat release rate is obtained as

$$\dot{Q} = 750 A_o \sqrt{H_o} \ \text{kW} \qquad (2)$$

MCCAFFREY, QUINTIERE AND HARKLEROAD [3]

The net heat loss to the boundaries is expressed as $q_{loss} = h_k A_T (T_g - T_\infty)$. Based on an analysis of test data from over 100 experiments, a correlation between ΔT ($\approx T_g - T_\infty$) and $\dot{Q}$ was established. Adopting a temperature rise, ΔT = 500°C for the occurrence of flashover, the corresponding heat release rate to achieve this is

$$\dot{Q} = 610\left(h_k A_T A_o \sqrt{H_o}\right)^{1/2} \ \text{kW} \qquad (3)$$

where h_k is the effective heat transfer coefficient (kW/m·K).

For a temperature rise of 600°C, the coefficient in equation (3) increases from 610 to 800. h_k may be approximated by k/δ where k is the thermal conductivity of the compartment boundary (kW/m·K) and δ if the thickness of the compartment boundary (m).

THOMAS [4]

From experimental data, Thomas developed an average for q_{loss} of 7.8 A_T. Using an upper layer temperature of 577°C or ΔT = 600°C for flashover criterion, the minimum heat release rate at which this occurs is

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o}\ \text{kW} \qquad (4)$$

DISCUSSION

Due to the similarity of the basis of the above approaches, varying only in the adoption of flashover criterion in terms of gas temperatures and assumptions in solving for the heat loss terms, it would be expected that the three methods provide reasonably close agreements in predicting the occurrence of flashover. To illustrate this, the three methods are applied to a 3 x 4 x 3 m high enclosure with a 3 x 1.5 m high window opening. The results are shown in Table 1 for various combinations of window sizes. It is clear that McCaffrey's predictions are the most conservative (ie giving lowest Q) whilst Babrauskas' are the least conservative. Thomas' predictions appear to lie in between McCaffrey's and Babrauskas'. This suggests that McCaffrey's adoption of a 500°C temperature rise is a relatively conservative estimate. Using a temperature rise criterion of 600°C, McCaffrey's revised predictions (shown in brackets in Table 1) approach that of Thomas' predictions.

Table 1. Comparison of Flashover Predictions

#	Window height (m)	Window width (m)	$A_o\sqrt{H_o}$	$\dot{Q}$ (MW) Babrauskas	McCaffrey et al	Thomas	CFAST
1	h	$w/2$	2.76	2.1	1.4 (1.8)†	1.5	2.0
2	h	w	5.51	4.1	1.9 (2.6)	2.6	2.8
3	h	$2w$	11.0	8.3	2.6 (3.5)	4.6	4.2
4	$2h$	w	15.6	11.7	3.1 (4.1)	6.3	5.0

† values in brackets are based on ΔT= 600 °C

With the availability of computer fire models, particularly zone models, the prediction of flashover may be better estimated taking into account more accurate ventilation flows, varying fire growth rates, room geometry and the associated heat losses through the enclosure boundaries. Using the enclosure from the previous example, a t-squared fire [9] is simulated using a zone model [5] to determine the time and corresponding heat release rate for the upper layer gas temperature to reach 600°C. An ultrafast t-square fire is adopted and the results are shown in the last column in Table 1. This compares well with Thomas' and McCaffrey's method based on a 600°C temperature rise criterion. In addition, both McCaffrey's and Thomas' methods have a variable allowance for the boundary surfaces as opposed to Babrauskas' fixed correlation of $A_T/A_o\sqrt{H_o} \approx 50$. The $A_T/A_o\sqrt{H_o}$ ratios in cases #1 to #4 ranged from 23.3 to 3.7 respectively and this may explain the departure of Babrauskas' predictions.

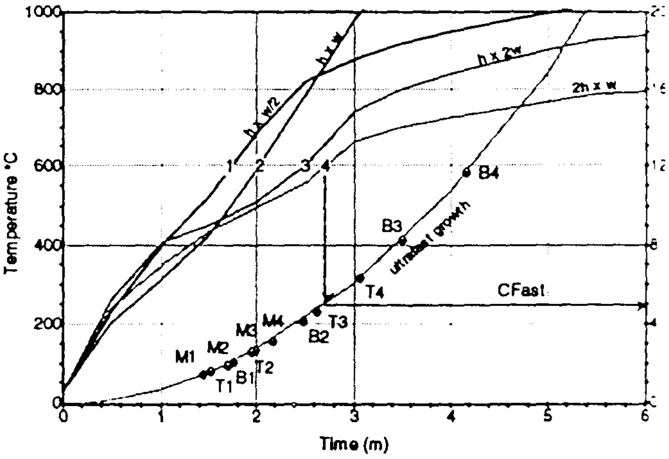

Figure 1. Comparison of Flashover Predictions, B1-B4: Babrauskas, M1-M4: McCaffrey, T1-T4: Thomas, 1-4: CFast

TIME TO IGNITION

Piloted ignition, particularly of wood, has been studied extensively over the past 40 to 50 years. The time to piloted ignition, t_{ig}, of a certain material is primarily a function of the incident heat flux. Ignitibility of the given heat flux depends on the thermal properties of the material, particularly the thermal inertia, $k\rho c$, where k is the thermal conductivity of the solid, ρ is the density of the solid, and c is the specific heat of the solid. Much of the work in correlating the time to ignition with irradiance, $\dot{q}_e''$, used a power law of the form [6]

$$\left(\dot{q}_e'' - \dot{q}_{cr}''\right)t_{ig}^n = C$$

where C is constant for a given material (usually correlated with $k\rho c$) and $\dot{q}_{cr}^{"}$ is the critical irradiance below which piloted ignition does not occur. However, the product term $k\rho c$ is temperature dependent and Janssens [6] suggested that the apparent $k\rho c$ should correspond to a temperature halfway between ambient and t_{ig}.

For thermally thick (semi-infinite) solid, the time to ignition is given by

$$t_{ig} = \frac{\pi}{4}\frac{k\rho c\left(T_{ig}-T_{\infty}\right)^2}{\dot{q}^{"2}} \qquad (5)$$

where T_{∞} is the initial temperature of the solid, and $\dot{q}^{"}$ is the net constant surface heat flux to the solid.

The above expression assumes no heat is lost. To allow for heat loss, the net surface heat flux can be represented as [7].

$$\dot{q}^{"} = \dot{q}_e^{"} - h(T-T_{\infty}) - \sigma T^4 \qquad (6)$$

where $\dot{q}_e^{"}$ is the external heat flux, h is the convective heat transfer coefficient and σ is the Stefan Boltzmann constant. However, in realistic situations, the combustible will be exposed to a variable (increasing) heat flux.

Tewarson [8] introduced a variation of the form of equation (5) by the use of two parameters: Critical Heat flux (CHF) and Thermal Response Parameter (TRP). The CHF (kW/m²) is the minimum heat flux at or below which a material cannot generate a combustible mixture for ignition to occur. The TRP (kW-s$^{1/2}$/m^2) is the resistance of a material to generate a combustible mixture. The higher the CHF and TRP, the longer it takes for the material to heat up, ignite, and initiate a fire, and thus lower the fire propagation rate. Tewarson's version of equation (5) is as follows:

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\sqrt{4/\pi}\left(\dot{q}_e^{"}-\mathrm{CHF}\right)}{\mathrm{TRP}}$$

where t_{ig} is the time to ignition (s), $\dot{q}_e^{"}$ is the external heat flux (kW/m²).

Rearranging,

$$t_{ig} = \frac{\pi}{4}\left(\frac{\mathrm{TRP}}{\dot{q}_e^{"}-\mathrm{CHF}}\right)^2 \qquad (7)$$

Hence, TRP is equivalent to $\sqrt{k\rho c}\left(T_{ig}-T_{\infty}\right)$ and CHF is simply a measure of the heat loss $h\left(T-T_{\infty}\right)+\sigma T^4$. The heat loss component is particularly significant at low external heat flux values as shown in Figure 2.

The time to ignition assumes a constant external heat flux which is unlikely to occur in real fires. From equation (7), the product $t_{ig} \times \left(\dot{q}_e^{"}-\mathrm{CHF}\right)^2$ is a constant equal to $\pi/4\times(\mathrm{TRP})^2$. Assuming that the constant does not change with a varying value of $\dot{q}_e^{"}$, the time of ignition can then be evaluated such that

$$\int_{t=0}^{t,ig}\dot{q}_n^{"2}\,dt = \pi/4\times\mathrm{TRP}^2 \qquad (8)$$

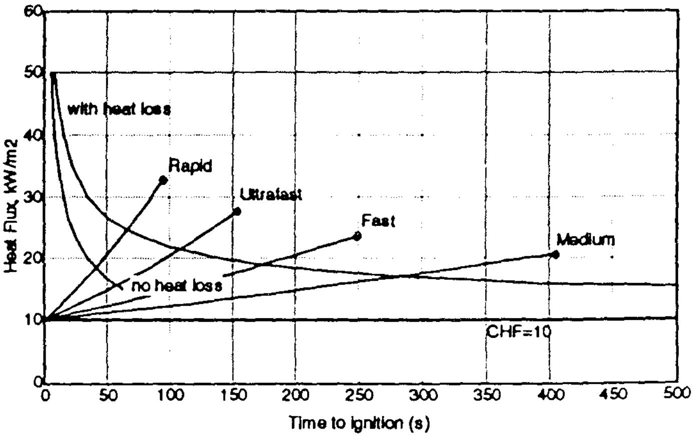

Figure 2. Time to ignition for Douglas Fir

where $\dot{q}_n^{*} = \left(\dot{q}_e^{*} - \text{CHF}\right)$ and t=0 corresponds to the time for $\dot{q}_n^{*}$ to reach the critical heat flux, CHF. Assuming that $\dot{q}_e^{*}$ develops at a rate similar to a t-square fire (discussed in the next section), the value of heat flux at which ignition occurs for the various growth rate categories of t-square fires are shown in Figure 2.

Hence for a t-squared fire growth, the time to ignition at its maximum heat flux is approximately 3.2 times the ignition time if the heat flux was held constant at this maximum.

FIRE GROWTH RATE

It is obvious from the preceding discussions that the solution to predicting time of flashover lies in the prediction of the fire growth itself and the time history of the heat flux on the exposed combustible. Considering that fire growth depends on the conditions local to the area of ignition, any form of prediction would therefore require certain assumptions of the prevailing conditions at the time of the fire. Despite these uncertainties, the rates of growths of many fires have been found to approximate a parabolic growth after an incubation period [9] as follows:

$$\dot{Q} = \alpha_f (t - t_o)^2$$

where α_f is the fire growth coefficient (kW/s²) and t_o is the length of the incubation period (s). The incubation period is highly indeterminate and is usually ignored in calculations for flashover fires. The fire growth coefficient is expressed as $1055/t_g^2$ where t_g is the growth period. t_g corresponding to 600, 300, 150, and 75 s have been used to categorise fires as slow, medium, fast and ultra-fast respectively. In the preceding example, a *rapid* rate was used to correspond to a growth period of 37.5 s.

In a number of full scale postflashover fire experiments involving typical office furnishings, [10], [11], the ultra-fast growth rate has been shown to provide a good fit for the growth rate prior to flashover [12]. This paper will discuss the use of such a growth rate to provide a time estimate for flashover.

PROJECT 4 FIRE TESTS [13]

A series of fire tests were carried out in a 5.39 × 3.69 × 2.4 m high enclosure to investigate the behaviour of flashover fires. The enclosure connects to a corridor (15.6 × 1.4 × 2.57 m high) via a door (0.8 × 2.0 m) on the north side and has a 2.4 × 1.5 m high glazed external window on the south side. In two of the tests (FO1 and FO4) the door to the corridor was opened and in another two (FO2 and FO3) the door was closed. The corridor leads to a stairwell but the door to it was closed except for Test FO4. The burn room had weighing platforms to monitor the mass loss. The fire loads in all the tests was about 568 kg wood equivalent (using an equivalent heat of combustion h_c=18.4 MJ/kg). The resulting heat release rates were calculated from the burning rates using an effective heat of combustion h_c=15 MJ/kg. The results for the four tests are shown in Figure 3.

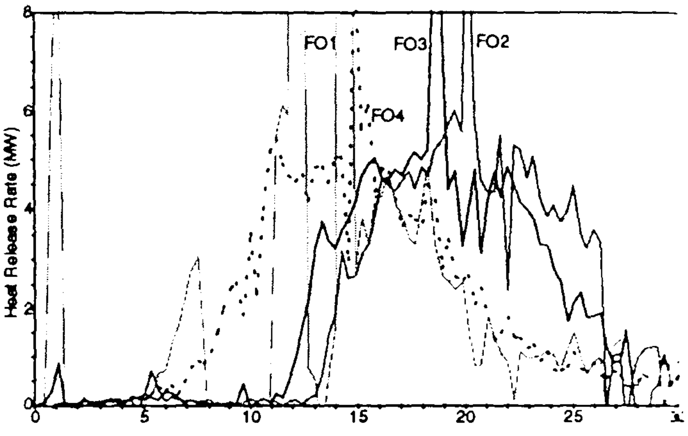

Figure 3. Heat release rates for Project 4 Tests FO1-FO4

Using the above methods for flashover predictions, the minimum heat release rates for flashover to occur (Q_{fo}) and the corresponding times of occurrence (t_{fo}) at which the measured heat release rate reached these values are shown in Table 2. Also shown are the observed times flashover occurred for each test and the corresponding heat release rates.

Table 2. Comparison of Flashover Predictions with Project 4 Tests

	Measured	Observed	Babrauskas		McCaffrey		Thomas	
Test	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)
FO1	2.9	7.3	5.0	11.2	3.1	11.1	3.1	11.1
FO2	3.1	14.3	3.3	15.5	2.6	14.1	2.3	14.1
FO3	3.1	13.0	3.3	13.1	2.6	12.9	2.3	12.8
FO4	2.3	9.0	5.0	10.9	3.1	9.9	3.1	9.9

All of the predictions for Q_{fo} are quite reasonable. The predictions for the corresponding times t_{fo} are also very good, apart from test FO1. It is suspected that the measurements for Test FO1 are erroneous and should be ignored. The reason for the departure in the prediction for Test FO1 is that the burning rate (and hence Q_{fo}) dropped near the point of flashover, due likely to measurement error. If the drop is ignored and the burning rate extended or interpolated, the resulting prediction times for flashover will approach the observed times

It does not appear that varying the door opening condition has a significant effect on the burning rate. There were, however, significant variations in the incubation periods. In all the four tests the burn room window cracked between 4:40 (min:sec) and 5:15 following ignition. In all except test FO4, the burn room window was lowered when the inside glass surface temperature reached 250°C. The first minor peak at around 3 MW was due to the occurrence of flashover. The burning rate for the tests appears to plateau at about 5 MW.

When the time axes are adjusted for each test such that the growth rates are aligned, the growth rates appear to be similar for all the tests as shown in Figure 4. Overlaid within Figure 4 are the t-squared fires described previously. Except for Test FO4, the growth rates all appeared to follow an ultra-fast growth rate to the point of flashover. The minor dips in FO4 prior to flashover are due to the natural process of glass breakage and dislodgement which tended to prolong the growth rate.

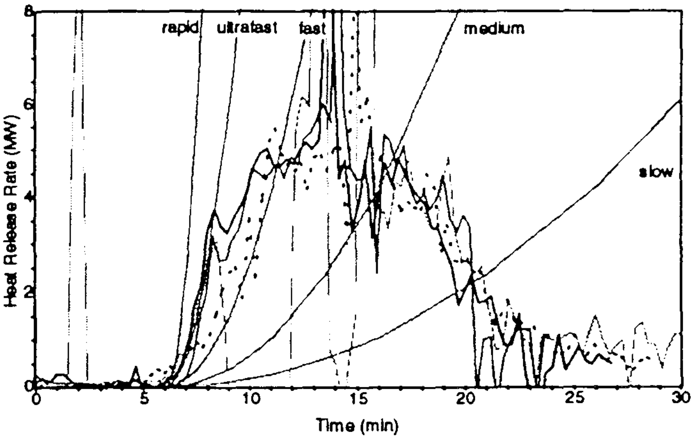

Figure 4. Adjusted Time Axis

PROJECT 6 FIRE TESTS [14]

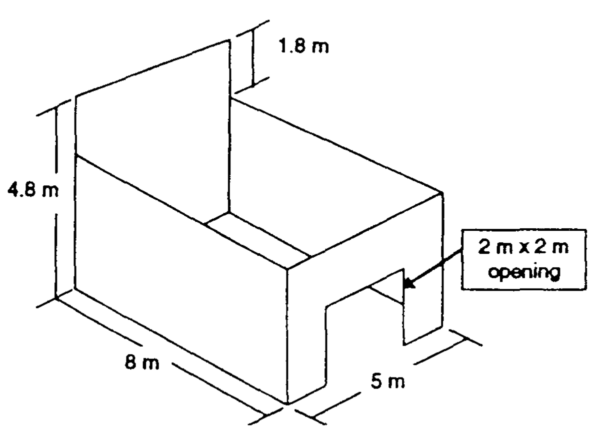

Figure 5. Fire Test Enclosure

A full scale test (#4) resembling the storage room of a specialty shoe shop was conducted in a 5 × 8 × 4.8 m high enclosure as shown in Figure 5. The walls on three sides were only 3 m high to replicate the ceiling space from the wall top ends to the floor soffit. The storage room had a 2 × 2 m opening to the public area. The burn enclosure was located in the middle of a burn hall with approximate plan dimensions of 30.2 × 55.2 m and an effective height of 8.5 m. The burn hall was effectively sealed (i.e. all doors closed) although observations of smoke from outside the building suggested that there was appreciable air leakage through the building. An allowance for leakage of about 0.1m over the enclosure height produce comparable smoke level predictions [15]. The combustibles were all shoes in boxes stacked in two double-sided steel racks up to about 3.5 m. The distance between the racks was 1.0 m. The total mass of shoes and boxes were 2704 kg and h effective heat of combustion of 26.3 MJ/kg. The calculated heat release rate is shown in Figure 6. an ultra-fast fire growth rate (offset at 22 mins) is seen to fit well.

Due to the vertical arrangement of the combustibles, the fire spread quickly up the shelving when th grew to a critical size. The period of rapid spread (*flameover*) which would be equivalent to 'flash occurred between 26 to 27 minutes into the test when flames were observed to spread across the ai the other shelf and rapidly involved most of the exposed boxes. The onset of flameover may be tak the point where the heat release rate begins to climb steeply from about 10 MW. Comparison wit calculated predictions are shown in the first row (#4-BE) of Table 3.

Table 3. Comparison of 'Flashover' Predictions

Test	Measured	Observed	Babrauskas		McCaffrey		Thomas	
	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)	Q_{fo} (MW)	t_{fo} (min)
#4-BE	10	~26	42.3	28.9	13.3	26.2	22.6	26.7
#4-BH	na	na	1.9	23.1	15.1	26.4	38.3	28.6

It is obvious that the predictions for Q_{fo} are not applicable in this case. This is because the flashover phenomenon is not due to radiation from a hot gas layer but from the extended plume due to burning of the storage rack. The second row (#4-BH) are predictions when the burn hall is considered as the enclosure. Assuming a restricted ventilation of 0.1 m over the building height, it is interesting to note that the predictions were within the heat output range of the fire. Although there were combustibles stored within the burn hall but away from the burn enclosure, flashover definitely did not occur. The equations for flashover prediction are therefore not applicable to an enclosure this size. Flame spread within an enclosure this high wo expected to come from radiation of the fire plume, which was indeed how the fire spread to the op shoe rack. The temperature of the hot gas layer of the burn hall only reached 300 °C (Figure 9) significant entrainment along its relatively tall plume height. It was therefore not sufficient to cause flashover.

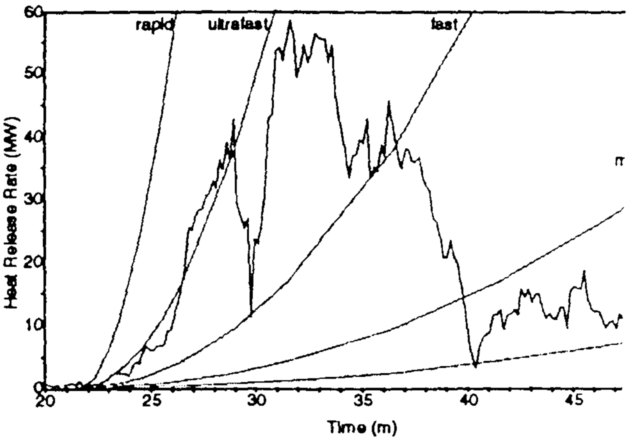

Figure 6. Tests 4 - Specialty shoe shop fire

RADIATION CONFIGURATION FACTORS

Up to this point the conventional methods for flashover prediction have been shown to be quite reasonable provided the following conditions apply:

- the size of the enclosure and openings lie within the range of the tests from which the equations were derived (this is typically up to about 12 m² floor area).

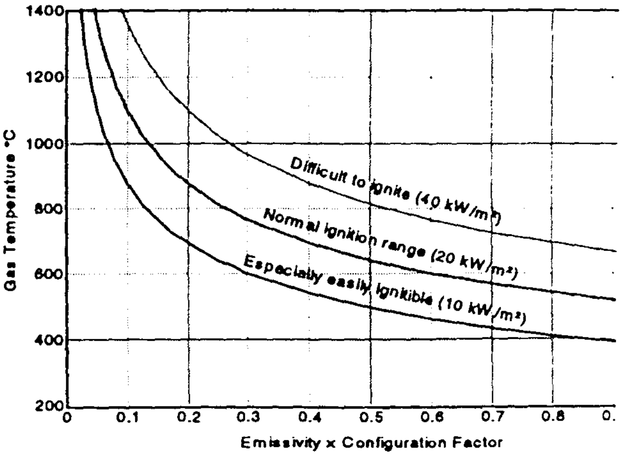

Figure 7. Radiation Levels from Gas Temperature

- the flashover phenomenon, in terms of rapid fire spread over the surface of exposed combustibles, is applicable only to radiation from the hot gas layer and not from a fire plume.
- the enclosure height is not excessively high (the test data correlations are mostly 3 m or less) otherwise entrainment effects will significantly lower the upper layer gas temperature.

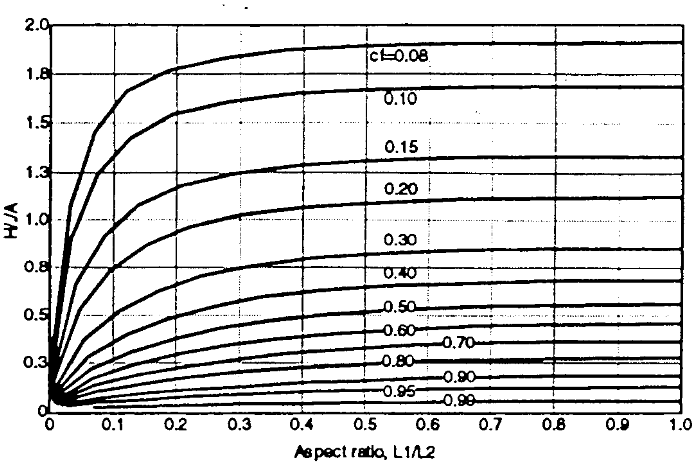

Figure 8. Configuration factors (cf) for various aspect ratios (*L1*,*L2*=dimensions of radiating panel (*L1*≤*L2*), *H*=normal distance from panel to target, *A*=area of radiating panel)

The flashover predictions above have all adopted a critical upper gas layer temperature and therefore assume that the radiation from the gas layer at the critical temperature is sufficient to cause ignition of exposed combustibles located at the floor below. For configuration factors in the range of 0.5 – 1.0, a gas temperature level of 600 °C based on an emissivity value of 1.0 does produce sufficient levels of radiation to ignite combustibles in the normal ignition range of 20 W/m² as classified by Babrauskas [16]. This is illustrated in Figure 7. However, in order to obtain a configuration factor within this range, the aspect ratio of the radiating surface must be within the limits shown in Figure 8 (i.e. $H/\sqrt{A} < 0.5$).

PROPOSED METHODOLOGY

The prediction for flashover could therefore be much more rigorous if it was based directly upon the ignition of combustibles rather than an upper gas layer temperature correlation for ignition. Its application can also be extended more appropriately for predicting *flameover* which is basically how the flashover phenomenon arises from if time to ignition of the appropriate combustibles were considered. Accordingly, it can be used for predicting ignition of combustible ceiling or walls from a growing fire plume located at a distance from the combustible surface. Because it is more fundamentally based, its application is not necessarily restricted to the range of tests upon which the existing methods were derived from.

Based on this, the following method of predicting flashover is proposed.

1. Determine the flame or gas temperature.
2. Determine the radiation configuration factor
3. Calculate the imposed radiation heat flux
4. Check if heat flux exceed ignition range of exposed combustibles

The above steps should be evaluated for radiation from a hot layer and from a plume, the latter being more appropriate for high rack storage or enclosure with high ceiling heights. Details of the methodology are illustrated using Project 6 Test #4 [14].

CASE 1. SPREAD VIA FIRE PLUME

The fire is assumed to grow at an ultra-fast rate. Hence $Q = 0.1876t^2$ kW. The visible or mean flame height h_f (m) is given by [17]

$$h_f = 0.23\dot{Q}_c^{2/5} - 1.02D$$

where D is the diameter of the fuel bed and Q_c (kW) is the convective portion of the fire and is approximately $0.7Q$. For all practical purpose, the equation may be simplified to

$$h_f = 0.2Q_c^{2/5} \tag{9}$$

The width of the plume to the point where the temperature rise has declined to half its centreline value approximated as [8]

$$b_p = 0.24\sqrt{T_f/T_\infty}\,h_f$$

where T_f is the centreline flame temperature (K). T_f varies from 921°C for 'sooty' flames (benzene 1218°C for 'clean' flames (alcohol) [18]. The effective area of the radiating plume A_p is therefore $h_p \times$ The configuration factor ϕ can now be calculated or estimated from Figure 8. The emissivity is calcul as

$$\varepsilon = \left(1-e^{-\kappa S}\right)$$

where κ is the effective absorption (emission) coefficient and S is the thickness or mean beam length of t flame. Typical values of κ for solid fuels are 0.5 for PMMA, 0.8 for wood and 1.2 for polystyrene. The imposed radiant heat flux q_e (kW/m²) is then determined as $H/\sqrt{A}$

$$q_e = \varepsilon\phi\alpha T_f^4$$

The time of ignition at the exposed combustible is then determined in accordance with Eqn. (8). T application of this procedure is illustrated for FCRC Project Test #4. The separation between the shel is 1.0 m and the ignition parameters taken from Table 3-4.2 of the SFPE Handbook [8] for corrugat paper with coating (10% by weight) are CHF = 10 kW/m² and TRP = 435 kW-s$^{1/2}$/m^2. The RHS of E (8) is therefore $\pi/4\times\mathrm{TRP}^2 = 148616$. The LHS can be evaluated using a finite difference approa Ignition occurs when the LHS exceeds the RHS. The calculations are illustrated in Table 4.

Table 4. Tabulated calculations for plume radiant ignition

t min	Q MW	h_p m	b_p m	A_p m²	ϕ	H m	ε	q_e kW/m²	$H/\sqrt{A}$	q_n kW/m²	$q_n^2\Delta t$	$\sum q_n^2\Delta t$
0.0	0.00	0.00	0.00	0.0	0.00	0.00	0.00	0.0				
0.2	0.03	0.65	0.31	0.2	0.06	0.31	0.22	1.3	2.23			
0.4	0.11	1.13	0.54	0.6	0.16	0.54	0.35	5.6	1.28			
0.6	0.24	1.56	0.75	1.2	0.25	0.75	0.45	11.8	0.92	1.8	20	20
0.8	0.43	1.96	0.94	1.9	0.34	0.94	0.53	18.7	0.73	8.7	328	348
1.0	0.68	2.35	1.13	2.7	0.42	1.00	0.55	23.7	0.61	13.7	1508	1856
1.2	0.97	2.72	1.31	3.6	0.49	1.00	0.55	27.5	0.53	17.5	2924	4779
1.4	1.32	3.07	1.48	4.5	0.54	1.00	0.55	30.7	0.47	20.7	4361	9140
1.6	1.73	3.42	1.64	5.6	0.59	1.00	0.55	33.4	0.42	23.4	5813	14953
1.8	2.19	3.76	1.81	6.8	0.63	1.00	0.55	35.7	0.38	25.7	7222	22175
2.0	2.70	4.09	1.97	8.0	0.67	1.00	0.55	37.7	0.35	27.7	8553	30728
2.2	3.27	4.41	2.12	9.4	0.70	1.00	0.55	39.4	0.33	29.4	9793	40521
2.4	3.89	4.73	2.28	10.8	0.72	1.00	0.55	40.9	0.30	30.9	10937	51459
2.6	4.56	4.80	2.43	12.2	0.75	1.00	0.55	42.3	0.29	32.3	11986	63444
2.8	5.29	4.80	2.57	13.8	0.77	1.00	0.55	43.4	0.27	33.4	12944	76389
3.0	6.08	4.80	2.72	15.4	0.79	1.00	0.55	44.4	0.25	34.4	13819	90207
3.2	6.91	4.80	2.86	17.1	0.80	1.00	0.55	45.4	0.24	35.4	14616	104823
3.4	7.81	4.80	3.01	18.8	0.82	1.00	0.55	46.2	0.23	36.2	15342	120165
3.6	8.75	4.80	3.15	20.6	0.83	1.00	0.55	46.9	0.22	36.9	16005	136170
3.8	9.75	4.80	3.29	22.5	0.84	1.00	0.55	47.5	0.21	37.5	16611	152781

Hence the RHS term is exceeded when approaching 3.8 minutes when Q is about 9.5 MW. In real t (i.e. including the offset of 22 mins) the flashover is predicted to occur at 25.8 mins. This checks out with Figure 6 and is also consistent with observations recorded at the test [14].

CASE 2. HOT LAYER IN LARGE ENCLOSURE

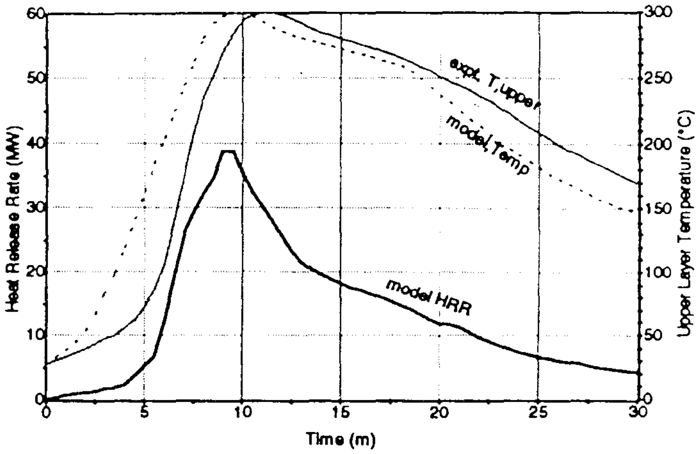

Figure 9. Results from CFast

The proposed method is now applied to assess if flashover could have occurred when considering the burn hall as the fire enclosure. In this particular test, the combustion was partially limited by restricted ventilation as would be expected. Because this is a highly transient process, it would be extremely difficult to incorporate within a closed-form solution. A zone model such as CFast [5] which can treat vitiated burning is therefore used. Hence when the test configuration is simulated using the heat release rate as shown in Figure 6, the resultant heat release rate and the temperature of the upper gas layer of the burn hall obtained are shown in Figure 9.

From Figure 8, the configuration factor for the burn hall is about 0.85 (L1/L2=0.55, $H/\sqrt{A}$ =0.21) and from Figure 7, the corresponding gas temperature for flashover is about 540 °C. The measured and predicted upper layer gas temperature only reached 300°C and therefore flashover would not (and did not) occur.

CONCLUSION

The present methods for predicting the occurrence of flashover are reviewed. These methods are based on a closed-form estimate of the upper layer gas temperature which corresponds to the occurrence of flashover using correlations derived from a wide range of test data. It was found that these methods gave reasonable predictions of flashover for enclosures within the range of test data from which the correlations were derived. However, the predictions were found to be not suitable for predicting rapid burning or conditions of flameover due to fire plumes and not the hot gas layer. It was also found to be not suitable for use in high ceilings because cooling of the upper gas layer from plume entrainment was not considered. None of the methods appropriately addressed the time for occurrence of flashover which is an important determinant for assessing life safety. In this paper, a more general methodology for determining both the conditions for flashover to occur and an estimate of the time at which it could occur has been outlined. The proposed method is more fundamentally based and can therefore be extended to predict conditions of flashover (and flameover) beyond the limits of the existing methods. Application of the proposed method has been presented for predicting the occurrence and time of flameover from a burning storage rack to an adjacent exposed rack based on a developing fire plume. The use of the method in determining the likelihood of occurrence of flashover in high ceiling enclosures was also presented.

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