**NISTIR 6030**

# THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

# VOLUME 1

Kellie Ann Beall, Editor

June 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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# CONCURRENT FLAME SPREAD IN FIRES -- STATE OF THE ART OF MODELING AND FUTURE PROBLEMS FOR ENGINEERING APPLICATION

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## ABSTRACT
Significance of concurrent flame spread for fire safety is summarized from experiences of unwanted fires and fire tests. State of the art of theoretical modeling and experimental findings on concurrent flame spread in fires is reviewed. Problems left unsolved for the rational assessment and design of fire safety are discussed. Similarity in the theoretical formulations of flame spread in different scales, configurations and fire scenarios and general complexity of the phenomena suggest needs of cooperation in different subfields of fire safety science which tend to deal with fires in specific environments.
*Key Words: flame spread, heat flux, heat release, flame length, configuration effect.*

## INTRODUCTION
Concurrent flame spread is an important driving force of fire at any phase of its development. Upward flame spread along a combustible wall lining is very often a trigger for the occurrence of flashover. Horizontal flame spread along the ceiling surface or along the ceiling-wall boundary is another significant example of concurrent flame spread in room fire, and is believed to be a direct cause of flashover. The investigations on the King's Cross Underground fire disaster in 1987[1] have revealed the significance of fire growth in such an inclined trench with combustible lining as the escalators lined with wood at the London subway stations; this can be another example of concurrent flame spread which can cause tremendous fire hazard. City fires and forest fires are also typical examples of flame spread assisted by wind. It is important to note that fire spreading velocity in such mass fires very often reaches several to over-ten km per hour[2]. Such acceleration of the development of mass fires can take place only by the assistance of strong wind; however, still mathematical models of wind-aided mass fires tend to use similar concept and formulation with other types of concurrent flame spread[3]. In spite of the primary importance of concurrent flame spread in fire, there was considerable delay in its modeling in comparison with such other areas as smoke control and structural firesafety. However, there has been considerable progress in the modeling of concurrent flame spread in fires since 1980's. This paper intends to review present status of the scientific understanding of this phenomenon, and discuss strategies to develop engineering methodology to assess fire safety in view of concurrent flame spread.

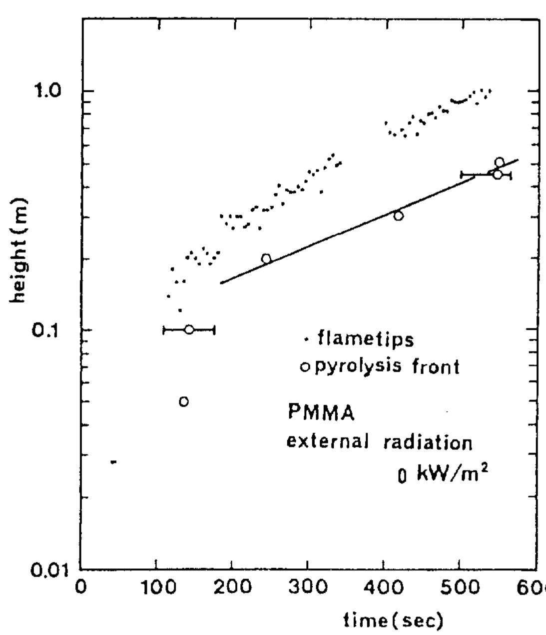
## EMPIRICAL AND EXPERIMENTAL EVIDENCES FOR THE IMPORTANCE TO MODEL CONCURRENT FLAME SPREAD IN FIRE
Modeling of concurrent flame spread in fires is not yet matured engineering. Although there are many mathematical models for idealized conditions, it is recognized experimentally that even slight change of configurations, or initial/boundary conditions can very often lead to extreme difference in experimental results. Also there are many empirical and experimental evidences demonstrating extreme fire hazard that can be hardly anticipated from conventional knowledge on fires. It should be useful to summarize evidences showing importance of concurrent flame spread in fires from previous experiments and fire investigations, before starting review of the theoretical framework for this process.

### Flame Spread along an Inclined Combustible Solid
Upward flame spread along a vertical solid is a typical concurrent flame spread process in

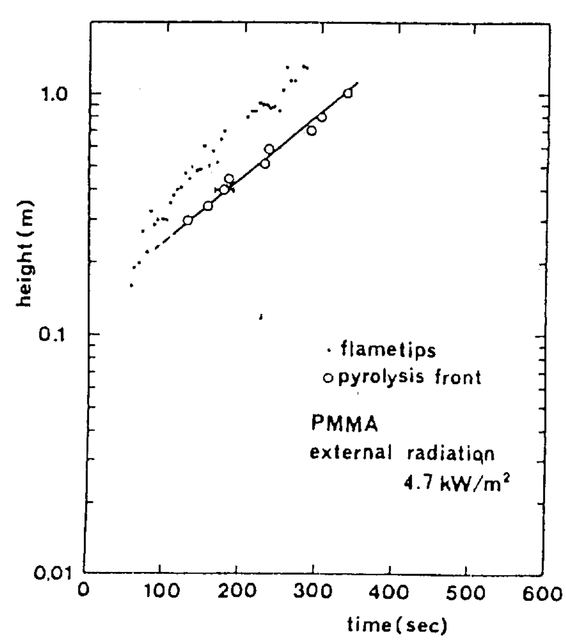
quiescent environment. Many flame spread experiments suggest several to several-ten times faster flame spread on a wall than on an upward horizontal surface. Flame spread on an upward horizontal surface is essentially an opposed-flow flame spread; therefore it is an interesting and practically important problem at what angle the mode of flame spread changes from opposed flow to concurrent one on an inclines combustible surface. This problem was first dealt with by Hirano et al[4] through measurement of flame spreading velocity along inclined computer cards. According to their result, flame spreading velocity starts to become noticeably higher at an angle of approximately 30° . The King's Cross fire in 1987 drew strong international attention to the importance of flame spread on inclined surfaces for fire safety, and computational and experimental works have been carried out in relation to this problem[1]. Experiments by Drysdale and Macmillan on inclined PMMA slabs in relation with this fire disaster[5] demonstrate significant increase of flame spread velocity with respect to the angle of inclination beyond 15° while flame spread velocity was nearly independent of the angle of inclination from 0° (horizontal) to 15° . Especially their experiments with inert sidewalls show almost a jump of flame spreading velocity between 15° and 25° . Experimental work on a slightly different inclined trench[6] showed that the flame will attach to the trench base at an angle of 27° . These suggest a sudden transition from the opposed-flow flame spread mode to the concurrent one in an inclined trench although the transition is rather gradual on an inclined surface without sidewalls.

**Acceleration by External Radiation**

From experiences of real fires, it is widely recognized that flame spread can be accelerated significantly by external radiation from fire sources. Figure 1 compares development of flame tips and pyrolysis front during turbulent upward flame spread over vertical flat PMMA slabs without external radiation and with $q_e''=4.7$ kW/m$^2$[7]. Although the level of the external radiation is considerably weaker than typical flame radiation, the slope representing the flame spread velocity with external radiation was still notably steeper than that without external radiation. Flame spreading velocity divided by the length of pyrolysis front, $V_p/x_p$, is approximately twice greater for $q_e''=4.7$kW/m$^2$ than for $q_e''=0$.




(a) without external radiation




(b)$q_e''=4.7$kW/m$^2$

Figure 1 Movement of flame front and pyrolysis front(vertical PMMA slabs, Ref.7)

Fernandez-Pello[8] first pointed out possible significant acceleration of laminar flame spread by external radiation through enhancement of preheating of the unburnt surface and the activation of pyrolysis. The significant influence of external radiation shown in Figure 1 can be explained from the similarity solution of the thermal modeling[7] as discussed later. It is also important to note that, under stronger external radiation enough to ignite the surface by itself, external radiation may become a problem of surface ignition rather than that of flame spread.

## Configuration Effects

The significant difference in the transition from opposed-flow flame spread to concurrent one between flat inclined open surfaces and inclined trenches suggests importance of configuration in the dynamics of flame spread. Such enhancement of flame spread in an inclined trench due to fluiddynamic effect has become widely known as the "trench effect" since the Kings Cross fire disaster, which is essentially a combination of the Coanda effect and the flame extension due to the restriction of entrainment. Air velocity measurements within open and closed parallel heated walls [9] suggest that stack effect can be another fluiddynamic effect to accelerate flame spread. Also the significant acceleration of concurrent flame spread over a flat wall by external radiation suggests potential importance of configuration effect on flame spread in a channel, wall corner and other 3-dimensional surface configurations through radiation feedbacks. Complexity in the cross-section of the combustible surface normal to the flow field, e.g. trench, groove and roughness, should generally increase effective surface area to feed fuel to the flame. This effect is believed to increase heat release rate, a driving force of flame spread. Configuration effects on flame spread in a real fire should be interpreted as a result of the combination of there three different mechanisms, i.e. the fluiddynamic effects, increase of heat transfer and increase of effective pyrolyzing surface.

There are also experimental evidences for the significance of configuration effects on concurrent flame spread. Acceleration of flame spread in parallel combustible-wall configuration with decreasing separation has been demonstrated experimentally on laminar flow[10] and on turbulent flow[11]. There are also many experimental evidences for the acceleration of flame spread in combustible wall-corner and in combustible corner-wall-ceiling configurations, and fire source in a wall-corner is already widely considered the worst scenario for a room fire. Notable acceleration of flame spread has been reported experimentally on grooved vertical wood panels[12], and vertical channels with combustible lining(Figure 2)[13].

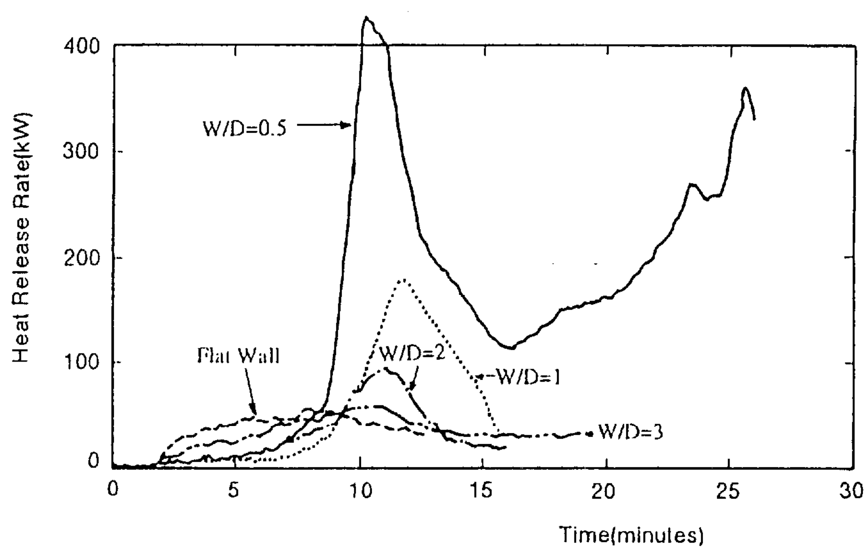



Figure 2 Time history of heat release rate by fires in vertical channels lined with particleboard (D=0.20m for W/D≧1 and D=0.40m for W/D=0.5, Fire source(surface area=WD) intensity in channel= 250kW/m$^2$, Ref.13)

## Concept

Main focus of flame spread for fire safety is the description of the movement of pyrolysis front. Location of flame front is often more important for practical purposes; however, in a concurrent flame spread, flame length is believed to be a function of length of pyrolysis zone and heat release rate, calculation of which essentially needs information on the location of pyrolysis front. Pyrolysis front is normally identified ad the location where the surface temperature has reached an ignition temperature. Modeling approach of flame spread assuming primary importance of the heating mechanism in the vicinity of the pyrolysis front is called "thermal modeling". This approach describes ignition and flame spread as a result of inert heating of the solid to an ignition temperature, $T_{ig}$. Mathematical modeling of flame spread over a combustible solid based on this concept was first applied to laminar flame spread by de Ris[14], and there was significant progress in quantitative understanding of various modes of laminar flame spread over a solid and liquid fuels during 1970's[4,8,10,15-20]. However, modeling of turbulent flame spread should be much more important for fire safety since turbulence is a principal feature characterizing flames in unwanted fires. Main difference between laminar and turbulent concurrent flame spreads is the mode of heat transfer from the flame to the surface; flame radiation dominates the surface preheating in turbulent flame spread, whereas gas phase thermal conduction is the main mode of the heat transfer in laminar one. Modeling of turbulent concurrent flame spread also needs formulation of flame length for the determination of the preheat distance. In spit of these notable differences between turbulent and laminar flame spreads, many of knowledges and modeling concepts obtained for laminar flame spread are probably useful for the understanding and the modeling of turbulent flame spread. Figure 3 shows a conception of the thermal modeling of turbulent concurrent flame spread(applied to a combustible wall). This model assumes a flame spread in the x-direction and a one-dimensional thermal conduction in the solid normal to the surface. Insignificance of the thermal conduction in the parallel direction to the surface has been established for vertical PMMA slabs by Ito and Kashiwagi[21]. If the char formation near the fuel surface is negligible, the surface temperature at x, $T_w(x,o)$ can be represented by the convolution as

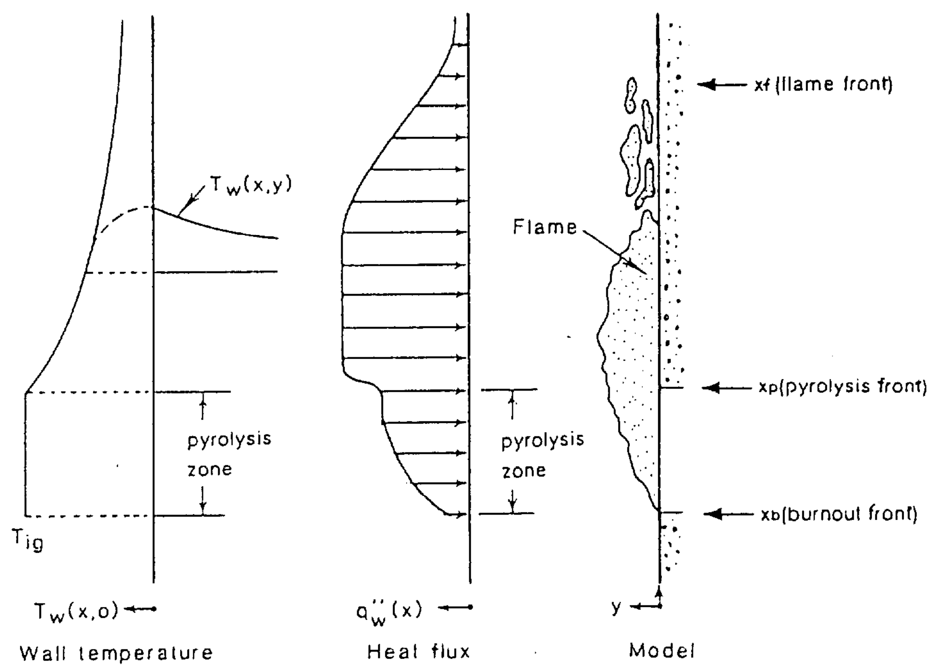



Figure 3 Schematic diagram of upward flame spread(Ref.30)

$$T_w(x,o) - T_o = \int q_w''(x,t-s) \cdot \phi(s)ds \tag{1}$$

where $q_w''(x, t-s)$ is the heat flux applied to the surface at (t-s) after the beginning of experiment. $\phi(s)$ is an impulse response of the surface temperature to heat application, and is a function of such thermal properties as thermal conductivity, density and specific heat. Functional form of $\phi(s)$ depends on the boundary conditions; $\phi(s)=(\pi k \rho cs)^{-1/2}$ for a semi-infinite slab is a simplest example. The location of the pyrolysis front is given as a function of time by solving

$$T_{ig} - T_o = \int q_w''(x_p,t-s) \cdot \phi(s)ds \tag{2}$$

for $x_p$. Thermal properties and ignition temperature in equation (2) are believed to be obtained from bench-scale material tests. It has been confirmed that both $h(T_{ig}-T_o)$ and $h^2/k\rho c$ can be estimated through practical analysis of the ISO5657 Ignitability test results. Use of only parameters which can be obtained in engineering manner is an important benefit of this approach. Other approaches, field model for example, cannot draw an overall picture to assess fire hazard using such engineering properties. Surface heat flux is an important part of the model, and has been represented as a function of distance normalized by flame length, $x/L_f$, for most of practical situations. As discussed later, flame length can be further correlated against dimensionless heat release rate, $Q^* \equiv Q/\rho C_p T_o g^{1/2} A D^{1/2}$[22]. Formulation of flame length is also important for the prediction of flame front height, and is represented as $L_f=\gamma \cdot Q^{*n}D$ for a flat wall with length of the pyrolysis zone to be substituted into the characteristic length scale D. Assuming the sole dependence of local heat release rate on local heat flux condition, contribution of the burning surface to total heat release can be formulated as

$$Q(t) = A_o \cdot q(t) + \iint q(x,t-s)V_p(s) \cdot \ell(s)ds \tag{3}$$

where $A_o$ is the surface area of the first ignited part, and $\ell(t)$ is the width of pyrolysis front at t.

Local burnout is often observed during surface burning especially of charring material and thin linings. Burn out itself does not have a direct relevance with fire safety; however, modeling of the movement of the burnout front is necessary for the prediction of the length of pyrolysis zone, an important element determining the flame length. Except for thin linings, there is not yet clear engineering criterion determining the occurrence of local burnout.

Prediction of flame spread can be essentially made through calculating the surface temperature of a burning solid surface. However, since equation(1) or (2) generally cannot be solved in analytical manner for realistic heat flux conditions, several approaches of the formulation as follows have been attempted.
(a)Numerical calculation
(b)Analytical solution based on similarity assumption
(c)Analytical solution based on linearized flame length approximation
Effectiveness and limitation of each model depends on the level of adopted assumptions and analytical capabilities.

**Numerical Calculation**
Numerical calculation using finite difference grids along the burning surface and calculating the temperature of each grid is perhaps the most elaborate but simple formulation. Delichatsios et al[23], Kulkarni et al[24], and Mitler and Steckler[25] have developed numerical models, slightly different to each other. Either assumption of the functional form for temperature profile within the

slab normal to the surface or convolution-type formulation for the surface temperature of each grid could be adopted for simplification. Finite difference approximation for the heat transfer in the normal direction to the surface generally needs data of conductivity, density and specific heat of the material independently, whereas semi-infinite or thin-bed approximation needs such combination of the properties as $k\rho c$ that makes the engineering estimation of the input data much simpler. Numerical calculation of the pyrolysis and degradation of the burning surface can be complicated especially for charring materials. Treatment of the heat release from the pyrolysis zone can be simplified by using the time history of heat release rate exposed to the identical level of heat flux into the local heat release rate per unit area.

Benefit of the numerical approach is the relatively large capability to deal with realistic heat flux distributions and other conditions without introducing any simplification. Numerical models have been developed not only for flat walls[23-26] but also for vertical group cables[27]. Similar approach has been adopted in the modeling of forest fires, e.g.[28]. However, effect of embers in the spread of mass fires is seldom modeled although embers generally dominate flame spread velocity in mass fires[3,29].

**Similarity Solution**

Analytical solution of equation(1) for $x=x_p$ as a function of $t$ can be obtained in a relatively simple from either if

a) $dx_p/dt$=constant

b) $x_p(t)/x_p(s)=f(t-s)$

The condition a) represents obviously the steady state, and $f(t)=\exp(\alpha t)$ is the only function satisfying small fire on the wall, and grows exponentially with time. Analytical solution for both assumptions for a semi-infinite combustible wall with realistic heat flux distribution have been reported by Hasemi[30] and Hasemi et al[7]. using the wall flame heat transfer represented as a function of $x_p/L_f \propto x_p/Q_f^{*2/3}\xi$ and $\phi(s)=(\pi k\rho cs)^{-1/2}$, equation(2) are solved for the two conditions as

$$a)\ V_{pa}=\left[\int Q_f^{*2/3} q_w''(\lambda+1/Q_f^{*2/3})/\lambda^{1/2}\, d\lambda\right]^2 \cdot x_p/\pi k\rho c(T_{ig}-T_o)^2 \qquad (4)$$

$$b)\ V_{pb}=\left[\int q_w''\{\exp(\lambda)/Q_f^{*2/3}\}/\lambda^{1/2}\, d\lambda\right]^2 \cdot x_p/\pi k\rho c(T_{ig}-T_o)^2 \qquad (5)$$

Constant $Q_f^*$ is assumed in the derivation of equations (4) and (5) from equation(2). It is important that the functional forms of equation(4) and (5) are very close; the integral part in the parenthesis [ ] is the only difference. With flame spreading velocity represented as a function of $x_p$, it is important that the preheating of unburnt surface by wall flame is the most significant for the steady flame spread and is the weakest for the case b) as the preheat length is essentially an increasing function of $x_p$. In the sense that any growing flame spread starting with a finite ignition source must fall in between the steady fire and the exponential fire, conditions a) and b) should be considered to give the upper and lower bound of the possible growing flame spread respectively. Figure 4 is a summary of the calculated $V_p/\{x_p/\pi k\rho c(T_{ig}-T_o)^2\}$ for a) and b) using the experimental $q_w''$ correlation summarized in Figure 6. $\Psi=V_{pa}(x_p)/V_{pb}(x_p)$ can be a measure of the predictability of flame spreading velocity in the sense that, if $\Psi$ value is close to unity, flame spreading velocity starting with arbitrary initial condition must fall within a narrow range between the two solutions.

In Figure 4, it is noteworthy that $\psi=\pi k\rho c(T_{ig}-T_o)^2 \cdot V_p/x_p$ is very sensitive to $Q_f^*$ especially in the low $Q_f^*$ region. Since $Q_f^*$ of a wall fire during an early stage of a building fire is generally lower than 0.5[7], this high sensitivity means that even a small change in the heat release rate from the burning wall can result in dramatic change in the flame spreading velocity. Equations(4) and (5) also suggest a strong sensitivity of flame spreading velocity on ($T_{ig}$-$T_o$). Surface temperature before the start of preheating by plume, $T_o$, can be raised by external heating, e.g. radiation from fire source or convective/radiative heat transfer from smoke layer. Equations(4) and (5) suggest general importance of the evaluation of such external heating to the combustible surface for fire safety assessment.

Equation(4) is a generalization of the earlier steady flame spread velocity formulations assuming specific heat flux distributions, e.g. de Ris[14], Orloff, de Ris and Markstein[31], and Sibulkin and Kim[32]. Especially Orloff, de Ris and Markstein[31] derived a flame spread velocity formula using their experimental finding, $x_f(t) = x_p(t+\tau)$, which was found to be effective for transient growing fires on vertical PMMA. This relation may lead to another type of formulation of flame spreading velocity by taking the Taylor expansion of this relation with regard to $\tau$ as $x_f(t)-x_p(t)=x_p(t+\tau) - x_p(t) = dx_p(t)/dt \cdot \tau + d^2x_p(t)/dt^2 \cdot \tau^2/2+\cdots$;

$$V_p(t)=dx_p(t)/dt=\{x_f(t)-x_p(t)\}/\tau - d^2x_p(t)/dt^2 \cdot \tau/2 - \cdots \qquad (6)$$

Equation(6) demonstrates equivalency of steady-state flame spread velocity to $\{x_f(t)-x_p(t)\}/\tau$. As discussed later, this relation is used as a main assumption for the modeling of concurrent flame spread based on the linearized flame length approximation. Equation(6) also suggests $\{x_f(t)-x_p(t)\}/\tau$ greater than $V_p(t)$ for a accelerated flame spread ($d^2x_p(t)/dt^2>0$) and $\{x_f(t)-x_p(t)\}/\tau$ smaller than $V_p(t)$ for a decelerated flame spread. However, it is also important that effectiveness of the empirical relation $x_f(t) = x_p(t+\tau)$ has been established only for growing flame spread[7,31, 33]. This relation should perhaps fail for decelerated flame spread.

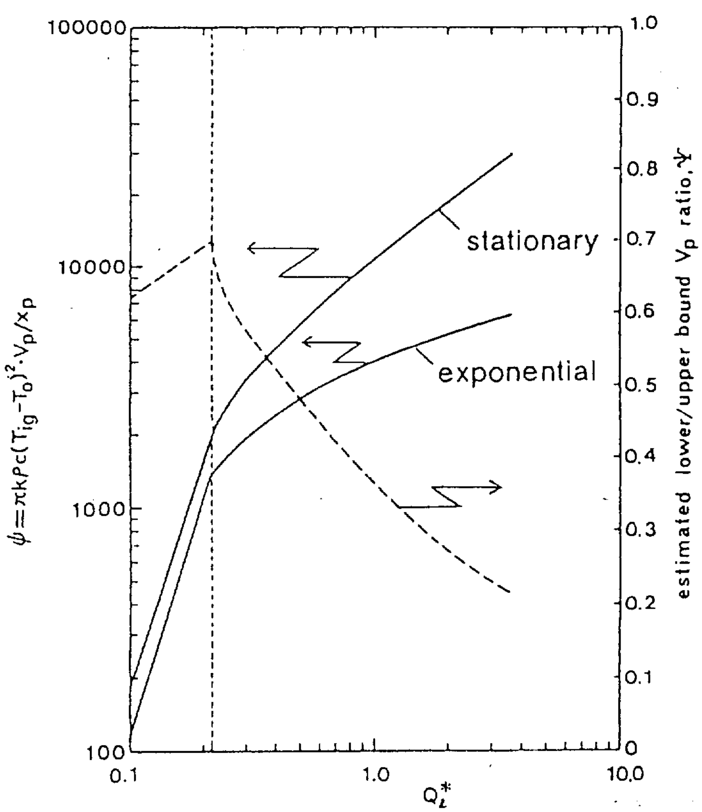



Figure 4 $\psi=\pi k \rho c(T_{ig}-T_o)^2 \cdot V_p/x_p$ for stationary and exponential flame spread modes and estimated lower/upper bound $V_p$ ratio(Ref.7)

Comparing equation(4) and (6), $\tau$ can be formulated as

$$\tau = K\{Q_\ell^{*2/3}-1\}\pi k\rho c(T_{ig}-T_o)^2/[\int Q_\ell^{*2/3} q_w''(\lambda+1/Q_\ell^{*2/3})/\lambda^{1/2} d\lambda]^2 \quad (7)$$

Benefit of the similarity solution is the simplicity of the solution. Influence of any conditions on flame spreading velocity could be estimated easily in analytical manner. Nevertheless, this approach is believed to have limitation in the practical application, since equation(4) nor (5) cannot be applied to any situation where flame die out is anticipated.

**Linearized Flame Length Approximation**

A Volterra type integral equation has been developed for upward flame spread by Saito, Quintiere and Williams[33] assuming the following two proportionalities:

a)proportionality of $V_p$ to the distance between the flame front, $x_f$, and the pyrolysis front, $x_p$, i.e.

$$V_p(t)=dx_p(t)/dt=\{x_f(t)-x_p(t)\}/\tau \quad (8)$$

b)proportionality of flame length to heat release rate per unit width, i.e.

$$x_f=KQ_\ell \quad (9)$$

where $Q_\ell$ is the total of heat release from the pilot flame, $Q_o$ and that due to the combustion of the wall, $Q_w(t)$. $Q_w(t)$ can be formulated as

$$Q_w(t)=\int q(t-s)V_p(s)ds+x_{po}\cdot q(t) \quad (10)$$

where $x_{po}$ is the initial condition of the pyrolysis front height. Saito et al assumes equivalency of $x_{po}$ with the pilot flame height, $KQ_o$[33]. Although flame length measurements support dependence of flame height on the 2/3 power of heat release rate[30,55], some measurements suggest apparent proportionality of flame height to the length of the pyrolysis zone[7,33]; it may reflect increase of surface heat flux in accordance with increasing the heat release rate[42]. Substitution of there relations into equation(8) makes a linear integral equation for $V_p(t)$ as

$$V_p(t)=[K\{Q_o+Q_w(t)\}-x_p]/\tau=[K\{Q_o+\int q(t-s)V_p(s)ds+x_{po}\cdot q(t)\}-\{x_{po}+\int V_p(s)ds\}]/\tau \quad (11)$$

Equation(11) is often refereed to as the SQW equation. SQW equation has been analyzed in detail[33,34,35,36], and its analytical solution has been obtained for several function al forms of heat release rate, q(t) by Laplace transform. These analyses have revealed that the asymptotic behavior of flame spread can be classified into three different categories, divergence, vibration, and convergence, according to the combination of the peak heat release rate, $a=Kq_o$, characteristic decay time of heat release, t, and $\tau$ (Figure 5). Flame spread is expected to stop at certain height if the solution is categorized in the convergence or vibration regimes, and the maximum pyrolysis front height, $x_{poff}$,divided by $x_{po}$ becomes a function of only $q_{max}$, $t_c$ and $\tau$. Modification of SQW equation to incorporate the effect of local burnout has been proposed recently[36,37]. Substituting $x_f = KQ_\ell+x_b = KQ_\ell + x_{po} + \int V_p(s)ds$ into equation(8) and ignoring the pilot flame after $x_b$ has reached the pilot flame height $x_{po}$, equation(8) yields

$$V_p(t)=[K[Q_o\{1-U(t-t_b)\}+\int q(t-s)V_p(s)ds+x_{po}\cdot q(t)\}]+\{x_{po}+\int V_p(s)ds]U(t-t_b)-\{x_{po}+\int V_p(s)ds\}]/\tau \quad (12)$$

which will be referred to as the generalized SQW equation. As reported in many burn tests, local burnout is rather common for charring materials and thin combustible linings. Consideration of the development of burnout front is important since it raises the bottom of the pyrolysis zone and can lead to higher flame front height and faster flame spreading velocity. Laplace transform of equation(12) can be summarized as

$$V_p(s)/x_{po}=[(KQ_o(s)/x_{po}-1)\{1-\exp(-t_b s)\}+sKq(s)]/[s\tau-sKq(s)+\{1-\exp(-t_b s)\}] \tag{13}$$

Change of the sign of the roots of the characteristic equation for equation(13) for a step-like heat release function, $q(t)=q_o\{1-U(t_b)\}$,

$$s\tau+\{1-\exp(-t_b s)\}(1-a)=0 \tag{14}$$

occurs at $\tau/t_b=a-1$; for $\tau/t_b>a-1$,the real root of equation(14) is negative and flame spread is expected to stop at certain height. Flame spreading velocity is expected to diverge for $\tau/t_b<a-1$. Similar criticality has been derived for thin linings by Mowrer and Williamson[38] through different definition of the local burnout time, $t_b$.

A model of a room corner fire assuming a two-dimensional development of pentagonal pyrolysis zone has been developed by Cleary and Quintiere[39]. This model formulates the growth of the pyrolysis zone according to the rule represented by equation(8), and is considered an extension of this approach from a one-dimensional wall fire to room fires. The model uses similar treatment of the local burnout time with the one-dimensional wall fire model for thin linings[38].

Linearized flame length approximation is useful to see what parameters are the most dominant for flame spread, and to obtain overall picture of the flame spread. One important practical relation that this approach can offer is the similarity of flame spread velocity and pyrolysis front height with regard to the pilot flame height, $x_{po}$. Figure 5 also summarizes solution of equation(12) for $x_{poff}/x_{po}$ with $q(t)=q_o\cdot\exp(-t/t_c)$ without consideration of the movement of burnout front for the location of the maximum pyrolysis front height, $x_{poff}$.

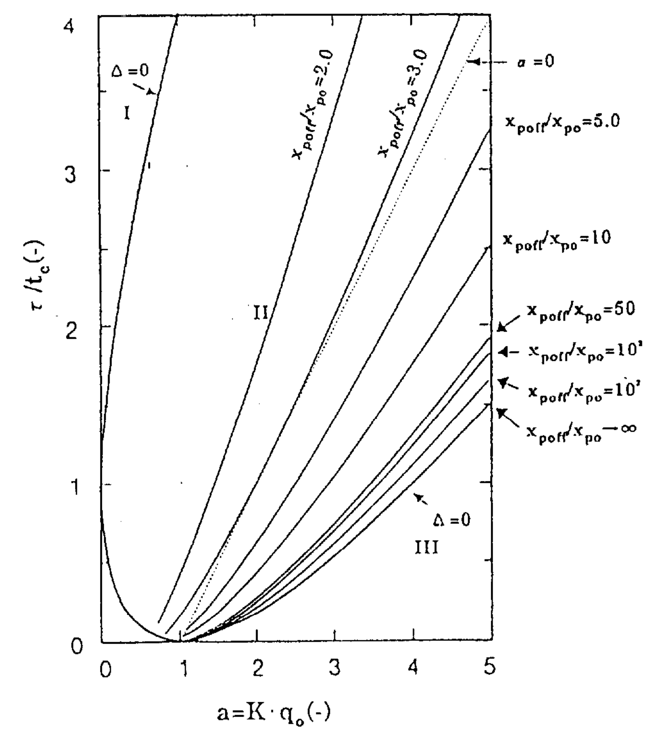



Figure 5 Division of the $Kq_o$ - $\tau/t_c$ plane for $q(t)=q_o\cdot\exp(-t/t_c)$(sustained pilot flame) · The solution is diverged in the region III.

In spite of the extensive analytical capability of this approach, this approach seems to have still unsolved difficulties in the basic assumptions and the treatment of local heat release rate. Equation(6) demonstrates that equation(8) can hold in general only for steady state flame spread, although this approach uses equation(8) as a basic assumption even for transient flame spread. In the interpretation of experimental results, use of measured time between the arrivals of pyrolysis front and flame front into $\tau$ should lead to greater $\{x_f(t) - x_p(t)\}/\tau$ than $V_p(t)$ for accelerated flame spreads, and that for decelerated flame spread should result in smaller $\{x_f(t) - x_p(t)\}/\tau$ than measured $V_p(t)$. Another condition in which the form $V_p=\{x_f(t) - x_p(t)\}/\tau$ can be effective is a wall fire developing exponentially with time. Solution of equation(12) for $q(t)=q_o$ and $Q_o(t)=0$, $x_p(t)=x_{po} \cdot \exp\{(a-1)t/\tau\}$, relation between and the time interval between the arrivals of pyrolysis front and flame front, $t^*$, can be obtained from $x_f(t)=x_p(t+t^*)=a \cdot x_p(t)$ as $t^*/\tau = ln(a)/(a-1)$, and $\tau$ can be quantified as

$$\tau = K\{Q_\ell^{*2/3}-1\}\pi k \rho c(T_{ig}-T_o)^2/[\int q_w''\{\exp(\lambda)/Q_\ell^{*2/3}\}/\lambda^{1/2} d\lambda]^2 \tag{15}$$

from comparison between equation(5) and equation(8). Application of this approach to transient fires needs such redefinition of $\tau$. The linearized flame length approximation may also cause unignorable discrepancy especially for an accelerated flame spread. Proportionality of flame length on a wall to 2/3 power of heat release rate has been established experimentally; this suggests gradual approach of the pyrolysis front to the flame front on a thick combustible wall with development of the pyrolysis front as far as heat release rate per unit area is kept constant and local burnout is ignorable[40]. However, effectiveness of this anticipation is critical since dependence of surface heat flux on scale and fire intensity has been reported experimentally[41]. Difficulty related to the local heat release rate comes from the limitation of the functional form of q(t) for analytical solution of equation(12). Complicated time history of heat release rate common for thick charring materials is perhaps difficult to describe with any function which fits Laplace transform.

Recent extension of this approach to a nonlinear flame length formulation by Kokkala and Baroudi[42] may resolve at least the heat release rate part and the flame length approximation part of the difficulties. They derived the following finite difference approximation for equation(8).

$$x_p(t_{i+1})=(1-\Delta t_{i+1}/\tau)x_p(t_i)+x_f(t_i)\Delta t_{i+1}/\tau \tag{16}$$

where $t_i$ and $t_{i+1}$ represent "$i$"th and "$i+1$"th time steps respectively. Flame front height is formulated in the front $x_f(t_i)=KQ(t_i)^n$, and the contribution of the wall flame to total heat release rate is calculated by using $V_p(t)=\{x_f(t) - x_p(t)\}/\tau$ in equation(3). This quasi-numerical model does not need linearized flame approximation any longer, and has been applied to the wall burning of thick charring materials. Comparison of this model with full scale tests shows considerable capability to deal with the dual peaks of local heat release characteristic to thick wood slabs.

## FLAME LENGTH AND FLAME HEAT TRANSFER CORRELATIONS

Distribution of surface heat flux especially from the flame is an important input for the prediction of upward flame spread. Since flame heat transfer is believed to be controlled by flame length, it is important to summarize flame length and surface heat flux as a function of properties available from fire source and building conditions. Previous experimental works on flame length and flame heat flux are summarized on different configurations in this section. However, heat flux measurement became common in fire research only in 1980's probably because of the only recent popularization of the use of heat flux gages in fire research; in spite of the importance of heat flux for fire growth, only few works have been done on ceiling fire, and inclined upward surfaces.

**Flat Wall**

Measurement of surface heat flux due to a wall fire was pioneered by Faeth et al[43,44] in 1970's, and practical correlations were obtained during 1980's[30,45]. Summary of wall flame heat flux distributions from line burners, vertical wicks and burning walls demonstrates nearly sole-dependence of heat flux on the height normalized by flame length, $x/L_f$. Since wall flame height from a line fire is represented as $L_f = \gamma\, Q_\ell^{*n} \cdot D$ with $n \doteqdot 2/3$, $q_w''$ could further be correlated against $x/Q_\ell^{*2/3} \cdot D$ as seen in Figure 6. Heat flux within the solid flame($x<1.2x/Q_\ell^{*2/3} \cdot x_p$) was nearly constant with height, and, for $Q_\ell$<100kW/m, $q_w''$ was found to be approximately 25-35kW/m$^2$ irrespective of fuel or heat release rate. However, recent measurement on larger heat release rate from a square burner against a inert wall by Back et al[41] demonstrates gradual increase of heat flux in solid flame with increasing source heat release rate, and $q_w''$ in the solid flame for approximately Q>500kW was found to exceed 100kW/m$^2$. The decay of heat flux characteristic in the intermittent flame and in the plume was still consistent with previous experimental correlations[30]. The very high heat flux in the solid flame observed for large source heat release rate is probably enough high to maintain pyrolysis from common charring materials, whereas it is common that forest products be self-extinguished if the surface is not exposed to external radiation. Height of wall flames from rectangular or square burning surfaces has been correlated against $Q_{mod}^* = Q/\rho C_p T_o g^{1/2}(DW)W^{1/2}$[13]; flame height becomes larger as the aspect ratio of the burning source, W/D, is increased until it reaches the line fire limit(Figure7(a)).

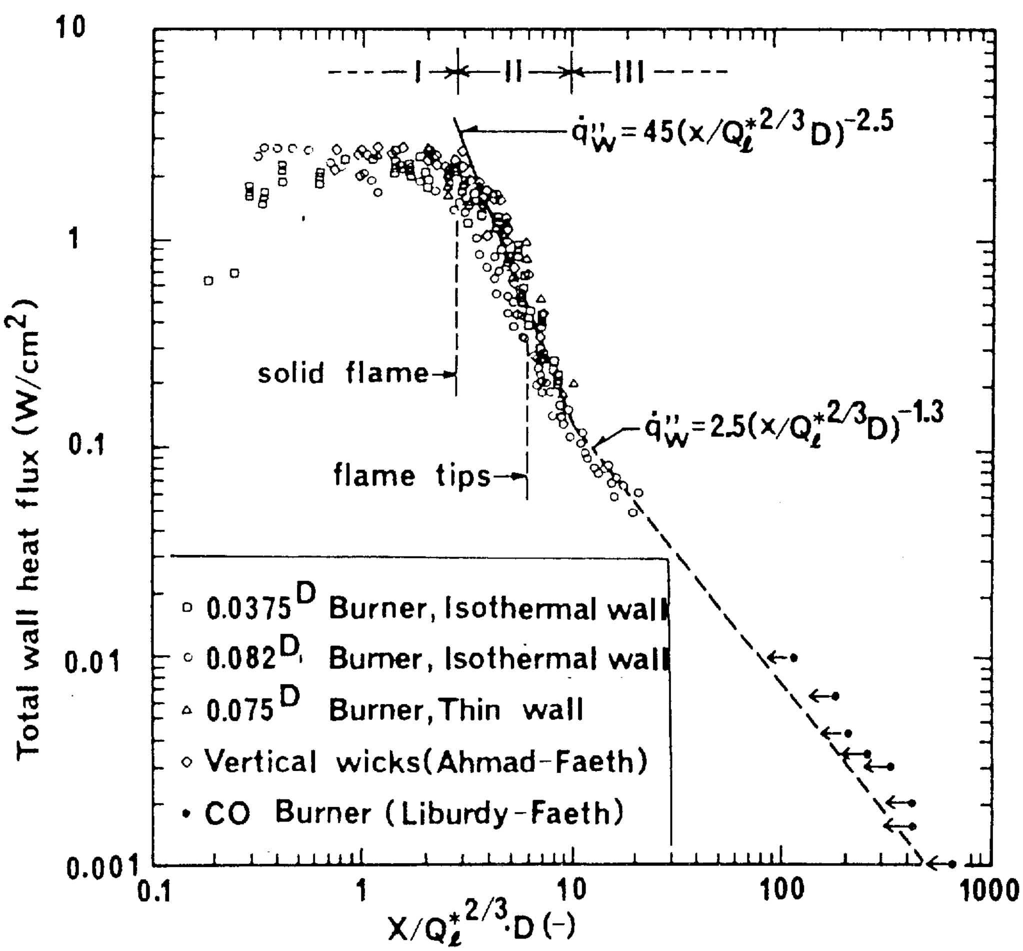
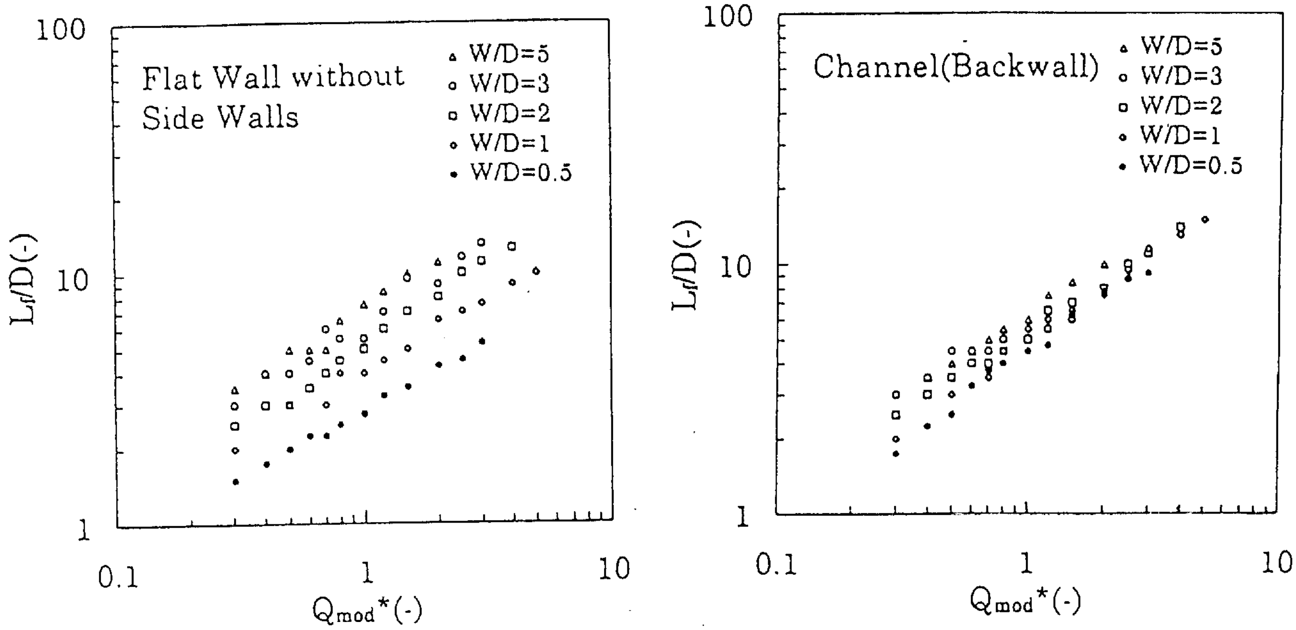



Figure 6 Total wall heat flux vs. height normalized by $Q_\ell^{*2/3} \cdot D$(data from various resources, Ref.30)




(a)Flat Wall

(b) Flame height measured at the center of the backwall of a channel

Figure 7 Flame height vs. Dimensionless heat release rate, $Q_{mod}$*(Ref.13)

**Wall Corner**

It is widely recognized that flame height from a fire source can become considerably higher in a wall corner than on a flat wall due to the restriction of entrainment[46,47]. Height of flame from a pool fire in a corner of walls without ceiling has been correlated against $Q^*=Q/\rho C_p T_o g^{1/2} D^{5/2}$ with D as the characteristic scale length of the fire source. More recent experiments on surface burning in a wall-corner[48] show approximately 40% larger flame height for wall burning than for a pool fire in the corner if $Q_{DH}^*=Q/\rho C_p T_o g^{1/2}(DH)H^{1/2}$ with H as the burner height is used for the dimensionless heat release rate. However, it is also important that, in a wall-corner configuration, heat flux to the wall surface within and above the flame can also become higher than on a flat wall due to the radiation between the two adjacent heated wall surfaces. According to the two-dimensional measurements of heat flux in open wall-corner configurations, this extra heating effect is particularly pronounced within the solid flame[47,48]. These measurements show sole dependence of heat flux along the corner edge on the height divided by the flame length.

**Corner-Wall-Ceiling**

Although horizontal flame spread along the ceiling and the upper part of the walls exposed to flame or smoke layer is an important part of fire growth in room fires, most of compartment fire models [49,50] seem to use unverified empirical estimates for the flame heat transfer or flame spread velocity for these horizontal concurrent flame spread. However, this only reflects the lack of experimental data and analysis for such configurations.

Flame length from a fire source in the open room corner configuration, with ceiling, has been reported by Gross[51]. His data showed failure of flame length correlation against Q* in this configuration; replacement of burner size by ceiling height in the expression of Q* has resulted in a remarkable concentration of his data along one curve[52]. However, physical implication of this redefinition is unclear since $D^{5/2}$ part of the definition of Q* is essentially the product of the area normal to the forced-flow direction and the square root of the length representing buoyancy. Some heat flux data have been published on a 7.6m tall open corner-wall ceiling configuration with and without combustible linings[53]. More recent experiments using a reduced-scale open corner-wall-ceiling rig[48] have correlated flame length from pool fires in the corner and from corner-wall fire against $Q_{DH}^*$ and have described the distribution of surface heat transfer to the ceiling surface and to the ceiling-wall boundary as a function of the horizontal distance normalized by horizontal flame length measured from the corner. According to this flame length correlation, horizontal flame length depends only very weakly on heat release rate; this suggests easier involvement of ceiling by flame with decreasing the size of enclosure. Gross' data of flame length have been found to be consistent with this correlation. Decay of heat flux with respect to relative distance to flame length has been found to be steeper in the wall-corner surface burning than in the pool fires.

**Vertical Channel**

Flame height and surface heat flux have been measured on inert vertical channels of different aspect ratios with porous rectangular propane burners settled at the bottom of the channels[13]. The measurements demonstrate notable augmentation of flame height for the aspect ratio, W/D, not larger than 1, compared with flames over a flat wall. The $L_f/D$ vs $Q_{mod}^*$ curve for each aspect ratio becomes closer to the line-fire limit probably because of the restriction of entrainment in the horizontal direction to the wall surface(Figure 7). Surface heat flux to the backwall within the solid flame reached almost 90kW/m$^2$, twice to three times larger than that on a flat wall. Surface heat transfer correlations against height divided by flame height in a channel beyond the solid flame have been found to be nearly consistent with the flat-wall correlations. A full-scale burn test of flame projection due to fully-developed room fires[54] has also reported significantly higher heat flux to the facade in vertical channel configuration of the facade than on a flat facade. The reported facade heat flux value exposed to a solid flame in a channel of the aspect ratio approximately 1.0, 130kW/m$^2$, is higher than the laboratory tests[13], and is believed to endorse the fire-source dependence of heat flux reported more systematically by Back et al[41]. 130kW/m$^2$ is equivalent to 1,000℃ black body radiation, and is believed to be close to the upper bound for possible heat flux in fire.

**Other Configurations and External Heating from Smoke Layer**

Other configurations in which concurrent flame spread can be accelerated include parallel walls and shafts. Foley and Drysdale[55] measured heat flux to the surfaces of parallel vertical walls from line fires against one wall and between the two walls and represented its vertical distribution as functions of $Q_f^*$ and $\delta$/D, the separation distance between walls divided by the burner length.

In the flame spread over a combustible lining surface exposed to smoke layer, heating of the surface by the smoke layer can influence the flame spreading velocity. Heat transfer from the smoke layer to the wall or ceiling surface should depend at least on the emissivity of the smoke and the surface, roughness of the surface, and the orientation; fire experiments using a porous burner with heat output 100 ~ 300kW as the heat source and approximately 3m × 12m × 2.4m(tall) enclosure with a continuous opening along the longer side reported 0.03 ~ 0.04kW/m$^2$K for the total heat transfer coefficient[56]. This heat transfer coefficient range suggests 6kW/m$^2$ gage output for 150~200K excess temperature which is believed to be rather typical in a preflashover fire. This heat flux is enough to cause considerable acceleration of flame spread as shown in Figure 7. Janssens[57] has reported consistent h values for the ISO5657 ignitability test apparatus.

## FIRESAFETY ASSESSMENT AND ENGINEERING APPLICATION OF THERMAL MODELS OF CONCURRENT FLAME SPREAD

Some of the flame spread models discussed in previous sections have been validated against relatively large scale burn tests[e.g. 7,24,26,37]. However, the tests were conducted on ideal materials from the experimental point of view to reproduce ideal conditions that the models try to simulate. It is believed that application of these models to firesafety assessment needs special consideration of the conditions of building occupancies, availability of practical test methods fitting the modeling methodology and other conditions which may have influence on fire behavior in the real world. In this section, research and technical informations concerned with the application of the concept of flame spread models are reviewed, although perhaps many of these studies may not have direct relevance with flame spread modeling.

**Practical Evaluation of Flame Spread Hazard**

Strong sensitivity of flame spread behavior to environmental conditions and configurations suggests necessity of the consideration of detailed design informations for the firesafety assessment with regard to flame spread. Direct application of the thermal models with such consideration could be made for the design of standardized mass products such as aircraft and other transportation vehicles or for the design of a big construction project. However, firesafsty assessment of buildings generally has to deal with small projects designed and built by amateurs on fire safety engineering. Application of mathematical models to small construction projects is believed to be difficult also in the sense that, although fire growth is believed to sensitive to furnishings in small enclosures, it is generally difficult to predict or identify what furnishings be used after the completion of the building.

Dimensional analysis and the use of the key parameters controlling the growth of fire are generally considered effective and robust approaches to evaluate rationally the fire hazard in any conditions characterized by such uncertainty. Quintiere[58] has shown clear bifurcation of the qualitative results of the ISO9705 Room Corner Test according to a dimensionless parameter which is essentially equivalent to the acceleration/deceleration criticality for upward flame spread derived from equation(14). The room fire behavior dominated by wall fires[58] may possibly be a result of the use of a small room; validation of this correlation against larger rooms should be interesting problem for the generalization of such approach. Dimensional analysis by Karlsson and Magnusson[59] using the thermal inertia, peak heat release rate and its decay parameter of material exposed to certain heat flux level and lateral flame spread parameter and that by Kokkala, Thomas and Karlsson[60] using time-to-ignition and integrated heat release rate at certain heat flux level reproduce results of numerical calculations of fire growth in the ISO9705 Room Corner Test. The analysis of Quintiere[58], and Kokkala, Thomas and Karlsson[60] use essentially data only from ignitability and dynamic heat release measurements.

**Material Properties for the Flame Spread Assessment**

Material properties necessary for the input for the thermal models are k, $\rho$, c, $T_{ig}$, and the time history of heat release rate under anticipated heat flux from flame and fire environment. For the engineering application of the thermal modeling, it is important to develop practical methodology to estimate these properties. The current activity at ISO/TC92/SC1(Reaction to fire) tries to develop bench-scale tests conforming to this approach and summarize the methodologies for the application of the test results to the prediction of fires[61,62].

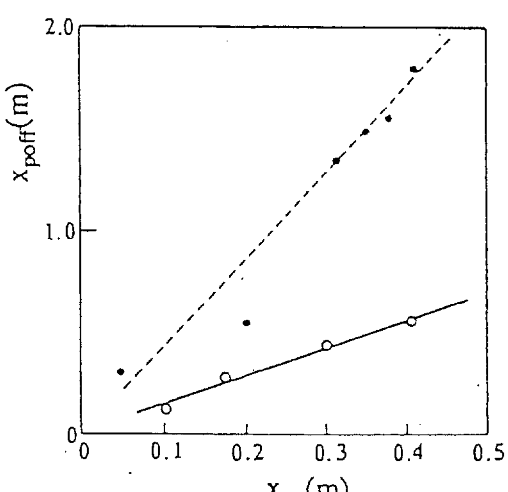
Among the parameters listed above, k, $\rho$, c and $T_{ig}$ are believed to represent the ignitability. Thermally-thick solid assumption is very often used to reduce the number of unknowns from k, $\rho$, c and $T_{ig}$ to $k\rho c$ and $T_{ig}$. These properties can be estimated from time-to-ignition, $t_{ig}$, data for different levels of external radiation, $q_e''$ generated from such radiation exposure test as ISO5657 Ignitability test. The methodology was first demonstrated in 1960's[61], and numbers of modification have been reported since then. Using an approximation of the equation(2) for a semi-infinite inert solid, Janssens[57] has obtained

$$q_e''=q_{cr}''\{1+0.73(k\rho c/h^2 t_{ig})^{0.547}\} \qquad (17)$$

where $q_{cr}''$ is the critical heat flux for ignition defined as $q_{cr}''=h(T_{ig}-T_o)$, and h is the total heat transfer coefficient. An apparent $k\rho c$ value can be estimated from the linear fit according to equation(17) whilst $q_{cr}''$ follows from the intercept with the abscissa. Simplicity of the procedure and testing method is an important benefit of this estimation method. However, estimated $k\rho c$ value is so sensitive to the slope of $t_{ig}^{-0.547}$ against $q_e''$ that data-scattering or failure of semi-infinite inert solid approximation should result in considerable uncertainty of the material properties.

Advancement of the measurement of combustion heat release based on the oxygen consumption method since late 1970's has made it possible to measure dynamic combustion heat release in an open environment within the accuracy acceptable for engineering purposes[64]. These have been numbers of applications of the oxygen consumption principle from bench scale tests to such full scale tests as Room Corner Test. Cone Calorimeter is the most popularized bench scale testing apparatus for the measurement of dynamic heat release under external radiation[64].

The state of the art of bench scale ignitability and heat release test methods suggests considerable possibility that concurrent flame spread be assessed through bench scale tests. Application of these tests to the prediction of flame spread has been reported already[25,26,37,39,40,49,50,58,61,63]. However, it is important that the capability of bench scale test apparatus to reproduce end-use conditions of tested materials and the correspondence of test conditions with fire environment are not yet very clear. Originally heat release rate from common combustible building and furniture materials is believed to be sensitive to the heating condition[37,58]. In spite of the primary importance of flame spread for firesafety at relatively weak external heating, say less than $10kW/m^2$, there is still general technical difficulty in running Cone Calorimeter at such weak level of irradiance. Heat release rate obtained from Cone Calorimeter at a level of external heat flux of $25kW/m^2$ or lower was considerably lower than that obtained for identical heating condition from full scale or intermediate scale heat release measurement[65], whereas only a slight difference has been observed at an external radiation of $30kW/m^2$ or higher[66]. This lower heat release rate obtained from Cone Calorimeter(vertical orientation) especially at low external heat flux is attributed to the lower combustion efficiency[63]. Intermediate scale heat release measurement[66] may lead to heat release rate value closer to that in fire. Determination of the ignitability parameters through time-to-ignition measurement may not need strict consideration of the reproduction of fire environment. However, it is generally recognized that ignition temperature can be affected by the orientation and configuration of the surface of the material[67].




open: 10mm thick Oak, $q_e''=0$
solid: 12mm Lauan plywood, $q_e''=4.0kW/m^2$, $T_{si}=120$℃

Figure 8 Relation between pilot flame height and maximum pyrolysis front height(Ref.37)

**Intermediate-Scale Flame Spread Test**

Independence of $x_{poff}/x_{po}$ on $x_{po}$ for upward flame spread is an important relation derived from the linearized flame length approximation. This relation suggests the possibility that $x_{poff}$ for a full scale fire can be estimated from a small scale test using a small pilot flame even if solution of equation(12) cannot be obtained either due to the complexity of the functional form of q(t) or even the lack of the data of material properties[36]. Figure 8 is a summary of the measured maximum pyrolysis front heights for different pilot flame heights, and show general support of the conservation of $x_{poff}/x_{po}$ value against the change of pilot flame height. Although reduced scale flame spread test is only a sort of ad-hoc test, this approach does not need any mathematical treatment of the test data nor sophisticated apparatuses.

**Evaluation of Ignition Source Intensity**

The conservation of $x_{poff}/x_{po}$ for $x_{po}$ suggests general importance of the evaluation of ignition source intensity for fire safety assessment of wall fires. Combustion of furniture is a typical ignition source to wall lining. Identification of possible fire sources for the ignition and external heating of lining surface and control of the combustion heat release from furnitures should be useful for rationalizing the evaluation procedure. The oxygen consumption principle has been applied to the measurement of heat release rate from possible fire sources in buildings[68], and has been implemented into furniture combustibility regulations[e.g. 69]. Methodologies to reduce heat release rate from furnishings without causing significant influence on other furniture performances have been developed[70].

Another important condition of ignition source which may have significant influence on wall fires is the relative location of the ignition source to the wall. Measurements of heat flux at the corner wall from fire sources at different distances in the room corner fire configuration[71] have demonstrated relatively large change of surface heat flux by only the differences of 5cm in ignition source location. The measurements also showed relatively large heat flux value, $60kW/m^2$, to the wall corner exposed to the solid flame from the burner attached to the corner. This strong heat flux is attributed partly to the radiation feedback between the two adjacent corner walls.

## CONCLUDING REMARKS

It was perhaps in ancient times or even prehistoric age that concurrent flame spread was first recognized as the primary cause for significant fire disaster. Ideas to prevent this phenomenon in built environment or in wildland can be seen in the tradition of any culture all over the world. However, until recently, it seems that significance of concurrent flame spread was excessively connected with its extreme sensitivity to environment and configurations. The state of the art of the understanding of concurrent flame spread in fire, especially upward turbulent flame spread, and advancement and popularization of measurement technology seem to show fairly good achievement in the establishment of the framework to deal with this important process of fire growth in sound scientific manner, although there are still unsolved problems and progress of its scientific understanding has revealed new uncertainty of this phenomenon.

There is considerable delay in the application of engineering concept in the control of fire growth in comparison with smoke control and structural fire safety. Although the present stream of mathematical models to predict structural behavior and smoke movement in fire started already in 1960's and the framework for engineering evaluation of these were nearly established in 1970's, only pioneering works were available on turbulent flame spread in fire until around the beginning of 1980's. As introduced in this review, there are already many trails to develop testing and evaluation method on concurrent flame spread especially in buildings. These efforts will probably develop engineering firesafety design method of interior and exterior linings and classification of materials based on firesafety engineering. However, another potential important subject which may result from the establishment of engineering approach to this phenomenon is the design of the material properties for firesafety. Of course control of material combustibility has a long history; however, it seems that conventional fire retardant technologies lack in the guidelines to demonstrate quantitatively what change in the structure or composition of materials can lead to the improvement of firesafety. Engineering modeling of pyrolysis, solid phase heat and mass transfer and heat release in conjunction with surface burning should be encouraged to develop strategies for the engineering design of materials from the firesafety viewpoint. Mathematical models to predict concurrent flame spread from material properties should be useful to develop techniques to control likelihood for fire development at various stages from chemical composition of the materials to the construction and finish of the materials. Effectiveness of other firesafety measures such as smoke exhaustion for the prevention of the acceleration of flame spread by the heating from smoke layer would also be worth studying.

There are fewer engineering modeling works on mass fires, inclined surfaces, vertical combustible shaft and other special configurations than on vertical surface and room fires. Comparison with upward flame spread may resolve some of the unsolved problems in these areas. Interactions in experts dealing with different modes or configurations of concurrent flame spread and related combustion and pyrolysis processes should be encouraged.

Only the diagrams from the publications by the author are used in this report only because of the anticipation of possible copyright limitation, and it does not imply any superiority of the work of the author to others. The readers are invited to consult with relevant papers in the list of reference. Also turbulent concurrent flame spread may relate with varieties of fire problems. Perhaps the list still misses many valuable works in this area worth studying for deeper understanding of the problems discussed in this report.

## TERMINOLOGY

A: surface area of burning surface, $C_p$ : specific heat of air, D:characteristic fuel size or channel depth, H: ceiling height or height of burning surface of wall, K: constant representing the proportionality of flame length to heat release rate based on the linearized flame length approximation, $L_f$: flame length, Q: heat release rate, Q*: dimensionless heat release rate($Q/\rho C_p T_o g^{1/2} D^{5/2}$), $Q_{DH}^*$:$Q/\rho C_p T_o g^{1/2}(DH)H^{1/2}$, $Q_H^*$:$Q\rho/C_p T_o g^{1/2} H^{5/2}$, $Q_\ell$:heat release rate per unit width, $Q_\ell^*$: dimensionless heat release rate per unit width($Q_\ell/\rho C_p T_o g^{1/2} D^{3/2}$), $Q_{mod}^*$: $Q/\rho C_p T_o g^{1/2}(DW)W^{1/2}$, $Q_o$: heat release rate from ignition source, $Q_w$: heat release rate due to surface burning, $T_{ig}$:ignition temperature, $T_o$: ambient temperature, $T_{si}$: initial surface temperature, $T_w$: wall surface temperature, U(t): Heaviside's Unit function, $V_p$: flame spreading velocity, W: width of burning surface or channel, a: $Kq_o$, c: specific heat of material, g: gravitational acceleration, h: surface heat transfer coefficient(total), k: thermal conductivity, q: local heat release rate, $q_e''$: heat flux due to external radiation, $q_o$: peak heat release rate, $q_w''$: heat flux from flame, $t_c$: characteristic decay time of heat release rate, $t_{ig}$: time to ignition, t*: time from the arrival of flame front to that of pyrolysis front, $x_b$: location of burnout front, $x_f$: location of flame front, $x_p$: location of pyrolysis front, $x_{po}$: height of pilot flame, $x_{poff}$: maximum pyrolysis front height, $\delta$ : separation distance between parallel walls, $\rho$ : density, $\tau$ : characteristic ignition time, $\phi$ (t): impulse response of surface temperature to surface heat flux. *A Symbol in italics* is the Laplace transform of the variable represented by that symbol.

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*Discussion*

Edward Zukoski: I was confused about the nomenclature. W is the width of the burner and D is the depth. What was the width of the depth of the sidewalls?

Yuji Hasemi: They are the same.

Edward Zukoski: So the burner filled up the space between the side walls and the back wall?

Yuji Hasemi: Yes.