SLIDE RULE ESTIMATES OF FIRE GROWTH

by

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Slide Rule Estimates of Fire Growth

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A series of prediction methods has been assembled to provide an analytical basis for estimating fire growth in compartments. Solutions for each prediction method can be made using programmable scientific calculators. Prediction methods are presented for: fire size and growth rates, mass loss rates, radiant heat flux, flame height, radial flame impingement, heat flux to a ceiling, smoke filling of a room, carbon monoxide hazard with smoldering fires, temperature rise in a compartment, ventilation flow rate, flashover occurrence, corridor smoke transfer and filling, smoke concentration, visibility, flame spread rates, and fire burn time.

These predictive methods are useful for estimating many of the critical elements related to fire behavior and help provide a better understanding of this complex phenomenon.

This report appears as Appendix B in *Fire Growth in Combat Ships* by J. G. Quintiere, H. R. Baum and J. R. Lawson, NBSIR 85-3159.

INTRODUCTION

THE PURPOSE OF THIS PAPER is to provide an analytical basis for estimating the growth of fire in compartments and its consequences. All prediction methods have been selected to allow for solutions to be made using programmable scientific calculators or pocket computers. The paper consists of a series of equations or data each of which describes a particular process in a fire's growth. Only minor discussions of theory are presented to provide some understanding of concepts related to the problem in question. For more information on each process discussed, refer to the appropriate reference materials. The equations presented will apply only to specific fuels or conditions and hence will be approximate when used for more complex or

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Reference: J. R. Lawson and J. G. Quintiere, "Slide Rule Estimates of Fire Growth," *Fire Technology*, Vol. 21, No. 4, November 1985, p. 267.

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different situations. Also, any consideration of these equations as constituting a dynamic interacting fire system will be filled with inconsistencies. Nevertheless, this series of equations can provide a reasonable sense of the quantitative features of fire growth. It will relate to material type — solids or liquids — not specific materials. For specific materials other than those addressed in the text, one would have to acquire data that are unique to the materials being studied. Moreover, the state of the art does not fully allow for fire predictions of specific materials.

FIRE SIZE AND GROWTH RATES

In order to make fire growth predictions, one must make a basic assumption about what material is burning. This assumption is used to calculate an estimated burning rate for the model and is a key factor for calculating other fire characteristics associated with fire growth. The four basic types of fuels identified with fire are usually classified as:

A. Solids (nonmetals).
B. Liquids.
C. Electrical equipment.
D. Metals.

In this paper we shall consider only some representative ways of estimating Class A and Class B materials. For Class A we will consider first a wood crib as representative of a complex structure; then a solid surface like a mattress, chair or slab of material. For Class B materials, a method for estimating burning rate is suggested and input data will be provided for some common liquid fuels.

In 1976, Delichatsios reported work accomplished on the study of fire growth in wood cribs.[1] In his work, it was shown that a simple model could be used to predict fire growth rates for wood cribs (see Figure 1). This model is put to use in this report for the same purpose. The model pays particular attention to crib geometry, surface area exposed for burning, and the wood's thermal properties. The equation used for estimating burning rate, $\dot{m}_f$, for cribs ignited in the center is,

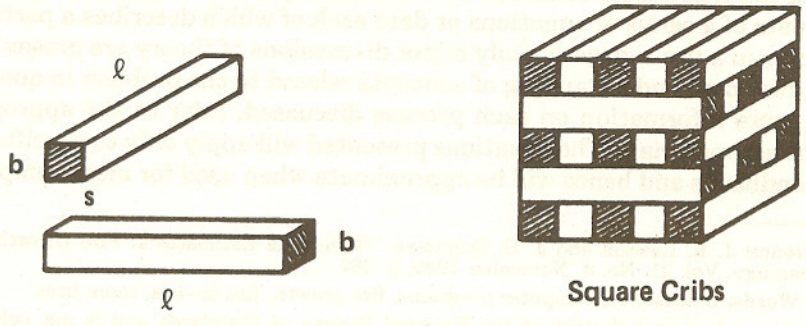


Figure 1. Sketch of a wood crib.

$$\dot{m}_f = \dot{m}'' A_s \frac{\pi}{2} \left(\frac{t}{t_o}\right)^2 \text{ for } t \le t_o \quad (1)$$

$\dot{m}''$ – specific burning rate found by: $\dot{m}'' = cb^{-1/2} f(P)$ where

$c \sim 10^{-3}$ g/cm$^{3/2}$ • sec
b – wood stick thickness (cm),
f(P) – found in Figure 2,
$P = A_v s^{1/2} b^{1/2} A_s$,

A_s – total exposed surface area of wood in the crib = $4\ell bnN$ where
ℓ – stick length (cm),
s – stick spacing (cm) = $\ell - nb$,
n – sticks per crib layer,
N – layers of sticks in crib,
A_v – total shaft cross-sectional area = s^2 • [number = $(n-1)^2$ of shafts],
t – time in seconds,
t_o – time for flames to spread to the outer edge of crib = $n/(\sqrt{2}\,\xi)$
$\xi \sim 0.045$ sec^{-1},

$$\dot{m}_f = A_s cb^{-1/2} f(P) \text{ for } t > t_o \quad (2)$$

where f(P) is plotted in Figure 2 and when $P > 0.07$, $f(P) = 1$.

Burning Rates for Furnishings

With more complex solids like furnishings, representative data are drawn from a report by Lawson, et al.[3] Figure 3 exhibits the mass loss rate for a typical stuffed chair and Figure 4 provides data on a typical three seat sofa. Mass loss rate data for burning mattresses is obtained from a report published in 1977 by Babrauskas.[4] Figure 5 presents data for cotton and mixed fiber core mattress specimens. Data from these and other reports can

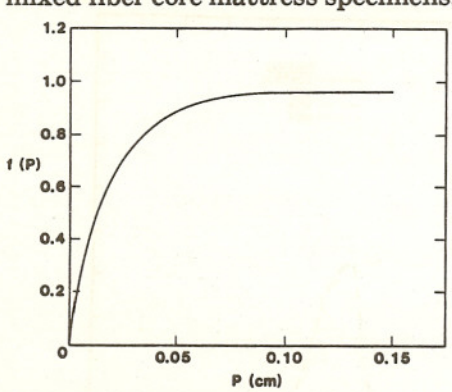


Figure 2. Reduced specific burning rate as a function of the crib porosity for ponderosa pine wood cribs (taken from Heskestad[2]).

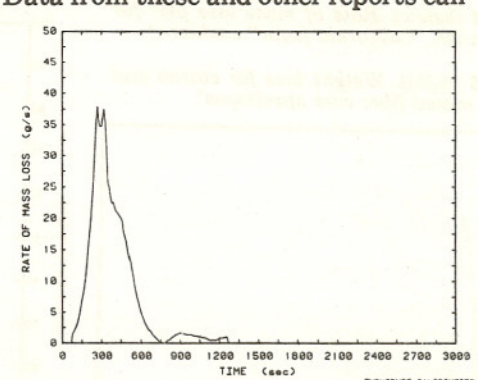


Figure 3. Rate of mass loss plot for easy chair[3].

be substituted in calculations on burning rates for furnishings. Furnishings are complex solids that do not currently lend themselves to simple fire modeling as other common solid materials do.

Burning Rates for Plastic Pool Fires

The burning rate for polyurethane foam was estimated with the following pool fire model developed by Orloff.[5]

$$\dot{m}_f = \alpha e^{(\alpha t - \beta)} \text{ g/sec} \tag{3}$$

where α = 0.033 sec^{-1},
β = 1.29 (corresponds to a time shift of 30.35 which accounts for a particular ignition character in this experiment),
t = time in seconds,

for the period $80 < t < 170$ sec.

A review of data from furniture fires[3] indicates that for polyurethane foam chairs, Equation 3 may also produce useful estimates for $t > 170$ sec.

Modak and Croce[6] studied the burning of polymethyl methacrylate (PMMA) plastic pool fires and found that experimentally measured burning rates per unit area, $\dot{m}''(t)$, at time t after ignition were correlated by the equation:

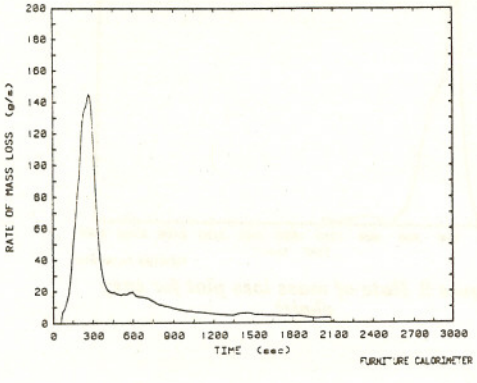
$$\frac{\dot{m}_s'' - \dot{m}''(t)}{\dot{m}_s'' - \dot{m}_i''} = e^{-t/\tau} \tag{4}$$

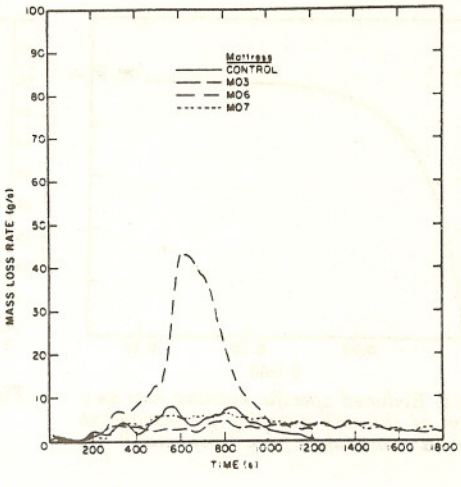
Therefore $\dot{m}''(t)$ can be estimated by,

$$\dot{m}''(t) = -[e^{-t/\tau}(\dot{m}_s'' - \dot{m}_i'') - \dot{m}_s''] \tag{5}$$

Figure 4 (below). Rate of mass loss plot for sofa with "California foam" cushions[3].

Figure 5 (right). Weight loss for cotton and mixed fiber core specimens[4].





where $\dot{m}_f'' \cong 4$ g/m² sec is the average burning rate per unit area; $\dot{m}_s''$ is the steady burning rate, and τ is the characteristic "gasification time" to reach steady state.

Table 1 contains data that can be used for calculating $\dot{m}''(t)$ for various size pools of PMMA.

TABLE 1. *Results for PMMA pool fires of varying scale.*[6]

Pool area m²	*Measured steady burning rate per unit area* $\dot{m}_s''$ (g/m² sec)	*Gasification time parameter*[b] τ (sec)	*Radiative fraction of total heat release rate* χ (—)
2.58×10^{-4}	4.6	NA	0.28[c]
5.81×10^{-4}	5.6	NA	0.32[c]
0.0232	7.7[b]	3448	0.32[c]
0.0523	9.0[b]	1587	0.42
0.0929	17.4[b]	1136	0.42
0.3716	18.0	500	0.42
0.5806	18.25	357	0.42
1.4865	20.0	118	0.42

[b] Best fit.
[c] Varied with time.
NA not available.

Burning Rates for Liquid Pool Fires

In order to estimate burning rates for liquid pool fires, data were taken from a report by Burgess, et al.[7] Their study shows the burning rate for a number of liquid fuels is a function of pool diameter. But for large diameter pools, flame radiation dominates and a maximum burning rate is achieved. Empirically they suggest that this maximum burning rate can be found by

$$\dot{m}_{max}'' = \left(6.5 \times 10^{-3} \frac{\text{cm}}{\text{min}}\right) \varrho \, \Delta H_c / \Delta H_v \tag{6}$$

where ϱ is the liquid density,
ΔH_c is the heat of combustion, and
ΔH_v is the heat of vaporization.

Some specific results are given in Table 2 for pool diameters greater than 1.5 m.

TABLE 2. *Burning rates for liquid pool fires.*

Liquid	$\dot{m}_{max}''$ (g/m² sec)	*x_r, flame radiation fraction (%)*
n-Hexane	76.9	42
Benzene	87.9	35
UDMH	44.3	24
Methanol	15.8	15
Gasoline	45.0	—
Diesel fuel	43.0	—

RADIANT HEAT FLUX TO A TARGET

After the initial fire has been defined, it is important to know something about the heat radiated from the source that could cause secondary ignitions. A technique discussed by Modak[8] will be used to estimate radiant flux. This method is depicted in Figure 6 and is detailed in Equation 7.

The incident heat flux at a target can be approximated as

$$\dot{q}_o'' \cong P/4\pi R_o^2 \tag{7}$$

where P is the total radiative output of the flame. P can be represented as $\chi_r \dot{Q}$ where χ_r is the radiative fraction and $\dot{Q}$ is total energy release rate. Usually χ_r ranges from 20 to 45 percent for many fuels. For a typical pool fire Modak[8] finds that the above formula is > 90 percent accurate when $R_o/R > 4$. At $R_o/R = 2$, the approximation is about 80 percent correct.

FLAME HEIGHT

Since burning rates and thermal radiation to targets have been defined, a third physical phenomenon relating to flame geometry must be considered. Flame height is an important characteristic which provides information needed for estimating heat transfer to a room's ceiling and other structures that may be located above a fire. It has been shown by McCaffrey[9] that flame height, Z_f, is related to the total energy release rate, $\dot{Q}$, and the diameter, D, of the fire base. This is illustrated in Figure 7 which is taken from a report by Zukoski, et al.[10]

For flame heights where $(Z_f/D) > 2$, Zukoski suggested the following equation which provides a reasonable estimate:

$$Z_f = (0.23 \text{ m/kW}^{2/5})\,\dot{Q}^{2/5}, \tag{8}$$

or use Figure 7 directly.

In addition, work reported by Hasemi and Tokunaga[11] for a 0.5 m diameter burner showed that the height of the continuous flame region could be estimated by

$$Z_{f\,min} = (0.11 \text{ m/kW}^{2/5})\,\dot{Q}^{2/5} \tag{9}$$

and the height to the flame tip could be estimated by

$$Z_{f\,max} = (0.21 \text{ m/kW}^{2/5})\,\dot{Q}^{2/5}. \tag{10}$$

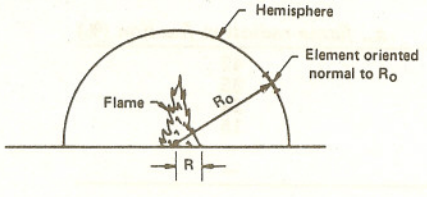


Figure 6. Fire radiant heat transfer to a target.

These results are consistent with Equation 8 and Figure 7, but explicitly address the variation of the flame structure from a continuous luminous region to a region above which are intermittent flames terminating at the flame "tip."

Their work also provides equations that are useful in estimating flame heights in a corner fire scenario. See Figure 8b. Equations 11 and 12 provide these estimates.

$$Z_{f,mm} = (0.075\ \text{m/kW}^{2/5})\,\dot{Q}^{2/5} \text{ for the continuous flame.} \tag{11}$$

$$Z_{f,max} = (0.118\ \text{m/kW}^{2/5})\,\dot{Q}^{2/5} \text{ for the flame tip.} \tag{12}$$

RADIAL FLAME IMPINGEMENT AND HEAT FLUX TO A CEILING

Now that flame height has been estimated, it is possible to estimate radial flame impingement on a ceiling and heat flux at a ceiling using equations offered in a report by You and Faeth.[12] When the height of a free burning flame exceeds the height of the ceiling, flame impingement would occur for that fire burning in a confined geometry. That effect is shown in Figure 9 where H_R gives the radial flame impingement length.

It has been found[12] that the height (H_f) of a free burning fire in the open generally exceeds the sum of the ceiling height (H) and impingement length (H_R) under these conditions. Thus, for a given fire energy release rate $\dot{Q}$, once H_f exceeds the ceiling height, the radial flame extension can be estimated from the following formulae.

For a ceiling with no side walls,

$$\frac{H_R}{D} = 0.5\,[(H_f - H)/D]^{0.96}; \tag{13}$$

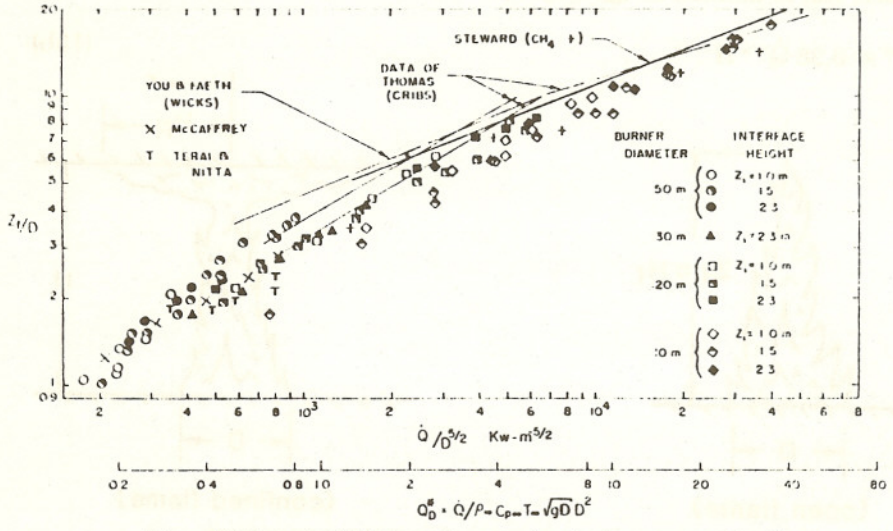


Figure 7. Flame height dependence on heat release parameters[10].

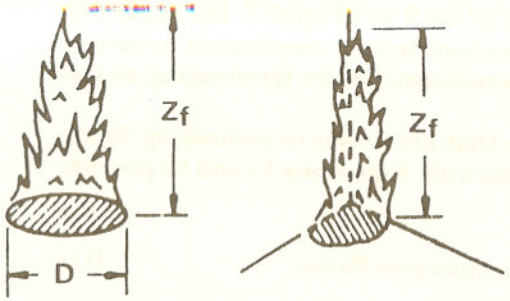


Figure 8a (left). For open flames.

Figure 8b (right). Corner fire scenario.

and for a ceiling with side walls,

$$\frac{H_R}{D} = 0.69\,[(H_r - H)/D]^{0.89}; \tag{14}$$

where D is the fire base diameter and H_r can be found from Equation 8. (Here Z_f and H_r are the same; since we have not attempted to unify our notation but have retained the notation of the original source.)

From the work of You and Faeth[12] an estimate of the incident (primarily convective) heat flux to the ceiling just above the fire can be found. This stagnation point heat flux $\dot{q}''$ is determined from the correlation:

$$\dot{q}''\,H^2/\dot{Q} = 31.2\,Pr^{-3/5}\,Ra^{-1/6} \tag{15a}$$

where H is the ceiling height and $\dot{Q}$ is the fire energy release rate. The equation was established for a Prandtl number of, $Pr = 0.7$, $H_r/H < 1.5$, $10^9 < Ra < 10^{14}$, and where flame radiative heat flux is small. The Rayleigh number, Ra, is defined as $(g\beta/\varrho c_p \nu^3) = 7.9 \times 10^{12}\ kW^{-1}m^{-2}$.

$$\dot{q}'' = 0.28\,\dot{Q}^{5/6}\,H^{-7/3} \tag{15b}$$

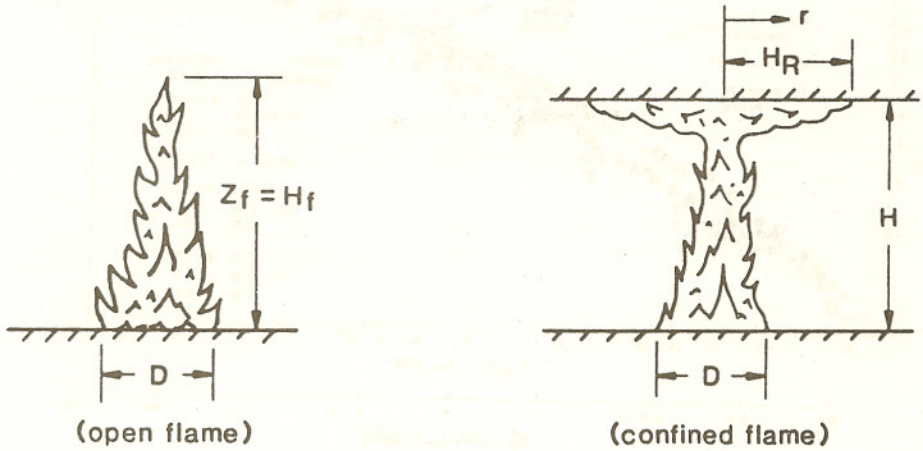


Figure 9. Flame length and geometric environment.

where $\dot{Q}$ is in kW and H is in m. Much of the data correspond to low Ra, or small scale so this formula may yield perhaps low estimates on extrapolation to large scale. For $H_f/H > 1.5$, they found the stagnation point heat flux to decrease significantly from the above formula. For large flames, flame radiation should be added, and also hot layer gas and surface radiation should be included after the room becomes hot (> 300° C).

SMOKE FILLING OF A ROOM

At this point in the calculation process, the basic fire has been characterized, and it is time to direct attention to changes in environmental conditions which result from the fire. In this section, estimates will be made on smoke filling time for a room. The "filling time," t_f, can be estimated as follows: i.e., t_f = time for the layer to reach a door soffit (see Figure 10) or a floor leak as in the case examined by Zukoski.[13] Figure 11 illustrates the dependence of ceiling layer height on time and heat input rate. For these results, heat loss from the smoke layer is neglected, and the room filling times are somewhat shorter than would be expected in a real fire. The governing equation and notation from Zukoski's analysis[13] are described below.

Smoke Filling Time

$$\frac{dy}{dt} + Q^* + \alpha (Q^*)^{1/3} y^{5/3} = 0 \tag{16}$$

where

$$y = Z/H - \text{nondimensional height of smoke layer interface,} \tag{17}$$

$$\tau = t\sqrt{g/H}\ (H^2/S) - \text{nondimensional time,} \tag{18}$$

t = time,
g = acceleration of gravity 9.8 m/sec^2,
H = room height,
S = floor area of the room.

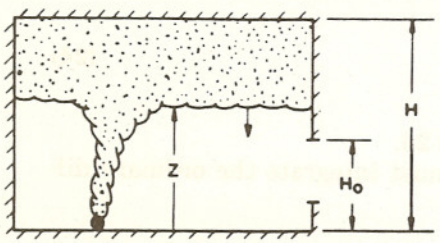


Figure 10. Room smoke filling model.

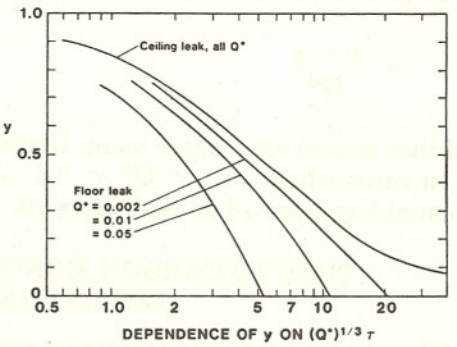


Figure 11 (right). Ceiling layer height versus time and heat input rate[13].

$Q^* = \dot{Q}/(\varrho_\infty T_\infty C_p \cdot \sqrt{gH} \cdot H^2)$ which is a nondimensional fire heat input parameter. (19)

$\dot{Q}$ = energy release rate of the fire,
ϱ_∞ = density of the air in room,
C_p = specific heat at constant pressure for air,
α = 1/5.4, the mass entrainment coefficient.

In Equation 16, if Q^* is small, < 0.01

$$y \approx \left[1 + \left(\frac{2\alpha}{3}\right)(Q^*)^{1/3}\tau\right]^{-3/2} \tag{20}$$

and if Q^* is large, > 0.4,

$$y \approx 1 - Q^*\tau. \tag{21}$$

To solve for t_f when $Q^* < 0.01$, Equation 20 is solved for τ,

$$\tau \approx \frac{\left(\frac{1}{y}\right)^{2/3} - 1}{\left(\frac{2\alpha}{3}\right)Q^{*1/3}}. \tag{22}$$

The time t_f to fill to a specific position y is then found by inverting Equation 18 as follows:

$$t_f = \frac{\tau}{\sqrt{g/H}\ (H^2/sec)}. \tag{23a}$$

Smoke layer height from the floor, Z, can be calculated by Equation 23b

$$Z = H\left[1 + \left(\frac{2\alpha}{3}\right)\left(\frac{\dot{Q}}{\varrho_\infty T_\infty C_p \sqrt{gH}\ H^2}\right)\left(t\sqrt{g/H}\ \frac{H^2}{s}\right)\right]^{-3/2}. \tag{23b}$$

To solve for t_f when $Q^* > 0.4$, Equation 21 is solved for τ,

$$\tau \approx \frac{1 - y}{Q^*} \tag{24}$$

and then solved for t_f again using Equation 23.

In cases where $0.01 < Q^* < 0.4$ one must integrate the ordinary differential Equation 16 or use Figure 10.

TIME TO CARBON MONOXIDE HAZARD WITH SMOLDERING FIRES

The previous section presented a method for estimating smoke filling in

a room when an opening is present in a wall or a leak is near the floor. This section uses smoke filling time and other data to estimate hazard time related to carbon monoxide exposure which results from a smoldering chair. Equations used in this estimate are taken from a report by Quintiere et al.[14] In that analysis the smoke filling time is calculated by using Equations 16 through 23 where the value of $\dot{Q}$ is estimated by

$$\dot{Q} = \dot{m}\Delta H \tag{25}$$

where $\dot{m}$ is the rate of mass loss due to smoldering and ΔH is the heat of reaction for the smoldering process. Here we adopt a simpler procedure based on that study to allow ease in making first order estimates.

It is shown that $\dot{m}$ could be approximated for a smoldering fire in polyurethane or cotton using

$$\dot{m} = ct \tag{26}$$

where $c = 0.206$ g/min^3 for polyurethane and $c = 0.33$ g/min^3 for cotton, and t represents time in minutes. The heat of reaction for polyurethane is $\Delta H = 15 \pm 8$ kJg^{-1} and cotton is $\Delta H = 11 \pm 1$ kJg^{-1}. These results were only for slabs of particular samples of cotton and polyurethane. Moreover the smoldering rate of an upholstered chair composed of cotton and polyurethane initially grew quadratically with time, then remained constant for the next hour. Thus, Equation 26 with the constants given can only be taken as a rough estimate for $\dot{m}$. It was, however, found that the mass generation of CO could be taken as proportional to the mass loss rate in smoldering, and that constant γ was estimated as about 0.1 g CO/g fuel lost for both the polyurethane and cotton samples discussed above. Thus for those cases the CO generation rate was estimated as

$$\dot{m}_{co} = \gamma ct. \tag{27}$$

As a first estimate we will use Equation 27 and consider a well-mixed closed volume (V) in which the smoldering takes place. The more general stratified case with "filling" was discussed in Quintiere,[14] but in actuality the dispersal of smoldering products is not so well defined. Consequently a uniformly mixed volume is a reasonable alternative. For this case the mass fraction of CO in the volume defined to be Y is given by

$$\frac{dY}{dt} = \frac{\gamma \dot{m}}{\varrho V} \tag{28}$$

where ϱ is the gas density. Finally adopting a critical dose of 4.5 percent CO/min for human incapacitation as suggested by the work of Stewart et al., see Quintiere,[14] and since the dose D can be expressed as $D = \int_0^t Y dt$ it follows from Equations 26, 27 and 28 that

$$D = \frac{c\,\gamma\,t^3}{6\,\varrho\,V} \tag{29}$$

where D = 0.045 min for the critical dose, the hazard time can be estimated.

Rewriting this equation to solve for t

$$t = \left(\frac{6\,D\,\varrho\,V}{c\,\gamma}\right)^{1/3} \tag{30}$$

where V = volume of the room,
ϱ = density of the gas,
c = values shown above for polyurethane and cotton,
γ = the mass fraction of CO produced per smoldering mass loss of fuel.

For example, with a cotton sample $t = 25.3\ V^{1/3}$ where t is in minutes and V is in m^3. The time to critical dose is finally calculated using Equation 30.

It should be emphasized that the above analysis is very approximate and not generally applicable to all smoldering conditions. It is only offered as a first order of magnitude estimate.

TEMPERATURE RISE OF HOT GASES IN A COMPARTMENT

A second environmental condition that requires consideration in a room fire is the resulting temperature rise. This has been studied and correlated by several different investigations. The method for estimating temperature rise, ΔT, here comes from reports by Quintiere[15] and McCaffrey, et al.[16] This model considers temperature rise in compartments containing single or multiple wall vents, and the venting action is created only by natural convection. Figure 12 describes a compartment example and defines some parameters.

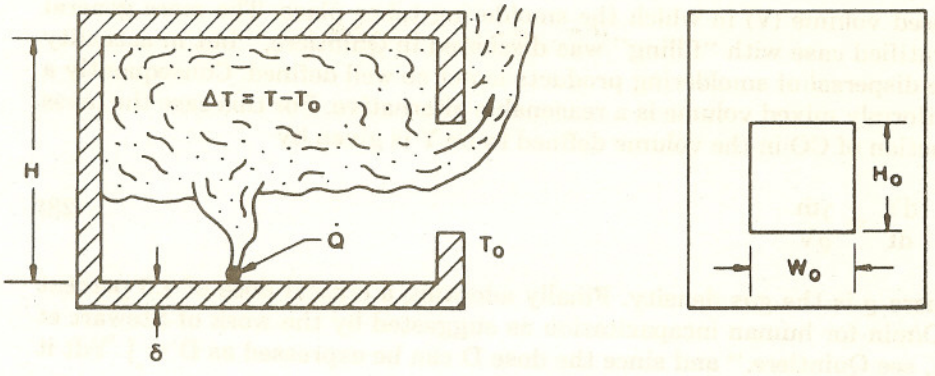


Figure 12. Compartment example.

The equation used for making this estimate of compartment gas temperature rise is

$$\frac{\Delta T}{T_o} = 1.6\left(\frac{\dot{Q}}{\sqrt{g}\,C_p \varrho_o T_o A_o \sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A}{\sqrt{g}\,C_p \varrho_o A_o \sqrt{H_o}}\right)^{-1/3} \tag{31}$$

where T_o = initial or ambient air temperature,
$\dot{Q}$ = rate of energy release,
g = acceleration of gravity 9.8 m/sec^2,
C_p = specific heat of air at constant pressure,
ϱ_o = density of ambient air,
A_o = $W_o H_o$, vent area,
W_o = horizontal vent dimension,
H_o = vertical vent dimension,

$$h_k = \begin{cases} \sqrt{k\varrho c/t}, & t \le t_p \text{ effective enclosure, or} \\ k/\delta, & t > t_p \text{ conductance,} \end{cases}$$

k = thermal conductivity of the enclosure structure,
ϱ = density of the enclosure structure,
c = specific heat of the enclosure structure,
δ = enclosure material thickness,

$$t_p = \left(\frac{\varrho c}{k}\right)\left(\frac{\delta}{2}\right)^2, \text{ thermal penetration time,}$$

A = total surface area.

Both $h_k A$ and $A_o\sqrt{H_o}$ should be summed for multiple structural materials and openings, respectively. The procedure for addressing multiple features is elaborated on in Quintiere.[15]

VENTILATION FLOW RATE

Now that methods have been presented for estimating burning rates and

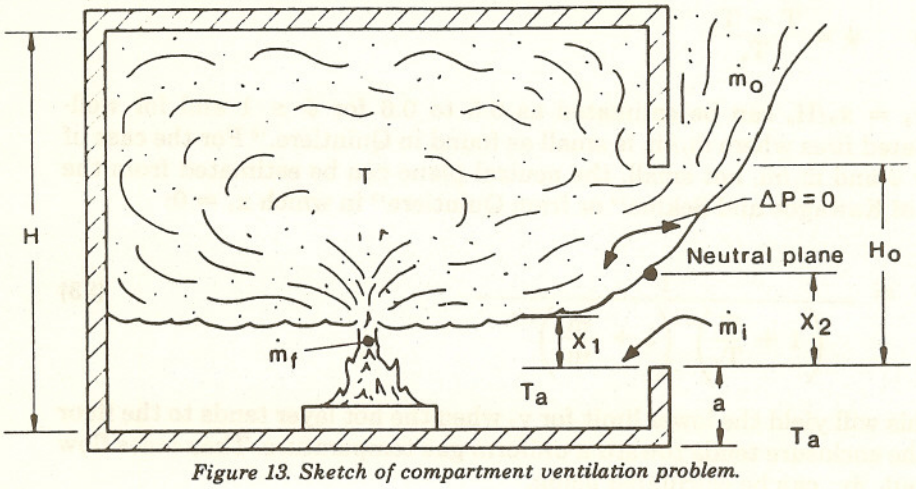


Figure 13. Sketch of compartment ventilation problem.

ΔT in a fire compartment, it is time to consider ventilation flow rates in the fire. It was pointed out by Steckler, et al.[17] that the flow of air and gases in room fires has a significant influence on the development of a fire. As a fire develops, the air and gas flow rates control compartment temperature and heat transfer which then affects the rate of fire growth. When a compartment fire reaches a fully involved state, the air flow rate usually controls the fire, and the fire is then considered to be ventilation controlled. The mass flow rate of air and gases will be estimated first in this section, and ventilation limit conditions will be examined later.

In order to further understand the terminology of vent flow, refer to Figure 13. Under natural convection conditions and after the hot gases fill the compartment and spill out of the vent, the flow will be countercurrent at the vent. Air will enter at a rate $\dot{m}_i$ and combustion products will flow out at a rate $\dot{m}_o$. These flows result from pressure differences (Δp) set up at the vent due to the differences in compartment and ambient gas temperatures. At the flow reversal point in the vent, the Δp is zero and this position is termed the neutral plane. The flow rates depend on the fuel mass release rate $\dot{m}_f$, the height of the neutral plane x_2, the height of the hot gas layer x_1, its temperature T, and the vent dimensions H_o and W_o. In general the vent equations are coupled nonlinear algebraic equations which we will avoid solving, but suggest the approximate procedure below.

To make this ventilation flow rate estimate, it is necessary to assume a free burning condition. The first step in making this estimate is to calculate a fuel mass burning rate, $\dot{m}_f$, with one of the methods discussed earlier, and then calculate the compartment gas temperature by the formula previously presented. At this point the dimensionless mass flow rate M_o can be calculated using,

$$M_o = [\psi^{1/2}/(1 + \psi)](1 - y_2)^{3/2} \tag{32}$$

where $$\psi \equiv \frac{T - T_a}{T_a}$$

and $y_2 = x_2/H_o$ can be estimated as 0.5 to 0.6 for $\psi \leq 1$ and for well-ventilated fires where $\dot{m}_f/\dot{m}_i$ is small as found in Quintiere.[18] For the case of larger ψ and $\dot{m}_f/\dot{m}_i$ not small, the neutral plane can be estimated from the work of Kawagoe and Sekine[19] or from Quintiere[18] in which $x_1 = 0$:

$$y_2 = \frac{1}{\left(1 + \frac{T}{T_a}\right)^{1/3}\left(1 + \frac{\dot{m}_f}{\dot{m}_i}\right)^{2/3}}. \tag{33}$$

This will yield the lower limit for y_2 when the hot layer tends to the floor and the enclosure tends toward a uniform gas temperature. Then mass flow rate out, $\dot{m}_o$, can be calculated using,

$$\dot{m}_o = \frac{2}{3} M_o C \varrho_a \sqrt{2g}\, W_o H_o^{3/2} \quad (34)$$

where C = opening flow coefficient which is ~ 0.7,
ϱ_a = density of ambient gas surrounding area,
g = acceleration of gravity (9.8 m/sec²),
W_o = opening width,
H_o = opening height.

The mass inflow rate of air, $\dot{m}_i$, can be calculated by,

$$\dot{m}_i = \dot{m}_o - \dot{m}_f \quad (35)$$

for which steady flow conditions have been assumed. Of course if $\dot{m}_f/\dot{m}_i$ is found to be large, then iteration is required in the above computations. Moreover the ratio $\dot{m}_f/\dot{m}_i$ should be compared with the mass stoichiometric fuel to air ratio to examine whether the fire is ventilation limited.

DOES FLASHOVER OCCUR?

The methods presented have provided a basis for predicting the fire environment up to the point of rapid transition in fire behavior. This critical point is called "flashover," and it has been defined in many different ways. A paper by Thomas, et al.[20] describes five different processes or combinations of processes that could lead to flashover. It is pointed out that flashover usually results in a sharp increase in room temperature and rate of energy release. Thomas shows that flashover is typically associated with compartment gas temperatures which range between 300–650° C. For the flashover estimates calculated in this paper it is suggested that a critical gas temperature rise of 500° C be selected. Thus for a given $\dot{Q}(t)$ the formulae for ΔT, given by Equation 31, can be solved to find the time, t, at which $\Delta T = 500°$ C or the flashover time.

Alternatively, the condition for flashover with a constant energy release rate $\dot{Q}$ follows from Equation 31 in which ΔT is set equal to 500° C. That result is given as

$$\dot{Q} = 610\,(h_k A\, A_o \sqrt{H_o})^{1/2} \quad (36)$$

for which $\dot{Q}$ is in kW, h_k is in kW/(m²K), H_o in m, and A and A_o are in m². This result says that the energy release rate to cause flashover depends on the compartment thermal properties, its surface area, and the vent size.

MASS BURNING RATE IN VENTILATION LIMITED FIRES

After flashover or in fires where small openings restrict ventilation, the fire will probably become ventilation limited. That is the supply of air to the

room is less than that amount needed for stoichiometric burning of the available gasified fuel. It can also be defined as the point when the oxygen level in the compartment reaches a low value (ideally zero) such that the reaction between fuel and oxygen ceases to produce products or proceeds very slowly.

In general, the energy release rate of the fuel burning in the compartment, is given as

$$\dot{Q} = \begin{cases} \dot{m}_f \Delta H \text{ for } \dot{m}_f/\dot{m}_a \leq \gamma \\ (0.233)\, \dot{m}_a \Delta H_{ox} \text{ for } \dot{m}_f/\dot{m}_a \geq \gamma \end{cases} \tag{37}$$

where γ = the mass stoichiometric fuel to air ratio,
ΔH = the fuel heat of reaction,
$\dot{m}_a$ = the air flow rate through the vent,
and ΔH_{ox} = the heat of combustion per unit mass of oxygen and is taken as 13 kJ/g.

The fire is termed "fuel-controlled" for $\dot{m}_f/\dot{m}_a < \gamma$, and the energy release rate depends on the fuel pyrolysis rate. Since the air flow rate is primarily controlled by vent size, the available air supply will reach the limit for combustion as $\dot{m}_f$ increases. Thus as the fire grows, the rate of energy release within the compartment will be governed solely by the air supply rate. The excess fuel will exit the compartment with combustion continuing in the vent flame. This limit condition in which the maximum possible energy release rate is achieved in the compartment roughly occurs when $\dot{m}_f/\dot{m}_a = \gamma$ and the fire is termed "ventilation-controlled" as long as $\dot{m}_f/\dot{m}_a \geq \gamma$. Fires are generally fuel-controlled before the occurrence of flashover, and ventilation-controlled afterwards.[20]

In order to estimate the point of transition to ventilation control, both the fuel mass loss rate and the air supply rate must be known. The mass loss rate $\dot{m}_f$ depends on the enclosure conditions as illustrated qualitatively below:

$$\dot{m}_f \approx \dot{m}_{fo}\left(\frac{Y_{O_2}}{0.233}\right) + \frac{\dot{q}_e}{L} \tag{38}$$

where $\dot{m}_{fo}$ = the free burning value,
Y_{O_2} = the local oxygen concentration around the combustion region within the enclosure,
$\dot{q}_e$ = the net heat transfer rate from the enclosure to the fuel,
and L = the fuel "heat of vaporization."

There is some evidence from full scale experiments[14] that up to flashover or shortly before, the mass loss rate in an enclosure is nearly equal to its free burn value. After flashover, the mass loss rate will differ distinctly from its free burn value. As a first estimate to assess whether the ventilation limit

has been reached, the free burn mass loss rate should be compared with the maximum vent air flow rate. The latter can be estimated by using Equations 32 and 33 for $\dot{m}_f/\dot{m}_i = 0$ (i.e., small). Thus, the maximum possible vent air flow rate is for $T/T_o > 2$:

$$\dot{m}''' = 0.5\, W_o H_o^{3/2} \text{ (kg/sec)} \tag{39}$$

with W_o and H_o in m. Hence the ratio of the free burn mass loss rate and maximum air supply rate can be compared with the stoichiometric ratio (γ).

After ventilation-limited conditions prevail, the mass loss rate of the fuel cannot be directly computed. Nevertheless, results for wood crib fires have been empirically correlated[19,21] to yield:

$$\dot{m}_f \cong 0.09\, W_o H_o^{3/2} \text{ (kg/sec)} \tag{40}$$

with W_o and H_o in m. An estimate of the corresponding compartment gas temperature rise might also be made by computing the energy release rate from the maximum possible air flow rate Equation 39. The result follows:[15]

$$\Delta T = 896\, [A_o \sqrt{H_o}/(h_k A)]^{1/3} \text{ (°C)} \tag{41}$$

where A_o is the vent area (m^2), H_o is the vent height (m), h_k is the enclosure structure conductance (kW/m^2k) and A is the structure surface area (m^2).

CORRIDOR SMOKE TRANSFER AND FILLING

Much work is currently being done to develop meaningful correlations and models for smoke transfer and filling in corridors. The interest in this subject springs from the need to predict changes in environmental conditions which occur throughout a building as a fire develops. This is of great importance to life safety. An estimate made for the smoke front velocity, V_f, will be taken from work in progress by Zukoski and Kubota.[22] Figure 14 displays the phenomenon of a smoke layer progressing along a corridor.

From their preliminary analysis, we have extracted a result that represents an upper limit to the front velocity. This corresponds to the

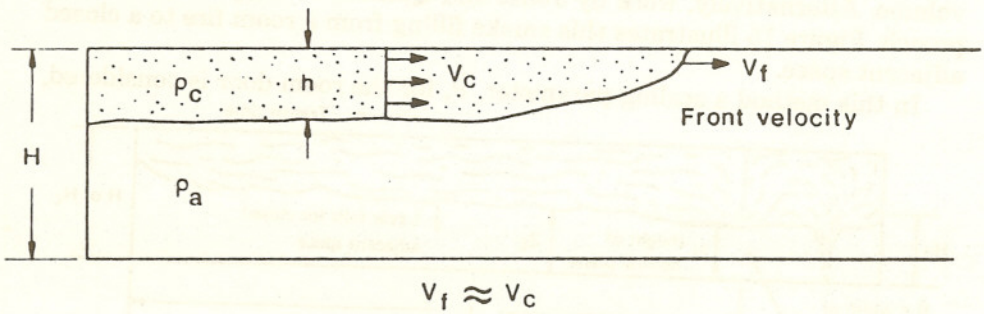


Figure 14. Corridor smoke transport.

limiting case of the smoke layer filling half the corridor height and does not consider viscous effects which would retard the front spread. Thus a simple order of magnitude estimate is given below.

$$V_f \approx \tfrac{1}{2}\left[g\left(\frac{\varrho_a - \varrho_c}{\varrho_a} \right) H \right]^{1/2} \tag{42}$$

where g = acceleration of gravity,
ϱ_a = density of ambient air,
ϱ_c = density of the corridor fluid,
H = corridor height.

Density can be related to the fire room temperature provided no heat loss occurs. Thus from the ideal gas law:

$$\frac{\varrho_a - \varrho_c}{\varrho_a} = 1 - \frac{T_a}{T}$$

where T_a = ambient temperature,

and T = gas temperature in fire room.

Subsequently the time (t_f) for velocity front movement through a corridor is estimated by

$$t_f = \frac{L}{V_f} \tag{43}$$

where L = corridor length.

Smoke filling time for a closed corridor or adjacent space to a room can be estimated using the appropriate formulas. But that approach would ignore the geometrical aspects of the room and corridor and their connecting doorway. It necessitates treating the corridor and room space as a single volume. Alternatively, work by Jones and Quintiere[23] suggest another approach. Figure 15 illustrates this smoke filling from a room fire to a closed adjacent space.

In this method a scaling parameter, $\dot{P}$, for the room door is considered,

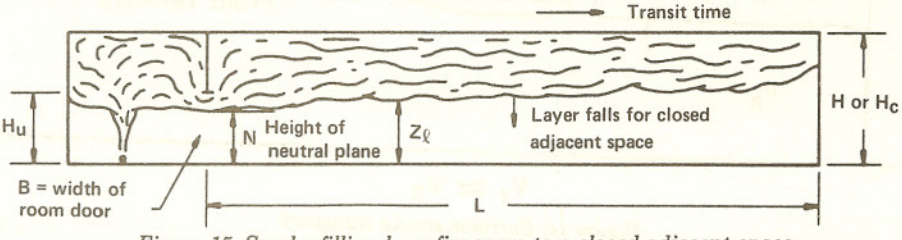


Figure 15. Smoke filling by a fire room to a closed adjacent space.

where

$$\dot{P} = B(H_u)^{3/2}/(H_c)^{5/2} \quad (44)$$

where B = width of the connecting door,
H_u = height of connecting door,
H_c = height of corridor.

A correlation based on dimensionless variables was developed using both experimental and computational results. The conditions examined were a room and closed corridor of equal height ($H_c = 2.32$ m), a fixed room door height ($H_n = 2.0$ m), variable door widths ($0.13 \leq B \leq 1.07$ m), and varying heat release rates ($25 \leq \dot{Q} \leq 225$ kW). These conditions are representative of many building and developing fire conditions. The correlation is presented in Figure 16 which gives the dimensionless filling time τ as a function of the fire and door parameters, $\dot{Q}$ and $\dot{P}$, respectively. The time for filling was selected as the time for the smoke layer to descend to 1 m above the corridor floor. The dimensionless parameters are defined as follows:

$\dot{Q}$ represents dimensionless heat release rate and is defined by the equation

$$\dot{Q} = \dot{Q}/(C_p T_a \dot{m}) \quad (45)$$

where $\dot{Q}$ = net heat release rate,
C_p = specific heat of air,
T_a = ambient temperature,
and $\dot{m}$ = a dimensionless characteristic mass flow which is defined as

$$\dot{m} = \varrho_a (gH_c)^{1/2} H_c^2 \quad (46)$$

where ϱ_a = ambient density,
g = acceleration of gravity,
H_c = height of corridor.

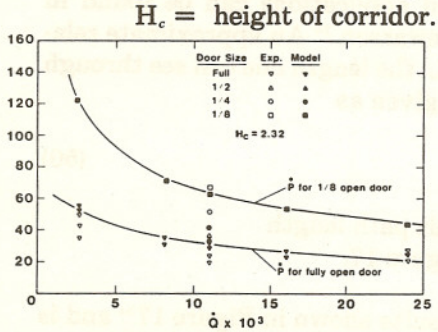


Figure 16. Dimensionless corridor smoke filling time[23].

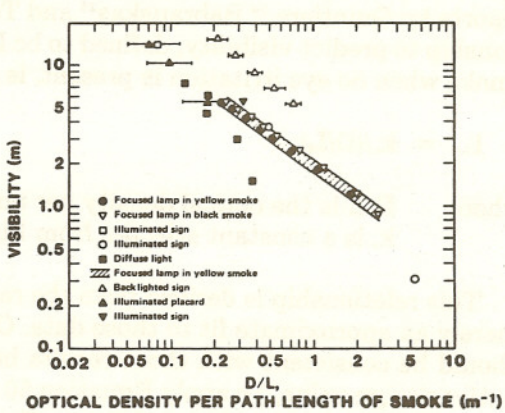


Figure 17. Visibility results derived from Rasbash[27], Jin[28] and Lopez[29].

The dimensionless time τ in Figure 16 is given as

$$\tau = t(\dot{m}^*/\varrho_a A H_c) \quad (47)$$

where t = time (sec)
and A = floor area for the corridor or adjoining space.

To make an estimate for filling time t, a $\dot{Q}$ is selected from which $\dot{Q}^*$ is calculated. Using this $\dot{Q}^*$, τ can be determined from Figure 16. Rearranging Equation 47 to solve for t yields

$$t = \frac{\tau}{(\dot{m}^*/\varrho_a A H_c)}. \quad (48)$$

SMOKE CONCENTRATION AND VISIBILITY

The production of smoke in fires is an important feature in evaluating life safety. Technically smoke might be considered to include particles, hot combustion products, and toxic gases. Here we will only address the particulate nature of smoke and its effect on visibility. Smoke obscures vision by the reduction of light transmission. Smoke may also reduce vision by irritating the eyes. In this section, estimates for smoke concentration and visibility will be calculated for a closed system which consists of a room and adjacent space.

The production rate of smoke particles ($\dot{m}_s$) in a fire can be expressed as

$$\dot{m}_s = \chi_s \dot{m}_f \quad (49)$$

where χ_s = fraction of particulate mass to fuel mass loss,
$\dot{m}_f$ = fuel mass loss rate.

The objective is to compute this production rate and relate it to visibility. Some background on needed data and applications can be found in reports by Quintiere,[24] Babrauskas[25] and Tewarson.[26] An approximate relationship to predict visibility, defined to be L_v the length one can see through smoke when no eye irritation is present, is given as

$$L_v = k_v/(D/L) \quad (50)$$

where D/L is the optical density per unit path length
k_v is a constant selected from Figure 17.

This relationship is derived from the results shown in Figure 17[24] and is merely an approximate fit to those data. Of course the selected value for k_v should be consistent with those results but could also represent a conservative design value. To apply Equation 50 to a particular situation we must compute (D/L) for that fuel and the configuration it burned in.

To compute (D/L) for a closed system, for example a room and adjacent space, the following relationship must be integrated over time:

$$\frac{d(D/L)}{dt} = \frac{\alpha\chi_s}{V}\dot{m}_f \qquad (51)$$

where t is time,
α is the particle optical density,
and V is the volume of the enclosed space.

The mass loss rate $\dot{m}_f$ should be initially estimated from free burn analysis as before. This will be valid in the early stages of the fire. Data on α and χ_s, properties of the burning fuel, are needed for each fuel. Seader and Ou[30] suggest $\alpha \approx 3300$ m²/kg for fuels burning in air, and these results for a wide range of fuels are given by Tewarson.[26] However Tewarson defines χ_s and Y_s, and reports σ, which is related to α, as $\alpha = \sigma/(2.303\ Y_s)$. Also $\alpha\chi_s$ can be estimated from the Smoke Density Chamber Test Method described in ASTM E-662. It can be shown that

$$\alpha\chi_s = \frac{D_{s,max}}{m''} \qquad (52)$$

where $D_{s,max}$ is the maximum specific optical density measured in ASTM E-662
and m″ is the mass of sample consumed per unit of exposed surface area.

Of course the values of α and χ_s for a given material will depend on the exposure conditions during the burning of those samples. For first order estimates these effects are ignored, but judgment must be used in the application of such data.

The estimate based on Equation 51 assumes that the volume of interest is well mixed and here the filling time has been ignored. Table 3 gives some representative values for α and χ_s.

An important point that should be noted is that in ventilation limited

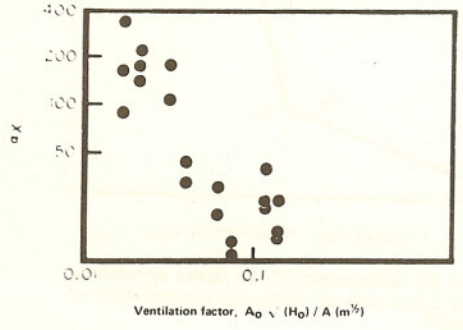


Figure 18. Smoke production for plywood as a function of ventilation factor from Saito[31].

conditions, $\dot{m}$, depends on air flow and χ_s has been shown to increase. The ventilation parameter $A_w\sqrt{H_w}$ is reduced. This is shown in Figure 18 from the work of Saito[11] for plywood burning in an enclosure of floor area A.

TABLE 3. *Smoke properties for selected materials burning in air.*[16]

Material	*Particle optical density* α ($10^3 m^2/kg$)	*Fraction of particulate mass to fuel mass loss* χ_s (−)
Oak	3.17	0.013
PMMA	4.65	0.021
Polyurethane foam flexible (GM-25)	0.426	0.32
Granular Polystyrene	2.11	0.15

ESTIMATION OF FLAME SPREAD RATES

After an unwanted fire has started, flames spread away from the point of origin. The rate of flame spread, V_f, is affected by several environmental factors and the thermophysical/thermochemical properties of the materials. For solids of thickness > 1 mm Equation 53 (Quintiere and Harkleroad[12]) illustrate some of these variables.

SOLIDS

$$V_f \propto \frac{(T_f - T_{ig})^2}{k\rho c(T_{ig} - T_s)^2} \tag{53}$$

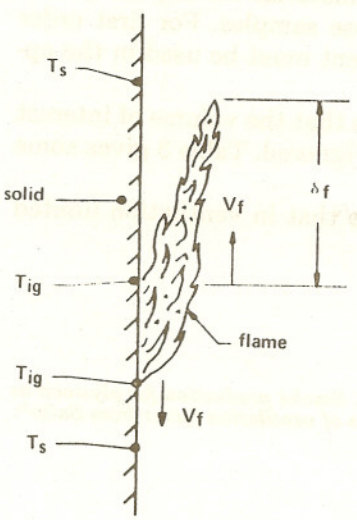


Figure 19. Sketch of flame spread model.

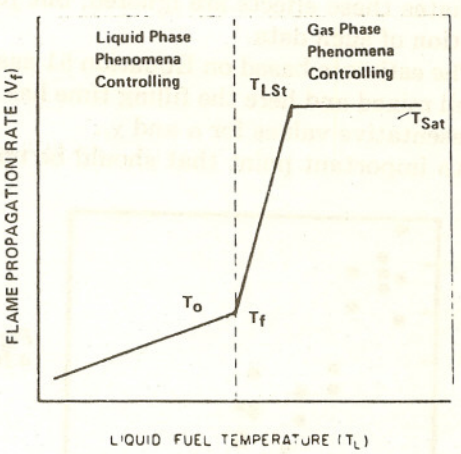


Figure 20. Schematic of the flame spreading rate as a function of the liquid temperature of the fuel[33].

where T_f – is the flame temperature which depends on available oxygen,
T_{ig} – is the ignition temperature,
T_s – is the upstream surface temperature resulting from an external heat flux.

Figure 19 schematically depicts the plume spread phenomena.

The relationship shown above can be converted into an estimate of downward flame spread rate using,

FLAME SPREAD OPPOSED TO FLOW (DOWNWARD)

$$V_f \approx \frac{\Phi}{k\varrho c(T_{ig} - T_s)^2} \tag{54}$$

where

$$\Phi = V_a (k\varrho c)_g (T_f - T_{ig})^2 \tag{55}$$

and

$$V_a = \frac{\left(\frac{k}{\varrho c}\right)_g g (T_f - T_\infty)^{1/3}}{T_\infty} \quad \text{opposed flow characteristic gas velocity under natural convection conditions} \tag{56}$$

where k_g = thermal conductivity of gas phase,
ϱ_g = specific heat of gas,
c_g = specific heat of gas,
g = gravitational acceleration (9.8 m/sec^2),
T_f = adiabatic flame temperature,
T_∞ = ambient and initial temperature.

It has been found for a wide range of materials that Φ generally ranges between 1 and 15 (kW)^2/m^3; T_{ig}, ranges between 250 and 600° C; and $k\varrho c$ ranges between 0.01 and 1.0 (kW/m^{2}K)^{2}sec.[32] These are to be considered pseudo properties valid for Equation 54 under opposed flow natural convection flame spread in vertical orientation.

For upward flame travel, flame spread rate can be described by:

$$V_f \approx \frac{(\dot{q}_f'')^2 \delta_f}{k\varrho c (T_{ig} - T_s)^2} \tag{57}$$

where $\dot{q}_f''$ = heat transfer per unit time and per unit area
and δ_f = flame extension length.

Practical applications of Equation 57 have not been developed, and general methods for predicting $\dot{q}_f''$ and δ_f do not exist.

FLAME SPREAD OVER LIQUIDS

Glassman[33] reports on recent research efforts and theories for flame spread over liquids. As is shown in Figure 20, there are basically two different regimes for fires on liquids. One regime relates to flame spread which is controlled by gas phase phenomena when the bulk liquid temperature (T_L) reaches its flash point or, for sustained burning, its fire point temperature T_f. The other regime occurs when the bulk liquid temperature is below its fire point temperature. This slower flame spread phenomenon depends on the evaporation of the liquid to sustain and control the process. As the liquid temperature rises above the fire point temperature of T_{LS_t}, a stoichiometric fuel-air mixture is formed near the surface, and consequently flame spread occurs in the gas phase. This rate of flame spread is related to the bulk liquid temperature and its surface tension.

A report by Williams[34] gives a qualitative formula for the flame spread rate, V_f, on liquid fuels.

$$V_f = \frac{\sigma'}{\mu_\ell}\left(\frac{\mu_\ell^2 \ell}{\varrho_\ell \sigma'}\right)^{1/3} \tag{58}$$

where σ' = gradiant in surface tension

$$\sigma' = \frac{d\sigma}{dT}(T_{ig} - T_o)/\ell, \tag{59}$$

T_{ig} = liquid ignition temperature,
T_o = initial liquid temperature,
ℓ = length characteristic forward flame heat transfer to the liquid,
μ_ℓ = liquid viscosity,
ϱ_ℓ = liquid density.

The application of this equation to practical problem solving is not straightforward since ℓ depends on the heat transfer characteristics of the particular problem. Referral to references 33, 34 will give some further background and insight on potential applications.

FULLY DEVELOPED FIRE BURN TIME

Once a fire has started and has become fully developed, it is of interest to be able to estimate the duration of burning. This can be easily estimated by

$$t_b \approx \frac{m_f}{\dot{m}_f} \tag{60}$$

or

$$m_f = \int_o^{t_b} \dot{m}_f \, dt \tag{61}$$

where m_f is the mass of fuel available to burn (vaporize) and $\dot{m}_f$ is the burning (vaporization) rate of the fuel under the specified environmental conditions. The value for $\dot{m}_f$ can be estimated using the equations for fire size and growth rates.

CONCLUSION

To conclude, it would be appropriate to use the techniques presented to make estimates for the development of a hypothetical fire. An exercise of this type will be presented in the next issue of *Fire Technology*.

This report has brought together a number of techniques developed by various researchers for evaluating the fire environment. These predictive methods can be useful in estimating many of the critical elements related to fire behavior and help provide a better understanding of this complex phenomenon. It should be remembered when using this report while making predictions that the results are only estimates. These estimates, which spring from the state of the art, are meant to provide a reasonable approximation and in some cases just an order of magnitude for the particular elements under study. More accurate predictions typically involve more complex calculations using more powerful methods than a simple calculation. In many cases, additional research is needed to formulate new solutions, derive more data, and to develop more sophisticated fire models than currently exist. Nevertheless the approach presented here provides, in addition to its estimates, a conceptual framework for what we can do and what we must learn to do.

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