JOURNAL OF PROPULSION AND POWER
Vol. 16, No. 4, July–August 2000

Fire Development Calculations

David G. Lilley*
Lilley and Associates, Stillwater, Oklahoma 74074

Information, analysis, and calculations of fire dynamic phenomena can assist in understanding and applying scientific information to real-world fire situations. Recent extensive study, research, experimentation, and field observations and measurements have led to the need for critical evaluation of fire phenomena and its simulation. Fire dynamicists can develop an appreciation for technical/scientific understanding of the phenomena and its applicability to real-world, practical situations. Some sample calculations are exhibited to illustrate several aspects of fire behavior.

Introduction

THE development of structural fires can be understood more readily when technical knowledge puts the phenomena on a firm scientific footing. The theory assists in understanding and applying scientific information to real-world fire situations. Recent extensive study, research, experimentation, and field observations and measurements have led to the need for critical evaluation of phenomena associated with fire dynamics, the term chosen to represent topics associated with fire behavior, including ignition, fire development, and fully developed fires. The scientific topics of chemistry, physics, aerodynamics, and heat transfer all play their part. Technical information about fuels, burning rates, fire spread, and flashover and backdraft phenomena is also relevant. These topics are now addressed in the light of the relevant equations being embodied in computer programs like HAZARD[1] and FASTLite.[2]

The purpose of the present paper is to review a few of the ideas involved in appreciating how technical understanding can help explain fire dynamic phenomena. Some sample calculations are exhibited to illustrate the phenomena. Technical engineering aspects of fire phenomena are addressed by Emmons,[3] Thomas,[4] and Karlsson and Quintiere.[5] The present paper builds on the author's previous fire-related papers, including his short course[6] and his general review.[7] Specific theories, equations and data about fuel burning properties are given in Refs. 8 and 9. Graphic illustrations are now given to exemplify the theories and their application to real-world situations.

Fire Severity

Assessment of fire hazard potential involves more than just enclosure surface area and total fuel load in terms of mass of equivalent ordinary combustibles per unit area (in kilograms per square meter or pounds mass per square foot). The arrangement of combustibles, their chemical composition, physical state, ease of ignition, rates of fire growth, etc., are all factors to be evaluated, in addition to room geometry and size, ventilation capability, and fire protection facilities. The faster a fire develops, generally the greater will be the threat. Typical fire loads are given in the National Fire Protection Association (NFPA) Handbook[10] for different occupancies.

The interior finish of walls, ceilings, and floors can significantly affect the initial fire growth. Fire spread over interior finishes, therefore, deserves special attention, and it may be noted that fire spread rates vary enormously. The relative hazard of an interior finish is usually determined by the so-called Steiner tunnel test in accordance with American Society for Testing and Materials (ASTM) E84, NFPA 255, and Underwriters Limited (UL) 723. Classification of interior finish materials is A, B, or C according to flame spread rating 0–25, 26–75, or 76–200. Smoke development and fuel contribution ratings are also found in the test via temperature and smoke density recordings. The Life Safety Code NFPA 101 limits the use of interior wall, ceiling, and floor finish. These issues are important because combustible interior finishes, such as low-density fiberboard ceilings and plastic floor coverings, offer significant factors in fire development permitting a fire to spread to objects remote from the fire origin.

Fires that reach flashover or full room involvement produce acutely lethal products of combustion, including smoke, carbon monoxide, hydrogen cyanide, acrolein, hydrogen chloride, nitrogen oxide(s), etc., in addition to heat and insufficient oxygen. These gases are produced in large quantities and driven to remote areas, causing life-threatening situations, inhalation of fire gases (toxic products of combustion) being the major cause of death in fires. For these reasons, any combination of finishes, combustible building materials, or contents and furnishings that could result in flashover (full room involvement) in a few minutes represents a severe fire hazard in many types of occupancies. Protection by automatic sprinklers and fire-rated construction separations is often needed and/or mandated by the relevant code. Computer fire models include the mathematical characterization of experimental information related to whether or not flashover will occur. It turns out that a particular fire size is required (in terms of heat release rate $\dot{Q}$ in kilowatts or British thermal units/hour), this value depending on the extent of ventilation, room size, insulation rating of the walls, etc. One can then assess whether an especially hazardous situation exists, whether a given fire scenario has the potential to develop flashover or full room involvement.

Burning Rates

Basics

Typically, the heat release rate (heat energy evolving on a per unit time basis) of a fire $\dot{Q}$ (kilowatts) changes as the size of the fire changes, as a function of time t (seconds) after fire ignition. That is, the variation of $\dot{Q}$ vs t is extremely important in characterizing the rate of growth of a fire.

Data are available for heat release rate vs time for many items, see, for example, the Society of Fire Protection Engineers (SFPE) Handbook,[11] Babrauskas and Grayson,[12] and the database in Ref. 1. Furniture calorimeter and cone calorimeter measurements are available. Notice that although data may well be available from careful laboratory experiments, the data may not apply directly to real-world fire situations. The laboratory data does not usually take into account the enhancement of burning rates because of radiation feedback.

Pool Fires

The thermal radiation hazards from hydrocarbon spill fires depend on a number of parameters, including the composition of the hydrocarbon, the size and shape of the fire, the duration of the fire, its proximity to the object at risk, and the thermal characteristics of

Presented as Paper 98-0267 at the 36th Aerospace Sciences Meeting and Exhibit, Reno, NV, 12–15 January 1998; received 8 August 1999; revision received 29 February 2000; accepted for publication 2 March 2000.

*Professor, Route 1 Box 151. Fellow AIAA.

the object exposed to the fire. The state of the art of predicting the thermal environment of hydrocarbon spill fires consists essentially of semiempirical methods, some of which are based on experimental data from small- and medium-scale tests. Needless to say, such semi-empirical methods are always subject to uncertainties when experimental data from small-scale fires are extrapolated to predict the thermal properties of very large-scale fires.

A systematic study of liquid hydrocarbon pool fires over the widest range of pool diameters was conducted by Blinov and Khudiakov.[13] Gasoline, tractor kerosene, diesel oil, and solar oil (and, to a limited extent, household kerosene and transformer oil) were burned in cylindrical pans (depth not indicated) of diameters from 0.37 cm to 22.9 m. Liquid burning rates and flame heights were measured, and visual and photographic observations of the flames were recorded. Hottel[14] plotted these data, and the results are readily available in the SFPE Handbook.[10] Note that for pool diameters less than 1 m, the burning rate expression is reduced because of a reduction in radiation feedback.

Model of t^2-Fire Growth

Slow, medium, fast, and ultrafast fire growths may be specified by the t^2-fire growth model, where, after an initial incubation period,

$$\dot{Q} = \alpha_f (t - t_0)^2$$

where α_f is a fire-growth coefficient (kilowatts per seconds squared) and t_0 is the length of the incubation period (seconds). The coefficient α_f appears to lie in the range 10^{-3} kW/s^2 for very slowly developing fires to 1 kW/s^2 for very fast fire growth. The incubation period t_0 will depend on the nature of the ignition source and its location, but data are now becoming available (see Ref. 12) on fire growth rates on single items of furniture (upholstered chairs, beds, etc.) that may be quantified in these terms. Suggested values for the coefficient α_f are also given in the formula section of Makefire, a subset of the FASTLite computer program.[2] The specification there for the fire-growth coefficient α_f (kilowatts per second squared) is slow, 0.00293 kW/s^2; medium, 0.01172 kW/s^2; fast, 0.04690 kW/s^2; and ultrafast, 0.18760 kW/s^2, and these gives growth times of 600, 300, 150, and 75 s, respectively, to reach a fire size of 1 MW.

Radiant Ignition of Nearby Items

The preceding example has provided information about the burning rate (heat release rate vs time) of a single specified item in the burn room. What happens next? Either the item burns out without further damage to the surroundings, or one or more nearby items ignite and add fuel to the fire. This can be by direct flame contact (if the second item is judged to be sufficiently close) or, more usually, by radiant heat energy becoming sufficiently large on the surface of the second item. Direct flame contact requires time to pyrolyze the fuel and time to heat the gases produced to their ignition temperature. The radiant flux ignition problem is a very complicated issue and depends on many factors. The radiant energy comes from the flame above the first item, the upper layer and room surfaces, but simplifying assumptions are sometimes used. As the radiant energy flux rate increases from the first item to the second, often a simple criterion for ignition of the latter is used. A good approximation is that the radiant heat flux (arriving on the surface of the second item) necessary to ignite the second item is 10 kW/m^2, easily ignitable items, such as thin curtains or loose newsprint; 20 kW/m^2, normal items, such as upholstered furniture; and 40 kW/m^2, difficult to ignite items, such as wood of 0.5 in. or greater thickness.

The peak mass loss rate of the first item (upholstered furniture) vs ignition distance capability is given in the HAZARD documentation by Bukowski.[1] These data have been deduced from a variety of experimental results. As an example, note that an upholstered chair has a peak burning rate of about 80 gm/s (mass) or 2100 kW (energy), which is associated with the ignition of easy, normal, and difficult to burn items igniting at distances of 1.5, 1, and 0.5 m, respectively. Methods for calculating the heat flux on to a target some distance away are considered more generally later, and also in the FPETool computer program.

Estimating Preflashover Compartment Fire Temperatures

Energy Generated by the Fire

The energy generated by the fire is the primary influence on the temperature in a compartment fire, and much research has been conducted in predicting the energy release rate of many fuels under a variety of conditions. The rate of energy release is equal to the mass loss rate of the fuel times the heat of combustion of the fuel:

$$\dot{Q} = \dot{m}_f \Delta h_c$$

where

$\dot{Q}$ = energy release rate of the fire, kW
$\dot{m}_f$ = mass burning rate of the fuel, kg/s
Δh_c = effective heat of combustion of the fuel, kJ/kg

The effective heat of combustion is the heat of combustion that would be expected in a fire where incomplete combustion takes place. This is less than the theoretical heat of combustion as measured in the oxygen bomb calorimeter. The effective heat of combustion is often described as a fraction of the theoretical heat of combustion. The effect of fluctuations is largely neglected.

In fuel-controlled fires, there is sufficient air to react with all of the fuel within the compartment. In ventilation-controlled fires, there is insufficient air within the compartment, and some of the pyrolysis products will leave the compartment, possibly to react outside the compartment. For calculating the temperatures produced in compartment fires, the primary interest is in the energy released within the compartment.

The pyrolysis rate of the fuel depends on the fuel type, its geometry, and on the fire-induced environment. The energy generated in the compartment by the burning pyrolysis products then depends on the conditions (temperature, oxygen concentration, etc.) within the compartment. Although the processes involved are complex, and some are not well understood, there are two cases where some simplifying assumptions can lead to useful methods for approximation of the energy released by the fire. These two cases are 1) ventilation limited fires and 2) nonventilation limited fires.

Ventilation Factor

For fires nearing flashover and postflashover fires, the interface between the upper and lower layers is located near the floor, and the flow reaches a maximum for a given upper gas temperature. It has been shown that the temperature dependence on the flow becomes small above 150°C, and the flow into the compartment can be approximated as a constant times the so-called ventilation factor

$$A_0 \sqrt{H_0}$$

The value of the constant is usually taken as 0.5 kg/s $\cdot$ m$^{5/2}$, which is the value most commonly found in the literature. The resulting approximation is then

$$\dot{m}_a = 0.5 A_0 \sqrt{H_0}$$

where

$\dot{m}_a$ = mass flow rate of air, kg/s
A_0 = area of opening, m^2
H_0 = height of opening, m

From early work analyzing such data, the empirical observation was made that wood fires in rooms with small windows appeared to burn at a rate approximately stoichiometric. Although flames emerging from the windows implied that some fuel was burning outside, calculations often suggested that enough air was entering the fire for stoichiometric burning. Empirical observations on wood fires led to

$$\dot{m}_f = 0.09 A_0 \sqrt{H_0}$$

Simplified Calculations for Enclosure Fires

Equations are available, based principally on experimental correlations, that permit the user to make estimates.

Flame Heights

Estimates of flame height L can be important in determining exposure hazards associated with a burning fuel. Experimentally determined mean flame heights have been correlated by several researchers. A simple correlation for flame heights for pool or horizontal burning fuels has been developed by Heskestad[15]:

$$L/D = -1.02 + 15.6N^{\frac{1}{5}}$$

where

L = mean flame height, m
D = diameter of fire source, m
N = nondimensional parameter,

$$N = \left[\frac{C_p T_\infty}{g\rho_\infty^2 (\Delta h_c / r_s)^3}\right]\frac{\dot{Q}^2}{D^5}$$

C_p = specific heat of air at constant pressure, (kJ/kg)/K
T_∞ = ambient temperature, K
g = acceleration of gravity, 9.81 m/s^2
ρ_∞ = ambient air density, kg/m^3
Δh_c = heat of combustion, kJ/kg
r_s = stoichiometric air/fuel mass ratio
$\dot{Q}$ = total heat release rate, kJ/s or kW

For noncircular fuel packages, an effective D can be estimated by

$$D = 2(A_f/\pi)^{\frac{1}{2}}$$

where D is the effective diameter in meters and A_f is the area of fire in square meters. This equation often can be simplified to

$$L = -1.02D + 0.23\dot{Q}^{\frac{2}{5}}$$

Because flames are unstable, the mean flame height L is generally taken to be the height above the fire source where the flame tip is observed to be at or above this point 50% of the time. The preceding correlation is considered suitable for pool fires or for horizontal surface burning.

Plume Centerline Temperature and Velocity

The plume centerline excess temperature and velocity at elevations above the mean flame height can be estimated from the following equations:

$$\Delta T_0 = 9.1\left[T_\infty / gC_p^2\rho_\infty^2\right]^{\frac{1}{3}}\dot{Q}_c^{\frac{2}{3}}(Z - Z_0)^{-\frac{5}{3}}$$

$$U_0 = 3.4[g/C_p\rho_\infty T_\infty]^{\frac{1}{3}}\dot{Q}_c^{\frac{1}{3}}(Z - Z_0)^{-\frac{1}{3}}$$

where

ΔT_0 = excess centerline temperature, $T_g - T_\infty$, K
T_g = gas temperature, K
$\dot{Q}_c$ = convective heat release rate, kJ/s or kW
Z = elevation above burning fuel fire source, m
Z_0 = location of virtual fire source, m
U_0 = centerline mean velocity, m/s

In many cases, these equations simplify to

$$\Delta T_0 = A\dot{Q}_c^{\frac{2}{3}}(Z - Z_0)^{-\frac{5}{3}}, \qquad U_0 = B\dot{Q}_c^{\frac{1}{3}}(Z - Z_0)^{-\frac{1}{3}}$$

where $A = 25.0$ km$^{5/3}$ kW$^{-2/3}$ and $B = 1.03$ m$^{4/3}$ s^{-1} kW$^{-1/3}$. Although methods exist to calculate excess temperature and velocities at locations other than along the plume centerline, the highest confidence is placed on centerline estimates.

Radiant Heat Flux to a Target

For many enclosure fires, it is of interest to estimate the radiation transmitted from a burning fuel array to a target fuel positioned some distance from the fire to determine if secondary ignitions are likely. The radiant heat flux received from a flame depends on a number of factors, including flame temperature and thickness, concentration of emitting species, and the geometric relationship between the flame and the receiver. Although considerable progress is being made toward developing a reliable method for calculating flame radiation, a high degree of accuracy is seldom required in real-world fire engineering problems, such as estimating what level of radiant flux an item of a plant might receive from a nearby fire so that a water spray system might be designed to keep the item cool. Two approximate methods are now considered.

Considerations of inverse square distance lead to

$$\dot{q}_0'' \approx P\big/4\pi R_0^2 \approx x_r\dot{Q}\big/4\pi R_0^2$$

where

$\dot{q}_0''$ = incident radiation on the target, kW/m^2
R_0 = distance (radius) to target fuel, m
P = total radiative power of the flame, kW
x_r = fraction of total heat radiated from flame

Usually, the radiative fraction x_r ranges from 20 to 60% depending on the fuel type. The distance R_0 should be measured from the center of the flame. Experimental measurements indicate that this equation has good accuracy for R_0/R greater than 4 where R is the flame radius. The point-source nature of the heat from the flame is then a reasonable assumption.

In a second approximate method, the flame is approximated as a vertical rectangle and the radiant flux is calculated using view factor information. This takes into account the large size of the flame, with angles and orientations being accounted for appropriately. Flux levels close to the flame are then more accurately handled (see Ref. 16 and the FASTLite computer program[2]).

Modeling Correlations

Simplified empirical equations for the calculation of other events during an enclosure fire are available in the NFPA and SFPE Handbooks.[10,11] Equations are available, based principally on experimental correlations, that permit the user to make estimates of the results of a fire burning inside a given structure. Algebraic equations are available that correlate experimental data and results vs other parameters: 1) room model for smoke layer depth and temperature, 2) atrium smoke temperature, 3) buoyant gas head pressure, 4) ceiling jet temperature, 5) ceiling plume temperature, 6) egress time, 7) fire/wind/stack forces on a door, 8) mass flow through a vent, 9) lateral flame spread, 10) law's severity correlation, 11) plume filling rate, 12) radiant ignition of a near fuel, 13) smoke flow through an opening, 14) sprinkler/detector response, 15) Thomas's[4] Flashover correlation, 16) upper layer temperature, and 17) ventilation limit.

The relevant equations are embodied in computer programs like FASTLite and HAZARD, so that making calculations of fire behavior becomes straightforward, provided one appreciates correctly the physics involved. Further details appear in Refs. 1, 2, and 17.

Flashover

Flashover is characterized by the rapid transition in fire behavior from localized burning of fuel to the involvement of all combustibles in the enclosure. High radiation heat transfer levels from the original burning item, the flame and plume directly above it, and the hot smoke layer spreading across the ceiling are all considered to be responsible for the heating of the other items in the room, leading to their ignition. Warning signs are heat buildup and rollover (small, sporadic flashes of flame that appear near ceiling level or at the top of open doorways or windows of smoke-filled rooms). Factors affecting flashover include room size, ceiling and wall conductivity and flammability, and heat- and smoke-producing quality

of room contents. Water cooling and venting of heat and smoke are considered to be ways of delaying or preventing flashover.

Often the determination of whether or not flashover is expected is the single most important fire computation. This topic is addressed specifically in Refs. 16–21, with the following three well-known methods now being described.

Method of Babrauskas

At flashover, about 50% of fire output goes to heat losses, and the minimum fire heat release rate in kilowatts is

$$\dot{Q}_{f0} = 750 A_0 \sqrt{H_0}$$

Method of Thomas

Recent evaluation and comparison of improved estimates has led the following expression for the minimum fire heat release rate in kilowatts at flashover as

$$\dot{Q}_{f0} = 378 A_0 \sqrt{H_0} + 7.8 A_W$$

where A_W is the wall area in square meters.

Method of McCaffrey, Quintiere, and Harkleroad

The method of McCaffrey, Quintiere, and Harkleroad for predicting compartment fire temperatures may be extended to predict the energy release rate of the fire required to result in flashover in the compartment. Specializing the equation for an upper gas temperature of 522°C and ambient temperature of 295 K or $\Delta T_g = 500$°C for flashover, and substituting values for the gravitational constant ($g = 9.8$ m/s^2), the specific heat of air ($c_p = 1.0$ kJ/kg·K), and the density of air ($\rho_\infty = 1.18$ kg/m^3) and rounding 607.8–610 yields

$$\dot{Q} = 610 \left(h_k A_T A_0 \sqrt{H_0} \right)^{\frac{1}{2}}$$

where h_k is the effective heat transfer coefficient in kilowatts per meter per Kelvin and A_T is the total area of the compartment surfaces in square meters.

Practical Details

In practice it has been observed that flashover occurs when the upper room temperature of the smoke layer reaches between 300 and 700°C (572 and 1292°F). It depends on many factors, but a lower temperature should be used if one wishes to obtain a conservative, safe estimate of the amount of time available before its occurrence. There is a need to assess which of the methods for predicting flashover is most appropriate. Babrauskas and Grayson[12] have compared the effect of room wall area on the energy release required for flashover, using the preceding methods. The results of their comparisons, along with some experimental data for rooms with gypsum board walls, show that the energy required for flashover depends intimately on both, normalized by the ventilation factor

$$A_0 \sqrt{H_0}$$

Note that over the range of compartment sizes of most interest, all of the methods produce similar results. The method of McCaffrey et al. diverts from the others for small room sizes. All of the methods are a conservative representation of the data.

Flashover is characterized by 1) temperatures reaching approximately from 500°C (932°F) to 600°C (1112°F) in the upper portions of the room; 2) heat flux of from 20 to 25 kW/m^2 (6340 to 7925 Btu/hft^2) occuring at floor level, with near-simultaneous ignition of combustibles not previously ignited; and 3) the filling of almost the entire room volume with smoke and flames.

Generally, very high heat release rates occur after flashover, and (subject to oxygen availability) most ignitable items in the room burn, it gets very hot, and the windows break and melt. The open window permits more oxygen to be made available and thereby increases the severity of the fire.

Illustrative Calculations

Heat Release Rate of Pool Fires

Figure 1 shows the calculated heat release rate for pool fires of various diameters. Three different fuels are illustrated via the three lines shown. Notice that gasoline burns very much more readily than alcohol; it is much more volatile with lower flash point. Not only does it burn quicker in terms of regression rate (meter/second) but the energy per unit liquid volume vaporized is also higher, leading via the theoretical equations to the calculations shown.

Flame Heights of Various Pool Fires

Figure 2 gives computed flame heights (according to the simplified Heskested[15] formula) for pool fires of various diameters, for the three different fuels being considered. Notice that the more volatile gasoline burns faster and produces a higher flame than the other fuels.

Maximum Upward Velocity in Fire Plume

Maximum upward velocities in the plume above the fires of different diameters are illustrated graphically in Fig. 3. Again, the same three fuels are considered. The more volatile and more quickly burning gasoline generates a faster maximum upward velocity in the fire plume than the other two fuels considered.

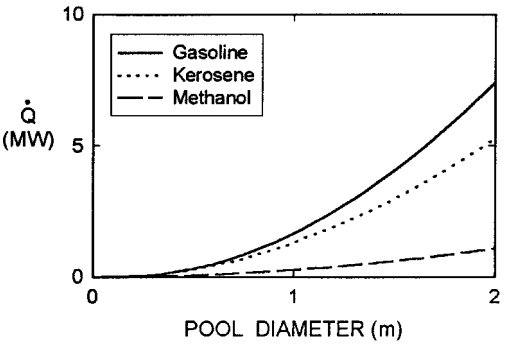

Fig. 1 Heat release rate vs pool diameter for different fuels.

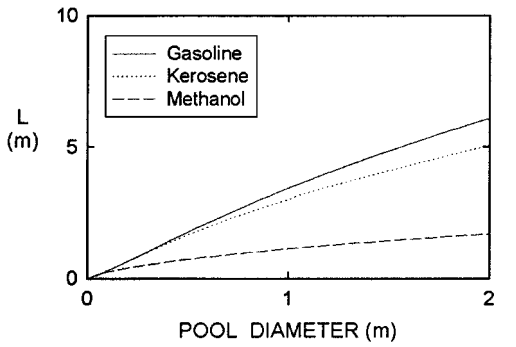

Fig. 2 Flame length vs pool diameter for different fuels.

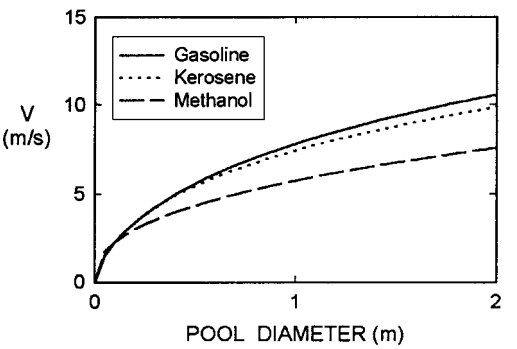

Fig. 3 Maximum upward velocity in flame plume vs pool diameter for different fuels.

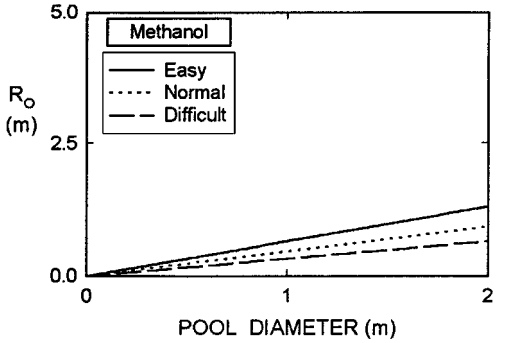

Fig. 4 Minimum safe distance from pool fires with methanol fuel.

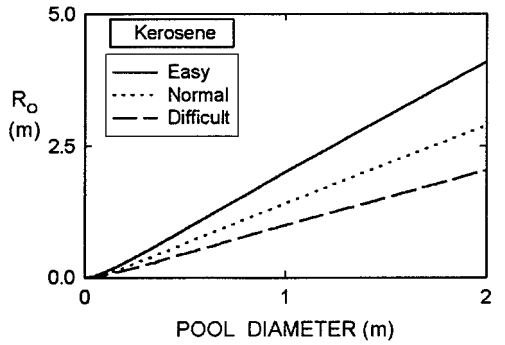

Fig. 5 Minimum safe distance from pool fires with kerosene fuel.

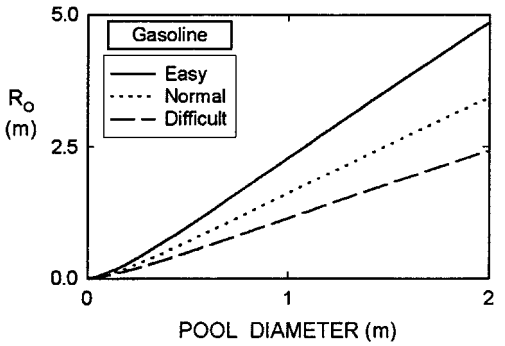

Fig. 6 Minimum safe distance from pool fires with gasoline fuel.

Minimum Safe Distance from Flames

Computations on the basis of the inverse square law and critical incident radiative heat fluxes of 10, 20, and 40 kW/m^2 for easy, normal, and difficult to ignite items lead to the information in Figs. 4–6. A radiative heat fraction from the flame of 40% is used in these calculations. The data illustrate the minimum safe distance from pool fires of different diameters for the three fuels being considered: methanol, kerosene, and gasoline, respectively. Notice that the more volatile, quicker burning gasoline has a very much greater propensity to ignite remote objects than does the slower burning methanol.

Typical Room Heat Release Rates for 20-Minute Burn

For the illustrative calculations, a typical fire load is taken (data from Ref. 10) in each of the following rooms: 1) living room, 2) family room, 3) bedroom, 4) dining room, and 5) kitchen, each of floor size 12 m^2. Each room is assumed to burn to completion steadily in 20 min. The fire loads are, respectively, 18.25, 12.64, 20.12, 16.85, and 14.98 kg/m^2 with constant burning rates of 3.40, 2.35, 3.74, 3.14, and 2.79 MW, respectively. Corresponding ventilation factors $A\sqrt{H}$ are calculated from the ventilation limit

$$\dot{Q} = \dot{m}_{\text{fuel}} \Delta H_{c,\text{fuel}}$$
$$= \dot{m}_{\text{air}} \Delta H_{c,\text{air}}$$

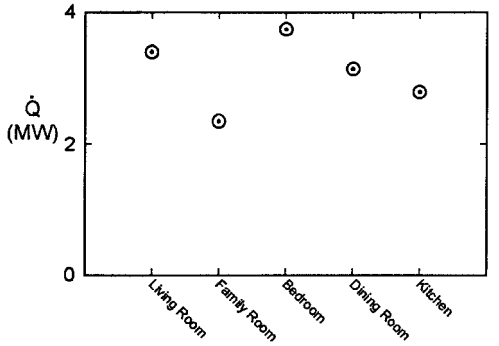

Fig. 7 Heat release rate for 20-min burn.

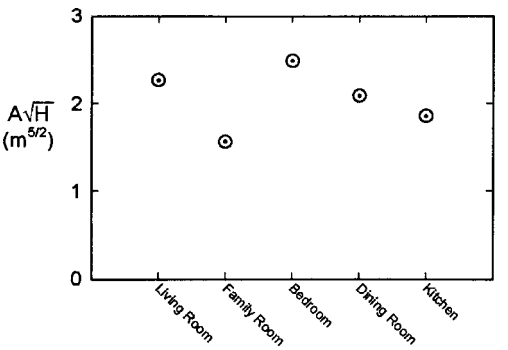

Fig. 8 Minimum ventilation factor needed for 20-min burn.

where

$\dot{m}_{\text{fuel}}$ = burning rate of fuel, kg/s
$\Delta H_{c,\text{fuel}}$ = heating value of fuel, kJ/kg
$\dot{m}_{\text{air}}$ = consumption rate of air participating in combustion, $0.5A\sqrt{H}$, kg/s
$\Delta H_{c,\text{air}}$ = heat release value of air participating in combustion, ≈ 3000 kJ/kg

Calculations corresponding to the typical fire loads just described in rooms of floor size 3 × 4 m in area are shown in Fig. 7 for total burns in a 20-min period. Figure 8 shows corresponding values of the ventilation factor. This value represents the ventilation opening size requirement to permit sufficient air for combustion to enter the enclosure and to permit the products of combustion to leave.

Calculations for Various Pool Fires

Calculations are illustrated for a 1-m^2 pool fire of 1) methanol, 2) ethanol, 3) gasoline, 4) kerosene, 5) jet A fuel, 6) polymethylmethacrylate (PMMA), 7) polypropylene, and 8) polystyrene. Assuming the room temperature is 20°C and taking the maximum temperature in the plume as $\Delta T_0 = 650$ K, we have a maximum temperature of 670°C. Maximum velocity is found from (see Ref. 11)

$$u_{0,\max} = 1.97\dot{Q}_c^{\frac{1}{5}}$$

where $\dot{Q}_c = (1 - x_r)\dot{Q}$ and where x_r is the radiative fraction of the total heat released $\dot{Q}$. Radiative fractions are taken from Ref. 11, alcohols with 0.2 and the other fuels with 0.4. Thus, for 1-m^2 pool fires, one computes the values of Table 1.

Maximum upward velocities in the fire plume for a 1-m^2 pool fire are shown in Fig. 9 for eight different fuels. Notice that the more volatile fuels (gasoline, kerosene, and jet A) exhibit higher velocities. Corresponding heat release rates $\dot{Q}$ in megawatts are given in Fig. 10 (for eight different fuels, each in a 1-m^2 pool fire). Notice again that gasoline, kerosene, and jet A fuels exhibit greater heat release rates for the same base area of burning. Flame heights are found using the Heskested[15] equation

$$L = -1.02D + 0.23\dot{Q}^{\frac{2}{5}}$$

Table 1 Maximum plume velocity

Fuel	Radiative fraction x_r	Burning rate $\dot{m}''$, kg/m^2 s	Heating value ΔH_c, MJ/kg	Maximum plume velocity, m/s
Methanol	0.20	0.017	20.0	6.0
Ethanol	0.20	0.015	26.8	6.3
Gasoline	0.40	0.055	43.7	8.4
Kerosene	0.40	0.039	43.2	7.9
Jet A	0.40	0.054	43.0	8.4
PMMA	0.40	0.020	24.9	6.2
Polypropylene	0.40	0.018	43.2	6.7
Polystyrene	0.40	0.034	39.7	7.5

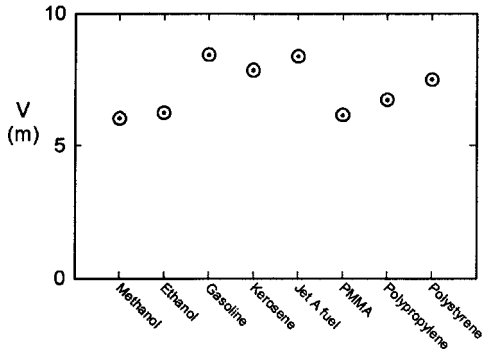

Fig. 9 Maximum upward velocity in flame plume of a 1-m^2 pool fire for different fuels.

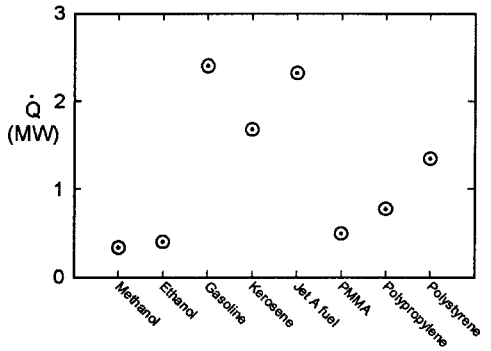

Fig. 10 Heat release of a 1-m^2 pool fire for different fuels.

or the alternative NFPA 921 equation[19]

$$H_f = 0.174(k\dot{Q})^{0.4}$$

with $k = 1$ (no nearby walls), where

L = flame length, m
D = pool diameter, m
H_f = flame length, m

Computed flame heights are shown in Fig. 11 for the range of eight different fuels considered, each pool of size 1 m^2. Both the Heskestad equation[15] (method 1) and the NFPA 921 equation[19] (method 2) are used, with slightly different values given for each case, with the latter equation giving, if anything, larger values. Notice again that the more volatile fuels considered (gasoline, kerosene, and jet A) have greater flame lengths.

Minimum Safe Distance from Various Pool Fires

By the use of the same data as in the last section and a simple inverse square distance law, the calculations determine the minimum distance away that 1) easily ignitable items, 2) normal items, and 3) difficult to ignite items would have to be for safety, for the same eight pool fires just considered. Calculations generate values as in Figs. 12–14, for the minimum distance away for safety reasons with

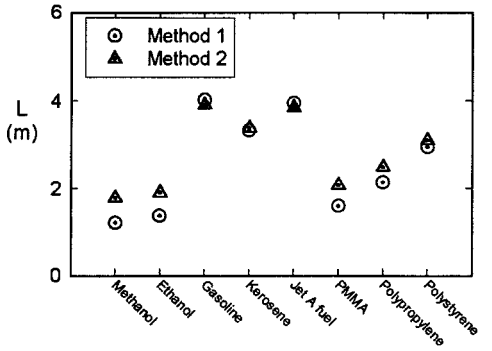

Fig. 11 Flame length of a 1-m^2 pool fire for different fuels.

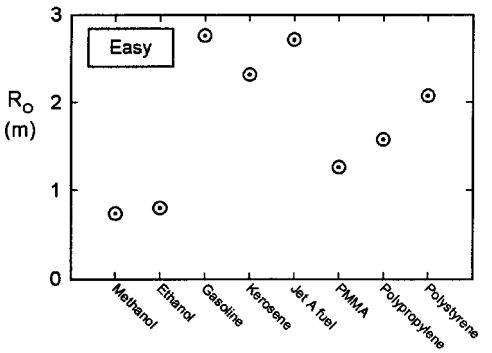

Fig. 12 Minimum safe distance from a 1-m^2 pool fire for different fuels for easily ignitable items.

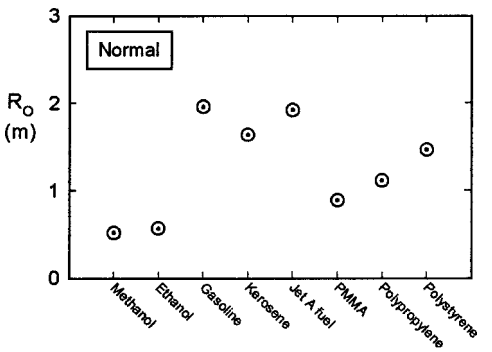

Fig. 13 Minimum safe distance from a 1-m^2 pool fire for different fuels for normally ignitable items.

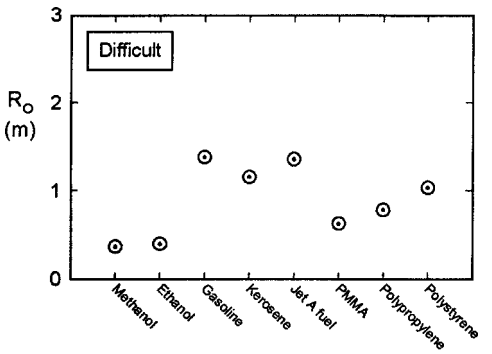

Fig. 14 Minimum safe distance from a 1-m^2 pool fire for different fuels for difficult to ignite items.

easy, normal, and difficult to ignite items. Clearly the volatile fuels (gasoline, kerosene, and jet A) have great propensity to ignite (in particular) easily ignitable items some distance away. Figures 15 and 16 show this same information in slightly different summary forms.

Useful related calculations are shown in Fig. 17. Here the heat flux in kilowatts per square meter landing on a target is given as a function of total heat release rate $\dot{Q}$ in megawatts and distance away in meters. A radiative fraction x_r of 0.4 is used in these calculations

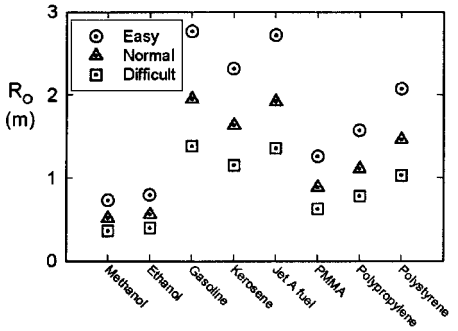

Fig. 15 Minimum safe distance from a 1-m^2 pool fire for different fuels.

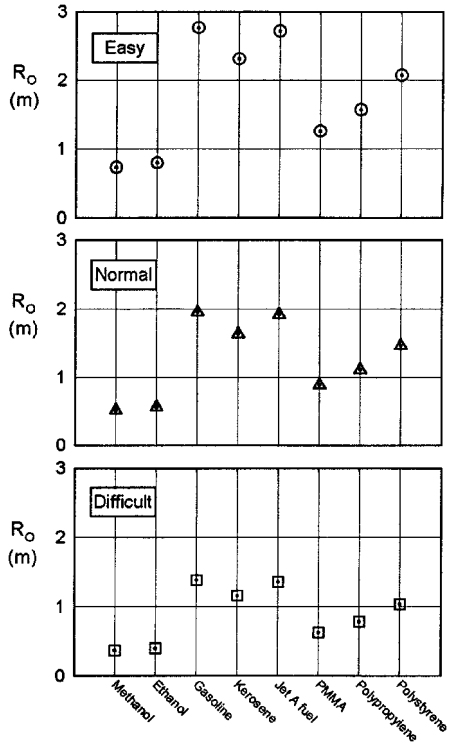

Fig. 16 Minimum safe distance from a 1-m^2 pool fire for different fuels, expanded form.

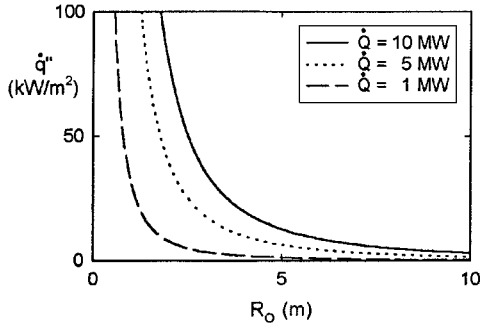

Fig. 17 Heat flux on target vs source heat release rate and distance away.

(of Fig. 17), so that the data may be compared readily with the total heat release rate of pool fires, for example, given earlier.

Flashover

Calculations will now illustrate how many seconds it will take for flashover to occur in a typical room 3 m wide, 4 m long, and 2.4 m high. The room is subjected to a t^2 fire with an incubation period of 75 s and 1) slow, 2) medium, 3) fast, and 4) ultrafast fire characterization with a single ventilation opening of size 2 m

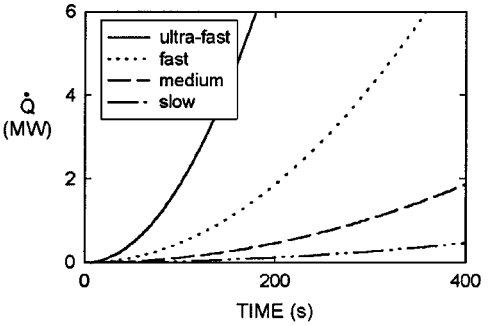

Fig. 18 Heat release rate vs time for different fire growth specifications.

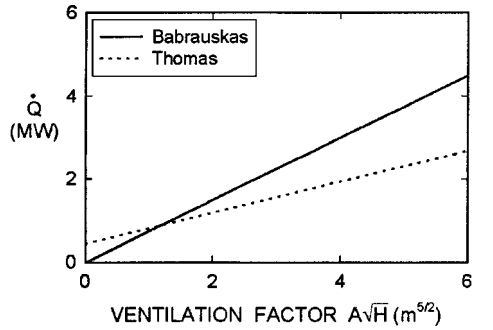

Fig. 19 Heat release rate required for flashover vs ventilation factor according to two different theories.

wide and 2 m high in one of the side walls. Taking the fire growth parameter α as 1) slow, 0.00293 kW/s^2; 2) medium, 0.01172 kW/s^2; 3) fast, 0.04690 kW/s^2; and 4) ultrafast, 0.18760 kW/s^2 gives growth times of 600, 300, 150, and 75 s, respectively, to reach a fire size of 1 MW. Using the flashover criterion of Thomas (see Flashover theory section earlier) the required heat release rate is

$$\dot{Q} = 378A_0\sqrt{H_0} + 7.8A_T$$

and the time to reach this value can be found from the t^2-fire characterization (after the initial incubation period) by

$$\dot{Q} = \alpha t^2$$

$$= \left(1000/t_g^2\right)t^2$$

where α is the fire growth parameter in kilowatts per seconds squared and t_g is the growth time in seconds to reach a heat release rate of 1 MW.

Figure 18 shows heat release rate vs time from the start of ignition for four different fire growth specifications. Note that the medium fire growth is typical of many room fires, and that even for this fire specification, the rate of heating is such that rates of 2–4 MW occur in as little as 200–300 s. The level of heat release rate necessary for room flashover is a function of several parameters, the most important of which is the ventilation factor. Illustrated in Fig. 19 is the heat release rate needed for flashover conditions to exist vs ventilation factor according to the two different theories of Babrauskas and Thomas (see Flashover theory section earlier). This calculation is specific to a room of floor size 3 × 4 m, with a 2.4-m-high ceiling. Another way of discussing the calculations is to consider the time needed from ignition to reach flashover conditions with the different types of fire specifications. The details are seen in Fig. 20 (using Thomas's theory) for three different values of the ventilation factor. Notice that the 75-s incubation period is included in these values. The trends are clearly evident: that the rapidity of fire growth is of extreme importance in determining flashover conditions, with the ventilation factor being of lesser importance. Notice that medium to ultrafast fire growths produce the onset of flashover in just a few minutes. Further details are given in Refs. 20 and 21.

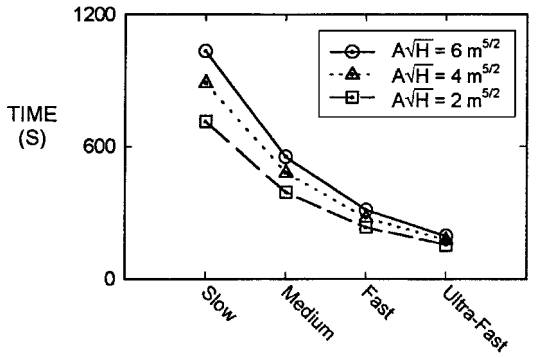

Fig. 20 Time to reach flashover conditions vs fire growth specification and ventilation factor.

Conclusions

Structural fire development can be understood more readily when technical knowledge puts the phenomena on a firm scientific footing. The theory assists in understanding and applying scientific information to real-world fire investigation situations. Recent extensive study, research, experimentation, and field observations and measurements have led to the need for critical evaluation of phenomena and its simulation. Fire dynamicists can develop an appreciation for technical/scientific understanding of the phenomena and its applicability to real-world, practical situations. Sample calculations were exhibited to illustrate several aspects of fire behavior.

References

[1]Bukowski, R., "The HAZARD-1 Computer Code Package for Fire Hazard Assessment," National Inst. of Standards and Technology, Gaithersburg, MD, 1989.

[2]Portier, R. W., Peacock, R. D., and Reneke, P. A., "FASTLite: Engineering Tools for Estimating Fire Growth and Smopke Transport," National Inst. of Standards and Technology Special Publ. 899, Gaithersburg, MD, April 1996; also update to Ver. 1.0b, Feb. 1997.

[3]Emmons, H. W., "The Needed Fire Science," *Fire Safety Science*, edited by C. E. Grant and P. J. Pagni, Hemisphere, New York, 1985, pp. 33–53.

[4]Thomas, P. H., "Fires in Enclosures," *Heat Transfer in Fires*, edited by P. L. Blackshear, Halsted–Wiley, New York, 1974, pp. 73–94.

[5]Karlsson, B., and Quintiere, J. G., *Enclosure Fire Dynamics*, CRC Press, Boca Raton, FL, 2000.

[6]Lilley, D. G., *Fire Dynamics*, Short Course, Lilley and Associates Course Notes and Sample Problems, Stillwater, OK, 1995.

[7]Lilley, D. G., "Fire Dynamics," AIAA Paper 95-0894, Jan. 1995.

[8]Lilley, D. G., "Structural Fire Calculations," American Society of Mechanical Engineers, Paper DETC 97/CIE-4428, Sacramento, CA, Sept. 1997.

[9]Lilley, D. G., "Estimating Fire Growth and Temperatures in Structural Fires," AIAA Paper 97-0266, Jan. 1997.

[10]Cote, A. E., and Linville, J. L. (eds.), *Fire Protection Handbook*, 18th ed., National Fire Protection Association, Quincy, MA, 1997.

[11]DiNenno, P. J. (ed.), *Handbook of Fire Protection Engineering*, 2nd ed., National Fire Protection Association and Society of Fire Protection Engineers, Boston, 1995.

[12]Babrauskas, V., and Grayson, S. J. (eds.), *Heat Release in Fires*, Elsevier Applied Science, New York, 1992.

[13]Blinov, V. I., and Khudiakov, G. N., "Laws Governing Diffusive Burning," *Doklady, Academiia Nauk, SSSR*, 1957, pp. 1094–1098.

[14]Hottel, H. C., "Certain Laws Governing Difusive Burning of Liquids," *Fire Research Abstracts and Reviews*, Vol. 1, 1959, p. 41.

[15]Heskestad, G., "Fire Plumes," *Handbook of Fire Protection Engineering*, 2nd ed., edited by P. J. DiNenno, Society of Fire Protection Engineers, Boston, 1995.

[16]Drysdale, D., *An Introduction to Fire Dynamics*, Wiley, Chichester, England, U.K., 1985.

[17]Peacock, R. D., "An Update Guide for HAZARD 1 Version 1.2," National Inst. of Standards and Technology Rept. NISTIR 5410, May 1994.

[18]Thomas, P. T., Bullen, M. L., Quintiere, J. G., and McCaffrey, B. J., "Flashover and Instabilities in Fire Behavior," *Combustion and Flame*, Vol. 38, 1980, pp. 159–171.

[19]"Guide for Fire and Explosion Investigations," National Fire Protection Association, NFPA 921, Quincy, MA, 1995.

[20]Kim, H.-J., and Lilley, D. G., "Flashover: A Study of Parameter Effects on the Time to Reach Flashover Conditions," American Society of Mechanical Engineers, Computers in Engineering Conf., Sacramento, CA, Sept. 1997.

[21]Kim, H.-J., and Lilley, D. G., "A Comparison of Flashover Theories," American Society of Mechanical Engineers, Computers in Engineering Conf., Atlanta, Sept. 1998.