AIVC 11913

CH-99-8-4

An Engineering Approach to Tenability Systems for Atrium Smoke Management

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ABSTRACT

This paper addresses atria smoke management systems where it is intended that occupants will be in contact with smoke. While this approach is unusual, it is recognized by several authoritative publications on atrium smoke management. A tenability analysis for an atrium smoke management system needs to account for the effects of (1) exposure to toxic gases, (2) exposure to elevated temperatures, and (3) smoke obscuration. Much of this paper consists of adapting and presenting well-established tenability methods for application to smoke management. However, this paper is unique in that new material is presented concerning (1) a method to evaluate the relative aspects of tenability of smoke in the absence of a smoke transport analysis, (2) a generic fuel approach to atrium tenability analysis, and (3) a method of comparing the tenability of smoke from different fuels on the same system design. It is shown that for an appropriate generic fuel, the tenability analysis can be significantly simplified.

INTRODUCTION

In recent years, atria have become commonplace in hotels and commercial buildings. Other large open spaces include enclosed shopping malls, arcades, sports arenas, exhibition halls, and airplane hangars. The methods of this paper also apply to these spaces. For simplicity, in this paper, the term "atrium" is used in a generic sense to mean any of these large spaces.

The subject of this paper is atria smoke management systems where it is intended that occupants will be in contact with smoke. While this approach is unusual, it is recognized by NFPA 92B (NFPA 1995), Klote and Milke (1992), and CIBSE (1997). It is essential that exposing occupants to smoke does not result in injury to the occupants or impair building evacuation, and a tenability analysis is needed to provide such assurance. A tenability analysis for an atrium smoke management system needs to account for the effects of exposure to toxic gases, exposure to elevated temperatures, and smoke obscuration.

While many publications address tenability (i.e., Clarke 1997; Purser 1995; Babrauskas et al. 1991; Levin et al. 1995), this paper treats the subject from the perspective of smoke management design. Much of this paper consists of adapting and presenting well-established tenability methods for application to smoke management. However, this paper is unique in that new material is presented concerning (1) a method to evaluate the relative aspects of tenability of smoke in the absence of a smoke transport analysis, (2) a generic fuel approach to atrium tenability analysis, and (3) a method of comparing the tenability of smoke from different fuels on the same system design.

There are many definitions of the term "smoke" used in fire protection engineering, and caution needs to be exercised to prevent misunderstandings. For this paper, the term "smoke" is used in accordance with the NFPA 92B (NFPA 1995) definition, which states that smoke is the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass. This definition is consistent with NFPA 92A (NFPA 1996), the *1995 ASHRAE Handbook—HVAC Applications* (ASHRAE 1995), and the joint ASHRAE/SFPE publication *Design of Smoke Management Systems* (Klote and Milke 1992).

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SMOKE MANAGEMENT CONCEPTS

Traditional Approaches

The traditional approaches to atrium smoke management are all based on keeping smoke away from the occupants. In North America, the most common approach to keeping smoke away from people is by the use of mechanical fans to exhaust smoke from the top of the atrium. In the United Kingdom, it is common to use natural vents to remove smoke from the atrium. Analysis of these systems primarily consists of smoke transport calculations.

Smoke filling is still another approach that can be applicable to some atria that are sufficiently large so that the time to evacuate the people is less than the time to fill the atrium with smoke. In addition to smoke transport calculations, smoke filling systems require an evacuation analysis that accounts for both the time to make decisions and the time for occupants to leave the building. For information about evacuation analysis, see Pauls (1995) and Nelson and MacLennan (1995).

For information about traditional atria smoke management systems including smoke transport analysis see NFPA 92B (NFPA 1995), Klote and Milke (1992), Klote (1994), Hansell and Morgan (1994), and Morgan and Gardner (1990).

Tenability Approaches

Systems where occupants are intended to be exposed to smoke are referred to as tenability systems, and such systems can rely on smoke filling, smoke venting, or smoke exhaust to maintain tenable conditions. Because tenability systems are relatively new, system concepts and design methods are not well established. In the experience of the author, professionals familiar with tenability concepts generally agree that design of tenability systems requires smoke transport analysis, evacuation analysis, and tenability analysis. It is shown later in this paper that for an appropriate generic fuel, the tenability analysis can be significantly simplified. The generic fuel approach to atrium smoke management design is discussed later in this paper.

EXPOSURE TO GAS

Carbon monoxide poisoning accounts for roughly one-half of total fire fatalities (Berl and Halpin 1980; Harland and Woolley 1979). While Klote and Milke (1992) list toxicity data for 21 gases, a few of the gases commonly considered in a tenability analysis are carbon monoxide (CO), hydrogen cyanide (HCN), carbon dioxide (CO_2), and oxygen (O_2). The toxic effects of CO and HCN are well known. Hyperventilation due to CO_2 exposure will increase the rate of intake of other toxic gases. Oxygen deprivation is a special case, and the reduction in the amount of O_2 available for tissue respiration is referred to as hypoxia. Because of the interaction of these gases, exposure effects discussed below consider the combined effects of these gases. The effect of exposure to toxic gases on a specific individual depends on the physiological characteristics of the individual.

Exposure and Time

Haber (1924) proposed that the effect of exposure to a gas is related to the product of the gas concentration and time duration of the exposure. Haber's rule is expressed as

$$E = C\tau \tag{1}$$

where

E = effect of exposure (ppm-min),

C = concentration (ppm),

τ = duration of exposure (min).

This elementary equation assumes a constant ingestion rate of the toxin. The effects of some gases do not follow Haber's rule, and concentrations of toxic gases due to building fires tend to change with time. Thus, Haber's rule has limited use for tenability calculations.

In the past few decades, tenability limits have been expressed in terms of time-integrated values. Time-integrated values account for the effect of exposure to a particular gas over a period of time rather than an instantaneous exposure. The E parameter in Haber's rule can be considered a time-integrated value with a constant gas concentration. If the concentration is a variable in time, then an integration must be conducted to obtain the area under the concentration time curve in order to determine a time-integrated value.

FED from Animal Test Data

Several test methods have been developed to evaluate the toxic effects of gases on animals (Babrauskas et al. 1991; Purser 1995). Most animal tests are conducted on rats or mice. These tests determine the concentration of airborne combustion products that is lethal to 50% of the test animals exposed for a specified time, and this lethal concentration is referred to as the LC_{50} (g/m^3). The specified time for animal tests is usually 30 minutes, and the number of fatalities consists of animals that die during the test and during a post-exposure time, usually 14 days after the test.

Using extrapolated animal test data, the fractional effective dose can be approximated as

$$\mathrm{FED} = \frac{\int_0^\tau C\,d\tau}{LC\tau_{50}} \tag{2}$$

where

FED = fractional effective dose (dimensionless),

C = concentration (g/m^{-3}),

τ = exposure time (min),

$LC\tau_{50}$ = lethal exposure dose from test data ($g/m^{-3} \cdot min$).

An FED greater than or equal to one indicates fatality. The concentration is in mass of the material burned per unit volume. The lethal exposure dose, $LC\tau_{50}$, is the product of the

TABLE 1
Approximate Lethal Exposure Dose for Common Materials [g m^{-3} min; adapted from Purser (1995)]

Material	Nonflaming Fire	Early Flaming Fire	Post-Flashover Fire
Cellulosics	730	3120	750
C, H, O plastics	500	1200	530
PVC	500	300	200
Wool/Nylon (low N_2)	500	920	70
Flexible Polyurethane	680	1390	200
Rigid Polyurethane	63	100	54
Modacrylic/PAN[1]	160	140	45

[1] PAN is polyacrylonitrile.

LC_{50} and the exposure time. Table 1 lists some values of $LC\tau_{50}$ for a number of common materials.

The above equation is the time-integrated form of the FED equation. For most applications, the time functional relationship of concentration is not known, and the following expression can be used for discrete pairs of concentration and time intervals.

$$\mathrm{FED} = \frac{\sum_{i=1}^{n} C_i \Delta\tau_i}{LC\tau_{50}} \tag{3}$$

where

C_i = concentration for time interval i (g/m^{-3}),
$\Delta\tau_i$ = time interval i (min),
n = number of discrete concentration time pairs.

Many references use the term "concentration time product," $C\tau$, to mean the integral term of Equation 2, and this meaning of $C\tau$ will be used for the rest of this paper.

The question arises, should incapacitation or fatality be used as the design criterion for gas exposure? A person who is incapacitated due to exposure to toxic gases will continue to be exposed to those gases. Unless the person is rescued or the gas concentrations improve dramatically, such exposure will result in fatality. Thus, it seems that incapacitation is the conservative criterion for smoke management design analysis. While a FED of one indicates fatality, Bukowski et al. (1989) state that a FED of 0.5 can be considered an approximate value of the incapacitating dose. The next section addresses incapacitation due to exposure to toxic gases.

Fractional Incapacitating Dose

Narcotic gases cause incapacitation mainly by effects on the central nervous system and the cardiovascular system. Based on data from animal tests, Purser (1995) developed a model to calculate fractional incapacitating dose. The notation in this section has been modified from that of Purser for consistency and to facilitate computer programming.

$$F_{IN} = \begin{cases} \sum_{i=1}^{n} [(F_{ICO,i} + F_{ICN,i}) V_{CO2,i} + F_{IO,i}] \Delta\tau_i \\ \text{or} \\ \sum_{i=1}^{n} (F_{ICO2,i}) \Delta\tau_i; \text{ whichever is greater,} \end{cases} \tag{4}$$

where

F_{IN} = fractional incapacitating dose of all narcotic gases (dimensionless),
$F_{ICO,i}$ = fraction of an incapacitating dose of CO per unit time (min^{-1}),
$F_{ICN,i}$ = fraction of an incapacitating dose of HCN per unit time (min^{-1}),
$V_{CO2,i}$ = factor for CO_2-induced hyperventilation (min^{-1}),
$F_{IO,i}$ = fraction of an incapacitating dose of low-oxygen hypoxia per unit time (min^{-1}),
$\Delta\tau_i$ = time interval i (min),
$F_{ICO2,i}$ = fraction of an incapacitating dose of CO_2 per unit time (min^{-1}).

The terms in the above equation are calculated from

$$\begin{aligned} F_{ICO,i} &= \frac{8.2925 \times 10^{-4} C_{CO}^{1.036}}{30} \\ F_{ICN,i} &= \frac{1}{\exp(5.396 - 0.023 C_{HCN})} \\ V_{CO2,i} &= \frac{\exp(0.1903 C_{CO2} + 2.0004)}{7.1} \\ F_{IO,i} &= \frac{1}{\exp[8.13 - 0.54(20.9 - C_{O2})]} \\ F_{ICO2,i} &= \frac{1}{\exp(6.1623 - 0.5189 C_{CO2})} \end{aligned} \tag{5}$$

where

C_{CO} = concentration of CO (ppm),
C_{HCN} = concentration of HCN (ppm),
C_{CO2} = concentration of CO_2 (percent),
C_{O2} = concentration of O_2 (percent).

Incapacitation is estimated by Equation 4 for either elevated CO_2 or the combined effects of CO, HCN, CO_2, and O_2. For environments produced by building fires, incapacitation due to totally elevated CO_2 exposure is highly unlikely.

The fractional incapacitating dose, F_{IN}, is useful when the composition of the fuel is known so that the composition of the combustion gases can be calculated. While such information may be available for fire reconstruction, it is generally not possible for design.

Other Toxicity Models

Considerable work has been done at the National Institute of Standards and Technology (NIST) using test data from rat experiments to relate toxic exposures to fatality. A computer model developed at NIST estimates the FED based on exposures to CO, CO_2, O_2, and HCN (Bukowski et al. 1989). Babrauskas et al. (1991) and Levin et al. (1994) describe the toxicity experiments and the N-Gas model based on these experiments, which not only addresses the gases considered by Bukowski et al. but also includes hydrogen chloride (HCl), hydrogen bromide (HBr), and nitrogen dioxide (NO_2).

EXPOSURE TO HEAT

Exposure to elevated temperature atmospheres can lead to skin burns and heat stroke (hyperthermia). The effect of exposure to elevated temperatures depends on the humidity of the air and the type and extent of clothing worn.

To determine the time to incapacitation, Purser (1995) recommends the following equation based on averaging the time to incapacitation for exposures to humid air and dry air:

$$\tau_{Ih} = \exp(5.1849 - 0.0273T) \tag{6}$$

where

τ_{Ih} = time to incapacitation (min),

T = temperature of air (°C).

For short-duration, high-temperature exposures, the above equation is conservative. For example, the time to incapacitation for exposure to 150°C is estimated from Equation 6 at about three minutes and from experimental data at about five minutes (Purser 1995). Alternatively, considering an exposure to an environment at 93°C, the time to incapacitation is calculated as 14 minutes, a result that is in better agreement with Purser's observations. For smoke control applications, incapacitation due to thermal exposure is not a concern for temperatures less than normal body temperature (37°C). Incapacitation times calculated from Equation 6 are listed in Table 2.

TABLE 2
Average Time to Incapacitation Due to Exposure to Elevated Temperature

Temperature		Time to Incapacitation (min)
°C	°F	
40	104	60
50	122	46
60	140	35
70	158	26
80	176	20
90	194	15

SMOKE OBSCURATION

When people cannot see because of smoke from a building fire, they walk slowly, which can significantly lengthen evacuation time, and they can become disorientated and lost, thus prolonging their exposure to toxic gases. In atrium fire situations, there is the added concern that a disorientated person could fall from a balcony. Because a person falling 5 m (16 ft) has about a 50% chance of fatality, falls are a serious concern for buildings with balconies.

The relation between visibility and smoke obscuration for a light-emitting sign is

$$S = \frac{8}{K}, \tag{7}$$

and for a light-reflecting sign,

$$S = \frac{3}{K}, \tag{8}$$

where

S = visibility (m),

K = extinction coefficient (m^{-1}).

The extinction coefficient can be expressed as

$$K = -\frac{1}{x}\log_e(T_r) \tag{9}$$

where

x = path length or distance of light travel (m),

T_r = transmittance (dimensionless).

The transmittance is the ratio of the light intensity remaining at the end of the pathlength to that at the beginning of the pathlength. A smoke meter is an experimental device used to measure transmittance, which often has a laser as the light source. Readers are cautioned that smoke obscuration terminology is not uniform. Other names (such as attenuation coefficient) are sometimes used for extinction coefficient, and many different mathematical expressions are used to describe smoke obscuration. Readers desiring further information about smoke obscuration are referred to Clark (1988), Collins et al. (1992), Mulholland (1995), and Klote and Milke (1992).

The visibility is the obscuration threshold that is the distance at which an object can just be seen. Visibility under the same conditions varies with different people based on their eyesight. Equations 7 and 8 were developed by Jin (1974, 1975, 1985) based on extensive tests where signs in a smoke-filled chamber were observed from outside through a glass window. Jin indicates that the visibility for reflecting signs may be applicable for the visibility of other objects such as walls, floors, doors, and stairs. Visibilities calculated from these equations are average values, and they may vary with the observer by as much as 35%.

The above information about visibility does not take into account the irritating effects of smoke on the eyes. Jin (1985) conducted tests correlating the visibility and walking speed of subjects exposed to irritating smoke with the extinction coefficient. There are shortcomings with correlating physiological effects with an optical property of smoke, since the effects would seem to be primarily caused by chemical components of smoke. However, the effects of eye irritation are so significant that Jin's work on the topic is discussed below.

Jin produced an irritating white smoke by burning wood cribs and a less irritating smoke by burning kerosene. The visibility relationships of Equations 7 and 8 are not appropriate when subjects are exposed to irritating smoke. In thick irritating smoke, subjects could not keep their eyes open long enough to read the sign. Figure 1 shows the relation between the extinction coefficient and walking speed of people walking down a corridor in irritating and non-irritating smoke. Both eye irritation and smoke density affect walking speed. Walking speed decreases with extinction coefficient for both smokes, but it is much worse for irritating smoke. For extinction coefficients greater than 0.5 m^{-1}, the walking speed decreased to about 1 ft/sec (0.3 m/s), the speed of a blindfolded person. The drop in walking speed was because subjects could not keep their eyes open, and they walked in a zigzag or went step by step as they held the side wall.

For an extinction coefficient of 0.35 m^{-1}, the walking speed through irritating smoke was nearly the same as that through non-irritating smoke. Using Equations 7 and 8, this extinction coefficient corresponds to visibility of about 23 m (75 ft) for light-emitting signs and about 9 m (30 ft) for light-reflecting signs. It can be expected that a person with average eyesight would be able to see walls, floors, doors, and balcony railings about 9 m away. At this smoke density, even an irritating smoke would have minimal impact on walking speed. For these reasons, a maximum extinction coefficient of 0.35 m^{-1} was chosen as the smoke obscuration criterion for this paper.

The design of a tenability system for smoke management needs to incorporate safety factors. For simplicity, safety factors are not included in this paper until near the end of the paper where they are part of the generic fuel design approach.

K and Particulate Production

The airborne particulates produced by a fire consist primarily of soot, and the production of particulates can be estimated as

$$M_p = y_p M_f \qquad (10)$$

where

M_p = mass of particulates produced (g),
M_f = mass of fuel consumed (g),
y_p = particulates yield (dimensionless).

Values of y_p are listed in Table 3 from small-scale experiments of turbulent flaming combustion for a number of materials. While it is expected that particulate production will vary with the size of the fire and the orientation of the fuel, the data in Table 3 are recommended in the absence of data from the kind of large fires for which atrium smoke management systems are designed. For additional information about particulate production, see Mulholland (1995) and Tewarson (1995).

The extinction coefficient and particulate concentration can be expressed as

$$K = K_m m_p \qquad (11)$$

where

K = extinction coefficient (m^{-1}),
K_m = specific extinction coefficient (m^2/g),
m_p = mass concentration of particulate (g/m^3).

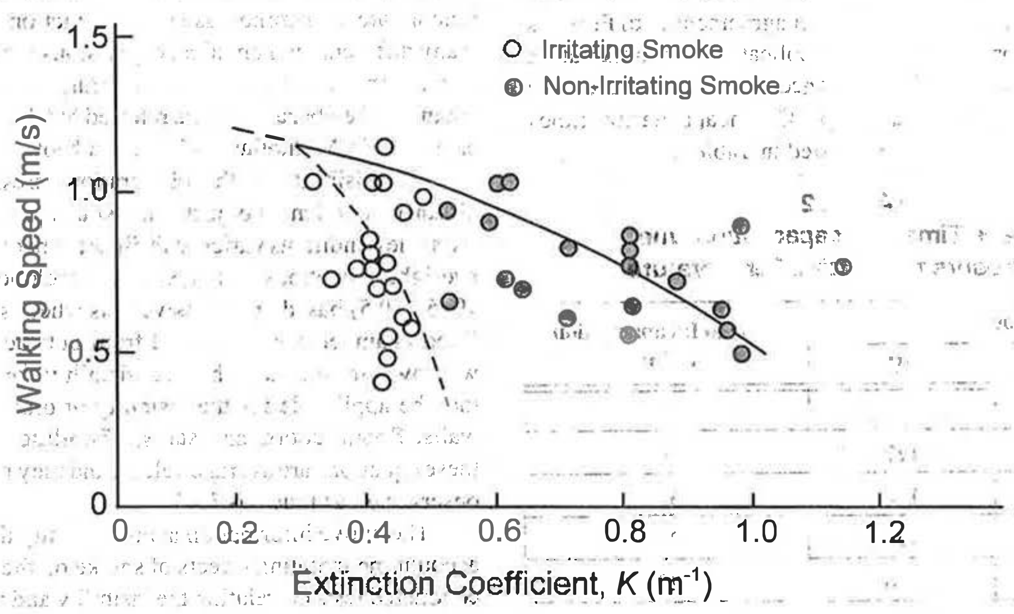

Figure 1 Walking speed in irritating and non-irritating smoke (Jin 1985).

TABLE 3

Particulate Yield and Heat of Combustion for Well-Ventilated Fires of Solid Fuels[1]

Material	Particulate Yield y_p	Particulate Yield per Heat Released[2] Y_p (g s^{-1} MW^{-1})	Chemical Heat of Combustion ΔH_{ch} (kJ/kg)
Natural Materials			
Wood (Red Oak)	0.015	1.2	12,400
Wood (Douglas Fir)[3]	0.018	1.4	13,000
Wood (Hemlock)	0.015	1.1	13,300
Fiberboard[3]	0.008	0.6	14,000
Wool 100%	0.008	0.4	19,500
Synthetic Materials			
Acrylonitrile-Butadiene-Styrene (ABS)	0.105	3.5	30,000
Polymethyl Methacrylate (PMMA; Plexiglas™)	0.022	0.9	24,200
Polypropylene	0.059	1.5	38,600
Polystyrene	0.164	6.1	27,000
Silicone	0.065	6.1	10,600
Polyester[4]	0.090	4.5	20,100
Nylon	0.075	2.8	27,100
Silicone Rubber	0.078	7.1	10,900
Polyurethane Foam (Flexible)[4]	0.188	10.7	17,600
Polyurethane Foam (Rigid)[4]	0.118	7.0	16,900
Polystyrene Foam[4]	0.194	7.6	25,500
Polyethylene Foam[4]	0.076	2.2	34,200
Phenolic Foam	0.002	0.2	10,000
Polyethylene (PE)	0.060	1.6	38,400
PE with 25% Chlorine	0.115	5.1	22,600
PE with 36% Chlorine	0.139	13.1	10,600
PE with 48% Chlorine	0.134	18.6	7,200
Polyvinylchloride (PVC)	0.172	30.2	5,700
PVC 1 (LOI = 0.50)	0.098	12.7	7,700
PVC 2 (LOI = 0.50)	0.076	9.2	8,300
PVC (LOI = 0.20)	0.099	8.8	11,300
PVC (LOI = 0.25)	0.078	8.0	9,800
PVC (LOI = 0.30)	0.098	9.5	10,300
PVC (LOI = 0.35)	0.088	8.1	10,800
Ethylenetetrafluoroethylene (ETFE; Tefzel™)	0.042	7.8	5,400
Perfluoroalkoxy (PFA; Teflon™)	0.002	0.4	4,700
Fluorinated Polyethylene-Polypropylene (FEP; Teflon™)	0.003	0.7	4,100
Tetrafluoroethylene (TFE; Teflon™)	0.003	0.7	4,200

[1] Data from Tewarson (1995), except as otherwise noted.

[2] The particulate yield per heat released is $Y_p = 10^6\, y_p/\Delta H_{ch}$.

[3] Particulate yield data from Mulholland (1995).

[4] Values listed are average of a number of different materials under this general name.

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Seader and Einhorn (1976) obtained values for K_m of 4.4 m^2/g for smoke from pyrolysis of wood and plastics and 7.6 m^2/g for smoke from flaming combustion of these same materials. Because atrium smoke management systems are designed to withstand flaming fires, $K_m = 7.6\ m^2/g$ is recommended.

Table 3 lists particulate production, Y_p, in terms of heat release. This value can be useful in calculating m_p with a smoke transport analysis. To the author's knowledge, all such smoke transport analyses used for smoke management neglect smoke particle aging (agglomeration and deposition) in the belief that such aging has an insignificant impact on calculated visibility.

SIMPLE ATRIUM FILLING

Computer models can calculate m_p and concentrations of gases for a wide range of smoke management applications including atria with unsteady fires, mechanical smoke exhaust, natural smoke venting, and atrium filling. However, this section presents a simple analysis of atrium filling with a constant fire that is used to illustrate tenability calculations. As is common practice, this analysis neglects aging of smoke particles, deposition of smoke particles, and deposition of combustion gases. In most cases, deposition of gases is not significant. The most notable exception is HCl, and the zone fire model CFAST (Peacock et al. 1993) is capable of simulating HCl deposition. However, neglecting gaseous deposition results in increased calculations of gas toxicity, which is conservative for smoke management analysis.

In atrium filling, all the gases and particulates from combustion are collected in a single volume that can be calculated from simple equations or computer smoke transport models, as already mentioned. In this volume, the average value of the mass concentration of the particulates is

$$m_p = \frac{M_p}{V_s}, \qquad (12)$$

where V_s is the volume occupied by the smoke (m^3).

Because the heat release rate of the fire is constant, the mass of fuel consumed by a fire can be expressed as

$$M_f = \frac{1000\dot{Q}t}{\Delta H_{ch}} \qquad (13)$$

where

M_f = mass of fuel consumed (g),
$\dot{Q}$ = total heat release rate (kW),
ΔH_{ch} = chemical heat of combustion (kJ/kg),
t = time from ignition (s).

Values of ΔH_{ch} for some materials are listed in Table 3. In fires, combustion is never complete. Combustion efficiency is the ratio of the chemical heat of combustion to the net heat of combustion. Using ΔH_{ch} eliminates the need to consider combustion efficiency.

The concentration of fuel in the smoke volume is

$$C = \frac{M_f}{V_s} \qquad (14)$$

This can be substituted into the equation for the FED to produce

$$\text{FED} = \frac{M_f \tau}{V_s L C \tau_{50}}. \qquad (15)$$

This equation is conservative in that it is based on the concentration at the end of atrium filling, which is the highest level of concentration during the atrium filling process.

Neglecting heat transfer from the smoke to the atrium walls and ceiling, the smoke temperature is

$$T_s = T_a + \frac{Q}{M_s C_p}, \qquad (16)$$

where

T_s = absolute temperature of smoke (K),
T_a = absolute temperature of ambient (K),
Q = heat released (J),
M_s = mass of smoke (kg),
C_p = specific heat of smoke (1000 J kg^{-1} K^{-1}).

Using the ideal gas equation, the mass of the smoke is

$$M_s = \rho_s V_s = \frac{P V_s}{R T_s}, \qquad (17)$$

where

P = absolute pressure (Pa),
R = gas constant (287 J kg^{-1} K^{-1}).

Atmospheric pressure is approximately 105 Pa, but it varies with elevation and weather conditions. Substituting Equation 17 into Equation 16 and rearranging yields

$$T_s = \frac{T_a}{1 - \frac{QR}{V_s P C_p}}. \qquad (18)$$

The smoke temperature and contaminant concentration are conservative because they are based on conditions in the atrium at the end of atrium filling. To explain this, a discussion of the atrium smoke filling process is needed. A smoke plume rises above the fire and forms a layer of hot smoke under the ceiling of the atrium. As time passes, the smoke layer descends. The end time for such considerations can be determined by an evacuation analysis, and V_s is the smoke volume at the end time. The plume entrains air from the atrium as it rises so that the plume mass flow increases with height and the plume temperature and contaminant concentrations decrease with height. Further, the smoke layer temperature and contaminant concentrations increase with smoke filling time for a steady fire. Thus, the concentrations and smoke temperature are the highest at the end of the smoke filling for a steady fire.

In addition, the smoke temperature estimated from Equation 18 is conservative because heat transfer was neglected. Further, the exposure time is when the smoke layer reaches the occupant until that occupant leaves the smoke layer. The total filling time is greater than any possible exposure time. An upper bound of tenability can be calculated using the temperature and concentration at the end of filling and an exposure time equaling the entire atrium filling time.

Example 1 below uses these conservative equations to calculate the upper bound of tenability for smoke filling. If a more accurate evaluation of tenability is needed, additional details from a smoke transport will be needed.

Example 1

A 2 MW fire is burning in an atrium without any venting. If the fuel burning is all cellulosic, what is the upper limit of tenability for this application? A smoke transport analysis was made including calculations of plume flow and smoke layer interface height. This analysis showed that at 20 minutes after ignition, the volume of the smoke layer under the atrium ceiling was 80,000 m^3.

Caution: Cellulosic fuel is used here only for example purposes. Most design fires would include other materials that can change the results significantly, as discussed later.

The particulate yield and heat of combustion are not specifically listed in Table 3 for cellulosic fuel, but the woods are all cellulosic materials, so values for wood (hemlock) will be used.

Part 1: Smoke Obscuration. From Equation 13, the mass of fuel consumed in 20 minutes is

$$M_f = \frac{1000 Q t}{\Delta H_{ch}} = \frac{1000(2000 \text{ kW})(1200 \text{ s})}{13{,}300 \text{ kJ/kg}} = 180{,}000 \text{ g of fuel} .$$

From Equation 10, the mass of particulate produced in 20 minutes is

$$M_p = y_p M_f = 0.015(180{,}000 \text{ g}) = 2700 \text{ g of particulate.}$$

The volume of the smoke is $V_s = 80{,}000 \text{ m}^3$. From Equation 12, the mass concentration of particulate is

$$m_p = \frac{M_p}{V_s} = \frac{2700 \text{ g}}{80{,}000 \text{ m}^3} = 0.034 \text{ g/m}^3 .$$

Using $K_m = 7.6 \text{ m}^2/\text{g}$ for a flaming fire, from Equation 11 the extinction coefficient is

$$K = K_m m_p = 7.6 \text{ m}^2/\text{g } (0.034 \text{ g/m}^3) = 0.26 \text{ m}^{-1}.$$

From Equation 8, the visibility of a light-reflecting sign and many other objects is

$$S = \frac{3}{K} = \frac{3}{0.26} = 12 \text{ m} .$$

Note that the above value of K is within the visibility criteria of this paper (maximum K of 0.35 m^{-1}).

Part 2: FED. Use the lethal exposure dose data for a flaming fire from Table 1 for cellulosic materials. A person would probably not be exposed to smoke for the entire 20-minute duration of the fire, but we will use the 20 minutes to calculate an upper limit to the FED.

From Equation 15,

$$\text{FED} = \frac{M_f \tau}{V_s L C \tau_{50}} = \frac{180{,}000 \text{ g (20 min)}}{80{,}000 \text{ m}^3 (3120 \text{ g m}^{-3} \text{min})} = 0.014 .$$

As previously stated, a FED of 1 indicates fatality and a FED of 0.5 roughly indicates incapacity. The above value is very small and indicates that the effects of toxic gases are not a concern for the conditions of this example.

Part 3: Heat. The heat released during 20 minutes of the fire is

$$Q = \dot{Q}\, t = 2000 \text{ kW } (1200 \text{ s}) (1000 \text{ J/kJ}) = 2.4 \times 10^6 \text{ kJ} = 2.4 \times 10^9 \text{ J}.$$

For an ambient temperature, T_a = 23°C (23 + 273 = 296 K), and a pressure of 105 Pa, the temperature of the smoke is calculated from Equation 18.

$$T_s = \frac{T_a}{1 - \frac{QR}{V_s P C_p}} = \frac{296}{1 - \frac{2.4 \times 10^9 \text{ kJ } (287 \text{ J kg}^{-1} \text{ K}^{-1})}{80{,}000 \text{m}^3 (10^5 \text{ Pa})(1000 \text{ kJ kg}^{-1} \text{ K}^{-1})}}$$

$$= 324 \text{ K or } 51^\circ\text{C}.$$

From Table 2, the time for incapacitation due to exposure to this temperature is about 45 minutes. For most applications, this would be more than enough time for evacuation.

DISCUSSION OF TENABILITY

In the above example, the FED was so small that it indicated that gas toxicity would not be a concern for that application. The author and other designers have encountered similar situations with calculations for other smoke management applications. For many situations when the airborne products of combustion are diluted to meet a visibility criterion like that of this paper, the toxicity of the combustion gases is not of concern. Furthermore, such dilution often results in acceptable smoke temperatures. This section examines these issues.

Dividing Equation 10 by V_s and substituting Equations 11, 12, and 14 results in

$$C = \frac{K}{K_m y_p} . \tag{19}$$

Substituting Equation 19 into the FED equation produces

$$\text{FED} = \frac{K\tau}{y_p K_m L C \tau_{50}} . \tag{20}$$

Combining Equations 14, 18, 19, and $Q = M_f \Delta H_{ch}$, yields

TABLE 4
Values Used for Tenability Discussions

Material	Flaming $LC\tau_{50}$ ($\mathrm{g\ m^{-3}\ min}$)	Post-Flashover $LC\tau_{50}$ ($\mathrm{g m^{-3}\ min}$)	Particulate Yield y_p	Chemical Heat of Combustion ΔH_{ch} (kJ/kg)
Wood (hemlock)	3120	750	0.015	13,300
PMMA	1200	530	0.022	24,200
PVC	300	200	0.098	7,700
Wool	920	70	0.008	19,500
Nylon	920	70	0.075	27,100
PU Foam (flexible)	1390	200	0.188	17,600
PU Foam (rigid)	100	54	0.118	16,900

$$T_s = \frac{T_a}{1 - \dfrac{\Delta H_{ch} K R}{C_p K_m y_p P}} \qquad (21)$$

Equations 20 and 21 are independent of the heat release rate and the duration of the fire. These equations for FED and T_s are expressed as functions of K. Table 4 lists some materials for which the lethal exposure dose is available from Table 1 and the particulate yield is available from Table 3.

If the smoke from these materials is diluted so that K is 0.35 $\mathrm{m^{-1}}$, visibility meets the criterion for this paper. For this visibility, the FED for flaming fires and post-flashover fires is shown in Figures 2 and 3. Flaming fires have unrestricted access to air, as can be expected of a fire in an open atrium, provided that the smoke layer is above the flames. While there are many definitions of the post-flashover fire, it can generally be said that the entire fire room is involved in fire.

In North America, most atria smoke management designs are based on protecting against a fire located in the atrium. This is based on the idea that fires in rooms or other spaces that are open to the atrium are protected by sprinklers. For these designs, the FED data for fires with unrestricted access to air (Figure 2) are appropriate.

Generally, atria are expected to be evacuated in less than 20 minutes with even less exposure time inside the atrium. From Figure 2, it can be seen that the FED values are less than 0.2 for all the materials evaluated with an exposure time of 30 minutes. As already stated, Figure 2 has sufficient dilution to provide acceptable visibility and a FED value of 0.5 indicates incapacitation. Thus, for any of these materials burning in an atrium, if the smoke is sufficiently diluted to meet the visibility criteria of this paper, toxicity is not a concern for exposure times less than 30 minutes. Figure 2 can be examined to see that for all these materials, the above statement includes a significant factor of safety.

In some locations (such as the United Kingdom) designs are based on protecting against fires in rooms or shops that open onto the atrium. For these designs, a post-flashover fire might occur and the FED data of Figure 3 could be appropriate. Post-flashover fires produce higher levels of CO, so it was expected that the FED values for post-flashover fires would be higher than those of fire with unrestricted access to air (Figures 2 and 3). With the exception of wool, it can be seen

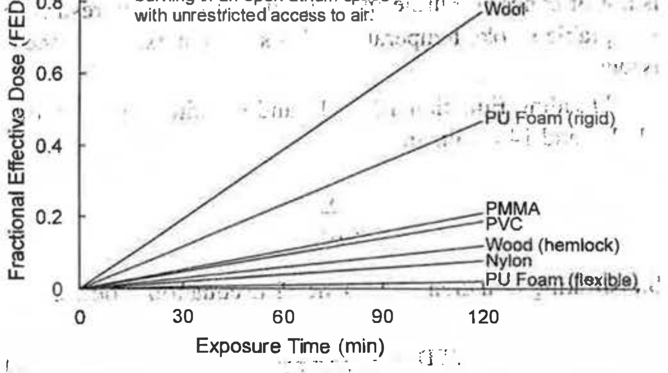

Figure 2 *FED produced by smoke of* K = *0.35* m^{-1} *from fires in an atrium.*

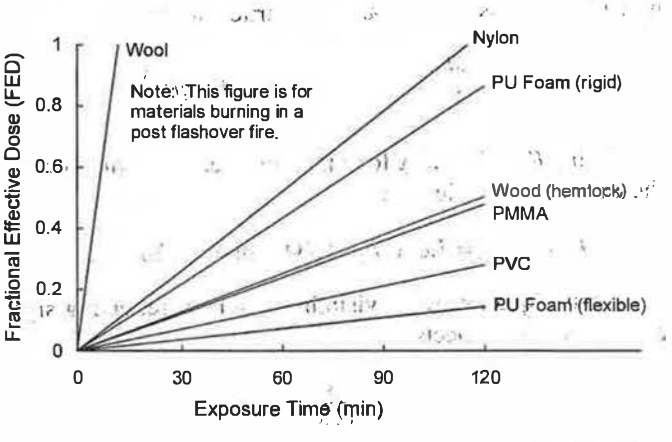

Figure 3 *FED produced by smoke of* K = *0.35* m^{-1} *from post-flashover fires.*

TABLE 5

Heat Exposures Produced by Smoke of $K = 0.35\ \mathrm{m}^{-1}$

Material	Adiabatic Smoke Temperature, T_s [1]		Incapacitation Time τ_{Ih} (min)
	°C	°F	
Wood (Hemlock)	62	144	33
PMMA	73	163	25
PVC	26	79	N/A[2]
Wool	160	320	2
Nylon	38	100	64
PU Foam (Flexible)	27	81	N/A
PU Foam (Rigid)	29	84	N/A

[1] The adiabatic smoke temperature does not include heat transfer to the atrium walls or ceiling, and the ambient atrium temperature is 23°C (73°F).
[2] N/A indicates that the temperature is insufficient to cause incapacitation.
[3] Values used for heat exposure calculations listed in Table 4.

(Figure 3) that the values of FED for post-flashover fires are less than 0.3 for all the materials evaluated with an exposure time of 30 minutes. Thus, for any of these materials except wool in a post-flashover fire, if the smoke is sufficiently diluted to meet the visibility criteria of this paper, toxicity is not a concern for exposure times less than 30 minutes.

For a K of 0.35 m^{-1}, adiabatic smoke temperatures and incapacitation times due to heat exposure are listed in Table 5. As previously stated, the adiabatic smoke temperature does not include heat transfer and is the upper limit on the smoke temperature. For all of these materials except wool, it can be seen that the incapacitation time is 25 minutes or more. Thus, for any of these materials except wool, if the smoke is sufficiently diluted to meet the visibility criteria of this paper, incapacitation due to heat exposure will not occur for exposures less than 25 minutes.

Wool is an interesting case; its apparent poor showing in the above analysis is due to a low particulate yield as much as to a relatively high toxicity. It will be shown that appropriate selection of a generic fuel can result in a system design for which a wool fire will not result in toxicity concerns.

GENERIC FUEL AND DESIGN FIRE

For a smoke management design, the system must be designed for a fire of unknown materials. In some applications, there is limited information about materials that could be involved in a fire. For commercial and residential buildings, the materials inside the building can be expected to change significantly over the life of the building. Further, most buildings are subjected to short-term fuel loads, especially during delivery of materials and building modernization. For these reasons, there is a need for generic fuels for design analysis.

A generic fuel should be part of the design fire. For traditional smoke management applications, the design fire only consists of the heat release rate (HRR). The HRR can be steady or unsteady, as discussed in many publications about smoke management. A generic fuel is one that consists of a number of specific materials that are common to buildings, and different generic fuels may be needed for different applications. The lethal exposure dose, particulate yield, and heat of combustion of the generic fuel are the weighted averages of those of its components. This can be expressed as

$$
\begin{aligned}
LC\tau_{50,\,G} &= \sum_{i=1}^{n} f_i LC\tau_{50,\,i} \\
y_{p,\,G} &= \sum_{i=1}^{n} f_i y_{p,i} \\
\Delta H_{ch,\,G} &= \sum_{i=1}^{n} f_i \Delta H_{ch,\,i}
\end{aligned}
\qquad (22)
$$

where

G = subscript referring to properties of the generic fuel,
f_i = fraction of component i of the generic fuel,
n = number of component materials in the generic fuel.

Table 6 is an example of a generic fuel made of five components. The generic fuel approach considers that all of

TABLE 6

Description of a Generic Fuel

Material	Fraction	Flaming $LC\tau_{50}$ ($\mathrm{g\ m^{-3}\ min}$)	Particulate Yield y_p	Chemical Heat of Combustion ΔH_{ch} (kJ/kg)
Cellulosics	0.5	3120	0.015	13,300
PVC	0.1	300	0.098	7,700
Nylon	0.1	920	0.075	27,100
PU Foam (Flexible)	0.2	1390	0.188	17,600
PU Foam (Rigid)	0.1	100	0.118	16,900
Generic Fuel[1]		1970	0.074	15,300

[1] $LC\tau_{50}$, y_p, and ΔH_{ch} of the generic fuel were calculated from Equation 22.

the components burn uniformly with time over the duration of the fire. In real fires, some materials burn before others, depending on their properties, orientation, and location.

An alternative approach would be to analyze the fire as a series of different fuel packages burning in a time sequence determined by ignition of one fuel package by the radiation received from packages already burning. This fuel package approach has been mostly used for fire reconstruction involving litigation. Because of the level of detail needed for the fuel package approach, it seems that it is not justified for design analysis.

Comparison with Other Fuels

It can be useful to compare the effects of two fuels, one or both of which being generic. For smoke management systems with the same mass flows, HRRs, and convective fractions, the following relationships apply:

$$\begin{aligned} T_{s,2} &= T_{s,1} \\ \tau_{Ith,2} &= \tau_{Ith,1} \\ K_2 &= K_1 \frac{y_{p,2}\Delta H_{ch,1}}{y_{p,1}\Delta H_{ch,2}} \\ \mathrm{FED}_2 &= \mathrm{FED}_1 \frac{\Delta H_{ch,1}}{\Delta H_{ch,2}} \frac{LC\tau_{50,1}}{LC\tau_{50,2}} \end{aligned} \tag{23}$$

where the subscript 1 refers to the fuel for which design information is known and subscript 2 is the fuel for which such information is desired. Because the smoke temperatures are the same for the two cases, incapacitation due to thermal exposure would be the same for both. While the value of the convective fraction depends on the material burning and the size of the fire, a convective fraction of 0.7 is used for most smoke transport analyses. For applications where consideration of specific convective fractions of different materials is desired, Equation 23 needs to be modified.

Equation 23 can also be used to adjust the results of a design analysis based on a smoke transport simulation from the original design fuel to another. For example, if the potential fuel composition in an existing facility were to significantly change, Equation 23 could be used to adjust the original design calculations to determine whether the existing design provides adequate smoke protection with the new fuel.

Example 2

For the generic fuel listed in Table 6, calculate C, FED, and T_s for smoke from the fuel that is diluted to meet the visibility criterion of $K = 0.35\ \mathrm{m}^{-1}$. Use an exposure time of τ = 20 minutes and an ambient temperature of 23°C (73°F).

The ambient temperature is $T_a = 23 + 273 = 296$ K.

From Equations 20 and 21,

$$\mathrm{FED} = \frac{K\tau}{y_p K_m LC\tau_{50}} = \frac{.35\ \mathrm{m}^{-1}\ (20\ \mathrm{min})}{0.074(7.6\ \mathrm{m}^2/\mathrm{g})(1970\ \mathrm{g\ min/m}^3)} = 0.006$$

$$T_s = \frac{T_a}{1 - \frac{\Delta H_{ch} K R}{C_p K_m y_p P}} = \frac{296}{1 - \frac{15{,}300\ \mathrm{kJ/kg}(.35\ \mathrm{m}^{-1})(287\ \mathrm{J\ kg}^{-1}\mathrm{K}^{-1})}{1000\ \mathrm{kJ\ kg}^{-1}\mathrm{K}^{-1}(7.6\ \mathrm{m}^2/\mathrm{g})(0.074)(10^5\ \mathrm{Pa})}}$$

$$= 304\ \mathrm{K}.$$

We can see from the low value of the FED that when the smoke from this generic fuel is diluted to the visibility criterion, gas toxicity is not a concern. The smoke temperature is 304 K (31°C [88°F]). Thus, incapacitation due to thermal exposure is also not a concern when the smoke from this generic fuel is diluted to the visibility criterion.

Example 3

For a design using the generic fuel of Example 2 (Table 6), how does a 100% wool fire with the same HRR compare? (Note that it is probably impossible to make a self-sustaining 100% wool fire, but it is used here to provide insight into the earlier poor showing of wool.)

Data for wool are listed in Table 4.

Using Equation 23 with subscript 1 for the generic fuel and subscript 2 for wool,

$$T_{s,2} = T_{s,1} = 304\ \mathrm{K}$$

$\tau_{Ith,2} = \tau_{Ith,1}$ (the smoke temperature is so low this is not a concern)

$$K_2 = K_1 \frac{y_{p,2}}{y_{p,1}} \frac{\Delta H_{ch,1}}{\Delta H_{ch,2}} = 0.35\ \mathrm{m}^{-1} \frac{0.008}{0.074} \frac{15{,}300}{19{,}500} = 0.03\ \mathrm{m}^{-1}$$

$$\mathrm{FED}_2 = \mathrm{FED}_1 \frac{\Delta H_{ch,1}}{\Delta H_{ch,2}} \frac{LC\tau_{50,1}}{LC\tau_{50,2}} = 0.006 \frac{15{,}300}{19{,}500} \frac{1970}{920} = 0.010$$

This shows that a design that provides tenability for the generic fuel would also protect against a wool fire. This should not be surprising, as the particulate yield of the generic fuel is much greater than that of wool. In general, it is anticipated that generic fuels selected for designs would have a relatively high proportion of polymers and high particulate yields. For the above generic fuels with a high particulate yield, the above examples show that analysis of the effects of exposure to toxic gases can be greatly simplified.

Generic Fuel Design Approach

Design of tenability systems for atrium smoke management requires design criteria and safety factors, but tenability design is so new that no consensus exists concerning criteria and safety factors. As a convenience to the readers, some suggested criteria and safety factors are listed in Table 7. The following is an outline of the generic fuel design approach.

1. Determine the materials and the fractions of each that make up the generic fuel. For example, see Table 6.
2. Calculate $LC\tau_{50,G}$, $y_{p,G}$ and $\Delta H_{ch,G}$ from Equation 22.
3. Using values from Step 2, calculate the FED and T_s from Equations 20 and 21 where the value of K is such that when

TABLE 7
Suggested Tenability Criteria for Atrium Smoke Management Design

Toxic Gas Exposure[1]	$FED \cdot SF_{FED}$ less than 0.5 for an exposure time from an evacuation analysis
Thermal Exposure	$\tau_{Ih} \cdot SF_{Ih}$ equals exposure time from an evacuation analysis
Visibility	$K \cdot SF_K$ less than 0.35 m^{-1}
Safety Factor[2], SF_{FED}	2 to 4
Safety Factor[2], SF_{Ih}	1.5 to 3
Safety Factor[2], SF_K	1.5 to 3

[1] For applications where the gas production of the design fire is known, an alternate criterion for gas exposure is $F_{IN} \cdot SF_{FIN}$ less than 1.0.

[2] The safety factor depends on both the level of confidence of the smoke transport analysis and the extent to which the smoke transport analysis predicts conservative values of the variable of interest.

multiplied by safety factor, SF_K, it equals the design criterion for visibility.

4. If the FED multiplied by a safety factor, SF_{FED}, is less than 0.5, then toxicity is not a concern for this generic fuel, provided that the visibility criterion is met by the final design.
5. Calculate τ_{Ih} from Equation 6 using the smoke temperature from Step 3.
6. If τ_{Ih} multiplied by a safety factor, SF_{Ih}, is greater then the evacuation time (decision time plus people movement time), then smoke temperature is not a concern for this generic fuel provided that the visibility criterion is met by the final design.
7. Design calculations are made, including a smoke transport analysis evaluating visibility.
8. Calculations of gas toxicity and incapacitation due to thermal exposure may be eliminated if indicated by Steps 4 and 6.

SUMMARY

1. An atrium system where occupants are intended to be exposed to smoke requires that the smoke be such that tenable conditions are maintained during evacuation of the occupants. A tenability analysis for the smoke management system of such an atrium needs to account for the effects of exposure to toxic gases, exposure to elevated temperatures, and smoke obscuration.
2. The following time-integrated approaches used to account for the effects of exposure to combustion gases were discussed in detail: (1) the fractional effective dose (FED) based on direct extrapolation of animal test data and (2) the fractional incapacitating dose (FIN) due to exposure to specific gases.
3. Based on experimental data for visibility, including the effects of eye irritation, an extinction coefficient of 0.35 m^{-1} was used as the visibility criterion for this paper. This criterion should minimize the effects of eye irritation and let a person with average eyesight see walls, floors, doors, and balcony railings about 9 m (30 ft) away.
4. The relationships between visibility and the particulate production of a fire are described in detail. A simple method of tenability analysis for atrium filling was developed and used to demonstrate tenability calculations.
5. Equations are developed to evaluate the FED and smoke temperature for smoke from a fuel that has been diluted to meet a visibility criterion. Several common materials found in buildings were evaluated.
6. It was shown that dilution of the smoke from such materials to meet the visibility criterion often results in such low concentrations of combustion products that exposure to toxic gases is not a concern during expected evacuation times. Further, such dilution often results in such low temperatures that thermal exposure is not a problem.
7. The concept of a generic fuel consisting of a number of component fuels was developed. Before a design analysis is made, the generic fuel can be evaluated for toxicity and thermal exposure. By appropriate selection of a generic fuel, dilution of its combus ion products to meet a visibility criterion can ensure that smoke toxicity and thermal exposure are not a concern. This means that for such a fuel, a design analysis including smoke transport calculations showing hat the visibility criterion is met is sufficient to show that all gas toxicity and thermal exposure criteria are also met.
8. A method of comparing the tenability of smoke from different fuels on the same design was developed. This method can be used to compare fuels in the absence of a specific design, or it can be used see how a specific design would perform with a fire of materials that differ from those of the design.
9. The idea of tenability systems for smoke management is new, and there are many aspects of tenability design that need further development, including formulating generic fuels for common applications and improving the recommendations for design criteria and safety factors.

NOMENCLATURE

C = concentration (ppm or g m^{-3})

$C\tau$ = integrated concentration time product (g m^{-3} min)

C_{CO} = concentration of CO (ppm)

C_{CO2} = concentration of CO_2 (percent)

C_{HCN} = concentration of HCN (ppm)

C_i = concentration for time interval i ($g\ m^{-3}$)

C_{O2} = concentration of O_2 (percent)

C_p = specific heat of smoke ($1000\ J\ kg^{-1}\ K^{-1}$)

E = effect of exposure (ppm-min)

FED = fractional effective dose (dimensionless)

f_i = fraction of component i of the generic fuel (dimensionless)

$F_{ICN,i}$ = fraction of an incapacitating dose of HCN per unit time (min^{-1})

$F_{ICO,i}$ = fraction of an incapacitating dose of CO per unit time (min^{-1})

$F_{ICO2,i}$ = fraction of an incapacitating dose of CO_2 per unit time (min^{-1})

F_{IN} = fraction of an incapacitating dose of all narcotic gases (dimensionless)

$F_{IO,i}$ = fraction of an incapacitating dose of low-oxygen hypoxia per unit time (min^{-1})

K = extinction coefficient (m^{-1})

K_m = specific extinction coefficient (for a flaming fire, $K_m = 7.6\ m^2/g$)

$LC\tau_{50}$ = lethal exposure dose from animal test data ($g\ m^{-3}$ min)

M_f = mass of fuel consumed (g)

m_p = mass concentration of particulate (g/m^3)

M_p = mass of particulates produced (g)

M_s = mass of smoke (kg)

n = number of components of a generic fuel or of discrete concentration time pairs

P = absolute pressure (usually about 105 Pa)

Q = heat released (J)

$\dot{Q}$ = total heat release rate (kW)

R = gas constant ($287\ J\ kg^{-1}\ K^{-1}$)

S = visibility (m)

SF_{FED} = safety factor for the FED

SF_{Ih} = safety factor for the thermal exposure

SF_K = safety factor for extinction coefficient

τ = time from ignition (s)

T = temperature of air (°C)

T_a = absolute temperature of ambient (K)

T_r = transmittance (dimensionless)

T_s = absolute temperature of smoke (K)

$V_{CO2,i}$ = factor for CO_2-induced hyperventilation (min^{-1})

V_s = volume occupied by the smoke (m^3)

x = path length or distance of light travel (m)

y_p = particulates yield (dimensionless)

Y_p = particulates yield per unit heat release ($g\ s^{-1}\ MW^{-1}$)

$\Delta\tau_i$ = time interval i (min)

ΔH_{ch} = chemical heat of combustion (kJ/kg)

τ = exposure time (min)

τ_{Ih} = time to incapacitation (min)

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