Design Fires for Fire Safety Engineering: A State-of-the-Art Review

by

Alex Bwalya, Mohamed Sultan and Noureddine Bénichou

ABSTRACT

In line with the worldwide trend of moving towards performance-based codes, Canada and many other countries are planning to introduce performance/objective-based codes in the near future. A performance-based approach allows for flexibility in design that may lead to improved cost-effectiveness. The success of these code systems will depend, to a large extent, on the ability of the available computational tools, most of which rely on suitably-defined design fires, to adequately predict the impact of fires on buildings and their occupants. It has always been recognized that the specification of design fires, derived from appropriate design fire scenarios, is a possible source of uncertainty in conducting any fire safety engineering assessment. This uncertainty stems from the difficulty in accurately calculating the combustion process (heat release rate, production of smoke and other gaseous species) based on the type, quantity, and arrangement of combustibles, as well as the point of ignition and subsequent fire spread to adjacent combustibles.

This literature review was carried out to determine the range of methods used to characterize design fires. The methods currently available were found to be largely empirical in nature and fairly unsophisticated. The two main quantities used to describe design fires were found to be the heat release rate (pre-flashover scenario) and temperature-time profiles (post-flashover). The most widely-used pre-flashover design fires are t^2 fires, whereas a host of empirical correlations are available for post-flashover design fires.

1 INTRODUCTION

The use of analytic tools, particularly computer models, to address fire safety requirements is set to increase with the imminent introduction of performance and objective-based building codes in many countries around the world. Much has been published over the last several years regarding the benefits in cost, quality, design flexibility and fire safety that can be realised through the use of performance and objective-based code systems. The success of these code systems will depend, to a large extent, on the ability of the available tools to adequately predict the impact of fires on buildings and their occupants. Many computational tools (computer models) are now available, ranging from simplified two-zone and single-zone models to sophisticated computational fluid dynamics (CFD) models. A comprehensive web-based database of computer models for fire and smoke is provided by Combustion Science and Engineering Inc [1] and a recent survey has been published by Olenick and Carpenter [2].

An important step in most fire safety evaluations, be they experimental or computational, is the selection of a suitable simulation fire, "the design fire", for the compartment under consideration [3]. In fact, in the case of computer models without a 'built-in' combustion model, the accuracy of the results of the simulation is strongly influenced by the specified design fire.

There is presently a concerted international effort, coordinated by the International Organization for Standardization (ISO), Technical Committee (TC) 92, Sub-Committee (SC) 4, towards the development of technical guidelines for design fires with a view to standardization. As a result of this effort, a series of technical reports [4 - 7] have been published, of which ISO Technical Report (TR) 13387-2 [5] focuses on design fire scenarios and design fires. The Society of Fire Protection Engineers (SFPE) has also made a significant contribution to the emerging pool of information on design fires by dedicating a chapter in one of their engineering guides [8] to a discussion of design fire scenarios. In addition, the SFPE currently have a Task Group on Design Basis Fires (synonymous with design fires) that is developing an engineering guide on quantifying design basis fires. Further information can be obtained from the SFPE's website [9].

A review of the ISO technical reports [4 - 6] and the SFPE engineering guide [8] is a prerequisite step for anyone undertaking the task of prescribing a design fire. It is recommended to perform a thorough fire scenario analysis prior to characterizing a design fire. ISO/TR 13387-1:1999(E) [5] and the SFPE engineering guide [8] contain comprehensive lists of items to consider in identifying design fire scenarios, such as: type of fire, location of fire, potential fire hazards, systems impacting on the fire and probability of occurrence.

Alex Bwalya, Noureddine Benichou and Mohamed Sultan are, respectively, research associate, research officer and senior research officer at the National Research Council of Canada (NRC), Institute for Research in Construction, Fire Risk Management program, Ottawa K1A 0R6, Ontario, Canada.

Recognizing the importance of design fires in fire safety engineering analysis, the objective of this literature review was to determine the state of deterministic computational technology in the subject of design fires. The literature review did not include initial steps that are usually undertaken in a fire safety evaluation before specifying design fires, such as establishing fire safety objectives, and tools and methods used to identify possible fire scenarios. A summary of the fire safety engineering assessment process outlined in ISO/TR 13387-1 [4], which the authors believe best illustrates where design fires fit in the process, is as follows:

1. Qualitative review: This stage deals with: a) definition of fire safety objectives and acceptance criteria, b) establishment of prescribed design parameters by reviewing the architectural design and the proposed fire safety features, c) characterization of the building and its occupants, d) identification of potential fire hazards and their possible consequences, c) selection of fire scenarios which should form part of the quantitative analysis, e) establishment of trial fire safety solutions, and f) indication of appropriate methods of analysis.
2. Quantitative analysis: At this stage, a temporal quantitative analysis is carried out using appropriate subsystems. Design fires and mathematical models are examples of subsystems.
3. Assessment of outcome of analysis against safety criteria: The process is repeated if the acceptance criteria are not satisfied.
4. Reporting and presentation of acceptable results.

Interested readers are referred to appropriate documents in the literature, such as the SFPE engineering guide [8] and ISO/TR 13387-1 and 2 [4; 5], for further information on steps 1, 3 and 4, and the impact they may have on the choice of design fires.

Another area that this literature review does not cover is that of design fires for extreme events such as blasts. These are clearly unusual situations that cannot be reasonably expected to occur in the vast majority of residential, public and commercial buildings without inherent explosive hazards. The focus here is on fires, which normally begin with a single burning item, in a room, before involving other items.

2 DESIGN FIRES

The definitions of terms commonly used in the discussion of design fires are given in Table 1.

Table 1. Terminology related to design fires

Term	**Definition by Source Reference**	
	ISO/TR-13387-2 [5]	**SFPE engineering guide [8]**
Design fire **Design fire curve**	<u>Design fire:</u> A quantitative temporal description of assumed fire characteristics based on appropriate fire scenarios. Variables used in the description include: heat release rate, fire size (including flame length), yield of products of combustion, temperatures of hot gases, and time to key events such as flashover.	<u>Design fire curve:</u> An engineering description of a fire in terms of heat release rate versus time (or in other terms elaborated in the stated reference) for use in a design fire scenario.
Design fire scenario	A specific fire scenario on which and analysis will be conducted. It includes a description of the impact on the fire of building features, occupants, fire safety systems and would typically define the ignition source and process, the growth of the fire on the first item ignited, the spread of the fire, the interaction of the fire with the building occupants and the interaction with the features and fire safety systems within the building.	A set of conditions that defines or describes the critical factors determining the outcomes of trial designs.
Fire scenario	A qualitative description of the course of a specific fire with time, identifying key events that characterize the fire and differentiate it from other possible fires.	A set of conditions that defines the development of fire and the spread of combustion products throughout a building or part of a building. The process of developing a fire scenario is a combination of hazard analysis and risk analysis. Further information can be found in NFPA 72 [10]

Another interesting definition of design fires given by one author [11] is that they are fires that can be built and instrumented in a test facility; that they should produce consistent results from one test to the next in the same facility and in other facilities, and they should show a consistency that can be described and used in fire modelling. This illustrates that some people perceive design fires differently and, perhaps, there is a need to have a common definition.

The course of a fire is generally described by the growth period, peak heat release rate, steady-state burning period, and decay period [12]. The heat release rate as a function of time is an important quantity that controls the main characteristics of the fire, such as flame height, hot gas temperatures, and the rate of descent of the hot gas layer [13].

There are three distinct combustion regimes of enclosure fires that are important in any fire safety evaluation: the pre-flashover regime, the flashover stage, and the post-flashover regime. Flashover is a perilous stage in the course of a fire during which exposed surfaces of most of the combustibles within the compartment suddenly ignite and the fire is no longer restricted to the first item ignited. At this stage, the heat release rate, temperature, smoke production and smoke toxicity increase rapidly [8], usually until a stage is reached at which there is not enough oxygen reaching the fire to support a further increase in the heat release rate and the fire enters the ventilation-controlled regime. The occurrence of flashover is generally believed to be promoted by hot-gas temperatures of between 500°C and 600°C, and heat flux levels of about 15 to 20 kW/m^2 at the floor level of the compartment [13]. Life safety of the occupants takes precedence during pre-flashover, whereas the structural integrity of the building and the safety of fire rescue personnel are the major concerns during the later post-flashover stage. Simple correlations are available in the literature [14 - 16], which can be used to determine the likelihood of flashover and whether or not a fire will be ventilation-controlled or fuel-controlled, based on the knowledge of the heat release rate, size of the room, thermal properties of the materials forming the compartment boundaries, and the size and number of ventilation openings.

The process of determining a design fire usually begins with the establishment of the objectives of the fire safety engineering tasks [5], which could be, for example, to evaluate the smoke management systems or smoke detector response, provide life safety or protect property. The design fire required for each of these objectives could be different. Once the objectives are established an appropriate fire load is selected and the nature of the combustibles likely to be involved in the fire is identified. The fire load is an important variable required to estimate the duration of a fire. It is an indication of the quantity of combustibles in an enclosure or the energy that can be liberated upon complete combustion. However, it must be borne in mind that fire load information on its own is insufficient to determine the shape of the heat release rate curve during the pre-flashover stage; the combustibles present must be specified and experimental data must also be used, if available. The heat release rate is affected by the following parameters: a) strength and location of the ignition source; b) type, amount, position, spacing, orientation, and surface area of the fuel packages (fire load); c) size and geometry of the enclosure; d) size and location of the compartment openings; and e) thermal inertia of the materials constituting the enclosure boundaries.

The fire load is commonly expressed as either the mass of combustibles (assuming solid combustibles) per unit floor area (kg/m^2) or the total heat energy content per unit internal surface area (MJ/m^2) or floor area (also commonly referred to as the “fire load energy density”), and it largely depends on the occupancy. It is recommended that both fixed and moveable fire loads (including transient fire loads) should be taken into consideration [17], and that if data from representative surveys is available, the 90 percentile value should be selected [18]. Transient fire loads are items that are in a space temporarily, for example, Christmas decorations [17]. Klote [17] suggested a method of accounting for transient fuels in which a fixed heat release rate density or heat release rate is assigned to these fuels. A great quantity of fire load data has been published over the last two decades, but due to regional differences in lifestyles and the subjective manner in which fire loads are quantified; there are large variations in values. Bwalya et al. [19] presented a survey of fire load data for residential occupancies found in the literature.

2.1 Pre-Flashover Fires

The heat release rate and quantity of smoke and combustion gases, such as carbon dioxide (CO_2) and carbon monoxide (CO), produced are considered to be the most important attributes of pre-flashover fires. During the growth stage, the heat release rate is commonly approximated by power law correlations of the form:

$$\dot{Q} = \alpha \, t^p \qquad (1)$$

where:

$\dot{Q}$ = Rate of heat release (kW)
p = Positive exponent

t = Time after effective ignition (s)
α = fire growth coefficient (kW/s^2)

The exponent is usually given a value of 2 and the resulting curves are popularly known as t^2 fires - the heat release rate varies proportionally to time squared and hence the name. The growth coefficient is sometimes determined using experimental data. Hoglander and Sundstrom [20] discussed such a t^2 expression.

The maximum heat release rate is the value at which any one of the following events occurs: a) the fire becomes ventilation-controlled and combustion proceeds at a steady-state rate; b) a fire suppression system activates; c) the decay phase begins (in a fuel-controlled fire). Fires involving multiple combustibles, which become involved in the fire at different times, may exhibit different behaviour. The t^2 fires, which were made popular by the NFPA [21], are given by:

$$\dot{Q} = \dot{Q}_o \left(\frac{t}{t_o} \right)^2 \tag{2}$$

where:

$\dot{Q}_o$ = Reference heat release rate (kW), usually taken to be 1055 kW

t_o = Growth time (s)

The recommended categories of fire growth are illustrated graphically in Figure 1.

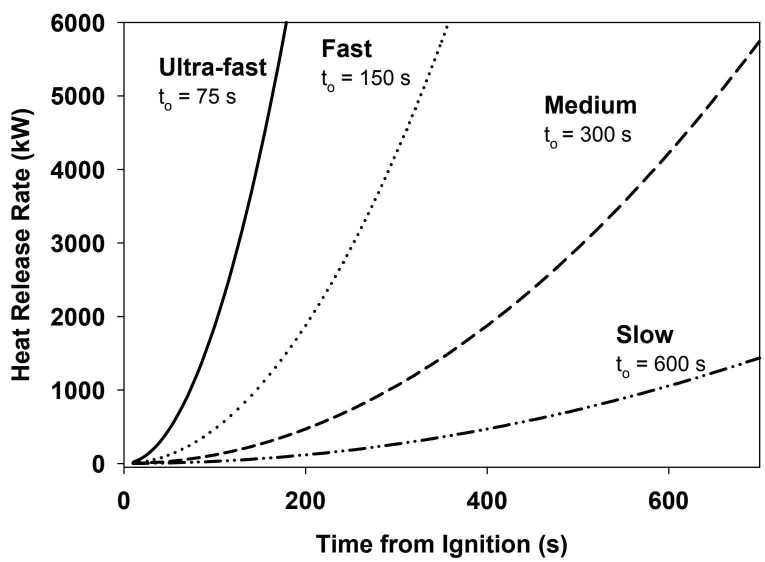

Figure 1. Rates of Energy Release of t^2 Fires

Barnett [22] suggested that the decay phase of a fire can also be represented by a t^2 curve with appropriate decay constants. He presented conceptual design fires with fuel-controlled growth and decay phases conforming to t^2 profiles to represent ventilation-controlled fires, which proceed to burn at a steady state after attaining the peak heat release rate, and fires, which never reach the steady-state ventilation-controlled regime.

t^2 fires, notwithstanding their widespread use, have been criticized by some authors [3; 23; 24], partly on account of the simple assumptions made in their derivation, which are deemed to be unrealistic, and also because, in one author's opinion [23], no engineering methods lend credence to their application. To the contrary, some fire researchers [25] have reported that t^2 fires matched their test data. Schifiliti [26] analyzed data collected from 40 fire tests [27; 28] conducted in a furniture calorimeter at the National Bureau of Standards (now the National Institute for Standards and Testing (NIST)) and found that t^2 fires modeled various stages of the growth period reasonably well when the growth constants were derived from the experimental data. The NFPA [21] outline the assumptions upon which the t^2 fires are based and argue that the approximation is sufficient for reasonable decisions to be made about fire safety.

Hoglander and Sundstrom [20] gave examples of design fires for multiple upholstered furniture items created by adding up their individual characteristic heat release rate curves. The heat release rate of each item was calculated using an empirical correlation, which was developed using data from well-ventilated full-scale (open burning) fire tests involving upholstered furniture. They acknowledged that there was a lack of data from complete room fires, and that it was difficult to prescribe design fires because of the extremely large combination of combustibles involved. Based on European statistics, which revealed that the greatest number of fatalities resulted from fires involving upholstered furniture, they suggested that the influence of such furniture should be included in a design fire if it will be present in the occupancy under consideration—a view shared by many workers engaged in fire research.

Hertzberg et al. [24] presented a concept that was intended to produce more realistic design fires. The method used heat release data from well-ventilated full-scale and bench-scale tests, in conjunction with a mathematical model, which incorporated the influence of a compartment on fire development and progression. The proposed method of incorporating heat release data from full-scale tests was similar to that suggested by Hoglander and Sundstrom [20].

The t^2 fires given by Equation (2) are typically for a single burning item. It is suggested, although not part of the NFPA [21] recommendations, to increase the size of the design fire if other combustibles are within the separation distance, R, defined by Equation (3) [21]:

$$R = \frac{1}{6.85}\left(\frac{\dot{Q}}{\pi\, \dot{q}_i''}\right)^{1/2} \qquad (3)$$

where:

R = Separation distance from target to centre of fuel package (m).

$\dot{q}_i''$ = Incident radiant heat flux required for non-piloted ignition (kW/m^2).

There was no clear guidance given on exactly how the size of the design fire should be increased.

2.1.1 Computer Tools

Two software modules, MAKEFIRE and FREEBURN, are available from NIST [29], which are able to generate heat release rate histories for design fires. These modules are incorporated into a fire simulation program called FPEtool. MAKEFIRE uses power law expressions for both the growth and decay burning phases. FREEBURN is more sophisticated than MAKEFIRE in that it calculates the cumulative heat release rate history for up to five independent fuel items based on their individual heat release and burning rate data, which is read from a file.

2.2 Post-Flashover Fires

Post-flashover fires are ventilation-controlled and produce large quantities of asphyxiating gases such as CO and hydrogen cyanide (HCN), in addition to smoke and other irritants[30]. During this stage, the design load is characterized by temperature-time profiles. The Eurocode [31] parametric equations are perhaps the most widely-used equations for estimating post-flashover temperatures. A temperature-time relationship is produced for any combination of fire load, ventilation openings and wall materials. Figure 2 shows one of Magnusson and Thelandersson's [32] sets of curves, from which the equations were derived. The sets of curves were produced for various opening factors, F_o. Buchanan [18] and Karlsson and Quintiere [13] discussed the method used by Magnusson and Thelandersson to produce the curves in greater detail.

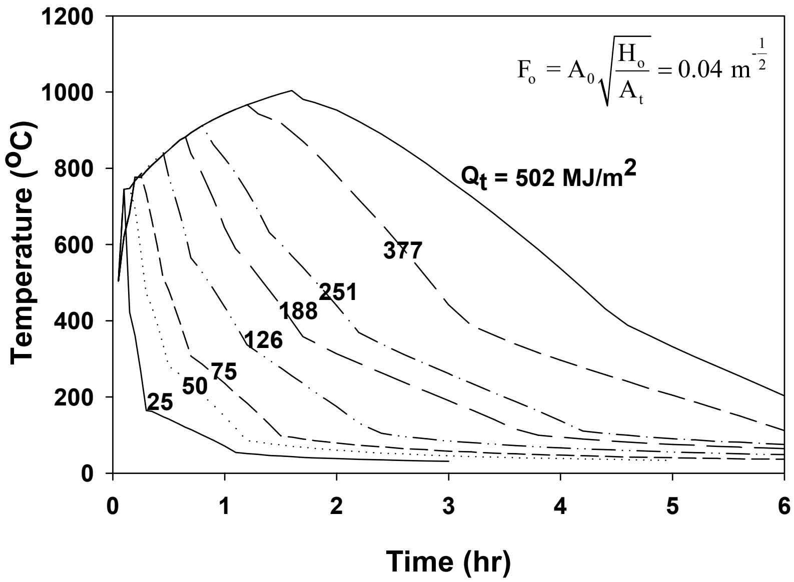

Figure 2. Time-Temperature Curves for Various Fire Loads [32]

The Eurocode method divides fire development into two phases: a heating phase (identical to the ISO 834 standard temperature-time curve [33]) and a decay phase. The equation for the heating phase is:

$$T = 1325\left(1\text{-}0.324e^{-0.2t^*}\text{-}0.204e^{-1.7t^*}\text{-}0.472e^{-19t^*}\right) \tag{4}$$

where T is the temperature and t^* is the modified time (in hours) given by:

$$t^* = t\left(\frac{(F_o/F_{ref})}{(b/b_{ref})}\right)^2 \tag{5}$$

where:

$b = \sqrt{k\rho c_p}$ ($Ws^{0.5}/m^2K$)

F_o = opening factor (-)

F_{ref} = reference value of the opening factor, taken to be 0.04

b_{ref} = reference value of $\sqrt{k\rho c_p}$, given the value of 1160 $Ws^{0.5}/m^2K$.

Figure 3 shows how the Eurocode temperature-time profiles generally compare with the ISO 834 temperature-time curve. The ISO 834 temperature curve is similar to the ASTM E119 [34] and CAN/ULC S101-M89 [35] temperature-time curves.

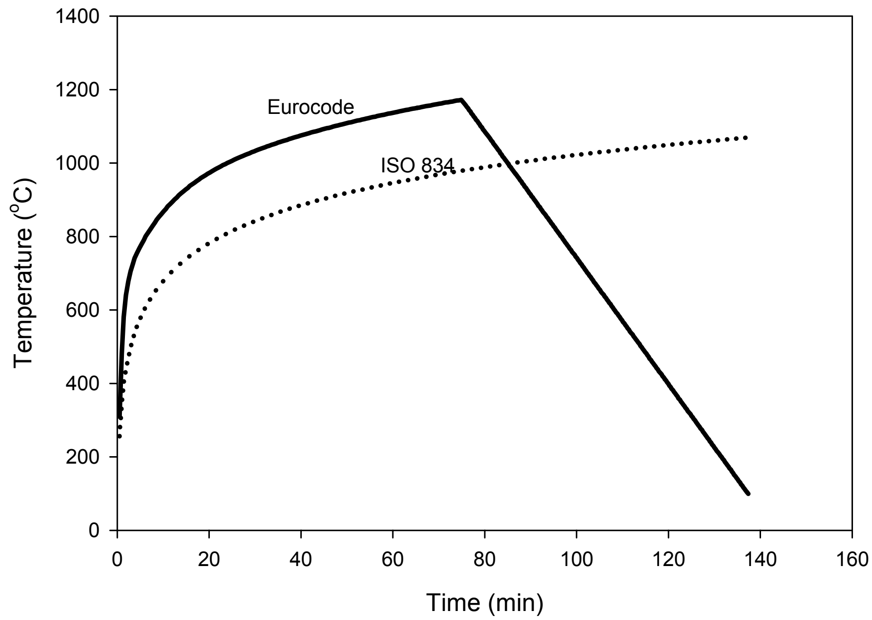

Figure 3. Comparison of the Eurocode Design Fire with the ISO 834 Temperature-Time Curve (fire load: 500 MJ/m^2; opening factor: 0.05 $m^{-\frac{1}{2}}$)

Feasey and Buchanan [36] used a simple computer model to generate a series of post-flashover design fires with the help of data from real fires and carefully defined fire loads (primarily wood cribs and real furniture) as input. Their intention was to modify the burning and decay phases of the Eurocode empirical fire curves in order to improve the estimation of temperatures in post-flashover compartment fires, which, they felt, were under-predicted, especially for ventilation-controlled fires.

Mehaffey [37] presented a simple framework for undertaking performance-based design for fire resistance in wood-frame residential and office buildings, which employed design fires based on the Eurocode equation and an empirical post-flashover model that was developed in Japan:

$$T(t) - T(0) = 3.0\, T(0) \left[\frac{F_v}{A_t \sqrt{k \rho c_p}} \right]^{1/3} t^{1/6} \tag{6}$$

where:

T = temperature of the hot gas (K)
t = time from ignition (s)

The application of the method was illustrated by using a three-storey wood-frame hotel building.

Ma and Makelainen [38] presented an empirical temperature-time curve for representing small to medium post-flashover fire temperatures based on data from various laboratories. Their equation is:

$$\frac{T_g - T_o}{T_{g,max} - T_o} = \left(\frac{t}{t_m} \exp\left(1 - \frac{t}{t_m} \right) \right)^{\delta} \tag{7}$$

where:

T_g = hot gas temperature (°C)
$T_{g,max}$ = maximum hot gas temperature (°C)
T_o = reference temperature (°C)
t_m = time at which maximum temperature occurs (min)
δ = shape constant for the curve (-)

Barnett [22] presented a technique for modelling temperatures, touted as being easy to use because only one equation represented the temperatures of both the growth and decay phases of a fire, and only three factors were required in the equation: maximum gas temperature, the time at which it occurred and a shape constant for the source. Barnett's equation is:

$$T = T_{\infty} + T_{max} e^{-\frac{(\log t - \log t_m)^2}{s_c}} \quad (8)$$

where:

s_c = shape constant for the temperature-time curve (-)
T = temperature at any given time t (^oC)
T_{∞} = ambient temperature (^oC)
T_{max}= maximum temperature generated above T_{∞} (calculated using the methods given in the SFPE handbook [14])
t = time from ignition of fire (min)
t_m = time at which T_{max} occurs (min)

The shape constant was correlated with the pyrolysis coefficient using experimental data.

Equation (8) was developed using data from 142 fire tests from various sources, the majority of which were conducted with wood cribs. The fuel masses ranged from 3 to 5100 kg and the temperatures measured ranged from 500^{o}C to 1200^{o}C. The growth rates ranged from ultra-slow to ultra-fast, in accordance with the NFPA [21] categories of fire growth.

3 HEAT RELEASE RATES

Given the importance of the heat release rate in quantifying a design fire, heat release rate data for a wide range of combustible items are some of the most sought-after combustion data. The invention of the furniture calorimeter [27] and the ISO 5660 cone calorimeter [39] in the early 1980s led to an increase in the amount of published heat release data for many combustible items, especially upholstered furniture. Some sources of data on heat release rates and other combustion data, such as CO and CO_2 production rates, are [40 - 43]. Compilations of heat release rate and combustion species production rate data can also be obtain from fire research organizations such as the Building Research Establishment Ltd [44] and NIST [29]. It is important to note that almost all of these data were obtained from fire tests performed under well-ventilated conditions. There is a school of thought that such fire tests may not represent realistic models for the development of life hazards from many fires occurring in multi-compartment buildings [45].

The heat release rate is affected by many factors such as: ventilation, fire load, location of fire load with respect to the walls, and ignition method. Furniture construction details and materials are known to substantially influence the peak heat release rate, such that heat release rate data are not available for all combustible items or for "generic" combustible items [21].

The concept of heat release density (kW/m^2), which is the heat release rate of a fire divided by the base area of the fuel package, is important in estimating the peak heat release rate of similar fuel packages occupying different base areas. Gemeny and Wittasek [46] gave an example of the use of heat release densities obtained from Cone Calorimeter [39] tests to estimate the peak heat release rate of a large item, which was then used to specify a design fire. Gemeny and Wittasek also gave another example of a design fire produced by a summation of the individual heat release histories of component combustible assemblies. This design fire was used as input to deterministic models to predict smoke filling and to calculate smoke exhaust requirements for an atrium lobby.

The prediction of heat release rates from information obtained from the burning characteristics of individual items obtained in small-scale tests such as the Cone Calorimeter, has been of interest ever since it was first attempted by Babrauskas and Krasny [47]. However, many efforts have so far been met with limited success mainly because of the difficulty of scaling complex phenomena from small-scale to full-scale items [18].

The European Commission-sponsored project, Combustion Behaviour of Upholstered Furniture (CBUF) [43] produced one of the largest collections of combustion data for upholstered furniture. In the CBUF project, the furniture calorimeter was used for testing full-scale furniture items, while the cone calorimeter was used for small scale testing of furniture components. Three different numerical models were developed for predicting heat release rates for full-scale furniture using cone calorimeter data. Equations to predict the peak heat release rate, time to reach untenable conditions, total energy released and smoke production rates were developed after an extensive statistical analysis of the database. Babrauskas et al. [48] presented a detailed discussion of the three models developed in the CBUF work. Much work [49; 50] has been carried out in New Zealand to determine the applicability of the heat release rate prediction methods developed in the CBUF work. It was found that the correlations were not as accurate for upholstered furniture used in New Zealand, which exhibited higher peak heat release rates.

Heat release rate data for electronic equipment and appliances, such as television sets, computer monitors and inkjet printers can be obtained from the National Association of State Fire Marshals' website [51].

4 DISCUSSION AND CONCLUSION

The ISO publications, ISO/TR 13387-1 and 2 [4; 5] provide an excellent overview of the general principles that should be followed when undertaking the task of creating design fires. However, apart from the t^2 pre-flashover design fire, the publications do not yet provide any other quantitative methods for pre-flashover and post-flashover fires.

The term "design fire" is used variously to refer to just about any fire characteristic perceived to give a measure of the fire environment, such that even a mere statement of the average heat release rate over the expected duration of a fire, for example, is a design fire. In the absence of widely accepted standards, the amount and accuracy of the quantitative information provided about a design fire is decided somewhat subjectively.

At present, the calculation schemes available are largely empirical in nature and unsophisticated insofar as using methods founded on rigorous fire science principles is concerned. This is one source of uncertainty when such methods are used to generate input data for fire models.

The two main quantities used to describe design fires are usually the heat release rate (pre-flashover scenario) and temperature-time profiles (post-flashover scenario). The most widely-used pre-flashover design fires are t^2 fires, whereas a host of empirical correlations are available for calculating temperatures in the post-flashover stage. Although tenability is the main concern during the earlier stages of a fire, there were no simple methods found that could be used to quantify design fires in terms of the concentration of asphyxiating gases with time.

The heat release rate is regarded to be the most important quantity that describes a design fire. Heat release rate data for many combustibles is available from the various sources cited earlier. However, it is impractical to present all the results in a single forum in a neat and organized fashion due to the extremely large variations in the physical characteristics of real combustibles.

5 FUTURE WORK

Fires involving real combustibles are inherently difficult to model accurately using current methods partly due to the complexity of fire dynamics, and also because the combustibles are not homogeneous in material composition and other physical aspects. A research project is being contemplated to study fires in simulated rooms, using suitably selected fuel packages, with a view to developing well-founded design fires for various occupancies. The initial focus will be on residential occupancies and the fire loads to be used in the study would be based on data collected from a Canadian fire load survey that is currently being undertaken for by the authors.

6 NOMENCLATURE

A_o	Area of a ventilation opening	(m^2)
A_t	Total internal area of bounding surfaces of an enclosure	(m^2)
b	A parameter in Equation (5), = $\sqrt{k\rho c_p}$	$(W.s^{0.5}/m^2K)$
b_{ref}	Reference value of b	$(W.s^{0.5}/m^2K)$
c_p	Specific heat capacity	(kJ/kg.K)
H_o	Height of ventilation opening	(m)
F_o	Opening factor = $\frac{A_o\sqrt{H_o}}{A_t}$	$(m^{1/2})$
F_{ref}	Reference value of the opening factor	$(m^{1/2})$
F_v	Ventilation factor = $A_o\sqrt{H_o}$	$(m^{5/2})$
k	Thermal conductivity	(kW/m.K)
$\dot{Q}$	Heat release rate	(kW)
$\dot{Q}_o$	Reference heat release rate	(kW)

Q_t	Total fire load energy density	(MJ/m^2)
$\dot{q}_i''$	Incident radiation heat flux	(MW/m^2)
R	Radial distance	(m)
s_c	Shape constant used in Equation (8)	(-)
T	Temperature	(^oC)
t	Time	(s)
t_b	Duration of burning	(s)
t_o	Time to reach a reference heat release rate	(s)
t_m	Time at which maximum temperature occurs	(min)
t^*	Fictitious time used in Equation (4)	(hrs)

GREEK LETTERS

α	Growth or decay constant for a t-squared fire	(kW/s^2)
δ	Shape constant	(-)
ρ	Density	(kg/m^3)

SUBSCRIPTS

g	Pertains to hot gas
max	Maximum value
∞	Ambient condition

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