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AN OVERVIEW OF DESIGN FIRES FOR BUILDING COMPARTMENTS

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ABSTRACT

The worldwide trend of moving towards performance-based codes has brought about a need for computational tools, most of which rely on suitably-defined design fires, to adequately predict the impact of fires on buildings and their occupants.

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 unsophisticated. The two main quantities used to describe design fires are 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.

Keywords: design fires, heat release rate, t squared fire, pre-flashover, post-flashover

INTRODUCTION

Many countries around the world favour the adoption of performance-based building codes due to the well-publicized benefits in fire safety, design flexibility, cost, and quality that can be achieved. A performance-based approach to fire safety evaluation and design of buildings is an elaborate process consisting of many steps and requires the use of decision-making tools based on analytical and computational methods. The selection of a suitable fire of assumed characteristics, which is referred to as the “design fire”, is one of the most important steps in this process [1]. A design fire is generally considered to be a quantitative description of the main time-varying properties of a fire based on reasonable assumptions about the type and quantity of combustibles, ignition method, growth of the fire and its spread from the first item ignited to subsequent items, and the decay and extinction of the fire [2]. The main time-varying properties that define a fire are the heat release rate (HRR), fire effluent (smoke and combustion gases, such

as carbon dioxide (CO₂), carbon monoxide (CO), and hydrogen cyanide (HCN)), and temperature. The definition of terms commonly used in the discussion of design fires is given in Table 1.

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 [2 - 5] have been published, one of which [2] 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 devoting a chapter in one of their engineering guides [6] to a discussion of design fire scenarios. In addition, the SFPE currently have a Task Group that is developing an engineering guide on “design basis fires” (synonymous with design fires).

This paper reviews some of the literature on design fires and related topics with a view to establishing the current state of fire technology in this area. The scope of the review did not include the initial steps that are usually undertaken early in the fire safety assessment process before a design fire is specified, such as establishing fire safety objectives, and tools and methods used to identify possible fire scenarios. Another area that this paper does not cover is that of design fires for extreme events such as blasts. These clearly unusual situations cannot reasonably be 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 item burning in a room.

THE FIRE SAFETY ASSESSMENT PROCESS

A summary of the fire safety engineering assessment process outlined in ISO/TR 13387-1 [3], which 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, e) selection of fire scenarios which should form part of the quantitative analysis, f) establishment of trial fire safety solutions, and g) 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 [6] and ISO/TR 13387-1 and 2 [2, 3], for further information on steps 1, 3 and 4, and the impact they may have on the choice of design fires.

REGIMES OF FIRE DEVELOPMENT

The different stages of fire development in a compartment have been studied intensely for many years and excellent treatises can be found in the widely available literature [7 - 10]. Following ignition, the course of a fire is generally described by the growth or pre-flashover period, whether flashover occurs or not, time to reach a peak HRR, fully-developed or post-flashover period, and decay period [11]. Figure 1 depicts the stages of fire development, from ignition to extinction, without the intervention of an active suppression system [2].

Figure 1. Stages of Fire Development in a Room in the Absence of an Active Suppression System

The growth period includes an incipient phase, the duration of which is dependent upon the strength and location of the source of ignition, ventilation conditions and the thermal properties of the combustible materials. In addition to these factors, fire development in a room is also influenced by the amount, type, position, spacing, orientation, and surface area of the fuel package, and the thermal inertia of the materials constituting the boundaries of the room [8].

Many studies have observed that the burning rate of fuel elements depends on the rate of flow of outside air into the enclosure. The flow of air through ventilation openings, such as windows and doors, into a room has been shown to be proportional to the ventilation factor, F_v ($\text{m}^{5/2}$), which is given by:

$$F_v = A_o \sqrt{H_o} \quad (1)$$

Where A_o is the area of the opening and H_o is the height of the opening. The dependence of the rate of burning on F_v is often expressed in terms of an opening factor, F_o ($\text{m}^{1/2}$), given by:

$$F_o = \frac{F_v}{A_t} \quad (2)$$

Where A_t (m^2) is the total internal surface area of the enclosing surfaces. For a room containing more than one opening, A_o and H_o in Equation (1) are taken to be weighted averages [8]. F_v and F_o are used in many empirical fire correlations.

The maximum HRR 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 a different behaviour.

Flashover Stage

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 HRR, temperature, smoke production and smoke toxicity increase rapidly, until a further increase is restricted by the rate at which air flows through the available room openings [6]. 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/m² at the floor level of the compartment [8]. Simple correlations and more elaborate expressions are available in the literature [10, 12 - 14], 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 HRR, size of the room, thermal properties of the materials forming the boundaries of the room, and the size and number of ventilation openings. Following flashover, fires usually progress rapidly to the fully-developed stage, where the rate of combustion is characterized by very high HRRs and temperatures under ventilation- or fuel-surface controlled conditions. Naturally, when most of the combustible materials are expended, the HRR diminishes and the decay phase ensues.

DESIGN FIRES

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.

The process of determining a design fire begins with the establishment of the objectives of the fire safety assessment task [2], which could be, for example, to evaluate a smoke management system or smoke detector response, provide life safety, protect property and prevent the spread of fire beyond the room of fire origin. The design fire required for each of these tasks could be different. After establishing the objectives, an appropriate fire load density (in MJ/m²) is selected and the nature of the combustibles likely to be involved in the fire is specified by considering the building category. The fire load is an important variable required to estimate the duration of a fire. It is an indication of the quantity of heat energy (in joules), which can be liberated by the complete combustion of all combustible materials in a room. The fire load density is the fire load per unit floor area. However, it must be borne in mind that information about the fire load density alone is insufficient to determine the shape of the HRR curve during the pre-flashover stage, as there is no correlation between the two. The HRR curve is usually determined with recourse to experimental data for similar combustibles.

Pre-Flashover Design Fires

The life safety of occupants takes precedence during pre-flashover. The HRR and quantity of fire effluent produced are the most important attributes of pre-flashover fires. During the growth stage, the HRR is commonly approximated by power law correlations of the form:

$$\dot{Q} = \alpha t^p \quad (3)$$

Where:

$$\dot{Q} = \text{HRR (kW)}$$

p = Positive exponent

t = Time after effective ignition (s)

α = Fire growth coefficient (kW/s²)

The exponent is usually given a value of 2 and the resulting curves are popularly known as t^2 fires. The growth coefficient is sometimes determined using experimental data, as demonstrated by Kim and Lilley [15].

A common form of Equation (3) has the growth coefficient, α , expressed as [16]:

$$\alpha = \frac{\dot{Q}_0}{t_0^2} \quad (4)$$

Where $\dot{Q}_0$ is the reference HRR, usually taken to be 1055 kW, and the growth time, t_0 (s), is the time to reach $\dot{Q}_0$. The recommended categories of fire growth are: ultra-fast, fast, medium, and slow. These are illustrated graphically in Figure 2. The growth constants (α and t_0) and examples of typical combustibles in each category are given in Table 2.

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

The decay phase of a fire can also be represented by a t^2 curve with appropriate decay constants [15, 17].

Notwithstanding their widespread use, t^2 fires have been criticized by some authors [1, 18, 19], 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 [18], no engineering methods lend credence to their application. To the contrary, some researchers [20] have reported that t^2 fires matched test data fairly well. The NFPA [16] 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 [21] gave examples of design fires for multiple upholstered furniture items created by adding up their individual characteristic HRR curves. The HRR of each item was calculated using an empirical correlation, which was developed using data from fully-ventilated full-scale 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 in residential buildings 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 building under consideration—a view shared by many workers engaged in fire research.

Hertzberg et al. [19] presented a concept that was intended to produce realistic design fires. The method used HRR data from fully-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 [21].

The t^2 fires given by Equation (3) are typically for a single burning item. It is suggested to increase the size of the design fire if other combustibles are within the separation distance, R , defined by Equation (5) [16]:

$$R = \frac{1}{6.85} \left(\frac{\dot{Q}}{\pi \dot{q}_i''} \right)^{1/2} \quad (5)$$

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/m²).

Computer Tools

Two software modules, MAKEFIRE and FREEBURN, are available from NIST [22], which are able to generate HRR 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 HRR history for up to five independent fuel items based on their individual heat release and burning rate data, which is read from a file.

Post-Flashover Design Fires

The structural integrity of the building and safety of fire rescue personnel are the main concerns during the later post-flashover stage of a fire. Therefore, the ability to predict the temperature history is more important during this stage.

The EUROCODE [23] parametric equations are widely-used for estimating temperatures in post-flashover fires. The equations produce a time-temperature relationship for any combination of fire load, ventilation openings, and wall lining materials. The time-temperature curves from which the equations were derived were produced by Magnusson and Thelandersson [24], and are shown in Figure 3. Buchanan [7] and Karlsson and Quintiere [8] discuss the methodology employed by Magnusson and Thelandersson to produce the curves in greater detail. The effect of ventilation on the maximum temperature and duration of burning is apparent from Figure 3, and it can be seen that fully-ventilated fires are characterized by rapid rates of burning and higher temperatures for a given fire load.

Figure 3. Time-Temperature Curves for Different Ventilation Factors and Fire Loads [24]

The EUROCODE method divides the fire development into two phases: the heating phase, which is identical to the ISO 834 standard temperature-time curve, and the decay phase. The equation for the heating phase is:

$$T = 1325 \left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \right) \quad (6)$$

Where T is the temperature and t^* is a fictitious time (in hours) given by:

$$t^* = t \left(\frac{(F_o/F_{ref})}{(b/b_{ref})} \right)^2 \quad (7)$$

Where b is $\sqrt{k\rho c_p}$ ($\text{Ws}^{0.5}/\text{m}^2\text{K}$), F_o is the opening factor given by Equation (2), F_{ref} is the reference value of the opening factor, taken to be 0.04, $k\rho c_p$ is the thermal inertia, and b_{ref} is the reference value of $\sqrt{k\rho c_p}$, given the value of 1160. Therefore, Equation (7) can be rewritten as:

$$t^* = t \left(\frac{F_o}{\sqrt{k\rho c_p}} \right)^2 \left(\frac{1160}{0.04} \right)^2 \quad (8)$$

Where t is the time (in hours).

The EUROCODE temperature-time curve in the cooling phase is given by:

$$\begin{aligned} T_g &= T_{g,\text{max}} - 625(t^* - t_d^*) & \text{for } t_d \leq 0.5 \\ T_g &= T_{g,\text{max}} - 250(3 - t_d^*)(t^* - t_d^*) & \text{for } 0.5 \leq t_d^* \leq 2.0 \\ T_g &= T_{g,\text{max}} - 250(t^* - t_d^*) & \text{for } t_d^* \geq 2.0 \end{aligned} \quad (9)$$

Where $T_{g,\text{max}}$ is the maximum temperature in the heating phase for $t^* = t_d^*$ and:

$$t_d^* = \frac{0.13 \times 10^{-3} Q_t^*}{F_o} \left(\frac{F_o}{\sqrt{k\rho c_p}} \right)^2 \left(\frac{1160}{0.04} \right)^2 \quad (10)$$

The duration of the heating phase, is given in terms of real time, by:

$$t_d = \frac{0.13 \times 10^{-3} Q_t}{F_o} \quad (11)$$

Therefore, the modified duration time can be rewritten as:

$$t_d^* = t_d \left(\frac{F_o}{\sqrt{k\rho c_p}} \right)^2 \left(\frac{1160}{0.04} \right)^2 \quad (12)$$

Mehaffey [25] presented a simple framework for undertaking a performance-based design for fire resistance in a wood-frame residential and an office building, which employed design fires based on the EUROCODE and a parametric post-flashover model developed in Japan. The model is given by Equation (13) [25]:

$$T(t) - T(0) = \beta t^{1/6} \quad (13)$$

Where:

T = temperature of the hot gas (K)

β = a constant ($Ks^{-1/6}$)

t = time from ignition (s)

For post-flashover Ventilation-controlled fires, the constant β is given by:

$$\beta = 3.0 T(0) \left[\frac{E_v}{A_t \sqrt{k \rho c_p}} \right]^{1/3} \quad (14)$$

Where:

ρ = Density of boundaries (kg/m^3)

c_p = Specific heat of boundaries ($kJ/kg.K$)

The duration of a post-flashover ventilation-controlled fire is given by:

$$t_b = \frac{M_f'' A_f}{0.1 F_v} \quad (15)$$

Where:

t_b = Duration of fire (s)

M_f'' = Fire load density (kg/m^2)

A_f = Floor area (m^2)

Mehaffey used Equation (13) to illustrate the application of the method to a three-storey wood-frame hotel.

Ma and Makelainen [26] presented a parametric temperature-time curve for representing small to medium post-flashover fire temperatures based on data from various laboratories. Their equation is:

$$\frac{T_g - T_o}{T_{g,max} - T_o} = \left(\frac{t}{t_{max}} \exp \left(1 - \frac{t}{t_{max}} \right) \right)^\delta \quad (16)$$

Where:

- T_g = Hot gas temperature ($^{\circ}\text{C}$)
 $T_{g,\max}$ = Maximum hot gas temperature ($^{\circ}\text{C}$)
 T_o = Reference temperature ($^{\circ}\text{C}$)
 $t_{\max}$ = Time at which maximum temperature occurs (min)
 δ = Shape constant for the curve.

Feasey and Buchanan [27] used a computer program, COMPF2, to generate a series of post-flashover design fires with the help of data from realistic test 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 parametric 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. They found that a b_{ref} value of 1900 gave results that are more accurate and recommended that this value be used in Equation (7).

Barnett [17] presented a technique for modelling temperatures, in which a single equation was used to represent the temperature of both the growth and decay phases of a fire, and only three factors were required: maximum gas temperature, the time at which it occurred and a shape constant for the source. Barnett's equation is:

$$T = T_{\infty} + T_{\max} e^{\frac{(\log t - \log t_m)^2}{\delta}} \quad (17)$$

Where:

- δ = Shape constant for the temperature-time curve (-)
 T = Temperature at any given time t ($^{\circ}\text{C}$)
 T_{∞} = Ambient temperature ($^{\circ}\text{C}$)
 $T_{\max}$ = Maximum temperature generated above T_{∞} (calculated using methods given in the SFPE handbook [12]) ($^{\circ}\text{C}$)
 t = time from ignition of fire (min)
 $t_{\max}$ = time at which $T_{\max}$ occurs (min)

The shape constant was correlated with the pyrolysis coefficient k_p , which is equal to R_p/F_v ; where R_p is the rate of pyrolysis. Therefore:

$$\delta = c k_p \quad (18)$$

Where c is a constant determined from experimental data.

Equation (17) 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°C to 1200°C. The growth rates ranged from ultra-slow to ultra-fast, in accordance with the categories given in Table 2.

THE HEAT RELEASE RATE

The HRR is the single most important variable that quantitatively defines a design fire [28]. HRRs for items of furniture are typically measured in the furniture calorimeter using the oxygen consumption principle under fully-ventilated conditions. The invention of the furniture calorimeter [29] and the ISO 5660 cone calorimeter [30] in the early 1980s led to an increase in the amount of published HRR data for many combustible items, especially upholstered furniture. Upholstered furniture has been studied in fire tests much more than any other household furniture because statistical information shows it to be the major item associated with fatalities in house fires [21, 31].

Babrauskas et al.[29] provided a detailed description of the design features and principles of operation of the furniture calorimeter. HRR results and other combustion data were also given for a number of upholstered furniture items. Lawson et al. [32] presented more combustion data, obtained using the HRR calorimeter developed by Babrauskas et al. [29] for various furnishings, such as: easy chairs, sofas, wardrobe closets, bookcases, and bedding. Additional sources of combustion data are [22, 32 - 44]

The European Commission-sponsored project CBUF (Combustion Behaviour of Upholstered Furniture) [39] 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 (ISO 5660) was used for small scale testing of furniture components. The four curves typifying the burning behaviour of the 27 different types of real furniture items tested are shown in Figure 4.

Figure 4. Illustration of Typical HRRs as Function of Time Measured in the Furniture Calorimeter for a Selection of European Upholstered Furniture and Mattresses [39].

Heat Release Density

The concept of heat release density (kW/m^2), which is the HRR of a fire divided by the base area of the fuel package, is important in estimating the peak HRR of similar fuel packages occupying different base areas. Gemeny and Wittasek [45] gave an example of the use of HRR densities obtained from Cone Calorimeter [30] tests to estimate the peak HRR of a large item, which was then used to specify a design fire. Gemeny and Wittasek also gave an 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.

Estimating the Heat Release Rate

Small- and large-scale fire experiments to obtain HRR data are expensive to conduct. Therefore, there have been many attempts [21, 39, 46, 47] to predict the HRR of full-size combustibles from information obtained from less-costly bench-scale tests, such as the Cone Calorimeter. However, many efforts have so far been met with limited success

mainly because of the difficulty of scaling complex phenomena from bench-scale to full-scale items [7].

In the CBUF work, three different models were developed for predicting HRRs for full-scale furniture using Cone Calorimeter data. Equations to predict the peak HRR, 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 [34, 49] has been carried out in New Zealand to determine the applicability of the HRR 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 HRRs.

GASEOUS PRODUCTS OF COMBUSTION

Information on the gaseous products of combustion is important in hazard assessments, particularly during the pre-flashover stages of a fire. There are two types of gaseous combustion products: asphyxiants and irritants. The main asphyxiants are CO, CO₂, low O₂ and HCN. Examples of irritants are: hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulphur dioxide (SO₂), nitrogen dioxide (NO₂) and acrolein. Smoke and soot are two other combustion products worthy of mention since inhalation of these products causes swelling of parts of the respiratory tract, thereby hastening asphyxiation. In addition, smoke and soot impede escape by obscuring vision. Detailed methods for the analysis of hazards from toxic products, heat and smoke in fires can be found in the SFPE handbook [12].

The quantity and type of gaseous products of combustion and rate at which they are produced largely depend on the ventilation conditions. A great many fire tests are conducted under well-ventilated conditions, and therefore the fires tend to develop rapidly and produce large quantities of heat, but not as much gaseous combustion products as would be produced in an oxygen-vitiated environment [50]. In a numerical study of HCN production in fires, Tuovinen [51, 52] showed that recycling of combustion products in the fire promoted an increased formation of HCN and CO, as did lower ventilation rates. Purser [53] summarized the results of fire experiments conducted with realistic fuels in simulated rooms. The results showed that the fires quickly became

vitiated and produced high yields of smoke, carbon dioxide and hydrogen cyanide. Blomqvist et al. [43, 44] measured a broad range of exotic chemical species, such as fire retardant agents, dioxins and furans, from simulated room fires involving household furnishings and electronic equipment. The tabulated results provided valuable insight into the range of chemical species that can be produced in real fires.

FIRE LOAD DENSITY

The fire load density is usually expressed as the total fire load per unit internal surface area (MJ/m^2) or floor area 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 [54], and that if data from representative surveys is available, the 90 percentile value should be selected [7]. Transient fire loads are items that are in a space temporarily, for example, Christmas decorations [54]. Klote [54] suggested a method of accounting for transient fuels in which a fixed HRR density or HRR 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. [55] presented a survey of fire load data for residential occupancies found in the literature.

If the total fire load in a room is known, the duration of burning can be calculated by estimating the total amount of energy released during the growth and decay phases of the fire using suitable correlations. In the case of a fire that experiences a ventilation-controlled or fully-developed burning phase after attaining the maximum HRR, the remainder of the energy can be assumed to be released during this phase and its duration is obtained by dividing the energy released by the average HRR. If the combustibles do not burn completely, this must be taken into account in the calculation. Examples of these calculations are given in a Fire Engineering Design Guide published in New Zealand [56].

DISCUSSION

The choice of a design fire is influenced by the nature of the fire safety assessment or design tasks being undertaken. Many parameters must be taken into consideration and many assumptions must be made in order to select an appropriate design fire. The ISO

and SFPE publications [2, 3, 6] provide an excellent overview of the general principles that should be employed when undertaking the task of specifying design fires. It is essential to have information on fire load data for the occupancy under consideration, combustion data for the combustibles expected to be present in the compartment, and the specific characteristics of the building in order to specify HRR, fire effluent and temperature history of a fire.

The guiding principle in selecting a design fire is that the assumptions about the type and quantity of combustible materials, ignition method, growth of the fire and its spread from the first item ignited to subsequent items, and the decay and extinction of the fire ought to be reasonable. In addition, there is a requirement for the design fire to represent a fire that presents a formidable challenge to whichever fire safety feature or aspect of a building is being evaluated.

The methodology for evaluating the level of fire safety offered by a proposed design, that is suggested in ISO Technical Report 13387-2:1999(E) [2], entails a risk-ranking process as the basis for the selection of design fire scenarios. The initial set of possible design fire scenarios can be based on fire incident statistics. Yung and Bénichou [57, 58] discussed the use of design fires to analyze fire hazards to the occupants of a building and listed six design fire scenarios for an enclosure with the entrance door either open or closed for the following types of fires: smouldering fire, flaming non-flash fire, and flashover fire.

CONCLUSION

At present, the calculation schemes available for design fires are largely empirical in nature. The two main quantities used to describe design fires are usually the HRR (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.

HRR 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.

NOMENCLATURE

A_f	Floor area	(m^2)
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 (7), $= \sqrt{k\rho c_p}$	($W.s^{0.5}/m^2K$)
b_{ref}	Reference value of b	($W.s^{0.5}/m^2K$)
c	Constant used in Equation (18)	(-)
c_p	Specific heat capacity	($kJ/kg.K$)
H_o	Height of ventilation opening	(m)
F_o	Opening factor	($m^{1/2}$)
F_{ref}	Reference value of the opening factor	($m^{1/2}$)
F_v	Ventilation factor	($m^{5/2}$)
k	Thermal conductivity	($kW/m.K$)
k_p	Pyrolysis coefficient	($kg/s.m^{5/2}$)
M_f''	Fire load density	(kg/m^2)
$\dot{Q}$	HRR	(kW)
$\dot{Q}_o$	Reference HRR	(kW)
Q''	Total fire load energy density	(MJ/m^2)
$\dot{q}_i''$	Incident radiation heat flux	(MW/m^2)
R	Radial distance	(m)
R_p	Rate of pyrolysis	(-)
T	Temperature	($^{\circ}C$)

T_o	Reference temperature	(°C)
t	Time	(s)
t_b	Duration of burning	(s)
t_d	Duration of heating phase, given by Equation (11)	(hrs)
t_o	Time to reach a reference HRR	(s)
t_{max}	Time at which maximum temperature occurs	(min)
t^*	Fictitious time used in Equation (6)	(hrs)

GREEK LETTERS

α	Growth or decay constant for a t^2 fire	(W/s)
β	A constant given by Equation (14)	($K s^{-1/6}$)
δ	Shape constant	(-)
ρ	Density	(kg/m^3)

SUBSCRIPTS

f	Floor
g	Pertains to hot gas
max	Maximum value
∞	Ambient condition

ABBREVIATIONS

HRR	Heat release rate	(kW)
Max	Maximum	
RHR	HRR (synonymous with HRR)	(kW)

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TABLES

Table 1. Terminology related to design fires

Term	Definition by Source Reference	
	ISO/TR-13387-2 [2]	SFPE Engineering Guide [6]
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.
Design fire scenario	A specific fire scenario on which an 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.
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: HRR, fire size (including flame length), quantity of fire effluent, 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 HRR versus time (or in other terms elaborated in the stated reference) for use in a design fire scenario.

Table 2. Categories of t^2 Fires and their Growth Constants [2]

Growth category	Typical examples	Fire growth coefficient, α (kW/s²)	Growth time, t_0 (s)
Slow	Floor coverings	0.00293	600
Medium	Shop counters, office furniture	0.0117	300
Fast	Bedding, displays and padded work-station partitioning	0.0468	150
Ultra-fast	Upholstered furniture and stacked furniture near combustible linings, lightweight furnishings, packing material in rubbish pile, non-fire-retarded plastic foam storage, cardboard of plastic boxes in vertical storage arrangement.	0.1876	75