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COMPARTMENT FIRES: TEMPERATURE—TIME CURVES

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ABSTRACT

Temperature history in a compartment is important for fire safety point of view as the knowledge of temperature is useful in the prediction of: i) the onset of hazardous conditions; ii) property and structural damage; iii) burning rate; and iv) ignition of objects and the onset of flashover. There are numerous ways to model the fire scenario in a building compartment such as zone modeling and computer fluid dynamic modeling. These models have a high accuracy in calculating the temperature history. However, these models are sophisticated and the appropriate software package is very large. This article describes simple calculation procedures with the help of empirical relation which will, to a suitable degree of precision, estimate the temperature history in a compartment fire. It is this kind of procedure which becomes useful for making quick fire design calculations, without using computer code. Traditionally, ISO 834 "standard fire curve" is used for classification of the structural elements according to the time of their failure when subjected to thermal exposure as per ISO 834 "standard fire curve." Some new parametric fire curves, such as iBMB, BFD, Ma and Makelainen claim to replace the ISO 834 "standard fire curve." In the present article, the above methods, including EUROCODE, have been discussed and an effort has been made to compare them using an office fire example and two zone models as given in reference [1]. These have also been compared with zone model such as CFAST and OZone. It is found that for the same fire, different models predict different temperatures. It is observed that in spite of new calculation methods, the temperature predicted by ISO 834 Curve is most popular due to its simplicity, minimum input requirement and user-friendly nature.

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INTRODUCTION

Habitats are fire prone as they contain combustibles. When a combustible is ignited, heat is released which is partly fed back to the source to continue burning and the balance goes to heat other materials in the room. A fire in a room goes through three phases—ignition and growth; fully developed; and decay. Escape and rescue are possible only in the growth period. The pre-flashover period or growth period is of special significance to fire protection systems, such as sprinklers which must necessarily operate early in this period to justify their provision. The absence of fire protection systems or their failure may allow the fire to grow to the fully developed stage endangering the building structure to collapse. Calculation of the load bearing and separating capacity in the design of structural components exposed to fire are based on the knowledge of their thermal exposure. So modeling (mathematical or physical) of fire scenario in a building compartment is essential for life and structure safety. Physical models are the experimental models created in a laboratory to study, for example, change in temperature with changing rate of burning, in a compartment with and without doors/windows. Physical models could be full scale/ reduced scale models. Fire being destructive, the cost of experimentation is quite high, so reduced scale models are preferred. The disadvantage with a reduced scale physical model is that complete similarity between full scale and reduced scale tests cannot be preserved. Alternatively, mathematical models based upon fundamental laws of conservation of mass, momentum, and energy are quite general in nature and once validated for their application, these models can predict complete fire scenario economically and within a reasonable timeframe as compared to physical models. Mathematical models can also be used to examine the consequences of adopting alternative fire protection designs. There are numerous ways of mathematical modelling the fire scenario in a building compartment, such as zone modeling and computer fluid dynamic modeling.

A number of field and zone models have been developed. Zone models are quite popular due to being simple, fast, and cheaper than the field models. ASET [2], CALFIRE [3], CALTREE [4], and FIRST [5], etc. are the single room zone models while CFAST [6], BRI [7], and HARVARD [8] represent the detailed and comprehensive zone models to have a great utility in predicting the fire behavior in multiroom scenarios. These models have a high accuracy in calculating the temperature history. However, these models are sophisticated and the appropriate software package for them is very large. Recently a number of simple empirical procedures such as iBMB curve [1], BFD curve [9], Ma and Makelainen curve [10] have been reported in literature for calculating temperatures in compartments. All these curves have been discussed in this article to show the equations and input parameters. These have been compared with other already prevalent empirical curves such as EUROCODE [11] and ISO 834 Curve [12]. They have also been compared with an experimental office fire and two zone models :CFAST [6] and OZONE [13].

METHOD I: IBMB CURVE [1]

iBMB curve [1], a parametric natural fire model, is derived on the basis of simulations with heat balance models for realistic natural design fires, taking into account the boundary conditions concerning fire load, ventilation condition, geometry, and thermal properties of typical compartments in residential and office buildings for a reference fire load density of $\dot{q}$ = 1300 MJ/m^2, which is taken as an upper value for residential and office buildings. The effect of variation of heat release rates with time has been considered on time–temperature profiles in iBMB curve [1] and simulated with the zone model CFAST [6] for various boundary conditions. It can be observed from the heat release curve and time–temperature curve from CFAST [6] that both the curves can be characterized by three distinctive points at the times t_1, t_2, and t_3 where slope of the curve is changing as shown in Figure 1. Up to time t_1 the rate of heat release rises quadratically to maximum and the upper layer temperature increases rapidly. During the period between t_1 and t_2, the heat release rates remain almost constant, so the temperature rises moderately. It is assumed that at t_2, 70% of fire load is consumed, so decay starts and temperature starts decreasing. At time t_3, the complete fire load is consumed, so rate of heat release becomes zero and upper layer temperature decreases at slower rate. The time t_1, t_2, and t_3 can be determined by the consideration of the functional course of heat release rate. iBMB curve [1] predicts the temperature at these three points (T_1, T_2, and T_3, respectively).

Ventilation-Controlled Fires

For a reference fire load density of q'' =1300 MJ/m^2, the upper layer temperatures T_1, T_2, and T_3, for ventilation-controlled fires, are predicted by

$$T_1 = \frac{-8.75}{O} - 0.1b + 1175°C \quad (1)$$

$$T_2 = \frac{0.004b - 17}{O} - 0.4b + 2175°C \leq 1340°C \quad (2)$$

$$T_3 = \frac{-5.0}{O} - 0.16b + 1060°C \quad (3)$$

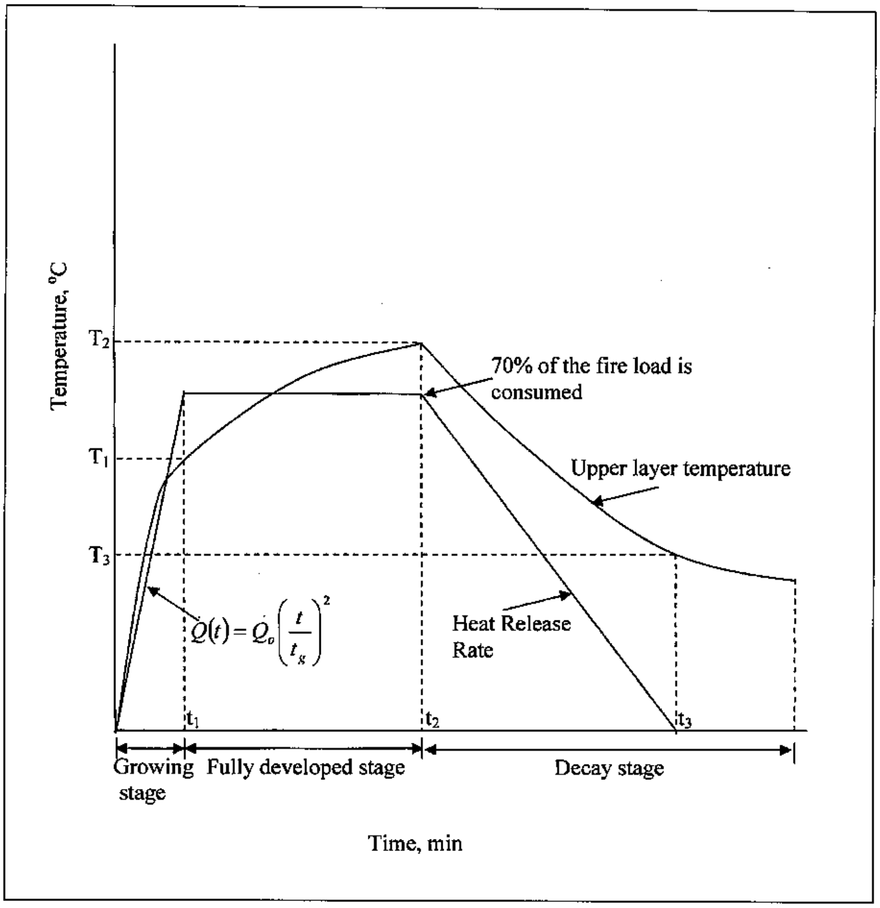

Figure 1. Principle of temperature prediction by iBMB parametric curve based on Heat Release Rate.

$$O = \frac{A_o \sqrt{H_o}}{A_t} \tag{4}$$

where

- O Opening factor, [ ]
- A_o Area of ventilation opening, m^2
- H_o Height of the opening, m
- A_t Total area of compartment boundaries including openings, m^2
- b Averaged thermal property of the enclosing components, $J/(m^2 s^{0.5} K)$

Fuel Controlled Fires

For the reference fire load density of $q'' = 1300 MJ/m^2$, the upper layer temperatures T_1, T_2, and T_3 for fuel controlled fires are given by

$$T_1 = 24000k + 20°C \text{ for } k \leq 0.04 \quad (5a)$$

$$T_1 = 980°C \text{ for } k > 0.04 \quad (5b)$$

$$T_2 = 33000k + 20°C \text{ for } k \leq 0.04 \quad (6a)$$

$$T_2 = 1340°C \text{ for } k > 0.04 \quad (6b)$$

$$T_3 = 16000k + 20°C \text{ for } k \leq 0.04 \quad (7a)$$

$$T_3 = 660°C \text{ for } k > 0.04 \quad (7b)$$

$$k = \left(\frac{\dot{Q}^2}{A_o \sqrt{H_o}\, A_T b} \right)^{1/3} \quad (8)$$

where

$\dot{Q}$ Rate of heat Release, MW

A_T Total area of compartment boundaries excluding opening, m^2.

The functional form of parametric curve between characteristic points can be described by three sections as represented in Figure 2.

Section 1 ($0 \leq t \leq t_1$)

$$T_g = \frac{(T_1 - T_\infty)t^2}{t_1^2} + T_\infty \quad (9)$$

T_∞ is ambient temperature, usually 20°C, and time t_1 is taken in minutes.

Section 2 ($t_1 < t \leq t_2$)

$$T_g = T_1 + (T_2 - T_1)\sqrt{(t - t_1) / (t_2 - t_1)} \quad (10)$$

where T_1, T_2 are the temperatures at time t_1, t_2 for required fire load $q'' = 1300 MJ/m^2$.

Section 3 ($t > t_2$)

$$T_g = T_2 + (T_3 - T_2)\sqrt{(t - t_2) / (t_3 - t_2)} \quad (11)$$

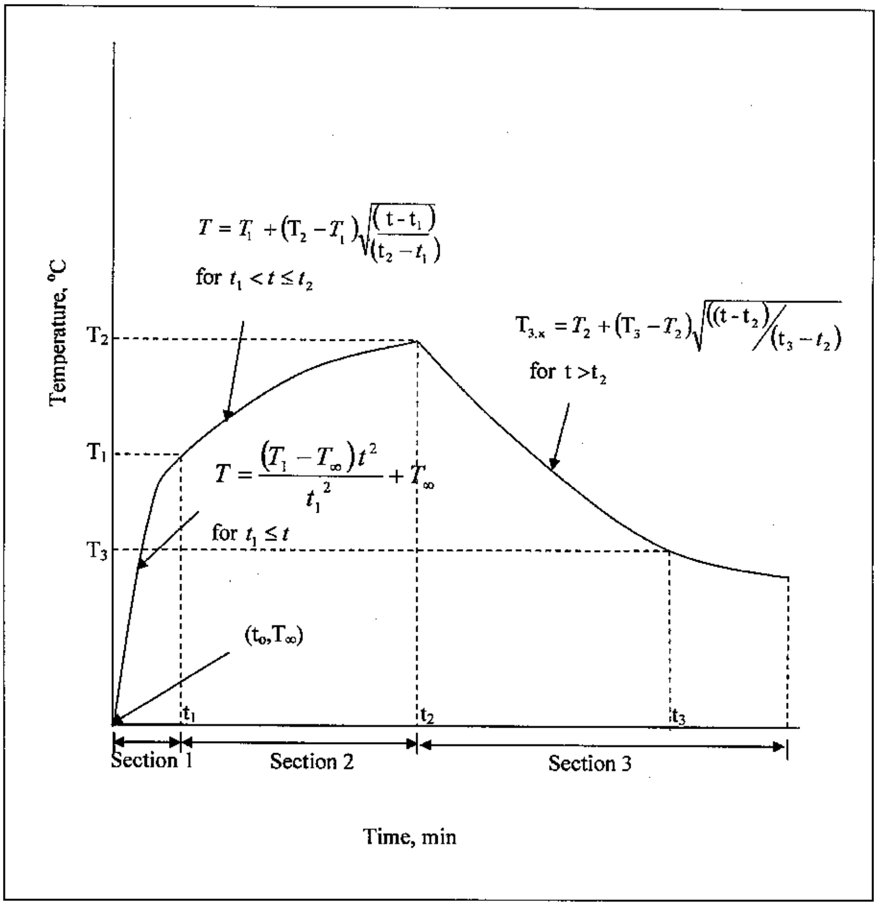

Figure 2. Mathematical representations of iBMB parametric curve in three sections.

The equation (1) to equation (3) predict the temperatures T_1, T_2, and T_3 at time t_1, t_2, and t_3, respectively, for ventilation controlled fire while equation (5) to equation (7) predict the temperatures T_1, T_2, and T_3 at time t_1, t_2, and t_3, respectively, for fuel controlled fires. Equation (9) to equation (11) represent variation of temperatures between these times, for fire load density $q'' = 1300$ MJ/m^2. After calculating the temperatures and curves for reference fire load density $q'' = 1300$ MJ/m^2, the temperature and curve for other fire load densities ($q_x'' \leq 1300$ MJ/m^2) can be determined.

The fire load Q_x is given by multiplying the fire load density q_x'' and the fire area A_f.

$$Qx = q_x'' A_f \tag{12}$$

The temperature during growing stage up to time t_1 is not much influenced by the fire load density, so temperature at time t_1 is taken as T_1. The curve during the period is given by equation (9). Heat Release rate, Q_1, up to time t_1 is given by

$$Q_1 = \dot{Q}_o \int_0^{t_1} \left(\frac{t}{t_g} \right)^2 dt \tag{13}$$

where $\dot{Q}_0 = 1.0$ MW and the time of fire growth with a medium fire growth rate in residential and office buildings can be assumed as $t_g = 300$ s, $t_1 = 600$s [1] $Q_1 = 800$ *MJ* from equation (13).

Let $t_{2,x}$ be the time at the a point where maximum temperature $T_{2,x}$ is observed at the end of fully developed stage and $Q_{2,x}$ is the fire load consumed during the period $t_{1,x} < t \le t_{2,x}$ for fire load density q_x'', then

$$Q_{2,x} = 0.7Q_x - Q_1 \tag{14}$$

$$t_{2,x} = t_1 + \frac{(0.7Q_x) - \dot{Q}_0 (t_1^3 / (3t_g^2))}{\dot{Q}_{\max}} \quad \text{for } Q_1 \le Q_{2,x} \tag{15a}$$

and

$$t_{2,x} = \sqrt[3]{0.7Q_x 3t_g^2} \qquad \text{for } Q_1 \ge 0.7Q_x \tag{15b}$$

By inserting $t = t_{2,x}$ in equation (10) we get the temperature $T_{2,x}$ for the period $t_{1,x} < t \le t_{2,x}$,

$$T_g = T_1 + (T_2 - T_1)\sqrt{(t_{2,x} - t_1) / (t_2 - t_1)} \,. \tag{16}$$

Similarly, for section 3, the time $t_{3,x}$ and $T_{3,x}$ for fire load density q_x'' are given by the following equations

$$t_{3,x} = t_1 + t_{2,x} + 0.3Q_x / \dot{Q}_{\max} \tag{17}$$

$$T_{3,x} = \left(\frac{T_3}{\log_{10}(t_3 + 1)} \right) \log_{10}(t_{3,x} + 1). \tag{18}$$

The decreasing branch of iBMB curve [1] in section 3 with $q_x'' < 1300$ MJ/m^2, can be given

$$T_g = T_{2,x} + (T_{3,x} - T_{2,x})\sqrt{(t - t_{2,x}) / (t_{3,x} - t_{2,x})} \,. \tag{19}$$

Calculation of $\dot{Q}_{max}$

$$\dot{Q}_{max} = \mathrm{MIN}\{\dot{Q}_{max,v}; \dot{Q}_{max,f}\} \tag{20}$$

where

$\dot{Q}_{max}$ = Maximum rate of heat release, MW
$\dot{Q}_{max,v}$ = Maximum rate of heat release for ventilation controlled fire, MW
$\dot{Q}_{max,f}$ = Maximum rate of heat release for fuel controlled fire, MW

For ventilation controlled fire, Heat Release Rate is given by

$$\dot{Q}_v = 0\cdot 1 A_o \sqrt{H_o}\ \chi \mathrm{H_{net}}, \mathrm{MW}. \tag{21}$$

The maximum rate of heat release for residential and office building in case of ventilation controlled fire can be derived by putting combustion efficiency, $\chi = 0.7$ and heat of combustion, $H_{net,wood} = 17.3$ MJ/kg in equation (21).

$$Q_{max,v} = 1.21 A_o \sqrt{H_o}\ . \tag{22}$$

For fuel controlled fire, the Heat Release Rate is given by

$$\dot{Q}_v = \dot{m}''_f A_f\ \chi \mathrm{H_{net}}, \mathrm{MW}. \tag{23}$$

For wooden fire loads, putting $m''_f = 0.02$ kg/(m^{2}s), $\chi = 0.7$ and $H_{net,wood} =$ 17.3 MJ/kg in equation (23), we get

$$\dot{Q}_{max,f} = 0.25 A_f, \mathrm{MW} \tag{24}$$

where A_f is maximum burning area of the fuel in the compartment.

METHOD II: BFD CURVE [9]

Barnett [9] derived an empirical equation for predicting temperature during growth and decay stages of fire by fitting the Cardington Large Scale Test data [14] and compared the results with the experimental data of the tests conducted by Kawagoe [15], JFRO [16], CIB [17], CTICM [18], and others. Fuel used in most of tests was wood cribs or cellulosic material. The basic equation of BFD curve [9] is as follows:

$$T_g = T_\infty + T_{gm} e^{-z} \tag{25}$$

where

T_g is the temperature (°C) at any time t (min),
T_∞ is the ambient temperature (°C)
T_{gm} is the maximum temperature generated above ambient temperature T_∞ (°C),

$$Z = (\ln t - \ln t_m)^2 / \delta \tag{26}$$

where t is the time (min) from ignition of fire and t_m is the time in min at which maximum temperature, T_{gm}, occurs. δ is the shape constant for temperature–time curve.

Calculation of Maximum Temperature, T_{gm}

Barnett [9] used the method of Law [19, 20] that uses the inverse opening factor $\eta_1 (= 1/F_{o2})$ and the fire load mass density $\varphi \left(= m_F \big/ \sqrt{A_o A_T} \right)$

$$T_{gm} = 6000((1 - \exp^{-0.1\eta_1})/\eta_1^{0.5})(1 - \exp^{-0.05\varphi}) \tag{27}$$

where η_1 is the reverse of opening factor, Fo_2, as given below

$$F_{o2} = \frac{A_o \sqrt{H_o}}{A_T} \tag{28}$$

where A_o and H_o are the area and height of the opening and A_T is given by $A_T = A_{FLOOR} + A_{CEILING} + A_{WALLS} - A_{OPENING}$

$$A_T = 2WL + 2(L + W)H - H_o W_o \tag{29}$$

where W, L, and H are the width, length, and height of the compartment and W_o is the width of the opening. The value of t_m, used in equation (26), for a fuel surface controlled fire can be calculated as follows if one assumes values for the total fuel load E (MJ) and the two coefficients t_g^* and t_d^*

$$t_m = t_g^*[3E/(t_g^* + t_d^*)]^{0.333} \tag{30}$$

where t_g^* and t_d^* are growth and decay coefficients. Growth coefficient is time in seconds to reach fire intensity to 1MW. Similarly, time taken for decay of 1MW fire to decay is decay coefficient. Generally decay coefficients are larger than the growth coefficients. These can be assessed directly from mass loss curves for experimental fires for different fuels which depend upon type of occupancy. The growth and decay coefficients t_g^* and t_d^* can be assumed as follows [9]:

Ultra fast	–	75
Fast	–	150
Medium	–	300
Slow	–	600
Ultra-slow	–	1200

The value of t_m for a ventilation controlled fire can be calculated

$$t_m = \frac{E}{\dot{Q}} - \left[\frac{1}{3t_d *} - \frac{2}{3t_g *}\right]\dot{Q}^{0.5} \tag{31}$$

$\dot{Q}$ is the fire intensity (MW) and can be calculated from rate of burning, $\dot{m}_f$ (kg/s), given by

$$\dot{m}_f = k_p A_o \sqrt{H_o} \tag{32}$$

where A_o is the opening area and H_o is opening height, k_p is the pyrolysis coefficient which can be determined by the equation

$$k_p = \frac{1}{148F_{o2} + 3.8} \tag{33}$$

Shape Constant δ

For uninsulated fire compartments

$$\delta = \frac{1}{4F_{o2} + 0.1} \tag{34}$$

Insulated fire compartment

$$\delta = \frac{1}{9.25F_{o2} + 0.24} \tag{35}$$

By replacing the values of T_{gm}, t_m, and δ in equation (25), we get temperature history with respect to time.

METHOD III: ZHONGCHENG MA AND PENTTI MAKELAINEN [10]

Ma and Makelainen [10] developed a simple method by non-dimensionalizing about 25 time-temperature curves from different researchers by maximum gas temperature and time to reach the maximum gas temperature. This method has three main characteristics: i) the temperature-time curves are determined by two key parameters of fire severity : maximum gas temperature and fire duration; ii) the maximum gas temperature and fire duration are determined by the fire load density, opening factor; and iii) both ventilation and fuel controlled fire are explicitly distinguished in this method. This method is applicable for the conditions given in Table 1.

$$\frac{T_g - T_\infty}{T_{gm} - T_o} = \left[\frac{t}{t_m}\exp\left[1 - \frac{t}{t_m}\right]\right]^\delta \tag{36}$$

where

- T_g Gas Temperature, °C
- T_{gm} Maximum Gas Temperature, °C
- T_∞ Room/Ambient Temperature, °C
- t Time from flashover, min
- t_m Time corresponding to maximum gas temperature, °C
- δ Shape constant of temperature-time curve [ ], = 0.5 for ascending phase and = 1.0 for descending phase.

Calculation of T_{gm} for Ventilation Controlled Fire

In rooms with small- or medium-sized windows, post flashover fires are ventilation controlled, so the rate of combustion depends on the size and shape of ventilation openings. In a ventilation controlled fire, the rate of combustion is limited by the volume of cool air that enters the room.

$$T_{gm} = 1240 - 11\eta \tag{37}$$

where η is inverse of opening factor, given by

$$\eta = \frac{A_t}{A_o\sqrt{H_o}} \tag{38}$$

where

- A_o Area of ventilation opening, m^2
- H_o Height of the opening, m
- A_t Total surface area of compartment boundaries including openings, m^2

Calculation of T_{gm} for Fuel Controlled Fire

Not all post flashover fires are ventilation controlled. The rate of burning may sometimes be controlled by the surface area of the fuel, especially in large well-ventilated rooms containing fuel items which have a limited area of combustible surfaces.

$$\frac{T_{gm}}{T_{gmcr}} = \sqrt{\frac{\eta}{\eta_{cr}}} \tag{39}$$

where

T_{gmcr} maximum fire temperature in the critical region (transition from ventilation to fuel control) of the compartment fires, °C

η_{cr} is the value of η in critical region, $m^{-1/2}$

Harmathy [21] analyzed many experimental data and gave the following semi-empirical correlation for the critical region where ventilation control fire changes to fuel control fire in compartment,

Table 1. Comparison of Various Methods

S. No.	Curve	Input	Output	Validity
1	iBMB curve [1]	i) Fire intensity ii) Fire load density iii) Room size iv) Opening size v) Thermal properties of room boundary materials vi) Time of growth, fully developed and decay stages as per heat release rate curve	Upper layer temperatures at three times and temperature profile between these times.	Valid for fire load densities $q \leq 1300$ MJ/m^2
2	BFD curve [9]	i) Fire load (MJ) ii) Room size iii) Opening size iv) Duration of fire v) Growth and decay coefficient (fuel burning curve)	i) Gas temperature ii) Maximum gas temperatures iii) Time required for maximum gas temperatures iv) Shape constant	Valid for growth and decay phases for following conditions: i) Fuel mass 3-5100 kg ii) Temperature 500°C-1200°C iii) Time 9 min-7h iv) Ultra slow to ultra fast growth rates

3	Ma & Makelainen [10]	i) Shape constant ii) Rate of burning iii) Fire load (kg) iv) Room size v) Opening size	i) Gas temperature ii) Maximum gas temperatures iii) Time required for maximum gas temperatures.	Valid for fully developed fire for the following conditions: 1. Fire load 10-40 kg/m^2 2. Ventilation factor 5-16 $m^{5/2}$ 3. Thermal inertia 555-1800 $J/m^2s^{1/2}K$ 4. Floor area 100 m^2 5. Maximum height 4.5 m
4	EUROCODE [11]	i) Time in hours ii) Room size iii) Opening size iv) Thermal properties of room boundary materials v) Fire load density	Gas temperatures in growth and decay stage both.	i) Uses two separate equations for growth and decay stages. ii) Decay is linear which is not found in actual fires.
5	ISO 834 curve [12]	Time in minutes	Gas temperature	Covers most of the fires in common buildings. Natural fires decrease after maximum temperature but ISO curve rises continuously.

$$\frac{\rho_\infty \sqrt{g}\, A_o \sqrt{H_o}}{A_f} = 0.263 \tag{40}$$

$$\frac{\rho_\infty \sqrt{g}\, A_t}{A_f}\left(\frac{A_o \sqrt{H_o}}{A_t}\right) = 0.263$$

$$\rho_\infty \sqrt{g}\left(\frac{A_t}{A_F}\right)\left(\frac{A_F}{A_f}\right)\left(\frac{1}{\eta_{cr}}\right) = 0.263$$

$$\rho_\infty \sqrt{g}\left(\frac{1}{k_1}\right)\left(\frac{A_F}{m_F}\right)\left(\frac{m_F}{A_f}\right)\left(\frac{1}{\eta_{cr}}\right) = 0.263$$

$$\rho_\infty \sqrt{g}\left(\frac{1}{k_1}\right)\left(\frac{1}{m_F''}\right)\left(\frac{1}{\phi}\right)\left(\frac{1}{\eta_{cr}}\right) = 0.263$$

Taking air density, $\rho_\infty = 1.205$ kg/m^3, and g = 9.81 m/s^2

$$\eta_{cr} = 14.34 / k_1 \phi m_F'' \tag{41}$$

where
- k_1 is ratio of floor area to the total boundary area = A_F/A_t
- m_F'' is fire load per unit floor area = m_F/A_F, kg/m^2
- ϕ is surface area ratio of fuel = A_f/m_F m^2/kg
- A_F is the floor area, m^2
- A_f is the fuel surface area, m^2

By substituting η_{cr} in equation (37), T_{gmcr} is calculated which is used in equation (39) to calculate T_{gm}.

Calculation of Time, t_m and Time Duration, τ

Time, t_m, at which maximum temperature occurs, is given by

$$t_m = 0.63\tau \tag{42}$$

where τ is fire duration in min, given by

$$\tau = \frac{m_F}{\dot{m}_F} \tag{43}$$

where
- m_F is fuel load of equivalent wood in kg
- $\dot{m}_F$ is the rate of burning in kg/min.

For Ventilation Control Fire

$$\dot{m}_F = 10.8 A_o \sqrt{H_o} \sqrt{\frac{W}{D}} (1 - e^{-0.036\eta}) \quad (44)$$

where D is the depth and W is the width of the compartment.

For Fuel Controlled Fire

$$\dot{m}_F = 0.372 \phi m_F \quad (45)$$

Replacing T_{gm} and t_m in equation (36), temperature history with respect to time is obtained.

METHOD IV: EUROCODE PARAMETRIC FIRE CURVE [11]

The EUROCODE [11] gives a parametric equation for fires, allowing a time-temperature relationship to be produced for any combination of fuel load, ventilation openings, and wall lining materials. The EUROCODE [11] method divides the fire development into two phases: the heating or growth phase and the cooling or decay phase.

The EUROCODE [11] temperature time curve in the heating phase is given by equation

$$T_g = 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}) \quad (46)$$

where temperature T_g is in degree °C

t* is a fictitious time in hours given by

$$t^* = \theta t \quad (47)$$

where t is the time in hours from ignition and θ is the modification factor given by

$$\theta = \frac{(O/0.04)^2}{(b/1160)^2} \quad (48)$$

where

b is Averaged thermal property of the enclosing components,

$$(= \sqrt{thermal\ inertia} = \sqrt{k\rho c}), \quad J/m^2 s^{0.5} K)$$

c is the specific heat of the boundary material, *J/kgK*

k is the thermal conductivity of the compartment boundary, *W/mK*

ρ is the density of the compartment boundaries, kg/m^3

O is the opening factor given by

$$O = {A_o \sqrt{H_o}} / {A_t} \tag{49}$$

where

A_o Area of ventilation opening, m^2
H_o Height of the opening, m
A_t Total area of compartment boundaries including openings, m^2.

The EUROCODE [11] temperature-time curve in cooling phase is given by

$$T = T_{gm} - 625\,(t^* - t_d^*) \quad \text{for} \quad t_d^* \leq 0.5 \tag{50a}$$

$$T = T_{gm} - 250(3 - t_d^*)\,(t^* - t_d^*) \quad \text{for} \quad 0.5 < t_d^* < 2 \tag{50b}$$

$$T = T_{gm} - 250\,(t^* - t_d^*) \quad \text{for} \quad t_d^* \geq 2 \tag{50c}$$

where T_{gm} is the maximum temperature in the heating phase for $t^* = t_d^*$ and

$$t_d^* = \frac{0.13x10^{-3} Q_t''}{O} \frac{\left({O}/{0.04}\right)^2}{\left({b}/{1160}\right)^2} \tag{51}$$

In terms of real time, the duration of the heating phase is given by

$$t_d = \frac{0.13x10^{-3} Q''}{O} \tag{52}$$

Q'' is the fire load density, MJ/m^2 and O is Opening factor $\left(= \frac{A_o \sqrt{H_o}}{A_t} \right)$.

So, the modified duration time can be written as

$$t_d^* = t_d \frac{\left({O}/{0.04}\right)^2}{\left({b}/{1160}\right)^2} \tag{53}$$

METHOD V: ISO 834 "STANDARD FIRE CURE" [12]

The standard temperature-time curve according to ISO 834 Curve [12] was developed in the 1930s summarizing data from fires in residential, office, and commercial buildings. The curve covers most of the potential courses of fires in common buildings. As fire tests have shown, the maximum temperature of a natural fire can exceed the ISO curve, but after the maximum it decreases again, whereas the ISO curve rises continuously.

The standard fire exposure is defined as

$$T - T_0 = 345\log_{10}(8t + 1) \quad (54)$$

where

t is the time in min
T is the furnace temperature in time t in °C
T_0 is the initial furnace temperature in °C

Traditionally structural fire designers use ISO 834 "standard temperature time curve."

COMPARISON OF THE ABOVE MODELS

The temperatures predicted by the above curves have been compared with the temperatures of experimental fire in a office compartment as reported in Zehfuss and Hosser [1]. The office compartment has floor area 3.6 m × 3.6 m and height of 2.60 m with a wall opening 0.70 m wide and 2.60 m high. The fire was ventilation controlled during fully developed stage. The office contains furnishings, hardware, folders, and papers. The fire load density was 468 MJ/m^2. The other parameters are given in Table 2. The experimental temperatures due to fire in the office have been digitalized from Figure 13 in the article by Zehfuss and Hosser [1]. The prediction by iBMB curve [1] and CFAST [6], and OZONE [13] models have also been read from the figure. In case of predictions for growth and decay stages by BFD [9], Ma and Makelainen curve [10], and ISO curve [12], single equation (25), equation (36) and equation (54) is used in each case, respectively, while the temperatures by EUROCODE [11] are calculated with the help of two equations (i.e., by equation (46) and equation (50) for growth and decay stage separately). The input parameters required for these equations have been given in Table 2. The comparison of predicted temperature by various model with experimental temperatures is shown in Figure 3.

RESULTS AND DISCUSSIONS

It can be observed from Figure 3 that the predicted temperature by zone model CFAST [6] conform to the experimental temperature during growth and decay stages. The maximum temperature during experiment reaches at about 17 minute while CFAST [6] predicts the time as 18 minutes. Rate of temperature rise predicted by OZONE [13] are similar to the experimental temperature, but fire becomes fully developed at lower temperature as compared to the experimental results. During decay, predicted temperature by OZONE [13] decreases at a faster rate. The trend of temperature predicted by iBMB curve [1] during all the stages is almost the same as has been observed in experiments. However, predicted peak temperature is slightly higher than the experimental peak

Table 2. Input Parameters[a]

Input parameters	Ma and Makelainen	BFD	EUROCODE	ISO 834
Room size	3.6 m × 3.6 m × 2.60 m	3.6 m × 3.6 m × 2.60 m	3.6 m × 3.6 m × 2.60 m	NR
Opening size	0.70 m × 2.60 m (high)	0.70 m × 2.60 m (high)	0.70 m × 2.60 m (high)	NR
Fire load density	468 MJ/m^2	468 MJ/m^2	468 MJ/m^2	NR
Growth coefficient	NR	300 s	NR	NR
Decay coefficient	NR	600 s	NR	NR
Shape constant	0.5 for growth 1.0 for decay	Calculated by equation (34)	NR	NR
$\sqrt{k\rho C}$ ($J/m^2s^{0.5}K$)	NR	NR	1500	NR

[a]Input parameters for iBMB, CFAST, and Ozone are not given as temperature predicted due to these models having been taken directly from Zehfuss and Hosser [1].
NR = Not Required

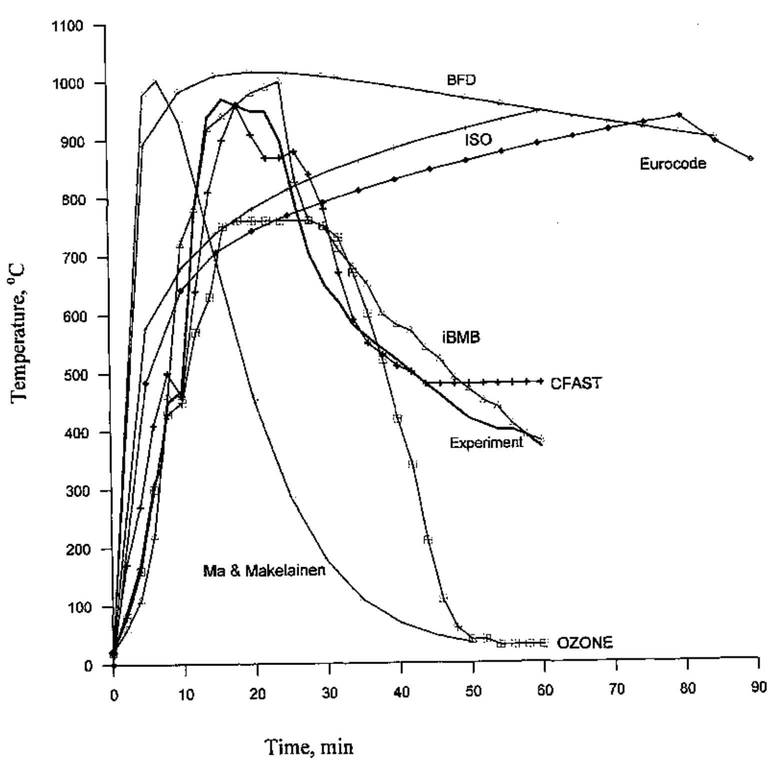

Figure 3. Comparison of predictions by different empirical curves with experimental temperatures [1] and CFAST [6] and OZONE [13].

temperature and occurs at 24 minutes instead of 17 minutes in experiment. The predictions by EUROCODE [11] and ISO 834 curve [12] are almost the same during growth stage. ISO 834 curve [12] predicts only growing temperature while EUROCODE [11] predicts growth as well as decay temperature, using another additional equation for decay period. The time to reach maximum temperature predicted by EUROCODE [11] is much higher than the time observed during experiment. The temperature predicted by BFD during growth, fully developed, and decay stages are much higher than the experimental temperature. Similarly, the temperatures predicted by Ma and Makelainen [10] are also higher. During growth, rise in predicted temperature by Ma and Makelainen [10] is much faster as compared to temperature rise in experimental data as can also be observed in temperature predicted by BFD curve [9].The peak predicted temperature by

Ma and Makelainen [10] is about 1002°C at about 8 minutes. The decay also takes place earlier. It is due to the fact that it predicts temperature after the flashover is reached, that is, when fire is fully developed. So the shifting of curve is needed in such case.

It is observed in Figure 3 that the temperature predicted by the iBMB curve [1] are very close to the experimental temperature as compared to other empirical relations. There are two sets of three equations (one: equation (1) to equation (3), and second one: equation (5) to equation (7)), which are used to calculate temperature at three times which represents the end of growth, fully developed, and decay stages of the fire for ventilation controlled and fuel controlled fires, respectively. These three times are determined with heat release rate curve which represent the design fire. The temperature profiles during the three stages are represented by three equations, equation (9) to equation (11). Thus these six equations give the complete temperature prediction for fire load density $q'' = 1300$ MJ/m^2. For calculating, the temperature for fire load density $q'' < 1300$ MJ/m^2, another set of equation (12) to equation (24) is used in conjunction with the above six equations, to calculate time and temperatures profile during growth, fully developed, and decay stages. A number of input parameter as shown in Table 1 are required for calculating these time and temperature. BFD curve [9] and Ma and Makelainen [10] calculate the temperature profile with the help of single equation (equation (25) and equation (36), respectively), which requires the maximum temperature and time of occurrence of maximum temperature as input. For calculating maximum temperature and its occurrence time, which is influenced by the ventilation condition, geometry, and boundary properties, a number of other equations are needed (equation (26) to equation (35) in case of BFD curve [9] and equation (37) to equation (45) in case of Ma and Makelainen [10]). There is need to determine growth and decay coefficients as well as shape constant of temperature curve, which depend upon the mass loss curves.

In case of EUROCODE [11], there are two separate equations (equation (46) and equation (50)) which are used for the prediction of temperature in growth and decay stage. It is observed that the temperature predicted decreases linearly during decay, while in actual fires, the cooling takes place exponentially [22]. In growing stage, EUROCODE [11] follows the ISO 834 "standard fire curve." Although, the temperature predicted by these curves are lower than that of experiments, yet these equations are quite simple and user-friendly. In case of empirical curves such as iBMB [1], BFD [9], Ma and Makelainen [10] and even in EUROCODE [11], the prediction or calculation becomes complex and cumbersome due to a number of equations and input required as can be observed from Table 1. In case of ISO 834 standard fire curve [12], only one equation (54) is needed for predicting temperature. ISO 834 Curve is quite popular in determining the fire severity in furnace tests due to its simplicity with minimum input data. There is no need of prior knowledge of design fire, geometry of room, properties of the boundaries, fire load, or fire load density for any compartment, for which structural component to be tested in the thermal exposure according to ISO 834 standard fire curve. In case of other parametric fire curves, all these parameters are needed. So any structural component tested as per the thermal exposure according to the other fire curves (i.e., iBMB [1], BFD [9], Ma and Makelainen [10], and even in EURCODE [11]), will be most suitable only for the fire scenario (design fire, geometry of compartment, properties of the boundaries, fire load, or fire load density, etc.) for which the structural component has been tested. For other fire scenario, it will either be under safe or over safe.

CONCLUSION

It, therefore, can be concluded that fire curves like BFD, Ma and Makelainen, and iBMB are complex and require a number of input data as compared to ISO 834 "standard fire curve" and these cannot be universally applied to all the fire scenarios. Therefore, they are not as popular as ISO 834 "standard fire curve." There is need to further simplify and make them user-friendly and universal.

NOMENCLATURE

A_f fuel surface area, m^2
m_F'' is fire load per unit floor area = m_F/A_F, kg/m^2
A_F is the floor area, m^2
A_o Area of ventilation opening, m^2
A_t Total area of compartment boundaries including openings, m^2
A_T Total area of compartment boundaries excluding opening, m^2
b Averaged thermal property of the enclosing components, J/(m$^2s^{0.5}K$)
D Depth of the compartment., m
E Fuel load, MJ
F_{O_2} Opening factor,(= $\left(\frac{A_o\sqrt{H_o}}{A_T}\right)$, $m^{1/2}$),
H_o Height of the opening, m
$H_{net,wood}$ Heat of combustion of wood, MJ/kg
b Averaged thermal property of the enclosing components, (= $\sqrt{k\rho c}$), J/m$^2s^{0.5}K$)
c is the specific heat of the boundary material, J/kgK
k Thermal conductivity of the compartment boundary, W/mK
k_1 Ratio of floor area to the total boundary area = A_F/A_t
k_p Pyrolysis coefficient
m_F Fuel load of equivalent wood, kg
$\dot{m}_f$ Rate of burning, kg/min
$\dot{m}_f''$ Rate of fuel burning per floor area, kg/(m^{2}s)
m_F'' Fire load per unit floor area (= m_F/A_F), kg/m^2

O Opening factor $\left(=\frac{A_o\sqrt{H_o}}{A_t}\right)$, $m^{1/2}$
q_x'' Fire load density, MJ/m^2
$\dot{Q}$ Heat Release Rate, MW
$\dot{Q}_{max}$ Maximum rate of heat release, MW
$\dot{Q}_{max,v}$ Maximum rate of heat release for ventilation controlled fire, MW
$\dot{Q}_{max,f}$ Maximum rate of heat release for fuel controlled fire, MW
Q'' Fire load density, MJ/m^2.
t Time, min
t_1 Time at the end of growth stage, min
t_2 Time at the end of fully developed stage, min
t_3 Time at the end of decay stage, min
t_m Time, where maximum temperature occurs, min
t* Fictitious time, h
t_g* Growth coefficients, s
t_d* Decay coefficients, s and modified fire duration, h
T Furnace temperature, °C
T_{gm} Maximum temperature generated above ambient temperature, °C
T_{gmcr} Maximum fire temperature in the critical region (transition from ventilation to fuel control) of compartment fires, °C
T_o Initial furnace temperature, °C
T_∞ Ambient temperature, °C
T_1 Temperature at time t_1, °C
T_2 Temperature at time t_2, °C
T_3 Temperature at time t_3, °C
W Width of the compartment, m

Greek

δ Shape constant for temperature-time curve.
χ combustion efficiency
η_1 Reverse of opening factor ($=1/F_{o2}$), $m^{-1/2}$
η Reverse of opening factor (=1/O) $m^{-1/2}$
η_{cr} is the value of η in critical region, $m^{-1/2}$
ϕ Surface area ratio of fuel = A_F/m_F m^2/kg.
ρ Density of the compartment boundaries, kg/m^3
τ Fire duration in min
θ Modification factor
φ Fire load mass density $\left(= m_F \big/ \sqrt{A_o A_T}\right)$, kg/m^2

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