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Fire Temperature — Time Relations

by T.T. Lie

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ABSTRACT

Analytical expressions are given that describe characteristic temperature curves as a function of the significant parameters for various fire conditions commonly met with in practice. Expressions are also given for the standard fire curve used in North America and for the fire curve adopted by the International Organization for Standardization (ISO). The curves are intended as basic fire exposure curves for fire resistive design.

RÉSUMÉ

L'auteur présente des expressions analytiques décrivant les courbes de température caractéristiques en fonction des paramètres significatifs pour diverses conditions d'incendie que l'on retrouve couramment en pratique. On donne également des expressions pour la courbe d'incendie standard utilisée en Amérique du Nord et pour la courbe d'incendie adoptée par l'Organisation internationale de normalisation (ISO). Les courbes d'exposition au feu sont destinées à servir de base pour la conception résistante au feu.

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FIRE TEMPERATURE-TIME RELATIONS

T. T. Lie

INTRODUCTION

The intensity and duration of fire in buildings can vary in a wide range, and several studies have been carried out to investigate the determining factors. At present it is possible to estimate the temperature course of fire in enclosures under various conditions, provided the values of the parameters that determine it are known.

Several of these parameters, however, such as amount and surface area of the combustible materials, are unpredictable as they change with time and often vary from compartment to compartment in a building. It is not possible, therefore, to know at the time a building is erected the temperature course of a fire to which objects in that building might be exposed during its service life.

It is possible, however, to indicate for any enclosure a temperature-time curve that, with reasonable likelihood, will not be exceeded during the lifetime of the building. Such curves are useful as a basis for the fire-resistive design of buildings. They can also facilitate studies of fire resistance of building components exposed to fires of various intensity and duration.

In this chapter, analytical expressions will be given that describe characteristic temperature curves as a function of the significant parameters for various fire conditions commonly met with in practice.

Expressions will also be given for the standard fire curve used in North America, and for the fire curve adopted by the International Organization for Standardization (ISO).

FIRE TEMPERATURES

The temperature course of a fire in an enclosure may be divided into three periods:

1. The growth period,
2. The fully developed period, and
3. The decay period.

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Fig. 3-5.1. Idealized temperature course of fire.

These periods are illustrated in Figure 3-5.1, where an idealized fire temperature course is shown. During the growth period, heat produced by the burning materials is accumulated in the enclosure. As a result, other materials may be heated so severely that they also ignite. At this stage of the fire, the gas temperatures rise very quickly to high values. The rather sudden ignition of materials in all parts of the room is called "flash over." After the flash over, the fully developed period starts. Because the temperatures in the enclosure are relatively low in the growth period, their influence on the fire resistance of structural members is negligible. In fire resistance studies, therefore, the growth period can be disregarded. Actual risk of failure of structural members or fire separations begins when the fire reaches the fully developed stage. In this stage, temperatures of about 1000°C or higher can be reached, and the heat transferred from the fire to structural members may substantially reduce their strength. This risk also exists in the decay period.

Parameters Determining the Fire Temperature Course

The most important parameters that determine the temperature course of a fire were first shown by Kawagoe and Sekine¹ and by Odeen,² who estimated the heat balance for fires in enclosed spaces. Usually part of the heat produced during a fire in an enclosure will be absorbed by the walls and contents, a part by the gases, and a part will be lost

- q_r = RADIATION LOSSES
 q_i = HEAT CONTENT OF INFLOWING AIR
 q_l = HEAT CONTENT OF OUTFLOWING GASES
 q_w = HEAT LOSSES TO THE WALLS
 q_c = HEAT PRODUCED BY COMBUSTION
 q_g = RISE OF THE HEAT CONTENT OF THE GASES IN THE ENCLOSURE

Fig. 3-5.2. Heat balance for an enclosure during a fire.

by radiation and convection from windows. (See Figure 3-5.2.) There is also loss of chemical energy that could have been released as heat because of outflow of unburned gases, which burn outside the enclosure. In addition, there is loss of unburned particles.

To be able to determine the temperature course, it is necessary to know at each moment during a fire, the rate at which heat is produced and the rate at which heat is lost to exposed materials and surroundings. Several of the parameters that determine heat production and heat losses, such as material properties, room dimensions, wall construction, window area, and emissivity of the flames and exposed materials, can be determined with reasonable accuracy. Others that are known approximately are the amount of gases that burn outside the room, the loss of unburned particles through windows, and the temperature differences in the room.

There are several parameters, however, whose magnitude cannot be predicted. Usually they change with time, and therefore, their value at the time of occurrence of a fire is determined by chance. Such parameters include the amount, surface area, and arrangement of the combustible contents, velocity and direction of wind, and the outside temperature. The influence of wind³ and that of fire load can be substantial. Surveys show, for instance, that the variability of fire loads in various types of buildings is such that deviations in the order of 50 percent or more from the most probable fire load are common.⁴ As a consequence, variability of fire load alone may easily cause deviations from the most probable temperature course of hundreds of degrees centigrade in temperature and 50 percent or more in fire duration.

POSSIBLE FIRE SEVERITIES

Owing to the substantial influence of uncertain factors, it is impossible to predict accurately the temperatures to which building components will be exposed during their service life. Even if the analysis to predict fire temperature

courses in enclosures is perfect, it is very improbable that a certain predicted temperature course will occur.

The fire temperature to which building components will most likely be exposed during the use of a building is the relatively low temperature of a fire that has been extinguished before it reaches the fully developed stage. There is a small although not insignificant change of occurrence of a fully developed fire. In this case, and assuming that the fire cannot be influenced by action of the fire brigade, the fire will be controlled either by the surface area of the materials that can participate in the burning or by the rate of air supply through the openings.^{2,5}

Whether the fire will be largely controlled by surface area or ventilation depends on the amount of combustible contents. Unless its quantity, surface area, and arrangement are controlled, or the size of the windows and floor area made such that the possibility of a ventilation-controlled fire becomes remote,^{6,7} the type of fire that may occur is unpredictable. According to statistical data, combustible contents of 10 to 60 kg per m² of floor area are normal, and there is a considerable probability of enclosures having a combustible content of 40 to 100 kg/m².⁴ It is probable that in the latter range, as confirmed by experiments,^{5,8} the fire will be mainly ventilation controlled, even when large window openings are present. It is likely that the greater the space behind the windows, or to a certain extent, the deeper the enclosure, the more material or surface area it will contain and therefore the greater will be the probability of a ventilation-controlled fire. Usually a ventilation-controlled fire is the more severe fire, and because of the substantial probability of its occurrence, it is common to base fire resistance requirements for buildings on the assumption that fire severities will be controlled by ventilation.

CHARACTERISTIC TEMPERATURE CURVES

It is possible to indicate for any enclosure a characteristic temperature-time curve whose effect, with reasonable likelihood, will not be exceeded during the lifetime of the building. Such curves are useful as a basis for the fire-resistance design of buildings. They can also facilitate studies of fire resistance of building components exposed to fires of different severity.

There are several reports which present the temperature course of fires in fully developed and decay periods.^{1,2,7,9,10} In all of these studies a procedure is followed in which the fire temperatures are determined by solving a heat balance for the enclosure under consideration.

For the fully developed period and ventilation-controlled fires, there is reasonable agreement in the temperatures found in the various studies, except for rather shallow rooms of limited size. In the latter case, the amount of combustible gases that burn outside may increase in such a way with increasing ventilation that the temperature decreases.⁷

There is less agreement in the results of the various studies for the decay period, partly due to the complexity of the processes that determine the temperature in that period. So far, rates of decay of temperature can only be established empirically or by making conservative or highly idealized assumptions. Because of the different approaches in deriving the rates of decay, there is a rather wide spread in the results of the various studies. Fortunately the influence of temperature variation in the decay period on the maximum temper-

Fig. 3-5.3. Temperature curves for fire resistance design.

atures reached in building components is relatively small.¹¹ For the purpose of deriving a temperature-time curve that, with reasonable probability, will not be exceeded during the lifetime of the building, it will be sufficient to use a curve that only approximately reflects the effect of heating in the decay period. This is further explained in Figure 3-5.3.

In Figure 3-5.3 curve a illustrates a fire temperature curve derived theoretically for a certain building. The probability of occurrence of a fire with a more severe effect than shown by the curve is once in 50 years. Curve b illustrates a fire temperature curve for the same building, but it is assumed that the rate of burning remains constant until all combustible materials are consumed, whereupon the fire temperature drops linearly to room temperature. Although curve b differs in shape from curve a, their heating effect is approximately the same. If curve b is used instead of curve a, the probability of occurrence of a more severe fire than that represented by the relevant curve may change somewhat, for instance, from once in fifty years to somewhat more or less than fifty years. In practice this means that virtually the same fire safety will be provided whether curve a or curve b is used for the fire-resistance design of a building. The use of curve b instead of curve a has the advantage that it is easier to define.

Expressions for Characteristic Temperature Curves

In the following, analytical expressions are given that describe characteristic temperature curves as a function of the significant parameters for various fire conditions commonly met with in practice. For the fully developed period, the derivation of these curves will be based on the temperature curves for ventilation-controlled fires calculated according to the method described by Kawagoe and Sekine.¹

The temperatures attained in ventilation-controlled fires are described (in addition to the thermal properties of the material bounding the enclosure) by a parameter, known as the opening factor F

$$F = \frac{A\sqrt{H}}{A_T} \quad (1)$$

where A is area of the openings in the enclosure, H is height of the openings, and A_T is area of the bounding surfaces (walls and floor and ceiling). The method of calculating $A\sqrt{H}$ for openings of unequal height is described in References 9 and 11.

The rate of burning, R , of the combustible materials in the enclosure is given by

TABLE 3-5.1 Thermal Properties of the Enclosure

Factor	Description
k	Thermal conductivity of bounding material: 1.16 W/m K for a heavy material ($\rho \geq 1600$ kg/m ³), 0.58 W/m K for a light material ($\rho < 1600$ kg/m ³)
ρc	Volumetric specific heat of bounding material: 2150×10^3 J/m ³ K for a heavy material ($\rho \geq 1600$ kg/m ³), 1075×10^3 J/m ³ K for a light material ($\rho < 1600$ kg/m ³)
A_T	Total inner surface area bounding the enclosure, including window area: 1000 m ²
H	Window height: 1.8 m
ϵ	Emissivity for radiation transfer between hot gases and inner bounding surface of the enclosure: 0.7
α_c	Coefficient of heat transfer by convection between fire and inner bounding surface area: 23 W/m ² K
α_u	Coefficient of heat transfer between outer bounding surface area and surroundings: 23 W/m ² K
c	Specific heat of combustion gases: 1340 J/Nm ³ C
G	Volume of combustion gas produced by burning 1 kg of wood: 4.9 Nm ³ /kg
q	Heat released in the enclosure by burning 1 kg of wood: 10.77×10^6 J/kg
T_0	Initial temperature: 20°C
V	Volume of enclosure: 1000 m ³
Δx	Thickness of elementary layers of bounding material: 0.03 m
Δt	Time increment: 0.0004167 hr
D	Thickness of bounding material: 0.15 m

* It can be shown that the influence of the volume of the enclosure on the fire temperature is negligible.

$$R = 330 A\sqrt{H} \quad (2)$$

and, thus, if Q is the fire load per unit area of the surfaces bounding the enclosure, the duration of the fire, τ , is determined by

$$\tau = \frac{QA_T}{330 A\sqrt{H}} = \frac{Q}{330 F} \quad (3)$$

For given thermal properties of the material bounding the enclosure, the heat balance can be solved for the temperature as a function of the opening factor F . Besides depending on F , the temperature course is also a function of the thermal properties of the material bounding the enclosure.

In this study, two materials have been chosen as representative bounding materials: one with thermal properties resembling those of a heavy material (high heat capacity and conductivity) and one representing those of a light material (low heat capacity and conductivity). The thermal properties of these materials are given in Table 3-5.1. In practice, materials with a density of approximately 1600 kg/m³ or more, e.g., normal-weight concretes, sand lime brick, and most clay bricks, can be considered as belonging to the group of heavy material. Those with a density of less than 1600 kg/m³, e.g., lightweight and cellular concretes and plasterboard, can be regarded as belonging to the group of light materials.

Using the method described in Reference 11, the temperature course of fires in enclosures has been calculated for the two chosen bounding materials and for various values of the opening factor.¹² The conditions for which the calculations have been performed are shown in Table 3-5.1 and the results of the calculations in Figures 3-5.4 and 3-5.5. The

Fig. 3-5.4. Temperature-time curves for ventilation-controlled fires in enclosures bounded by dominantly heavy materials ($\rho \geq 1600 \text{ kg/m}^3$), calculated for various opening factors by solving a heat balance for the enclosure.

curves in these figures were used as a basis for the derivation of temperature curves for fire-resistance design. It was found that these temperature curves could be reasonably described by the expression

$$T = 250(10F)^{0.1/F^{0.5}} e^{-F^2 t} [3(1 - e^{-0.6t}) - (1 - e^{-3t}) + 4(1 - e^{-12t})] + C \left(\frac{600}{F} \right)^{0.5} \quad (4)$$

where T = the fire temperature in $^{\circ}\text{C}$, t = time in hr, F = opening factor in $\text{m}^{1/2}$, and C = a constant taking into account the influence of the properties of the boundary material on the temperature. $C = 0$ for heavy materials ($\rho \geq 1600 \text{ kg/m}^3$), and $C = 1$ for light materials ($\rho < 1600 \text{ kg/m}^3$).

The expression is valid for

$$t \leq \frac{0.08}{F} + 1 \quad (5)$$

and

$$0.01 \leq F \leq 0.15 \quad (6)$$

If $t > (0.08/F) + 1$, a value of $t = (0.08/F) + 1$ should be used. If $F > 0.15$, a value of $F = 0.15$ should be used.

The temperature-time curves evaluated from Equation 4 and those obtained by solving the heat balance for the

Fig. 3-5.5. Temperature-time curves for ventilation-controlled fires in enclosures bounded by dominantly light materials ($\rho < 1600 \text{ kg/m}^3$), calculated for various opening factors by solving a heat balance for the enclosure.

Fig. 3-5.6. Comparison between temperature-time curves obtained by solving a heat balance and those described by an analytical expression for ventilation-controlled fires in enclosures bounded by dominantly heavy materials ($\rho \geq 1600 \text{ kg/m}^3$).

enclosure are shown in Figures 3-5.6 and 3-5.7 for various values of the opening factor.

It is seen that with the aid of the analytical expression, temperature curves can be developed that reasonably describe the curves derived from solving the heat balance.

As discussed previously, the temperatures in the decay period are more difficult to calculate due to the complexity of the processes that determine the temperature in this period. On the other hand, if the temperature variations are not very large, the influence of such variations in the decay period on the temperature attained in exposed building components is in general relatively small. Therefore, describing the temperature course in the decay period by a temperature-time relation that approximately reflects the decrease of temperature in this period is sufficient.

According to experimental data of Kawagoe⁸ the rate of temperature decrease of a fire with a fully developed period of less than one hour is roughly 10°C per minute, and that of a fire with a fully developed period of more than one hour is 7°C per minute. The Swedish code assumes a rate of decrease of 10°C per minute irrespective of the duration of the fully developed period of the fire.⁹ A comparison with semi-empirical data developed by Magnusson and Thelandersson⁹ shows that the assumption of a rate of decrease of 10°C per minute is too fast for fires of long duration and too slow for fires of short duration. According to Harmathy,⁷ who studied several experimental fires of relatively short duration,^{13,14} the rate of decrease of temperature for such fires is in the order of 15 to 20°C per minute.

Fig. 3-5.7. Comparison between temperature-time curves obtained by solving a heat balance and those described by an analytical expression for ventilation-controlled fires in enclosures bounded by dominantly light materials ($\rho < 1600 \text{ kg/m}^3$).

Fig. 3-5.8. Characteristic temperature curves for various fire loads, Q , (opening factor, $F = 0.05 \text{ m}^{1/2}$, heavy bounding material).

In general, the longer the duration of the fully developed period the lower the rate of decrease of temperature. Using this information the following expressions have been derived for the temperature course of fire in the decay period

$$T = -600\left(\frac{t}{\tau} - 1\right) + T_r \quad (7)$$

with the condition

$$T = 20 \quad \text{if } T < 20^\circ\text{C} \quad (8)$$

In the above equations T = fire temperature, τ = time at which the decay starts as given by Equation 3, t = time under consideration ($t > \tau$), and T_r = temperature given by Equation 4 at the time $t = \tau$.

The temperature curves obtained from Equations 4 and 7 are illustrated in Figure 3-5.8 for various fire loads and an opening factor of $0.05 \text{ m}^{1/2}$. In Figure 3-5.9 the influence is shown of the openings on the fire temperature course. It can be seen that the fire load determines the duration of the fire, whereas the openings determine both the duration and the intensity of the fire. In Figure 3-5.10 a characteristic temperature curve is compared with the temperatures measured at several places in a room during an experimental fire.¹ It is seen that the curve developed from the analytical expression reasonably characterizes the temperatures obtained during the experimental fire. It is somewhat conservative but satisfactory to use as a design curve for fire resistance.

STANDARD FIRE CURVE

In studies of fire resistance, it is common to expose building elements to heating in accordance with a standard

Fig. 3-5.9. Influence of opening factor on fire temperature course.

Fig. 3-5.10. Comparison of design temperature curves derived from analytical expressions with temperatures measured during an experimental fire (fire load per unit internal area of the bounding surfaces $Q = 18.75 \text{ kg/m}^2$, opening factor $F = 0.047 \text{ m}^{1/2}$, heavy bounding material).

temperature-time relation. The standard temperature-time curves used in various countries are shown in Figure 3-5.11. It can be seen that there are no significant differences between the various standard curves. The values of the curve adopted by ISO¹⁵ are given in Table 3-5.2. Those used in North America¹⁶ are given in Table 3-5.3.

There are also analytical expressions for several of the standard curves. The expression that describes the ISO curve is

$$T - T_0 = 345 \log_{10}(8t + 1) \quad (9)$$

where t = time in minutes, T = fire temperature in $^\circ\text{C}$, and T_0 = initial temperature in $^\circ\text{C}$.

For the curve used in North America, several analytical expressions exist.¹⁷ One of the expressions is of the form of a sum of exponential functions

$$T - T_0 = a_1(1 - e^{a_2 t}) + a_3(1 - e^{a_4 t}) + a_5(1 - e^{a_6 t}) \quad (10)$$

where $a_1 = 532$ for $^\circ\text{C}$, 957 for $^\circ\text{F}$; $a_2 = -186$ for $^\circ\text{C}$, -334 for $^\circ\text{F}$; $a_3 = 820$ for $^\circ\text{C}$, 1476 for $^\circ\text{F}$; $a_4 = -0.6$; $a_5 = -3$; $a_6 = -12$.

Fig. 3-5.11. Standard fire temperature-time relations used in various countries for testing of building elements.

TABLE 3-5.2 Standard Temperature-Time Relation According to ISO 834¹⁵

Time h:min	Temperature °F	Temperature °C	Time h:min	Temperature °F	Temperature °C
0:00	68	20	3:10	1,938	1,059
0:05	1,000	538	3:20	1,950	1,066
0:10	1,300	704	3:30	1,962	1,072
0:15	1,399	760	3:40	1,975	1,079
0:20	1,462	795	3:50	1,988	1,086
0:25	1,510	821	4:00	2,000	1,093
0:30	1,550	843	4:10	2,012	1,100
0:35	1,584	862	4:20	2,025	1,107
0:40	1,613	878	4:30	2,038	1,114
0:45	1,638	892	4:40	2,050	1,121
0:50	1,661	905	4:50	2,062	1,128
0:55	1,681	916	5:00	2,075	1,135
1:00	1,700	927	5:10	2,088	1,142
1:05	1,718	937	5:20	2,100	1,149
1:10	1,735	946	5:30	2,112	1,156
1:15	1,750	955	5:40	2,125	1,163
1:20	1,765	963	5:50	2,138	1,170
1:25	1,779	971	6:00	2,150	1,177
1:30	1,792	978	6:10	2,162	1,184
1:35	1,804	985	6:20	2,175	1,191
1:40	1,815	991	6:30	2,188	1,198
1:45	1,826	996	6:40	2,200	1,204
1:50	1,835	1,001	6:50	2,212	1,211
1:55	1,843	1,006	7:00	2,225	1,218
2:00	1,850	1,010	7:10	2,238	1,225
2:10	1,862	1,017	7:20	2,250	1,232
2:20	1,875	1,024	7:30	2,262	1,239
2:30	1,888	1,031	7:40	2,275	1,246
2:40	1,900	1,038	7:50	2,288	1,253
2:50	1,912	1,045	8:00	2,300	1,260
3:00	1,925	1,052			

The extreme deviation from the values given in Table 3-5.2 are -26°C at 45 min; $+48^{\circ}\text{C}$ at 3.5 hours; and -78°C at 8 hours.

This form is suitable for use in analytical heat flow calculations, because when it is used as a boundary condition the heat transfer equations are integrable.

A set of expressions that more accurately approximate the values given in Table 3-5.2 is

$$T - T_0 = a_1 \tanh a_4 t + a_2 \tanh a_5 t + a_3 \tanh a_6 t, \quad t < 2 \quad (11)$$

$$T - T_0 = 906.7 + 41.67t, \quad t \geq 2 \text{ for } ^{\circ}\text{C} \quad (12)$$

$$T - T_0 = 1632 + 75t, \quad t \geq 2 \text{ for } ^{\circ}\text{F} \quad (13)$$

TABLE 3-5.3 Standard Fire Temperature-Time Relation Used in North America (NFPA No. 251)¹⁶

Time in Minutes	Temperature rise of fire ($^{\circ}\text{C}$)
0	0
5	556
10	659
15	718
30	821
60	925
90	986
120	1,029
180	1,090
240	1,133
360	1,193

where $a_1 = 580$ for $^{\circ}\text{C}$, 1044 for $^{\circ}\text{F}$; $a_2 = -276.8$ for $^{\circ}\text{C}$, -498.2 for $^{\circ}\text{F}$; $a_3 = 714.4$ for $^{\circ}\text{C}$, 1286 for $^{\circ}\text{F}$; $a_4 = 0.8429$; $a_5 = 0.9736$; $a_6 = 8.910$.

The maximum duration of the temperature, given by Equations 11, 12, and 13, from the values tabulated in Table 3-5.2 is -7°C at 40 min.

Another temperature-time relation, given in Reference 18, has the form

$$T - T_0 = a[1 - \exp(-3.79553\sqrt{t})] + 306.74\sqrt{t} \quad (14)$$

where $a = 750$ for $^{\circ}\text{C}$, 1350 for $^{\circ}\text{F}$; and $t =$ time in minutes.

This expression is frequently used and is a reasonably accurate approximation of the relation between temperature and time given in Table 3-5.2.

NOMENCLATURE

- A area of the openings in the enclosure, m^2
- A_T area of the internal bounding surfaces, m^2
- C constant
- F opening factor, $\text{m}^{1/2}$
- H height of openings in the enclosure, m
- Q fire load per unit area of the internal bounding surfaces, kg/m^2
- R rate of burning, kg/hr
- T fire temperature, $^{\circ}\text{C}$
- T_τ fire temperature at the time τ , $^{\circ}\text{C}$
- t time, hr
- τ time at which the temperature starts to decline, hr

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