STATENS
PROVNINGSANSTALT
National Testing Institute

Fire Technology

Ulf Wickström

TEMPERATURE CALCULATION OF INSULATED STEEL COLUMNS EXPOSED TO NATURAL FIRE

Technical Report SP-RAPP 1981:15
Borås, Sweden 1981

NATIONAL TESTING INSTITUTE
Division of Fire Technology

SP-RAPP 1981:15

P.O. Box 857, S-501 15 BORÅS
Tel.int. + 46 33-10 20 00

Submitted to Fire Safety Journal

ULF WICKSTRÖM

TEMPERATURE CALCULATION OF INSULATED
STEEL COLUMNS EXPOSED TO NATURAL FIRE

BORÅS, SWEDEN 1981

SUMMARY

A method is developed, suitable for design purposes, which allows approximate post-flashover compartment fire temperature to be plotted versus time in one curve, the *general natural fire curve*; time is then modified or scaled for the consideration of ventilation conditions and wall properties. In the analysis the common assumptions of constant and ventilation controlled combustion, uniform temperature, and wall losses proportional to the thermal inertia are made.

The general natural fire curve is given an analytical expression, which is then used for calculating temperature in fire exposed insulated columns by a simple integration procedure. The results are plotted in handy diagrams and temperatures received in columns exposed to natural fires and standard fires according to ISO 834 are compared.

CONTENTS

	<u>Page</u>
INTRODUCTION	1
HEAT BALANCE OF A FIRE COMPARTMENT	3
TEMPERATURE CALCULATION IN STRUCTURES EXPOSED TO NATURAL FIRES	7
Insulated steel columns	7
Limited fires	8
Equivalent fire duration	11
CONCLUSIONS	12
ACKNOWLEDGEMENTS	14
NOMENCLATURE	15
REFERENCES	16

INTRODUCTION

The internationally prevalent fire engineering design of structures and structural elements is characterized by a procedure based on a classification system and an associated standardized fire test, the ISO 834 with fixed heating conditions. There is, however, an increasing interest in many countries to derive the fire exposure from real or natural fire conditions. For such cases the post-flashover phase of a fire is considered. In the Swedish building code this approach has been possible for several years as an alternative to a system based on a standardized fire exposure. Various time-temperature curves of total fires are derived by calculation where ventilation condition, fuel load and thermal properties of surrounding structures are considered. The major assumptions in the calculation model are [1-3]

- the fires are ventilation controlled
- the fuel burns inside the compartment
- the gas temperature is uniform in the fire compartment
- the compartment is ventilated by natural convection

The above assumptions are used in this paper for the study of the heat balance equation of a fire compartment. The paper then applies the concept to the temperature response of insulated steel columns.

The fire temperature in the heating phase of a fire increases with a rise of temperature in the surrounding walls (including ceiling and floor). At the same time the heat flux rate to the wall surfaces declines and finally becomes negligible. In theory the ultimate fire temperature will therefore be little influenced by either wall properties or ventilation conditions.

The rate of temperature rise in the beginning of a fire is, however, proportional to the square of the opening factor $A\sqrt{h}/A_t$ divided by the thermal inertia $\sqrt{k\rho c}$ of the walls. By normalizing for a standard fire compartment with an opening factor $(A\sqrt{h}/A_t)_{0.04} = 0.04 \text{ m}^{1/2}$ and a thermal inertia $(\sqrt{k\rho c})_A = 1\,165 \text{ W s}^{1/2}/\text{m}^2\text{K}$, the fire compartment time factor γ^2 and the general natural fire curve are defined. Temperature is thus a function of the modified time $t^* = \gamma^2 t$.

By plotting temperature versus modified time for various opening factors, the resultant curves coincide and thereby verify this theory, particularly for relatively long duration fires. The curve thus obtained will be called the general natural fire curve. By curve-fitting it is expressed analytically in a simple exponential formula. Insulated steel columns exposed to natural fires are then analyzed and closed form analytical expressions are derived for the steel temperature response. In the cooling phase of total fires a simple time versus temperature relation is assumed and the maximum steel temperature is calculated and plotted in diagrams.

HEAT BALANCE OF A FIRE COMPARTMENT

Since the theory of post-flashover fires has been amply reported elsewhere, no discussion of this theory will be made in this paper.

The heat balance of a compartment as shown in figure 1 may be written as

$$I_C = I_L + I_W + I_R \quad (1)$$

where

- I_C = rate of heat release by combustion
- I_L = rate of heat loss by convection out the fire compartment opening
- I_W = rate of heat transfer to the walls
- I_R = rate of heat radiated out the window

Figure 1. Heat flow balance of a fire compartment.

Kawagoe and Sekine [4] determined that the induced air inflow into a heated compartment can be expressed simply as $\dot{m}_a = C_o \rho \sqrt{g} A \sqrt{h}$. Here ρ is the air density, g the acceleration of gravity and C_o is a dimensionless quantity which depends on various combustion, geometry, and flow characteristics. The area of the ventilation opening is A and the height is h , (the quantity $A \sqrt{h}$ is then termed the "ventilation factor"). Since ρ and g are essentially constants and C_o is but a weak function of fire conditions, the scaling for $\dot{m}_a$ is conventionally taken as being proportional to the ventilation factor. Thus the heat loss rate by convection out the opening may be expressed as

$$I_L = C_1 A \sqrt{h} \theta_f \quad (2)$$

where C_1 is a constant encompassing the influence of air flow characteristics and the specific heat capacity of the fire gas.

One of the assumptions is ventilation controlled combustion and since the heat gained from a given amount of oxygen is approximately constant, even for an incomplete combustion [5], the rate of heat release in the compartment is proportional to the ventilation factor:

$$I_C = C_2 A \sqrt{h} \quad (3)$$

where C_2 is a constant.

Since the rate of the heat release term is assumed constant, the heat loss to the walls will remain the only time dependent quantity in the heat balance equation. For typical fire durations the thermal thickness of most walls is so great that the unexposed side of the walls has negligible influence on the heat flux rate on the fire exposed side, q_w .

Thus the walls are thermally semi-infinite and q_W is a function of the thermal inertia $\sqrt{k\rho c}$ of the wall material and of the heat transfer resistance at the surface. The influence of the latter is, however, small and for the sake of simplicity it is ignored in this study. Thus the wall surface temperature and the fire temperature are assumed equal. This approximation yields a somewhat lower fire temperature in the beginning of a fire.

The wall surface heat transfer rate response for a unit surface temperature rise is proportional to the thermal inertia divided by the square root of time. Hence, if the fire temperature rise $\theta(t)$ varies arbitrarily with time, the heat transfer rate is obtained by superposition (Duhamel's theorem) [6] as

$$q_W = \int_0^t \frac{\sqrt{k\rho c}}{\sqrt{\pi\xi}} \theta'(t - \xi) d\xi \quad (4)$$

Here $\theta'(t)$ denotes the time derivative of the fire temperature rise; ξ is a dummy variable.

The radiation out the window is

$$q_R = A\sigma(T_f^4 - T_o^4) \quad (5)$$

where A is the opening area of the compartment, σ the Stefan-Boltzmann constant, and T_f and T_o are fire temperature and initial temperature, respectively.

Inserting equations (2 - 5) into equation (1), followed by rearranging the heat balance equation, yields

$$C_2 = C_1 \Theta(t) + \frac{1}{\sqrt{\eta}} \int_0^t \frac{1}{Y\sqrt{\xi}} \Theta'(t - \xi) d\xi + \frac{\sigma T_f^4}{\sqrt{h}} \quad (6)$$

where $Y = (A\sqrt{h}/A_t)/\sqrt{k\rho c}$. The concept of modified time $t^* = \gamma^2 t$ is now introduced where the dimensionless fire compartment time factor γ^2 is defined by $\gamma = Y/Y_A$ where $Y_A = (A\sqrt{h}/A_t)_{0.04}/(\sqrt{k\rho c})_A$. Here $(A\sqrt{h}/A_t)_{0.04} = 0.04 \text{ m}^{1/2}$; it is the standard opening factor and $(\sqrt{k\rho c})_A = 1165 \text{ W s}^{1/2}/\text{m}^2\text{K}$ is the thermal inertia of a standard wall material in a fire compartment [3].

After changing the time variables, equation (6) yields

$$C_2 = C_1 \Theta(t^*) + \frac{Y_A}{Y^2 \sqrt{\eta}} \int_0^{t^*} \frac{\Theta'(t^* - \xi)}{\sqrt{\xi}} d\xi + \frac{\sigma T_f^4}{\sqrt{h}} \quad (7)$$

Since the height h of compartment openings varies only within a small range, and the radiation term is relatively small, the influence of h on fire temperature is also small and is therefore ignored in this analysis.

An examination of equation (7) then reveals that fire temperature is a function of modified time only.

By assigning values to the constants C_1 and C_2 the fire temperature is easily computed e.g. by numerical integration. Such calculations have, however, not been carried out in connection with this study. Instead, the fire temperature for various opening factors as reported by Magnusson et al. [1,3] has been plotted versus modified time as shown in figure 2. Although there are discrepancies for low values of modified times which depend mainly on the assumption of negligible heat transfer resistance, the curves for various opening factors almost coincide.

For design purposes a curve, the general natural fire curve, has been defined, and by curve fitting an analytical expression has been found

$$\theta_f(t^*) = \sum_{i=0}^3 B_i \exp(-\beta_i t^*) \quad (8)$$

where the values for B_i and β_i are given in table 1. For comparison the ISO standard curve and the general natural fire curve for $\gamma = 1$ are plotted in figure 3. Note that temperature for the ISO standard curve is unlimited while the general natural fire curve always yields a reasonable temperature.

The concept of modified time and the general natural fire curve facilitate calculation and make it possible to attain diagrams suitable for design purposes by plotting the temperature in structures exposed to various fires. In the following sections it is shown how the temperature in fire exposed steel columns is obtained by analytical integration and how the results are plotted in diagrams.

Figure 2. Fire temperature as reported in [3] versus modified time of natural fires in compartments with wall thermal inertia $(\sqrt{k\rho c})_A$ and various opening factors $A\sqrt{h}/A_t$.

Figure 3. General natural fire curve for $\gamma=1$ and the ISO standard curve.

TEMPERATURE CALCULATION IN STRUCTURES EXPOSED TO NATURAL FIRES

Temperature in fire exposed structures of most materials can be calculated by the Fourier heat conduction equation which for one-dimensional cases reads

$$c\rho \frac{dT}{dt} = \frac{d}{dx} \left(k \frac{dT}{dx} \right)$$

If a modified time $t^* = \gamma^2 t$ is introduced, the above equation yields

$$\gamma^2 c\rho \frac{dT}{dt} = \frac{d}{dx} \left(k \frac{dT}{dx} \right)$$

Thus the fire compartment time factor γ^2 is grouped with the product $c\rho$ when calculating temperature. Therefore various compartment time factors may be considered by carrying out calculations with fictitious specific heat capacity, and the computation may thereby be reduced.

Insulated steel columns

The special case of a fire exposed insulated steel column, as shown in figure 4, will now be considered with the following assumptions:

- the material properties are constant.
- the concept of lumped heat capacity is adopted.
- the heat capacity of the insulated material is neglected.
- the temperature in the steel section is uniform.

Then the heat resistance $R = d_i / k_i A_i$ is defined, where d_i is insulation thickness, k_i heat conductivity of the insulation material, and A_i the area of the surrounding insulation per unit length of column. The heat transfer

Figure 4. Insulated steel column with thermal resistance $R = A_i d_i / k_i$ and heat capacity $Q = V_s \rho_s c_s$ per unit length.

resistance at the insulation surfaces is small and therefore neglected. The heat capacity of the steel section per unit length is $Q = c_s \rho_s V_s$, where c_s and ρ_s are the specific heat and density of steel and V_s is the steel volume per unit length of column. The product $\tau = RQ$ is termed the thermal column time constant.

The column temperature time response function for a unit fire temperature change is $\phi(t) = [1 - \exp(-t/\tau)]$. Hence the time variation of the steel temperature rise $\theta_s(t)$ of a column exposed to an arbitrary fire temperature rise $\theta_f(t)$ is obtained by superposition as

$$\theta_s(t) = \int_0^t \theta_f(t-\xi) \phi'(\xi) d\xi \quad (9)$$

where ϕ' is the time derivative of the response function.

The expression for the general natural fire as defined by equation 8 is now inserted, the integration is carried out, and the steel temperature is obtained as a function of modified time as

$$\theta_s(t^*) = \sum_{i=0}^3 \frac{B_i}{1 - \beta_i \tau^*} [\exp(-\beta_i t^*) - \exp(-t^*/\tau^*)]$$

The values for B_i and β_i are found in table 1. Thus the variation of steel temperature with modified time may be plotted as in figure 5 versus modified time with the modified column time constant $\tau^* = \gamma^2 \tau$ as parameter.

Figure 5. Steel temperature versus modified time in the heating phase of natural fires for various modified column time constants τ^* .

Table 1 Constants in the analytical expression of the general natural fire curve.

i	0	1	2	3
B ($^{\circ}\text{C}$)	1 110.0	-369.7	-200.4	-539.9
β (h^{-1})	0	0.61	4.94	23.1

Limited fires

Fire temperature as expressed by equation 8 is valid for the heating phase of a fire only. The intensity of a real fire will, however, decrease after a certain time due to depletion of the fuel or other reasons such as fire fighting activities.

Fire duration, although critical to the maximum temperature a fire exposed structure will attain, is difficult to predict. It depends on ventilation conditions, fuel geometry and fuel distribution in the compartment as well as on such fuel properties as ease of pyrolysis and heat of combustion.

Magnusson et al. [1,3] assumed fire duration to be proportional to the fuel load divided by the ventilation factor. The cooling phase time-temperature relationship was then calculated by assuming a combustion rate that was shown to give good agreement with full scale experiments.

In the ISO 834 standard, linear time temperature curves are defined for the cooling phase which can not be derived from the physical aspects of a compartment fire. In spite of this and other limitations, these curves will be used in this study for the sake of simplicity. But other cooling phase relationships could be assumed without essentially changing the calculations and type of diagrams plotted.

Figure 6 shows the ISO 834 standard curve with the cooling phase for various fire durations. For comparison the general natural curve is also plotted in the diagram. In the ISO 834 standard the temperature decrease in the cooling phase is specified as

$$\begin{array}{lll} 625 \text{ }^{\circ}\text{C/h} & \text{for} & t_d \leq 0.5 \text{ h} \\ 250 (3-t_d) \text{ }^{\circ}\text{C/h} & \text{for} & 0.5 < t_d < 2 \text{ h} \\ 250 \text{ }^{\circ}\text{C/h} & \text{for} & t_d \geq 2 \text{ h} \end{array}$$

The same linear time-temperature relationship is applied to the general natural fire curve. Steel temperature can then be calculated by integrating equation 9 in two intervals.

The steel reaches a maximum temperature after a certain modified time t_m^* which may be obtained either by derivation or, as in this case, by finding the intercept between the steel and fire gas temperature curves. The diagram in figure 7 shows the variation of temperature versus modified time for a steel column with the modified time constant $\tau^* = 3.5 \text{ h}$ exposed to a limited fire; the dashed curve is the temperature response for an unlimited fire duration.

Although the modified fire duration t_d^* for the limited fire in this case is only 0.5 h, the maximum steel temperature is not obtained until approximately one hour of the cooling phase has elapsed and $t_m^* = 1.5 \text{ h}$.

Figure 6. ISO time-temperature standard curve with cooling conditions and the general natural fire curve with the fire compartment time factor $\gamma=1$.

TEMPERATURE RISE ($^{\circ}\text{C}$) θ

Figure 7. Temperature response of a steel column with a modified time constant $\tau^* = 3.5$ h exposed to a natural fire with a modified duration $t_d^* = 0.5$ h. (The cooling phase time-temperature curve is assumed linear according to the ISO standard.)

If several similar diagrams as in figure 7 are plotted, the locus of maximum steel temperature can be found. Thus a diagram as in figure 8 in which the maximum steel temperature is plotted versus modified time t_m^* is obtained for various modified column time constants τ^* . (Only short fire durations are considered for illustration purposes). Modified fire duration t_d^* is also indicated in the diagram.

The diagram may be used for various purposes. For example, it reveals that an insulated column with the modified time constant equal to one and exposed to a fire with the modified fire duration of 0.5 h reaches a maximum steel temperature of 420°C after 1.15 h. The diagram can also be used in the opposite way that is starting with a maximum steel temperature and finding the time constant needed for a column to resist a given fire duration.

Figure 8. Maximum temperature rise of steel columns with various modified time constants τ^* exposed to natural fires of various modified duration t_d^* as a function of modified time t_m^* when maximum steel temperature occurs.

Equivalent fire duration

In a situation where the available design basis permits a theoretical determination of the transient temperature fields but not of the design loadcarrying capacity of a fire exposed structure, an equivalent time of fire duration can be used [3]. The equivalent time is then defined as the fire duration of a standard test according to ISO 834 in which the steel temperature obtained in the heating phase equals the maximum temperature obtained during the cooling phase of a complete fire process. The left side of the diagram in figure 9 shows the variation of steel temperature versus fire duration according to ISO 834 for various column time constants τ . On the right side of the diagram maximum steel temperature of columns with various modified time constants τ^* exposed to total natural fire is plotted versus modified fire duration t_d^* .

Figure 9. Maximum temperature rise of steel columns of various time constants τ exposed to the ISO standard fire as a function of time t (to the left). Maximum temperature of steel columns of various modified time constants τ^* exposed to total natural fires as a function of modified fire duration t_d^* (to the left).

CONCLUSIONS

This study of the fire compartment heat balance has shown that the post-flashover temperature of natural fires characterized by opening factors and wall properties is a function of modified time only.

The theory was verified by plotting the fire temperature as defined in the Swedish Steel Manual [3] versus modified time and by obtaining curves of various opening factors which show little discrepancy. The modified time was normalized to the case of a natural fire of a standard compartment opening factor equal to $0.04 \text{ m}^{1/2}$ and the walls with a thermal inertia equal to $1165 \text{ W}_s^{1/2}/\text{m}^2\text{K}$. The obtained curve is similar to the ISO 834 standard curve, particularly for short fire duration.

The temperature in insulated steel columns exposed to natural fire is analyzed assuming lumped heat capacity. The thermal response was then characterized by the column time constant and the steel temperature was calculated and plotted versus modified time with a modified column time constant as the only parameter.

The concept of modified time facilitates calculation and makes it possible, in many cases, to put forth a compact presentation of temperature. It also provides the basis for an understanding of the influence of the two main parameters for predicting fire temperature, namely, opening factors and thermal inertia of the walls.

This report considers only insulated steel columns for which, as has been shown, an analytical expression for the temperature response has been established. The same method, although likely to be more complicated, can also be used for other structures. Useful diagrams in which modified time is an important variable have already been prepared for predicting the approximate temperature in concrete structures exposed to real fires [9].

ACKNOWLEDGEMENTS

Thirapong Varangoon was most helpful with the calculation work of this paper. His contribution to the design and plotting of the diagrams is also greatly appreciated. The assistance of Cecile Grant in editing this paper is gratefully acknowledged.

NOMENCLATURE

A	=	area, opening area (m^2)
A_t	=	surrounding area (m^2)
C_0, C_1, C_2	=	constants
c	=	specific heat capacity (J/kg K)
g	=	acceleration of gravity (m/s^2)
h	=	opening height (m)
I	=	rate of heat (W)
k	=	conductivity (W/m K)
R	=	heat resistance (K/W)
Q	=	heat capacity (Ws/K)
T	=	temperature (K)
t	=	time (s, h)
V	=	volume (m^3)

GREEK LETTERS

γ	=	square root of compartment time factor (-)
ρ	=	density (kg/m^3)
σ	=	Stefan Boltzmann constant ($W/m^2 K^4$)
θ	=	temperature rise $T-T_0$ ($^{\circ}C, K$)
τ	=	time constant (s, h)

SUBSCRIPTS

C	=	by combustion
d	=	duration
f	=	fire
i	=	insulation
L	=	by convection
m	=	maximum
R	=	by radiation
s	=	steel
W	=	walls
o	=	ambient, initial

SUPERSCRIPT

*	=	modified
---	---	----------

REFERENCES

- [1] Magnusson, S-E., Thelandersson, S., *Acta Polytechnica Scandinavica*, Civil Eng. Bldg. Const. Ser. No. 65, 1970; or Temperature-time Curves of Complete Process of Fire Development, *Bulletin 19*. Division of Struct. Mech. and Conc. Constr., Lund Inst. of Tech., Lund, 1970.
- [2] Magnusson, S-E., Thelandersson, S., Comments on Rate of Gas Flow and Rate of Burning for Fires in Enclosures, *Bulletin 19*. Division of Struct. Mech. and Conc. Constr., Lund Inst. of Tech., Lund, 1971.
- [3] Pettersson, O., Magnusson, S-E., Thor, J., *Fire Engineering Design of Steel Structures*. Stålbyggnadsinstitutet, Stockholm, 1976.
- [4] Kawagoe, K., Sekine, T., Estimation of Fire Temperature-Time Curve in Rooms, *BRI Occasional Report 11*. Building Research Institute, Tokyo, 1963.
- [5] Hugget, C., *Fire and Materials*, Vol 4, No 2, 1980.
- [6] Carslaw, H.S., Jaeger, J.C., *Conduction of Heat in Solids*, 2nd ed., Oxford University, Press, 1969.
- [7] Ödeen, K., Theoretical Study of Fire Characteristics in Enclosed Spaces, *Bulletin 10*. Div of Bldg. Constr., Royal Inst. of Tech., Stockholm, 1963.
- [8] Babrauskas, V., Fire Endurance in Buildings, *Report No. UCB FRG 76-16*, Fire Research Group, Department of Civil Engineering, University of California, Berkeley, 1977.
- [9] Anderberg, C., Pettersson, O., Thelandersson, S., Wickström, U., A Manual for Analytical Fire Engineering Design of Concrete Structures, Department of Structural Mechanics, Lund Institute of Technology, Lund, (in preparation).