Fire Phenomena and Verification of Structural Fire Resistance
-Technical Basis on Structural Fire Resistance Design in Building Standards Law of Japan-

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INTRODUCTION

The building code of Japan (Building Standards Law of Japan, BSLJ, hereafter) was revised in 1998 to include functional requirements in place of detailed technical specifications of materials and constructions. Even though it is not perfect, the law has shifted towards performance-based manner. Following the changes in law, enforcement order (detailed items of regulation) and notifications (technical standards) were revised in June 2000. The major points of changes were reported by Yusa and Tsujimoto [1].

Concerning with the structural fire resistance, performance evaluation framework and a set of simplified calculation formula have been added as *Kenshoho* (verification method) for fire resistance. By using verification method, it is possible to check the adequacy of fire resistance of structural elements easily and quickly.

FUNCTIONAL APPROACH FOR FIRE RESISTANCE

Changes of BSLJ was made during 1998-2000. After the revision, it is possible to adopt functional approach in fire resistance design. The objective implied in BSLJ is to prevent;

(1) collapse due to fires that are foreseeable to take place in the building,
(2) fire spread to the buildings during fires that normally takes place around the building.

The functional requirements to satisfy the objective are;

(1) Load-bearing structural part shall sustain load throughout the complete process of fire.
(2) Building envelope (exterior walls and roofs) shall not create a gap that may penetrate flame from inside to outside
(3) Floors and internal fire walls shall not create a gap to penetrate flame nor transmit heat enough to ignite combustibles in the opposite side of fire compartment in both directions.
(4) Exterior walls shall not transmit heat enough to ignite combustibles in the building.

The above requirements are summarized in Figure 1. To examine adequacy, two kinds of fires are referred. One is the internal fire applied to structural frame (columns, beams and floors) for checking load-bearing capacity and to compartment boundaries for checking integrity (external walls and roofs) and insulation (floors and partition walls). The severity of internal fire is deemed *foreseeable*, because the fire severity depends only on the condition of the building itself. In the verification method, the calculation method of internal fire is provided.

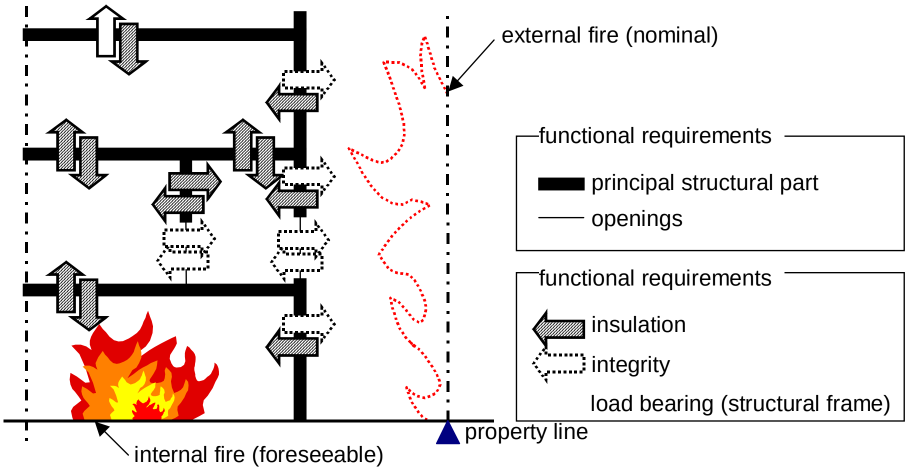

Figure 1 Functional requirements for fire resistance

The other is the external fire that may take place around the building. It is referred as *normal* (unforeseeable) fire because the severity depends on neighboring conditions that the owner of building cannot control. In the evaluation method, no calculation method for external fire is provided, but ISO 834 fire is assured.

TECHNICAL BASIS OF VERIFICATION METHOD FOR FIRE RESISTANCE

In the followings, technical basis for verification method (Route B) is discussed. Verification method includes design equations for steel, reinforced concrete and timber structures. However, focus is put only on steel structures.

General Principle

The general principle for structural fire resistance is to limit the strength reduction of load bearing elements. Namely the strength (resistance) R must be larger than the service load S throughout the fire process,

$$R(t) > S(t),\ t = 0 \sim \infty. \qquad (1)$$

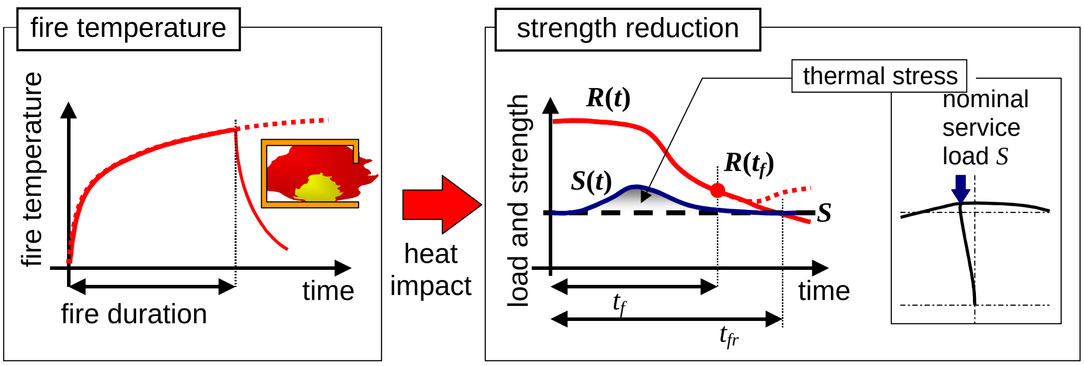

Figure 2 Typical changes in load and strength of steel column during fire

The typical changes in strength and service load are shown in Figure 2. Service load increases due to the thermal stress in the early stage of fire. As steel temperature is increased, steel strength is reduced. At the same time, thermal stress is reduced. At the critical condition of structural endpoint, thermal stress is negligible[2]. This assumption is valid for ductile steel structures designed against wind and earthquake motion. As a result of seismic resistance design, structural frame is equipped with large deformation capacity so that the frame is insensitive to perturbations caused by thermal stress in the early stage of fire.

Simplified Performance Evaluation Methods (Route B)

Following above assumption, it is practical to check the strength at the fire duration (plus some post fire period) $t = t_f$. Equation (1) could be

$$R(t_f) > S \, , \qquad (2)$$

where S is the load applied by external force. It is more convenient to express by time margin,

$$M = t_{fr}(S) - t_f > 0 \qquad (3)$$

where $t_{fr}(S)$ is the critical time to failure under the service load S .

Calculation procedure consists of two parts. The first half is to calculate the fire severity of all the potential fire rooms (Figure3). The second half is to calculate the time to failure of structural element as shown in Figure 8. In the followings, only schmatics are briefly reviewed followed by technical evidence. The detailed method of application [3] and practical design examples [4] are not described in this paper.

Calculation of Fire Severity and Duration

The calculation procedure is shown in Figure 3. First of all, fire compartment boundaries are to be fixed. At the same time, principal structural part is identified. Calculations are carried out for all the identified fire rooms.

For each fire room, total fire load (Q_r), heat release rate (q_b), fire temperature coefficient (α , where T_f=$\alpha t^{1/6}$, T_f is fire temperature) and local fire temperature coefficient (α_l , where T_{fl}=$\alpha_l t^{1/6}$, T_{fl} is local fire temperature) are calculated. Summarizing the calculation results, we can identify the fire- temperature time curve as shown in the last box of Figure 3. Two fires are identified for each room. One is an average fire temperature rise whose severity is characterized by (α , t_f). The other is a local fire temperature that takes into account of the high temperature area close to combustibles. Its severity is characterized by (α_l , 20).

(1) Total fire load (Q_r)
To calculate the fire severity and duration in accordance with Figure 3, we start with total fire load of a room. It consists of movable and fixed fire load. The characteristic values of movable are shown in Table 1. These values were selected so as to cover existing survey results of fire load. For example, characteristic value for office use is 560 MJ/m^2. As shown in Figure 4, characteristic value corresponds with suffuciently large values for office area.

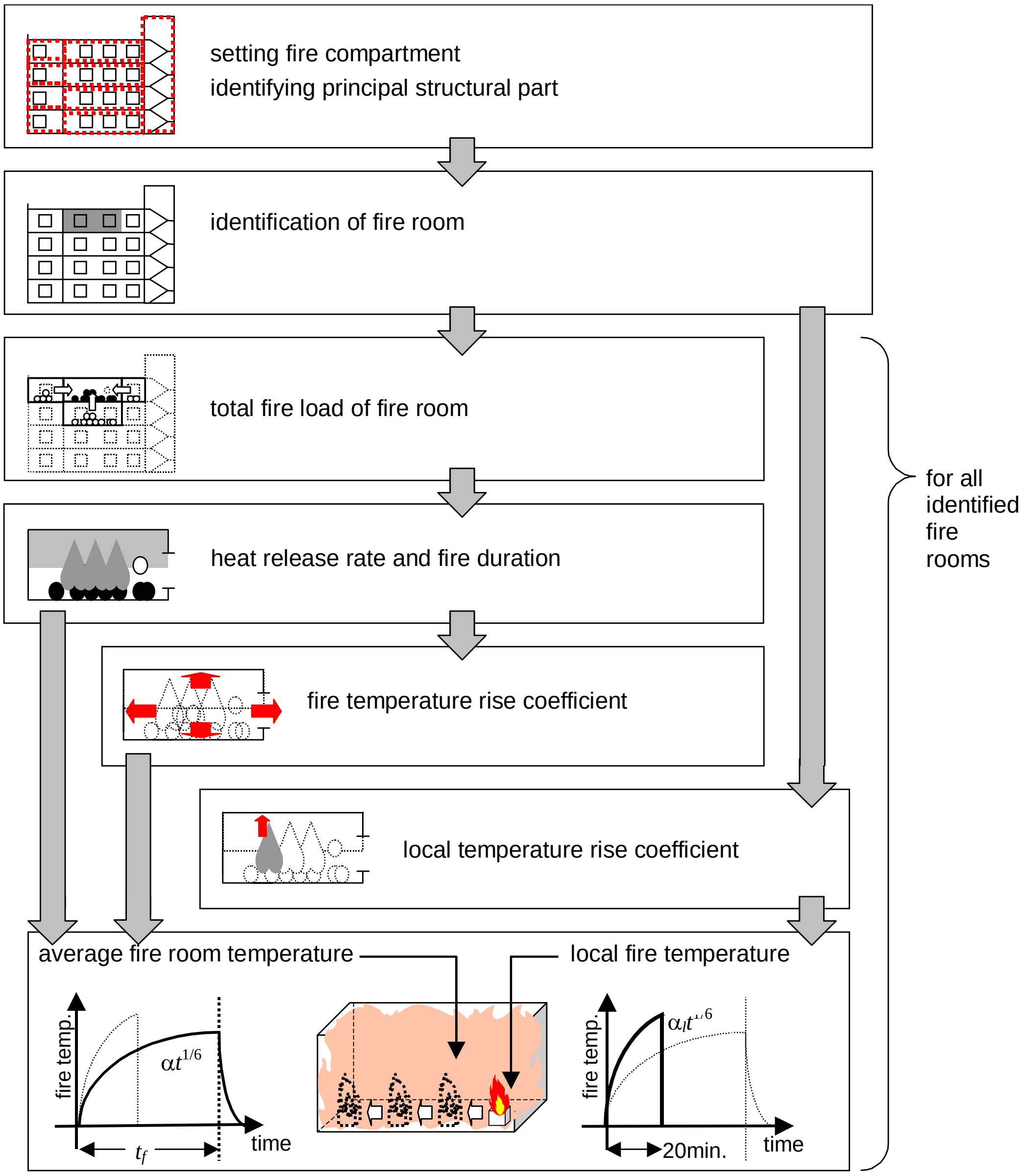

Figure 3 Calculation procedure of fire severity adopted by Route B

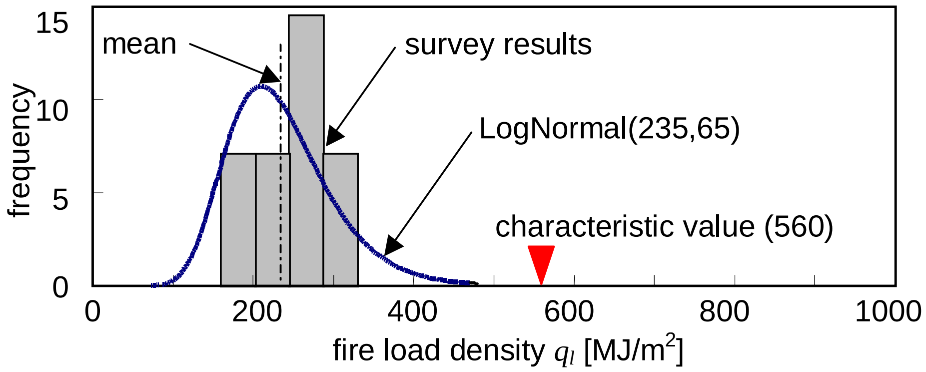

Figure 4 Charactersitic Fire Load Density and Survey Results for Office Area[5]

Table 1 Design Fire Load Density (Movable Load)

group	room usage			fire load density [MJ/m^2-floor]	structural load density [N/m^2-floor]
1	dwelling			720	1,300
	bedroom except those in dwelling			240	
2	office or similar use			560	1,800
	meeting room or similar use			160	
3	classroom			400	2,100
	athletic hall			80	
	museum or similar use			240	
4	market store or similar use	furniture shop, booksellers or similar use		960	2,400
		others		480	
	restaurant	cafeteria		240	
		others		480	
5	theater, cinema, assembly hall or similar use	seat area	fixed seating	400	2,600
			others	480	3,200
		stage		240	
6	car park	parking lot		240	3,900
		runway or similar use		32	
7	corridor, staircase or other pathways			32	-
	entrance lobby or similar use	those in group 5		160	
		others		80	
8	hoist ways or other machinery room			160	
9	roof terrace or balcony			80	1,300 (2,400)
10	warehouse or similar use			2,000	-

(2) Heat release rate (q_r)

Heat release rate is described by burning type index (air supply rate per unit fuel surface area). An empirical formula is fitted to ventilation-controlled and fuel-controlled fires of wood fuels. As shown in Figure 5, the accuracy is fair for wood fuels.

$$q_b = \begin{cases} 1.6\times\chi\times A_{fuel} & (\chi\le 0.081) \\ 0.13\times A_{fuel} & (0.081<\chi\le 0.1)\ \text{[MW]}. \\ (2.5\times\chi\times\exp(-11\times\chi)+0.048)\times A_{fuel} & (0.1<\chi) \end{cases} \quad (4)$$

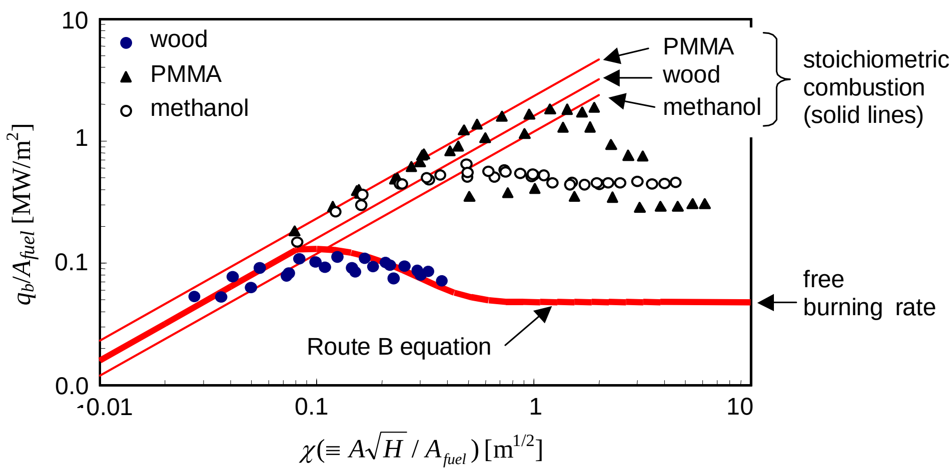

Figure 5 Heat release rate in compartment fires for various type of fuels as a function of burning type factor[6] and Route B design formula

(3) Fire duration (t_f)

Assuming constant heat release rate, the fire duration is calculated by dividing total fire load by heat release rate,

$$t_f = Q_r / 60 q_b \text{ [min.]}. \qquad (5)$$

(4) Fire temperature rise coefficient (α)

McCarffery's equation for compartment fire temperature is well studied that it can be applied also to post flashover fires [7]. It gives,

$$T_f = \alpha t^{1/6} \text{ [°C]},\ \alpha = 1{,}280 (q_b / \sqrt{\Sigma A \sqrt{k\rho c}} \sqrt{\Sigma A \sqrt{H}})^{2/3} \text{ [°C/min}^{1/6}\text{]}. \qquad (6),(7)$$

The accuracy of calculation was checked against full scale experiments. The results are summarized in Figure 6. For most cases, calculation gives conservative estimate of fire temperature rise coefficient α.

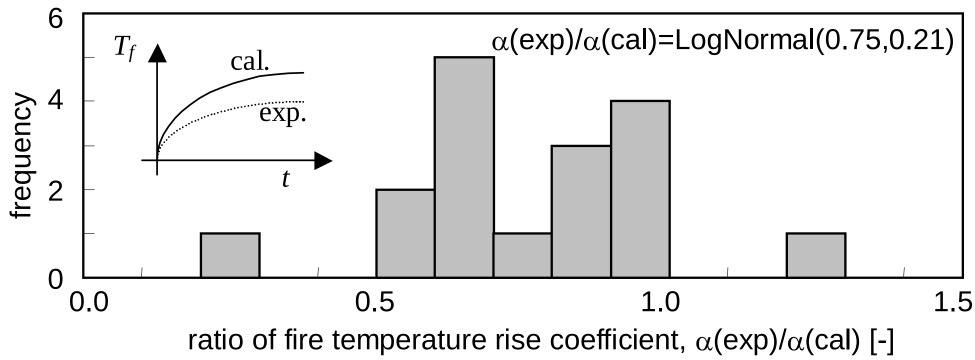

Figure 6 Comparison between experimental and calculated fire temperature rise coefficient[8]

(5) Local fire temperature rise coefficient (α_l)

Local fire temperature rise coefficient is introduced to take into account of the spatial distribution of fire temperature. As shown in Figure 3 in the last box, temperature might be considerably higher than the average temperature. The time- dependence is assumed to be similar to equation (6), but the local temperature rise coefficient (α_l) is determined to correspond with a localized fire that grows to 3MW at 20 minutes.

$$T_f = \alpha_l t^{1/6} \text{ [°C]},\ \alpha_l = \begin{cases} 500 & (z \le 2) \\ 500 - 100(z-2) & (2 < z \le 7) \\ 0 & (7 \le z) \end{cases},\ 0 \le t \le 20 \text{ [°C/min}^{1/6}\text{]}. \qquad (8)$$

The maximum temperature by the design equation (8) is compared with axial flame temperature of 3MW-localized fires in Figure 7. Comparing with the axial temperature profile of unconfined (apart from wall) fire, the design equation gives higher temperature.

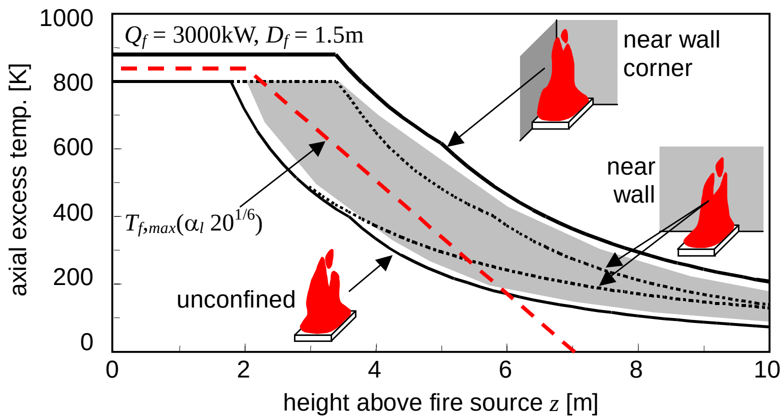

Figure 7 local fire (flame) temperature by 3MW source and the Route B formula

Calculation of Critical Time to Failure of Structural Steel Element

Figure 8 shows the calculation procedure for time to structural end point The procedure starts with calculation of structural forces during normal condition. Using the results, the critical steel temperature is calculated in accordance with possible structural failure modes. Then steel temperature rise is calculated considering the construction of steel and insulation. Finally the time to critical condition is calculated and compared with fire duration.

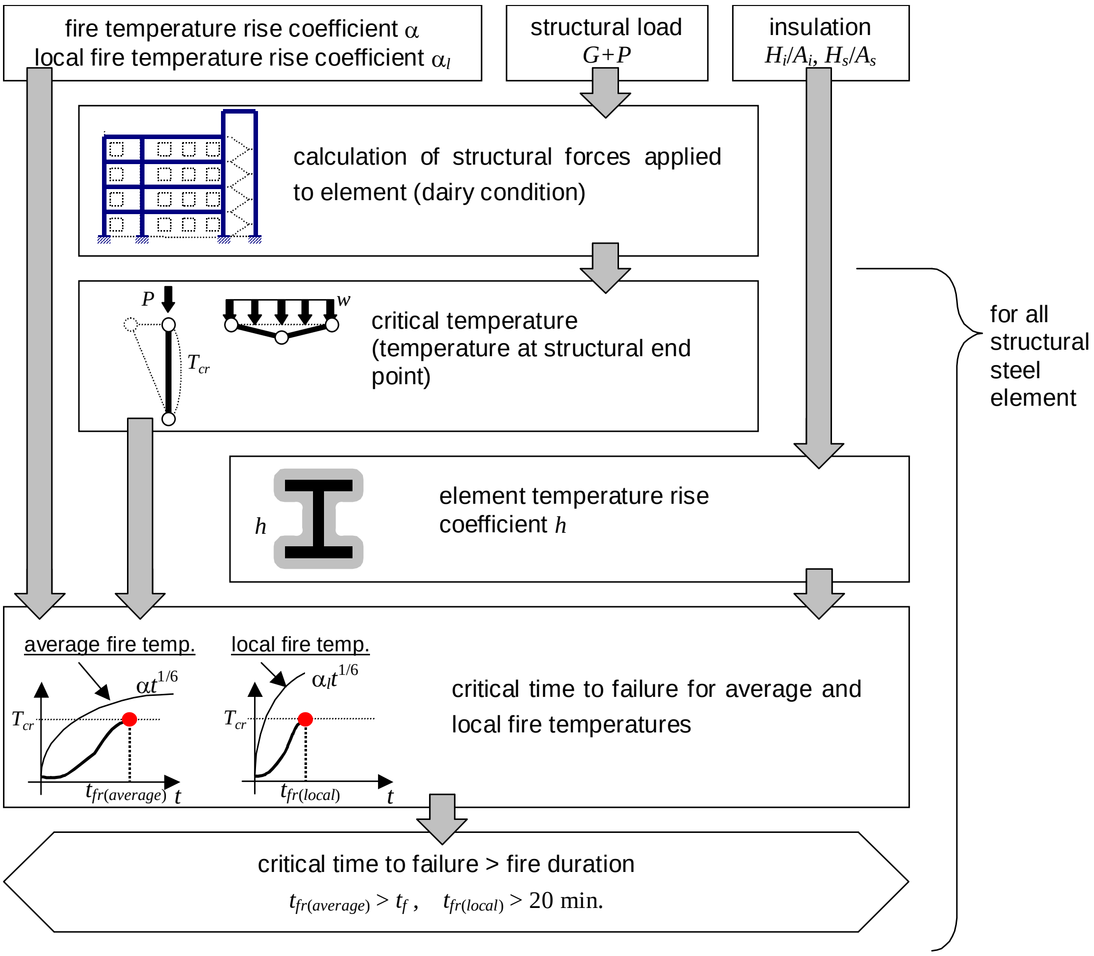

Figure 8 Calculation procedure of critical time to failure adopted by Route B.

NOMENCLATURE

A_{fuel}	surface area of combustible fire load (wood equivalent) [m^2]
p	axial force ratio $p = P / FA_c$ [-]
$A\sqrt{H}$	ventilation parameter of fire room [$m^{5/2}$]
$\Sigma A\sqrt{k\rho c}$	heat absorption conductance to bounding walls [$W.s^{1/2}/ K$]
q_b	heat release rate [kW]
Q_r	total fire load of fire room [MJ]
t_f	fire duration [min.]
t_{fr}	critical time to structural failure [min.]
T_{cr}	critical temperature of steel element [^oC]
z	height above floor [m]
α	fire temperature rise coefficient [$K/min^{1/6}$]
α_l	local fire temperature rise coefficient [$K/min^{1/6}$]
χ	burning type index [$m^{1/2}$]

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