Evaluation of Models of Fully Developed Post-flashover Compartment Fires

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ABSTRACT: Closed-form models of fully developed enclosure fires are evaluated by comparing model predictions to temperature and burning rate data from experiments. The experimental data selected represent a wide spectrum of ventilation conditions, including fuel-controlled and ventilation-controlled burning. Most methods are found to underpredict either compartment fire temperatures or duration of burning under some conditions. Based on the comparisons, a recommendation is made as to which method should be used in a design or analysis context to model post-flashover fires in compartments that are nearly cubic in shape.

KEY WORDS: enclosure fires, fire modeling, validation, post flashover.

INTRODUCTION

FULLY DEVELOPED, POST-FLASHOVER fire scenarios are typically used in the design and analysis of building fire safety systems, such as structural fire resistance or in estimating the potential for building-to-building fire spread. Several models are available to predict the temperature and duration of fully developed enclosure fires. These models predict compartment fire temperature based on input data relating to the amount of fuel in the compartment and compartment characteristics, such as compartment geometry, ventilation geometry, and thermal characteristics of construction materials.

While much attention has been focused on computer modeling in recent years, closed-form models are still representative of the state of the art in post-flashover enclosure fire modeling. With one exception [1], all of the

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methods identified are relatively simple closed-form equations, and even the exception has a closed-form approximation, which provides predictions to within 3–5% of predictions made using the computer version [2]. Most computer fire models predict the temperature in a compartment as a function of a user-defined fire [3]. Computational fluid dynamics modeling holds promise for the future in calculating heat release rates in fires; however, it presently must be used with caution, since a number of simplifications are used due to computational, resolution, and knowledge limitations. As stated in the *FDS User's Guide*, 'The various phenomena (associated with modeling combustion) are still subjects of active research, (thus the user ought to) be aware of the potential errors introduced into the calculation' [4].

Although there are a number of models available for predicting fully developed post-flashover fire exposures, until the analysis presented in this paper was undertaken, there was not any guidance available on the relative accuracy of these methods. This paper presents an evaluation of models of fully developed fire exposures by comparing model predictions with data from a series of experiments conducted under the auspices of CIB [5].

The CIB experiments were selected for evaluation because they represent a rich diversity in experimental conditions. A total of 321 experiments were conducted in still air conditions by nine different laboratories worldwide. The compartments in these experiments were roughly cubic, although some of the compartments had aspect ratios (length to width) of 0.5 or 2. The compartments used in the experiments had characteristic length scales of 0.5, 1.0, or 1.5 m, and the fuel loading (m''_f) in the compartments ranged from 10 to 40 kg/m^2 of wood cribs with stick spacing to stick width ratios of 1/3, 1, and 3.

Methods developed by Wickström [6], Lie [7], Magnusson and Thelandersson [8], Harmathy [9,10], Babrauskas [2], Ma and Mäkeläinen [11], Law [12], and Tanaka et al. [13] were evaluated.

Consideration of Scale

The CIB experiments were conducted in enclosures that were less than full-scale, although the experiments in the larger of the enclosures used (1.5 m in height) approached full-scale. Figures 1 and 2 show the temperature and burning rate data, respectively, from the CIB experiments differentiated by enclosure scale. Any systematic bias associated with enclosure scale is masked by the scatter in the data. Since no systematic bias associated with scale is observed, and the larger enclosures used in the experiments approached full-scale, it is concluded that analysis based on the CIB data should be applicable to full-scale fires.

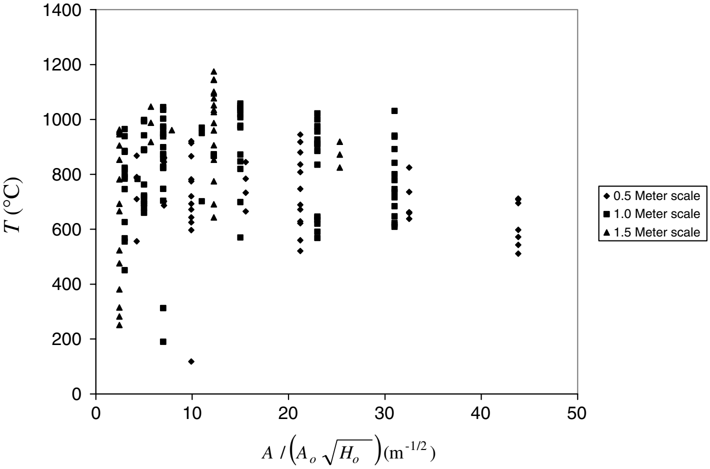

Figure 1. *CIB temperature data differentiated by enclosure scale.*

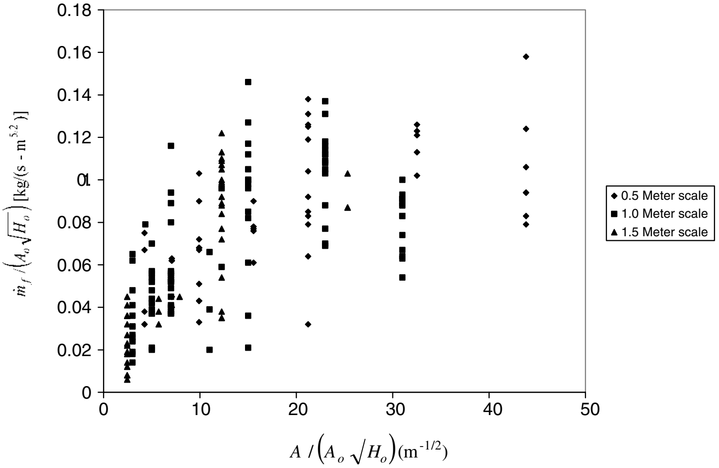

Figure 2. *CIB burning rate data differentiated by enclosure scale.*

COMPARISON OF PREDICTIONS WITH DATA

In the CIB experiments [5], the stage of fully developed burning was defined as the period when the mass of fuel was between 80 and 30% of the original, unburned fuel mass. Average temperatures during the period of fully developed burning from these experiments were presented as a function of $A/A_o\sqrt{H_o}$.

Average burning rate data for the fully developed stage was presented as $(\dot{m}_f/A_o\sqrt{H_o})\sqrt{D/W}$ as a function of $A/A_o\sqrt{H_o}$. Data were also included where the average burning rate during the fully developed burning stage was presented in tables of $\dot{m}_f/A_o\sqrt{H_o}$ as a function of $A/A_o\sqrt{H_o}$. Although the CIB report [5] shows that the aspect ratio of a compartment can influence the burning rate for fully developed, ventilation-limited fires, most predictive methods do not explicitly account for this effect. Therefore, predictive methods that do not account for compartment aspect ratio were evaluated using the CIB burning rate data that was normalized by the area and square root of the height of the ventilation opening, but not by the square root of the ratio of compartment depth to width. Methods that do specifically account for the compartment aspect ratio were evaluated using the CIB data that was normalized by both the area and square root of the height of the ventilation opening and the square root of the ratio of compartment depth to width. When the CIB data were not normalized by the square root of the ratio of compartment depth to width, there was more scatter in the data. Evaluation of post-flashover enclosure fire models for long, narrow compartments has been published separately [14].

The fully developed post-flashover fire models were evaluated by comparing predictions of average temperature during the fully developed stage to the CIB data. The models were also evaluated by dividing the initial mass of fuel by the predicted burning duration and comparing this quantity to the CIB data.

Some of the predictive methods required the surface area of the fuel as input. The ratio of fuel surface area to total room surface area (defined as including the area of the ceiling and walls, but not the area of the ventilation opening or the floor) was calculated for each of the CIB experiments. The average ratio of fuel surface area to total room surface area in these experiments was 3.56, with a standard deviation of 2.11. For methods that require the fuel surface area as input, a value of $3.56A$ was used.

Many laboratories used different species of fuels to construct wood cribs. The CIB report [5] did not provide a heat of combustion for the wood; however, the report stated that all wood used was ‘softwood.’ Therefore, when a model required a heat of combustion as input, a value of 12.4 MJ/kg was used, which is an effective heat of combustion for pine [15].

The experiments in the CIB study were conducted in a variety of enclosures, since multiple laboratories participated. The data in the CIB report [5] used statistical means to overcome systematic differences between the laboratories. The majority of the laboratories used a test enclosure constructed of 10-mm thick asbestos millboard with a reported thermal conductivity of 0.15 W/m °C, and this is the value that was used for methods that required specific heat as an input. The density of the asbestos millboard and the specific heat were not reported, so values of 816 J/kg °C and 1100 kg/m^3 were selected [16,17].

In the CIB study, temperature and burning rate data were presented in two graphs each. One set of graphs presented temperature and burning rate data for cribs with 20 mm thick wood sticks spaced 20 mm apart. A second set of graphs presented temperature and burning rate data for cribs with 20 mm wide sticks spaced 60 mm apart and cribs with 10 mm wide cribs spaced 30 mm apart. However, for purposes of comparing predictions with the CIB data, all temperature and burning rate data was aggregated into single graphs.

Wickström

Wickström stated that his method assumes that the fire is ventilation controlled and all fuel burns within the compartment [6]. Wickström modified an approximation of the ISO 834 standard fire curve by altering the time scale based on the ventilation characteristics and enclosure thermal properties. The modified time scale compares the enclosure of interest to Magnusson and Thelandersson's 'type A' enclosure with an opening factor of 0.04 m$^{1/2}$. Wickström found that the resulting curve approximated the ISO 834 standard fire curve.

Wickström's method has been adopted within the Eurocode [18]. The Eurocode states that this method may be used for fire compartments up to 100 m^2, without openings in the roof and for a maximum compartment height of 4 m. The Eurocode does not provide any basis for these limits. Subsequent to adoption of Wickström's method in the Eurocode, Buchanan [19] and Franssen [20] suggested improvements, which are evaluated here as well.

In the CIB experiments, the mass of fuel per unit area ranged from 20 to 40 kg/m^2 (a few tests used a mass of fuel per unit area of 10 kg/m^2, but since the CIB report [5] indicated that only a 'few' tests were conducted at this density, this value was not modeled.) For an effective heat of combustion for pine of 12.4 MJ/kg, $q_{t,f}$ would range from 248 to 496 MJ/m^2, and multiplying this by the ratio of A_{floor}/A in the CIB compartments results in a range of $q_{t,d}$ of ≈50–100 MJ/m^2.

Predictions of temperature as a function of time were made using Wickström's method for values of $A/A_o\sqrt{H_o}$ ranging from 5 to 50 m$^{-1/2}$. Predictions were made at time increments ranging from 0.005 to 5 h, depending on the values of $q_{t,d}$ and $A/A_o\sqrt{H_o}$ used. For each value of $A/A_o\sqrt{H_o}$, averages of the temperature predictions during the time in

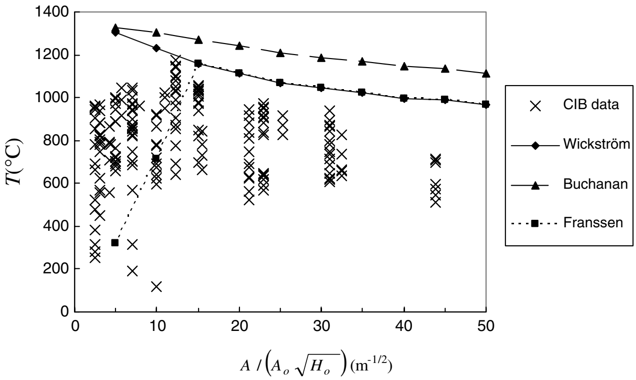

Figure 3. *Comparison of CIB temperature data to predictions made using Wickström's, Buchanan's, and Franssen's methods for* $q_{t,d} = 50\,MJ/m^2$.

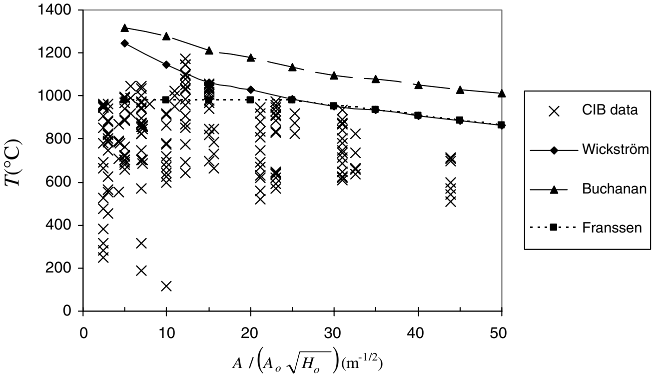

Figure 4. *Comparison of CIB temperature data to predictions made using Wickström's, Buchanan's, and Franssen's methods for* $q_{t,d} = 100\,MJ/m^2$.

which $t^* < t_d^*$ were compared to the CIB data. A graph of predictions made using Wickström's method and using modifications to his method by Buchanan and by Franssen are presented in Figures 3 and 4 along with the CIB data.

Comparison of predictions made using Wickström's method to the CIB data requires some manipulation of the equations used to predict the duration of burning. When using Wickström's method, the predicted duration of the fully developed burning stage is the time at which $t^* = t_d^*$. Wickström's method provides that

$$t_d^* = \frac{0.13 \times 10^{-3} q_{t,d} \Gamma A}{A_o \sqrt{H_o}} \tag{1}$$

and

$$t^* = t\Gamma \tag{2}$$

Substituting Equation (2) into Equation (1) and rearranging terms, the predicted duration would be

$$\tau = \left[\frac{0.13 \times 10^{-3} q_{t,d}\Gamma}{\left(A_o\sqrt{H_o}/A\right)}\right] \div \Gamma \tag{3}$$

where τ is in hours, which can be rewritten as:

$$\tau = 0.13 \times 10^{-3} q_{t,d}\frac{A}{A_o\sqrt{H_o}} \tag{4}$$

The variable $q_{t,d}$ is defined as:

$$q_{t,d} = q_{f,d}\frac{A_{\text{floor}}}{A} \tag{5}$$

Substituting Equation (5) into Equation (4) yields

$$\tau = 0.13 \times 10^{-3} q_{f,d}\frac{A_{\text{floor}}}{A}\frac{A}{A_o\sqrt{H_o}} \tag{6}$$

The burning rate can be calculated as:

$$\dot{m}_f = \frac{m_f}{\tau} \tag{7}$$

Substituting Equation (6) into Equation (7) results in

$$\dot{m}_f = \frac{m_f}{0.13 \times 10^{-3} q_{f,d}(A_{\text{floor}}/A)\left(A/A_o\sqrt{H_o}\right)} \tag{8}$$

The variable $q_{f,d}$ is defined as:

$$q_{f,d} = m_f''\Delta H_c \tag{9}$$

The mass of fuel per unit area is calculated as:

$$m_f'' = \frac{m_f}{A_{\text{floor}}} \tag{10}$$

Substituting Equations (9) and (10) into Equation (8), and rearranging and canceling terms yields

$$\dot{m}_f = 7700\frac{A_o\sqrt{H_o}}{\Delta H_c}(\text{kg/h}) \quad \text{or} \quad \dot{m}_f = 2.1\frac{A_o\sqrt{H_o}}{\Delta H_c}(\text{kg/s}) \tag{11}$$

Substituting $\Delta H_c = 12.4\,\text{MJ/kg}$, the predicted burning rate would be

$$\dot{m}_f = 0.17 A_o\sqrt{H_o} \tag{12}$$

This is compared to the CIB burning rate data in Figure 5.

Franssen's modification results in a calculated burning duration of 20 min when t_d^*/Γ is $<20\,\text{min}$. For the CIB data and $q_{t,d} = 50\,\text{MJ/m}^2$, t_d^*/Γ is $<20\,\text{min}$ for cases where $A/A_o\sqrt{H_o}$ was $\leq 10\,\text{m}^{-1}$. With $q_{t,d} = 100\,\text{MJ/m}^2$, t_d^*/Γ is $<20\,\text{min}$ for cases where $A/A_o\sqrt{H_o}$ was $\leq 30\,\text{m}^{-1}$.

Lie

Lie suggested that if the objective is to develop a method of calculating fire resistance requirements, then it is necessary only to find a fire temperature–time curve 'whose effect, with reasonable probability, will not be exceeded during the use of the building' [7]. Lie developed an expression based on the series of temperature–time curves computed by Kawagoe and Sekine [21] for ventilation-controlled fires, which he proposed could be used

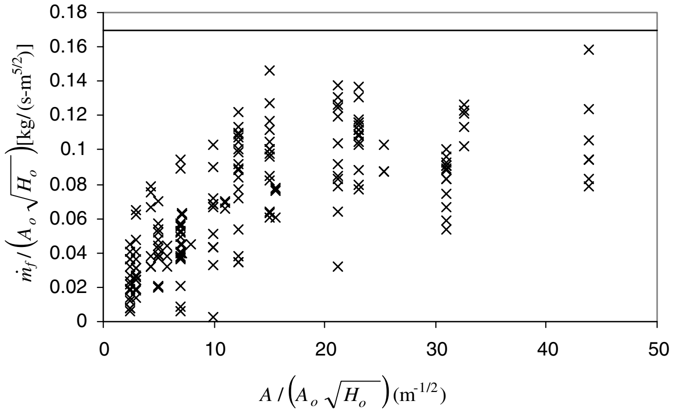

Figure 5. *Comparison of CIB burning rate data to predictions made using Wickström's method.*

as an approximation for the most severe fire that is likely to occur in a particular compartment [7].

Since it was not possible to determine the duration of burning for each data point in the CIB data set in a straightforward manner, to compare predictions using Lie's method to the CIB data, average temperature predictions were made for a fire of two hours duration with opening factors $A_o\sqrt{H_o}/A$ ranging from 0.02 to 1. A comparison of Lie's predictions and the CIB data can be found in Figure 6.

Lie's correlation for burning rate is compared to the CIB burning rate data in Figure 7.

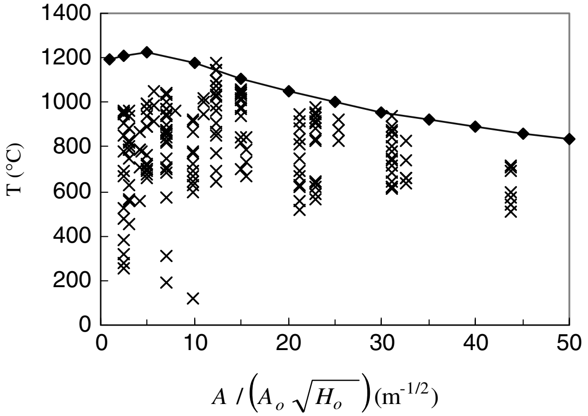

Figure 6. *Comparison of CIB temperature data to predictions using Lie's method.*

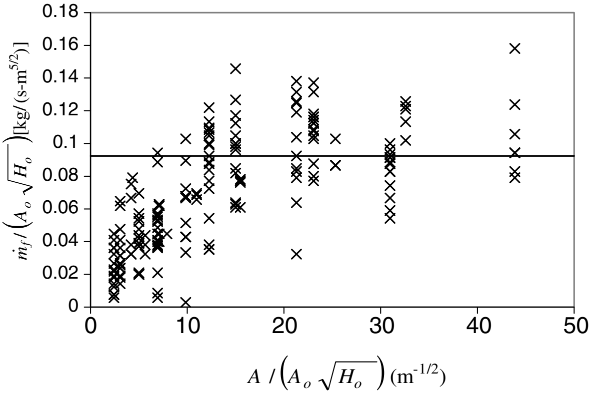

Figure 7. *Comparison of CIB burning rate data to predictions made using Lie's method.*

Tanaka et al.

Tanaka et al. [13] extended the equation for pre-flashover room fire temperature developed by McCaffrey et al. [22] to obtain equations for ventilation-controlled fire temperatures in the room of origin and the corridor connected to the room. Tanaka presents 'simple' and 'refined' methods.

For the methods of Tanaka et al., it was not possible to determine the duration of burning for each point in the CIB data set in a straightforward manner. To compare predictions using the methods of Tanaka et al. to the CIB data, average temperature predictions were made for a fire of two hours duration with $A/A_o\sqrt{H_o}$ ranging from 1 to 50 $\mathrm{m}^{-1/2}$. Any calculated temperature below 600°C was assumed not to represent fully developed burning, and was hence neglected. The result of this comparison can be seen in Figure 8.

Both of the methods of Tanaka et al. use the same correlation for burning rate, which is compared with the CIB data in Figure 9.

Magnusson and Thelandersson

Magnusson and Thelandersson [8] studied the variations in the development of energy, the effects of air supply, and the resulting evolution of gases with time in the course of a fire. They estimated the temperature of the combustion gases from wood fires in enclosed spaces as a function of time under different conditions.

Magnusson and Thelandersson evaluated eight specific types of enclosures and developed temperature–time curves for each, assuming wood fuel.

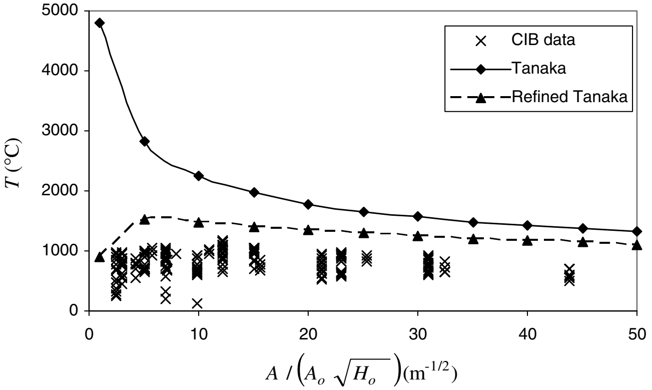

Figure 8. Comparison of CIB temperature data to predictions using methods of Tanaka et al.

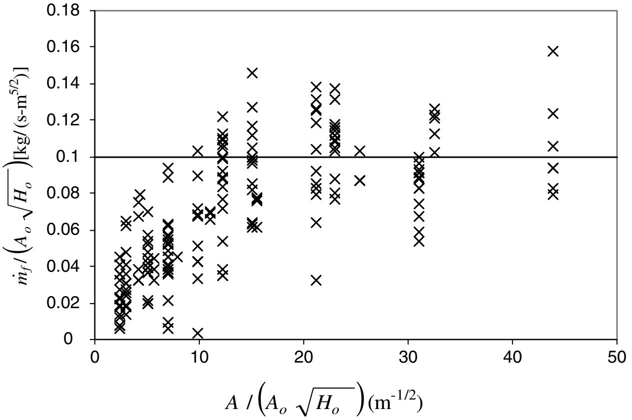

Figure 9. *Comparison of CIB burning rate data to predictions made using Tanaka's methods.*

The opening factor and the fuel load were varied for each of the eight types of enclosures, and temperature as a function of time was presented in both graphic and tabular formats.

The enclosures that were used in the CIB tests were modeled as Type C (as defined by Magnusson and Thelandersson [8]), since the Type C enclosure most closely represents the material properties of the CIB enclosures.

Given that it was not possible to estimate the burning rates applicable to the CIB data in a straightforward manner, a duration of 2 h was arbitrarily selected. A comparison of predictions made in this manner with the CIB data is shown in Figure 10.

This method predicts burning duration as follows:

$$\tau = \frac{qA}{25A_o\sqrt{H_o}}(\text{min}) \tag{13}$$

Using a heat of combustion of 12.4 MJ/kg and converting units, this can be reduced to

$$\tau = 8.1\frac{m_f}{A_o\sqrt{H_o}}(\text{min}) \tag{14}$$

Applying Equation (7), the burning rate predicted using Magnusson and Thelandersson's method would be

$$\dot{m}_f = 0.12A_o\sqrt{H_o} \tag{15}$$

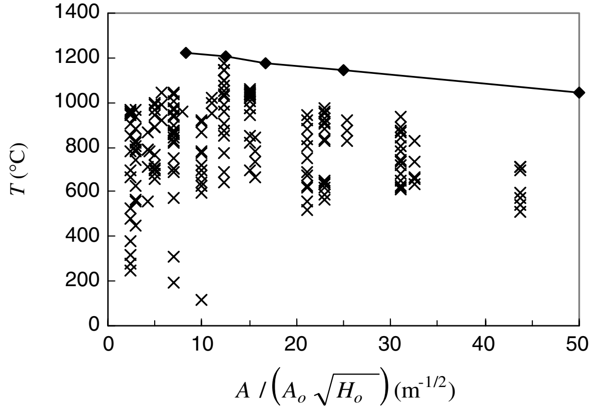

Figure 10. Comparison of CIB temperature data to predictions using Magnusson and Thelandersson's method.

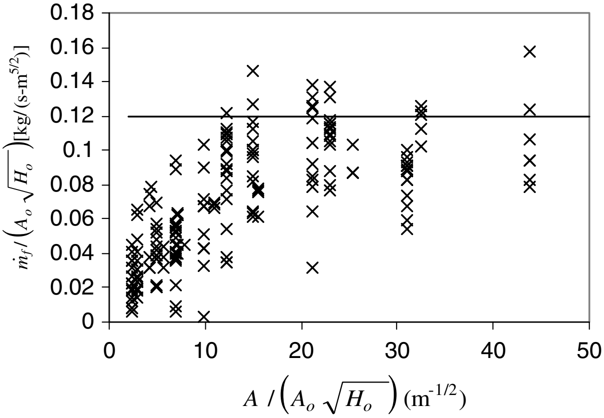

Figure 11. Comparison of CIB burning rate data to predictions using Magnusson and Thelandersson's method.

A comparison of predictions of burning rate made using Magnusson and Thelandersson's method to the CIB data is shown in Figure 11.

Harmathy

Harmathy published a method for predicting burning rates and heat fluxes in compartment fires with cellulosic fuels [9,10]. Harmathy's method is based on theory, with a number of simplifications and comparisons to experimental data to define constants. Harmathy's model is applicable to fully developed fires in compartments that are ventilation limited or fuel controlled.

Due to the iterative nature of Harmathy's method for predicting compartment fire temperatures, it is not possible to compare temperature predictions using Harmathy's method to the CIB data in a straightforward manner.

Harmathy distinguishes fuel-limited burning from ventilation-limited burning as the point where

$$\frac{\rho_0\sqrt{g}A_o\sqrt{H_o}}{A_f} = 0.263\,\frac{\mathrm{kg}}{\mathrm{m^2 s}} \tag{16}$$

Substituting $\rho_0 = 1.2\,\mathrm{kg/m^3}$ and $g = 9.8\,\mathrm{m/s^2}$, Equation (16) can be rewritten as:

$$\frac{A_o\sqrt{H_o}}{A_f} = 0.07\,\mathrm{m^{1/2}} \tag{17}$$

In the CIB tests, the average value of A_f was $\approx 3.56A$. Substituting this into Equation (17) and inverting, the threshold between fuel-limited and ventilation-limited burning would be

$$\frac{A}{A_o\sqrt{H_o}} = 4.01\,\mathrm{m^{-1/2}} \tag{18}$$

For fuel-limited burning, Harmathy gives

$$\tau = \frac{151 m_f}{A_f} \tag{19}$$

Substituting $A_f \approx 3.56A$ and Equation (7) into Equation (19) yields

$$m_f = 0.0236A \tag{20}$$

For ventilation-limited burning, Harmathy gives

$$\tau = 39.7\,\frac{m_f}{\rho_0\sqrt{g}A_o\sqrt{H_o}} \tag{21}$$

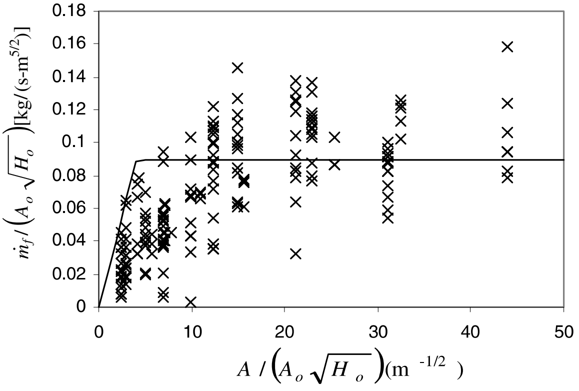

Figure 12. *Comparison of CIB burning rate data to predictions made using Harmathy's method.*

Substituting $\rho_0 = 1.2\,\text{kg/m}^3$ and $g = 9.8\,\text{m/s}^2$ into Equation (21) results in

$$\tau = 10.6\frac{m_f}{A_o\sqrt{H_o}} \tag{22}$$

Substituting Equation (22) into Equation (7) yields

$$\dot{m}_f = 0.09 A_o\sqrt{H_o} \tag{23}$$

This is compared to the CIB data in Figure 12.

Babrauskas

Babrauskas used COMPF2 [1] to create a series of closed-form algebraic equations that can be used to estimate temperatures resulting from fully developed fires [2]. According to Babrauskas, estimations made using the closed-form equations are within 3–5% of COMPF2 predictions, and are typically closer to 3% [2].

Babrauskas provides the equivalence ratio as:

$$\phi = \frac{\dot{m}_f}{\dot{m}_{st}} \tag{24}$$

where,

$$\dot{m}_{st} = \frac{A_o\sqrt{H_o}}{2s} \tag{25}$$

and s is the ratio such that

$$1\,\text{kg fuel} + s\,\text{kg air} = (1+s)\,\text{kg products} \tag{26}$$

Harmathy [9] notes that a typical wood would have the chemical formula $CH_{1.455}O_{0.645} \cdot 0.233H_2O$, which would result in a value of s of 6.0, which is slightly larger than the value of 5.7 proposed by Babrauskas [23]. Using $s = 6.0$, and Equation (25) yields

$$\dot{m}_{st} = 0.083 A_o \sqrt{H_o} \tag{27}$$

Substituting this into Equation (24) yields

$$\phi = \frac{\dot{m}_f}{0.083 A_o \sqrt{H_o}} \tag{28}$$

Babrauskas provides methods for modeling burning rate for ventilation-controlled burning and for fuel-controlled burning, for wood cribs, and for thermoplastic or liquid pools [2]. Babrauskas' model for calculating the burning rate of ventilation-controlled fires is used here; however, in most design situations, the input data needed to use Babrauskas' models for fuel-controlled burning are not available. Therefore, Harmathy's model for the burning rate of overventilated fires was used for the present analysis.

Using Equation (19) to calculate the duration of fuel-controlled burning and substituting Equation (7) into Equation (28) yields

$$\phi = 0.074 \frac{A_f}{A_o \sqrt{H_o}} \tag{29}$$

For stoichiometric burning, $\phi = 1$. In the CIB tests, the average value of A_f was $\approx 3.56A$. Substituting this into Equation (29) and solving for $A/A_o\sqrt{H_o}$, the threshold between fuel-limited and ventilation-limited burning would be

$$\frac{A}{A_o \sqrt{H_o}} = 3.8\,\text{m}^{-1/2} \tag{30}$$

Substituting the relevant values for enclosure properties from the CIB tests and assuming that $b_p = 0.9$ and $H_o \approx 1\,\text{m}$ (In the CIB tests, H_o ranged from 0.5 to 1.5 m, but given that Babrauskas' method varies with $H_o^{-0.3}$,

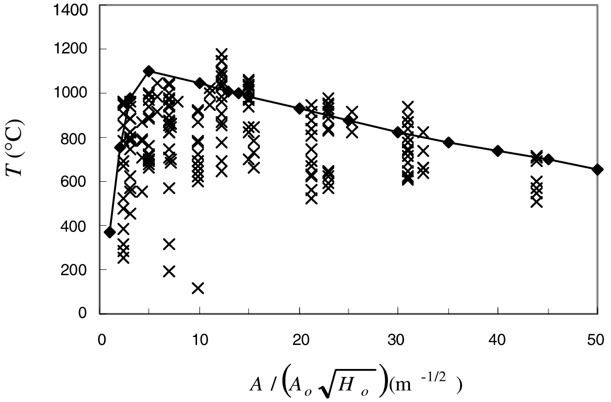

Figure 13. *Comparison of CIB temperature data to Babrauskas predictions.*

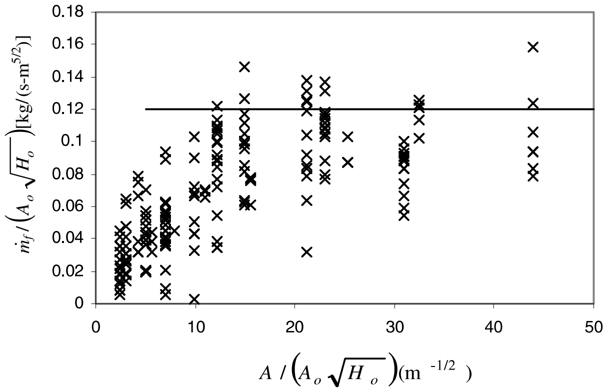

Figure 14. *Comparison of CIB burning rate data to predictions using Babrauskas' method.*

predictions are not highly sensitive to this parameter) results in the predictions of the CIB temperatures shown in Figure 13.

A comparison of Babrauskas' burning rate correlation for ventilation-controlled burning is compared to the CIB data in Figure 14.

Given that Harmathy's method of estimating burning rate for fuel-controlled burning was used for Babrauskas' method, the comparison of that method with the CIB data is applicable to the assumption made here.

Ma and Mäkeläinen

Ma and Mäkeläinen developed a parametric time–temperature curve for compartments that are small or medium in size (floor area < 100 m^2) [11].

The method was developed for use mainly with cellulosic fires. Their aims were to develop a simple calculation procedure that would reasonably estimate the temperature, with time, of a fully developed compartment fire.

A general shape function was developed by nondimensionalizing temperature–time data from 25 different data sets based on the maximum gas temperature, T_{gm}, and the time to reach the maximum temperature, t_m.

Ma and Mäkeläinen define the critical value of $A/A_o\sqrt{H_o}$ that separates the fuel-controlled and ventilation-controlled regimes as:

$$\frac{A_o\sqrt{H_o}}{A} = 0.07\frac{\mathrm{A}_{\text{floor}}}{A}m''_f\frac{A_f}{m_f} \tag{31}$$

In the CIB tests, the ratio A_{floor}/A ranged from 0.18 to 0.25. Ma and Mäkeläinen noted that A_f/m_f typically ranges from 0.1 to $0.4\,\mathrm{m}^2/\mathrm{kg}$, and that in a series of Japanese tests, $A_f/m_f = 0.131\,\mathrm{m}^2/\mathrm{kg}$. Substituting $A_{\text{floor}}/A = 0.2$, $A_f/m_f = 0.131\,\mathrm{m}^2/\mathrm{kg}$ and $m''_f = 40\,\mathrm{kg/m}^2$ into Equation (31), the critical value of $A_o\sqrt{H_o}/A$ that separates the fuel-controlled and ventilation-controlled regimes would be

$$\frac{A}{A_o\sqrt{H_o}} = 13.68\ \mathrm{m}^{-1/2} \tag{32}$$

Ma and Mäkeläinen estimate the maximum temperature that would be achieved for ventilation-controlled fires would be

$$T_{gm} = 1240 - 11\frac{A}{A_o\sqrt{H_o}}(^\circ\mathrm{C}) \tag{33}$$

For fuel-controlled fires, Ma and Mäkeläinen state that the maximum temperature would be

$$T_{gm} = T_{gmcr}\sqrt{\frac{A}{\eta_{cr}A_o\sqrt{H_o}}} \tag{34}$$

where η_{cr} is the value of $A/A_o\sqrt{H_o}$ that differentiates between fuel and ventilation controlled burning and T_{gmcr} is the value of T_{gm} for $\eta = \eta_{cr}$. It should be noted that the above temperature correlations provide an estimation of the maximum temperature that would be attained during a fire; for the majority of the fire duration the temperature would be lower, and hence the average temperature during the fire would be lower.

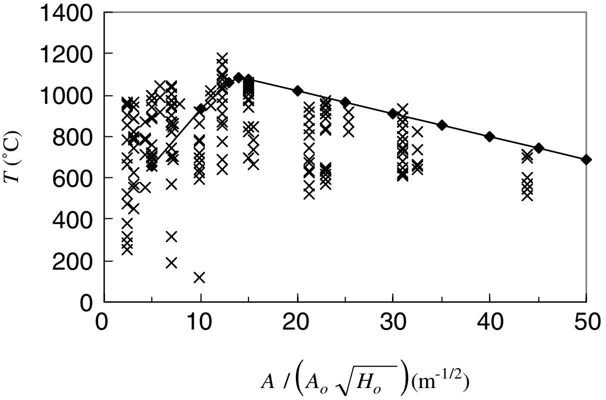

Figure 15. *Comparison of CIB temperature data to predictions using Ma and Mäkeläinen's method.*

Figure 15 provides a comparison of predicted maximum temperatures with the CIB data.

Ma and Mäkeläinen use Harmathy's correlation to predict the burning rate for fuel-controlled burning and Law's correlation to predict the burning rate for ventilation-controlled burning. See the discussion of those methods for an evaluation of their burning rate predictions.

Law

Law derived a method of predicting compartment temperatures resulting from fully developed fires based on data from the CIB experiments [12]. Unlike other methods, Law's method takes into account the aspect ratio of the compartment.

Figure 16 shows predictions of maximum temperature using Law's method to the CIB data. Law's method includes a means of reducing the predicted temperature based on the fuel loading and compartment geometry; however, for the range of conditions in the tests from which the CIB data were collected, utilizing this factor (referred to as 'Ψ' in Law's method) would result in unrealistically low temperatures for some combinations of scale, opening factor, and ventilation area. Therefore, this method of reducing the temperature was not utilized.

Figure 17 shows a comparison of burning rate predictions made using Law's method to the CIB data. Note that because Law's method considers the effect of compartment depth and width, the CIB burning rate data that was normalized by $\sqrt{D/W}$ was utilized.

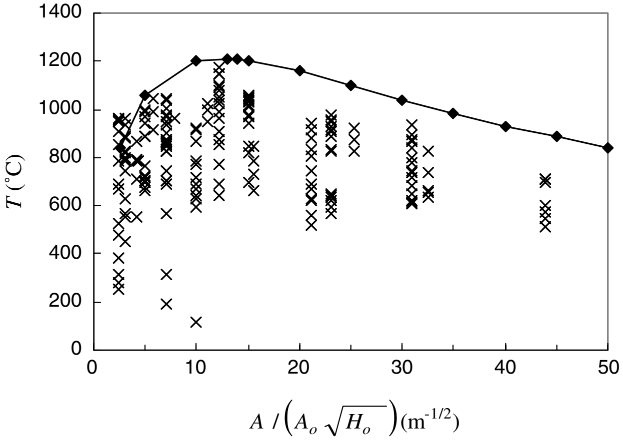

Figure 16. *Comparison of CIB temperature data to predictions using Law's method.*

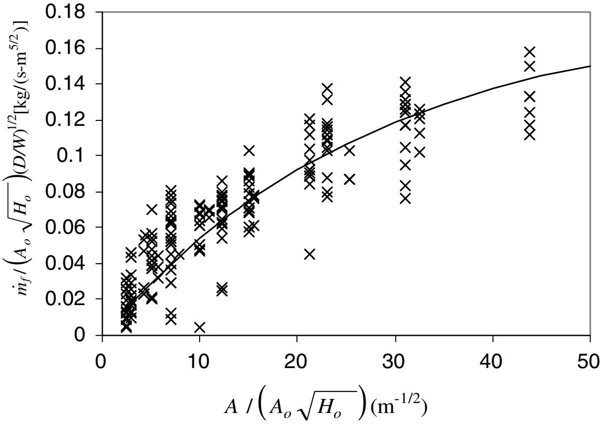

Figure 17. *Comparison of CIB burning rate data to predictions using Law's method.*

Law's method was developed based on the same CIB data that was used here to evaluate predictions of temperature and burning duration. Therefore, it is not surprising that this method correlated well in this evaluation. To provide an additional assessment, additional test data were used to evaluate predictions of post-flashover compartment fire temperatures and burning duration using Law's method.

British Steel Technical and the British Research Establishment conducted a series of nine experiments at the Cardington facility [24]. While most of

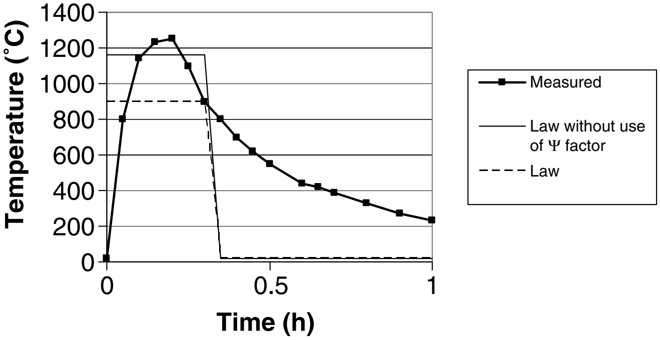

Figure 18. Comparison of predictions using Law's method to data from Cardington Experiment #8.

these experiments were conducted in a long, narrow enclosure that was ≈23 m long, 6 m wide, and 3 m high, one experiment was conducted in a compartment that measured 5.595 × 5.595 × 2.750 m high. Ventilation was available through two openings that were 2.750 m high by 0.685 m wide. These two openings were separated by a vertical column, and for this analysis, were treated as a single opening of 2.750 m high by 1.370 m wide.

The floor of the compartment was made of sand-covered concrete. The walls were made of lightweight concrete blocks, and were lined with a 50-mm thick ceramic fiber blanket. The ceiling was constructed of 200-mm thick aerated concrete slabs, and was lined in the same manner as the walls. The fuel loading consisted of 20 kg/m^2 of wood cribs.

Predictions using Law's method are compared to the data from this experiment, in Figure 18. Predictions using Law's method were developed both with and without use of the 'Ψ' factor.

OBSERVATIONS

For the CIB experiments, transition from fuel-controlled burning to ventilation-controlled burning occurred for $A/A_o\sqrt{H_o} \approx 13\,\mathrm{m}^{-1/2}$. At this value, temperatures reached a maximum value and a further increase in compartment size or reduction in ventilation area did not affect the burning rate.

Many of the methods evaluated have been based on an assumption that burning is ventilation limited. Methods that do account for fuel-limited burning include Franssen's modification to Wickström's method and the methods developed by Harmathy, Babrauskas, Ma and Mäkeläinen, and Law.

Wickström's method, without modifications, bounds all CIB data for $q_{t,d} = 50\,\mathrm{MJ/m^2}$ and most data for $q_{t,d} = 100\,\mathrm{MJ/m^2}$. Wickström's method, without modification, overpredicts the burning rate of all of the CIB data, and hence, underpredicts the burning duration. It is noteworthy that if a total heat of combustion [15] is used instead of an effective heat of combustion, Wickström's method of predicting burning rate reduces to $\dot{m}_f = 0.12 A_o \sqrt{H_o}$, which would fall within the upper range of the data for ventilation-limited burning.

Predictions using Buchanan's modification bounds all the CIB temperature data, more so than Wickström's method without modification, both for $q_{t,d} = 50\,\mathrm{MJ/m^2}$ and $q_{t,d} = 100\,\mathrm{MJ/m^2}$. Predictions using Franssen's modification fall within the scatter of temperature data for predictions of fuel-controlled burning. As would be expected, higher temperatures are predicted for $q_{t,d} = 100\,\mathrm{MJ/m^2}$ than for $q_{t,d} = 50\,\mathrm{MJ/m^2}$.

Lie's method bounds almost all of the CIB temperature data. Both of Tanaka's methods bound all of the CIB temperature data; however, predictions made using the refined method are closer to the data. For values of $A/A_o\sqrt{H_o}$ for which Magnusson and Thelandersson provide predictions, Magnusson and Thelandersson's predictions bound the temperature data from the CIB tests.

Lie's, Tanaka's, and Magnusson and Thelandersson's methods generally overpredict burning rate, and underpredict burning duration for $A/A_o\sqrt{H_o} \lesssim 10\,\mathrm{m^{-1/2}}$. For $A/A_o\sqrt{H_o} \gtrsim 10\,\mathrm{m^{-1/2}}$ predictions of burning rate using Lie's, Tanaka's, and Magnusson and Thelandersson's methods fall within the scatter of data.

Due to the iterative nature of Harmathy's method, it is not possible to compare predictions to the CIB temperature data. However, burning rate predictions made using Harmathy's method fall within the scatter of the data for both fuel-controlled and ventilation-controlled burning.

Predictions using Babrauskas' method are within the scatter of data measured in the CIB tests. For ventilation-controlled fires, predictions made using Babrauskas' burning rate correlation fall in the scatter of data.

Ma and Mäkeläinen's maximum temperature predictions bound the average temperatures measured in the CIB tests for ventilation-limited fires, but underpredict average temperatures for fuel-limited fires. Given that maximum temperature predictions using Ma and Mäkeläinen's method are compared to the CIB data, which represents average temperatures measured during the fully developed stage, and predictions of average temperature would be lower than maximum temperatures, Ma and Mäkeläinen's method would underpredict much of the CIB temperature data. See the conclusions regarding Harmathy's and Law's methods for an evaluation of burning rate predictions made using Ma and Mäkeläinen's model.

Without applying the fuel load adjustment factor Ψ, which would reduce predicted temperatures, Law's temperature predictions bound all of the CIB data for $A/A_o\sqrt{H_o} > 2\ \text{m}^{-1/2}$. Use of Law's Ψ factor for some combinations of fuel load and compartment geometry used in the CIB experiments result in unrealistically low temperature predictions. Law's model reasonably predicts the CIB burning rate data. Also, Law's method reasonably predicts the temperature and duration of fully developed burning in Cardington experiment #8 when the fuel load factor is not used. When the fuel load factor is used, Law's method underpredicts temperatures measured in that experiment.

RECOMMENDATIONS

In design situations, it is generally desired to use correlations that provide predictions that err on the side of safety. For calculations of fully developed post-flashover fire exposures, this would translate to predictions of temperatures and burning duration that are expected not to be exceeded.

Law's method is recommended for modeling fully developed post-flashover fire exposures in all roughly cubic compartments (compartment width to depth ratio within the range of 0.5–2.0).

However, Law's method should be used with caution for compartments that are highly overventilated $\left(A/A_o\sqrt{H_o} < 2\,\text{m}^{-1/2}\right)$, since Law's method did not bound all of the experimental data for such compartments.

Additionally, it is recommended that Law's Ψ factor that would reduce temperature predictions for compartments with reduced fuel load not be used.

While Law's method compares better to the CIB data than the others investigated, it does not bound all data, so adjustments to predictions would need to be considered to account for scatter in the data.

Temperature predictions made using the method of Tanaka et al. are higher than predictions made using Law's method; however, they are also much higher than the experimental data, and hence, overly conservative.

NOMENCLATURE

A = surface area of interior of enclosure (m^2)
A_f = surface area of fuel (m^2)
A_{floor} = surface area of floor (m^2)
A_o = area of ventilation opening (m^2)
b_p = factor (–)

C = factor (–)
D = depth of compartment (m)
g = gravitational constant (9.81 m/s^2)
H_o = height of ventilation opening (m)
m_f = mass of fuel (kg)
$\dot{m}_f$ = mass burning rate of fuel (kg/s)
m''_f = mass of fuel per unit area (kg/m^2)
$\dot{m}_{st}$ = stoichiometric mass burning rate (kg/s)
q = fuel load density (Mcal/m^2)
$q_{t,d}$ = fuel load density related to the surface area of enclosure (MJ/m^2)
$q_{f,d}$ = fuel load density related to the surface area of the floor (MJ/m^2)
s = stoichiometric air to fuel ratio (–)
t = time (units as stated)
t_m = time to reach maximum temperature (units as stated)
t^* = scaled time (h)
t^*_d = scaled burning duration (h)
T_{gm} = maximum temperature (units as stated)
T_{gmcr} = maximum temperature in the critical region (units as stated)
W = width of wall containing ventilation opening (m)

Greek

Γ = scaling factor (–)
ϕ = equivalence ratio (–)
ΔH_c = heat of combustion (MJ/kg)
η = factor (–)
η_{cr} = factor (–)
ρ_0 = density of air (kg/m^3)
τ = duration of fully developed fire (units as stated)
Ψ = fuel load factor $= m_f/\sqrt{A_o(A - A_o)}$

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A complete presentation of the methods presented in this paper can be found in [14].

REFERENCES

1. Babrauskas, V., "COMPF2 – A Program for Calculating Post-Flashover Fire Temperatures (Tech Note 991)," US National Bureau of Standards, 1979.
2. Babrauskas, V., "A Closed-form Approximation for Post-Flashover Compartment Fire Temperatures," Fire Safety Journal, Vol. 4, pp. 63–73, 1981.
3. Babrauskas, V., "Fire Modeling Tools for Fire Safety Engineering: Are They Good Enough?," Journal of Fire Protection Engineering, Vol. 8, No. 2, pp. 87–96, 1996.
4. McGrattan, K. and Forney, G., "Fire Dynamics Simulator (Version 4) – User's Guide," NIST Special Publication 1019/6784, National Institute of Standards and Technology, Gaithersburg, MD, 2004.
5. Thomas, P., and Heselden, A., "Fully Developed Fires in Single Compartments, A Co-operative Research Program of the Conseil International du Batiment (CIB Report No. 20)," Fire Research Note No. 923, Fire Research Station, Borehamwood, UK, 1972.
6. Wickström, U., "Application of the Standard Fire Curve for Expressing Natural Fires for Design Purposes," Fire Safety: Science and Engineering, ASTM STP 882, Harmathy, T., ed., American Society for Testing and Materials, Philadelphia, pp. 145–159, 1985.
7. Lie, T., "Fire Temperature-Time Relationships," SFPE Handbook of Fire Protection Engineering, 3rd Edn., National Fire Protection Association, Quincy, MA, 2002.
8. Magnusson, S.E. and Thelandersson, S, "Temperature-Time Curves of Complete Process of Fire Development," ACTA Polytechnica Scandinavica, Civil Engineering and Building Construction Series No.65, Stockholm, 1970.
9. Harmathy, T., "A New Look at Compartment Fires, Part I," Fire Technology, Vol. 8, No. 2, 1972.
10. Harmathy, T., "A New Look at Compartment Fires, Part II," Fire Technology, Vol. 8, No. 4, 1972.
11. Ma, Z. and Mäkeläinen, P., "Parametric Temperature-Time Curves of Medium Compartment Fires for Structural Design," Fire Safety Journal, Vol. 34, pp. 361–375, 2000.
12. Law, M. "A Basis for the Design of Fire Protection of Building Structures," The Structural Engineer, Vol. 61A, No. 5, January, 1983.
13. Tanaka, T., Sato, M. and Wakamatsu, T., "Simple Formula for Ventilation Controlled Fire Temperatures," In: 13th Meeting of the UJNR Panel on Fire Research and Safety, March 13–20, 1996, NISTIR 6030, National Institute of Standards and Technology, Gaithersburg, MD, 1997.
14. SFPE Engineering Guide to Fire Exposures to Structural Elements, Society of Fire Protection Engineers, Bethesda, MD, 2004.
15. Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, 2002.
16. Dinenno, P. (Ed.), The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, 2002, Appendix B.
17. http://www.zaintraders.com/thermosil.html
18. Eurocode1 – Basis of Design and Actions on Structures Part 2.2 Actions on Structures – Actions on Structures Exposed to Fire, ENV 1991-2-2: 1995, CEN.
19. Buchanan, A. Structural Design for Fire Safety, John Wiley and Sons, UK, 2001.
20. Franssen, J., "Improvement of the Parametric Fire of Eurocode 1 Based on Experimental Test Results," In: Fire Safety Science – Proceedings of the Sixth International Symposium, International Association for Fire Safety Science, London, 2000.

21. Kawagoe, K. and Sekine, T., "Estimation of Fire Temperature-Time Curve in Rooms," Occasional Report No.11, Building research Institute, Tokyo, 1963.
22. McCaffrey, B., Quintiere, J. and Harkelroad, M., "Estimating Room Fire Temperatures and the Likelihood of Flashover Using Fire Test Data Correlations," Fire Technology, Vol. 17, No. 2, pp. 98–119, 1981.
23. Babrauskas, V., "Heat Release Rates," The SFPE Handbook of Fire Protection Engineering, National Fire Protection Association, Quincy, MA, 2002.
24. Kirby, B., Wainman, D., Tomlinson, L., Kay, T. and Peacock, B., "Natural Fires in Large-Scale Compartments – A British Steel Technical, Fire Research Station Collaborative Project," British Steel, Rotherdam, UK, 1994.