$$T_t = 250(10F_v)^{\frac{0.1}{F_v^{0.3}}} e^{-F_v^2 t}\left[3(1-e^{-0.6t})-(1-e^{-3t})+4(1-e^{-12t})\right] + C\left(\frac{600}{F_v}\right)^{0.5} \quad (5\text{-}22)$$

where

$$F_v = \frac{A_v(H_v)^{1/2}}{A_t} \quad (5\text{-}23)$$

Figures 5-5 and 5-6 compare this expression to Kawagoe's theoretical model for various opening factors.

To model the decay phase of the fire that must be applied to the curves generated by the primary expression, Lie proposed the following:

$$T_t = -600\left(\frac{t}{\tau}-1\right)+T_\tau \quad (5\text{-}24)$$

where

$$\tau = \frac{L_{td}A_t}{330A_v(H_v)^{1/2}}, \quad (5\text{-}25)$$

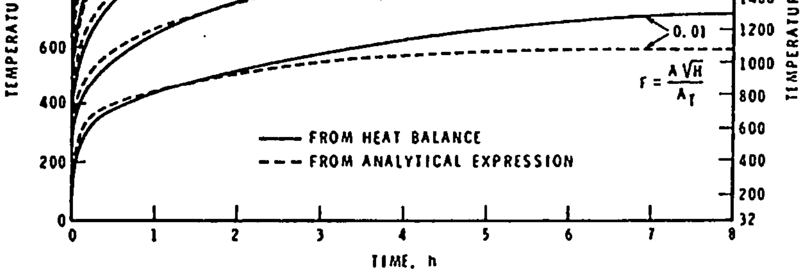

FIGURE 5-5. Theoretical vs. Experimental Time–Temperature Curves—Heavyweight Construction (Lie)
Source: Parkinson and Kodur 2006.

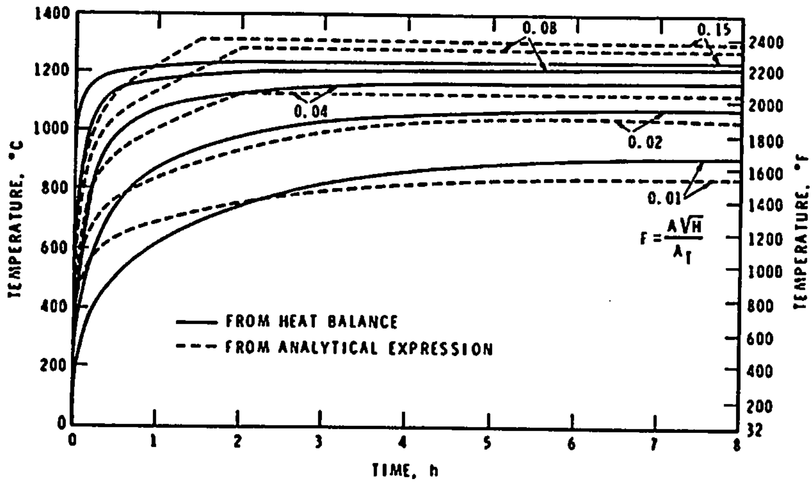

FIGURE 5-6. Theoretical vs. Experimental Time–Temperature Curves—Lightweight Construction (Lie)
Source: Parkinson and Kodur 2006.

recognizing that the above equation is based on the expression for burning rate developed by Kawagoe.

The two expressions were used to compare against actual temperature measurements from a compartment fire, with results shown in Fig. 5-7 and with the results of Pettersson et al. shown in Fig. 5-8.

It is clear from these figures that the expression proposed by Lie reasonably approximates both experimental data and the Swedish approach. The benefit is that the expression proposed by Lie is simplistic enough that it may be applied to a real-life problem with a hand calculator or spreadsheet. It is important to remember that Lie's expression is based on curves developed with the heat balance approach, and that Lie has developed an expression that allows the designer to avoid the significant calculations necessary to perform a heat balance in order to develop a reasonable time–temperature curve for design purposes.

One concern is that Buchanan (Buchanan 2001) argues that Lie's curves are unrealistic for rooms with small openings because the calculated compartment temperatures are not sufficient for the occurrence of flashover.

5.2.4 Comparison of Parametric Design Curves

Given the variation in the possible approaches available for calculating realistic compartment fire time–temperature curves, it seems that a

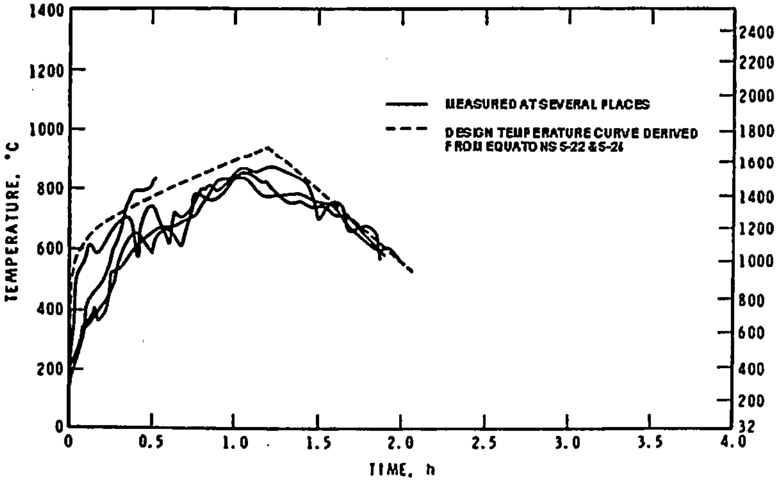

FIGURE 5-7. Comparison of Theoretical vs. Experimental Time–Temperature Curves—Lie
Source: Lie 1992.

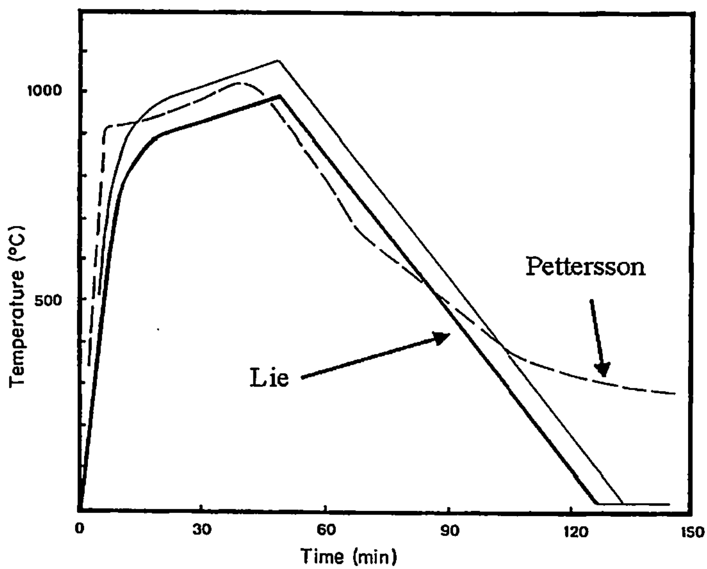

FIGURE 5-8. Comparison of Theoretical Time–Temperature Curves—Lie and Pettersson
Source: Parkinson and Kodur 2006.

comparison of the curves would be helpful in determining which model produces the more conservative results. In Table 5-1 the variables used in the comparison of Pettersson's, Lie's, original Eurocode (European Committee for Standardization 1993), and Modified Eurocode (Buchanan and Feasy 2002) are summarized.

For this comparison, a typical 5 m wide by 5 m long by 3 m high (16.4 ft wide by 16.4 ft long by 10 ft high) compartment was selected in addition to the tabulated values in Table 5-1. For these comparisons the tabulate values from Pettersson (Pettersson 1978) and the calculated curves from the equations described previously have been used for the other three models (Lie, Eurocode, and Modified Eurocode). The results of the comparison are indicated in Figs. 5-9 through 5-14. It is important to remember that these models are post-flashover models and that they are only applicable if temperatures exceed 600 °C.

Typically, as discussed in previous sections, the period of most interest from a structural fire safety standpoint is the fully developed phase of the fire up to the point where decay begins. Based on the above graphs, the Modified Eurocode curve would result in the most conservative results since it predicts the highest temperature. Pettersson's curve does predict a longer fire duration but does not obtain as high a temperature as the Modified Eurocode curve. Also, the Modified Eurocode curve represents a more severe fire (area under the curve) up to a temperature of about 150 °C. Both the Eurocode and Lie curves under-predict compartment temperatures relative to the other two curves.

As with Fig. 5-9, the Modified Eurocode curve predicts higher temperatures. However, it does have the shortest duration. Although not specifically calculated, the severity resulting from each curve appears roughly similar. However, given the importance of overall room

TABLE 5-1. Summary of Data for Comparison of Time–Temperature Models

Variable	Comparison					
	1	2	3	4	5	6
$\sqrt{k\rho c_p}$ [a]	1,160	1,160	1,160	1,160	1,160	1,160
F_v	0.02	0.02	0.06	0.06	0.12	0.12
L_{td} [b]	25	251	75	753	75	1,507

[a]Thermal inertia is based on the value used for the Swedish curves for Typical Compartment Type A. For Lie's curve, heavy construction was assumed.
[b]Fuel loads shown are from Pettersson's tables (Parkinson and Kodur 2006) and represent the range of fuel loads used for the opening factors indicated.

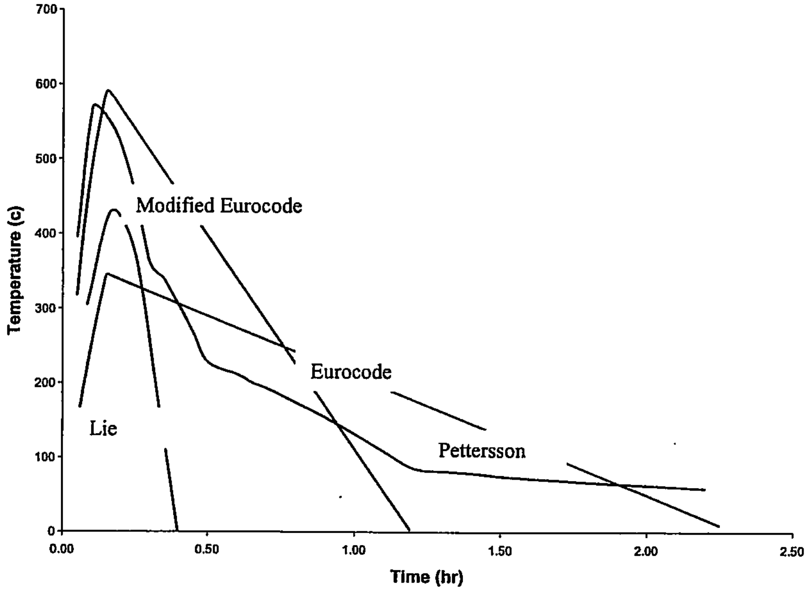

FIGURE 5-9. Comparisons of Lie's, Pettersson's, Eurocode, and Modified Eurocode Based on Comparison 1 from Table 5-1

temperatures on the impact on the structure, the Modified Eurocode curve may result in a more conservative prediction of the real fire scenario for the compartment configuration used in the modeling.

As with Figs. 5-9 and 5-10, the Modified Eurocode curve represents the most conservative prediction of both compartment temperatures and fire severity.

Again, the Modified Eurocode curve predicted the fire with the highest compartment temperatures and fire severity. It is worth noting that the decay rate for this scenario predicted by the Eurocode curve was to be governed by Eq. 5-18. However, use of this equation resulted in a continuing increase in temperature. As a result, the decay rate was generated from Eq. 5-19 for purposes of this figure. In reality, the decay rate for this scenario will be somewhere between the line shown and a horizontal line tangent to the highest point on the curve.

One thing that can be seen from Figs. 5-9, 5-10, and 5-11 is that the models are not as consistent at predicting compartment temperatures for rooms with small fuel loads. In each of the three scenarios for these figures, the fuel load was approximately half of that typically expected in a typical office.

Although the Modified Eurocode does predict the highest compartment temperatures, the Lie curve predicts the greatest fire severity with similar temperature predictions. For all previous scenarios the Modified Eurocode

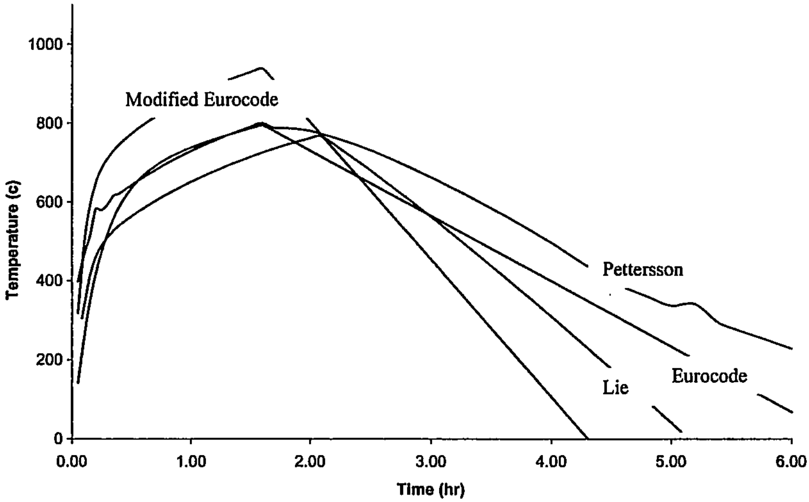

FIGURE 5-10. Comparisons of Lie's, Pettersson's, Eurocode, and Modified Eurocode Based on Comparison 2 from Table 5-1

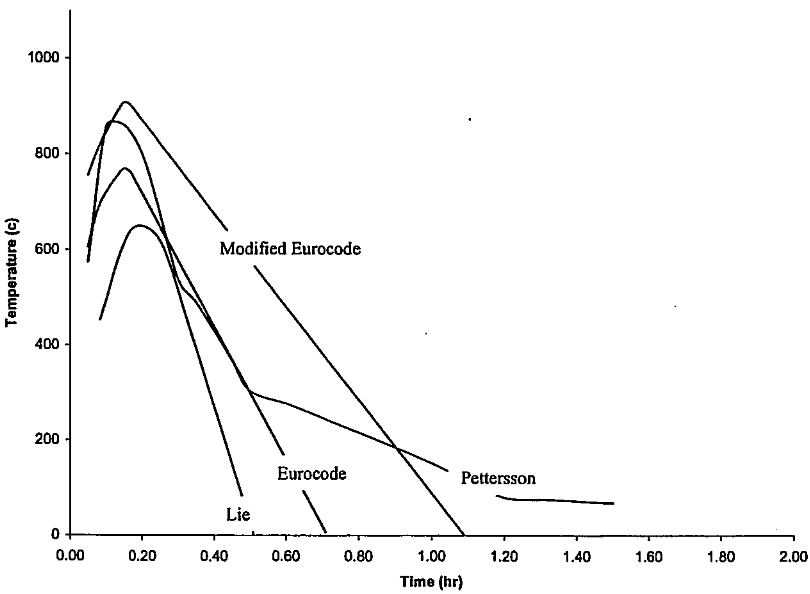

FIGURE 5-11. Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison 3 from Table 5-1

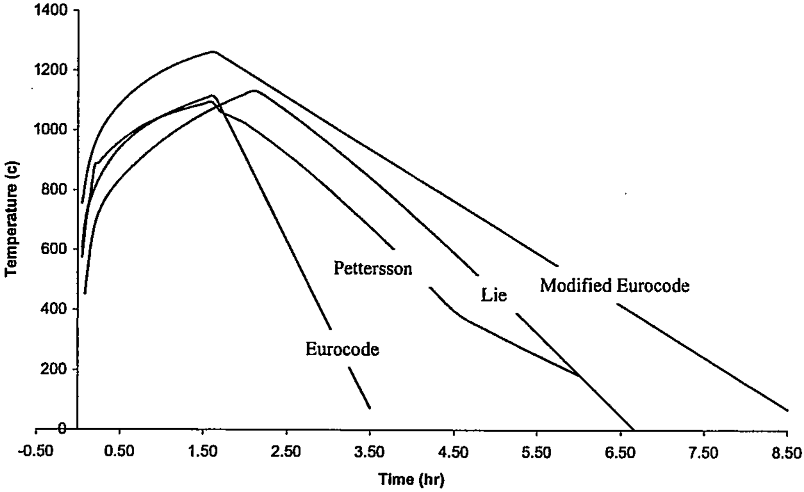

FIGURE 5-12. Comparisons of Lie's, Pettersson's, Eurocode, and Modified Eurocode Based on Comparison 4 from Table 5-1

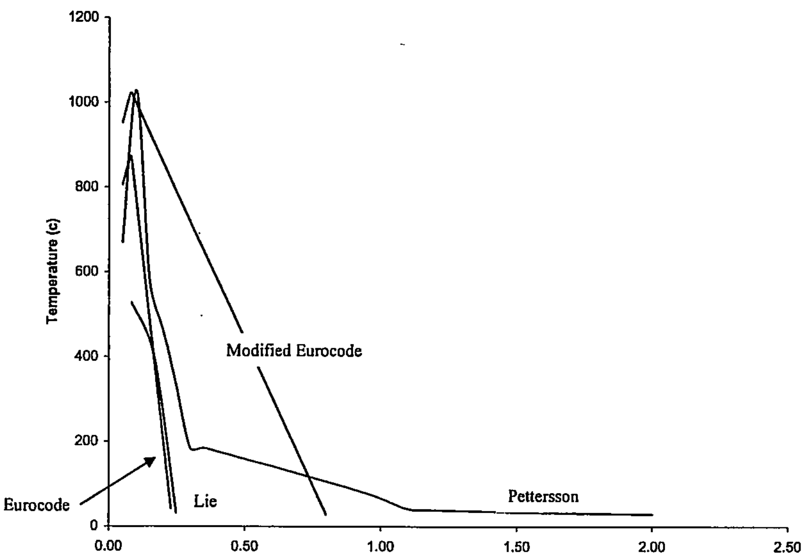

FIGURE 5-13. Comparisons of Lie's, Pettersson's, Eurocode, and Modified Eurocode Based on Comparison 5 from Table 5-1

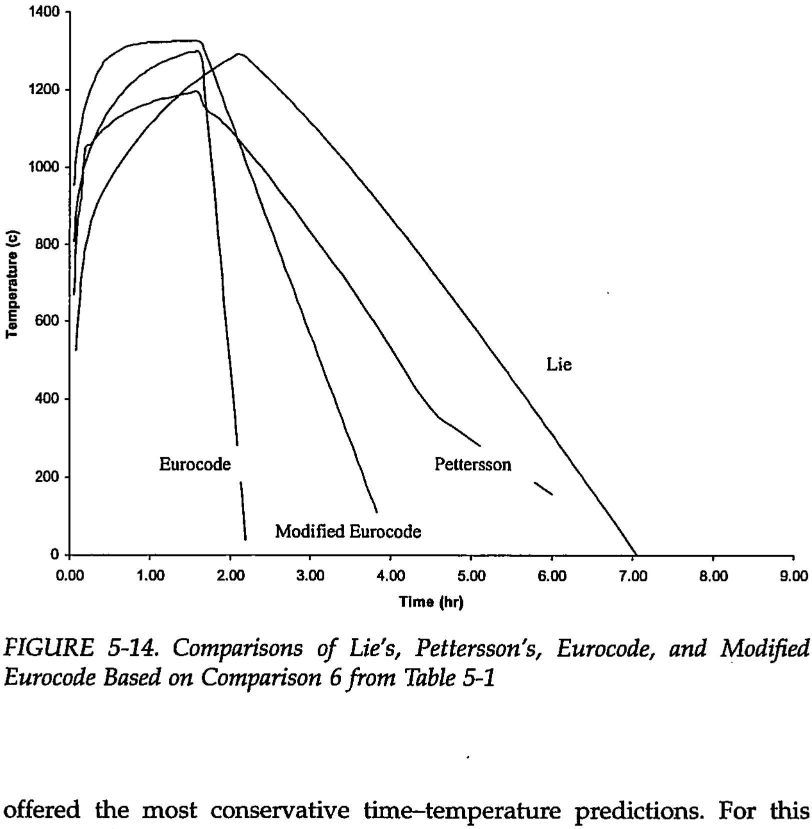

FIGURE 5-14. Comparisons of Lie's, Pettersson's, Eurocode, and Modified Eurocode Based on Comparison 6 from Table 5-1

offered the most conservative time–temperature predictions. For this scenario the ventilation opening is 28% of the wall area and the fuel load is twice the high end of what might be expected in an office, which does not necessarily represent a typical compartment scenario. Therefore, for a typical compartment scenario the Modified Eurocode would be expected to yield the most conservative results.

CHAPTER 6

BASIC CONCEPTS OF STRUCTURAL FIRE DESIGN

The reason why structural systems in buildings are protected is to provide a means to ensure the stability of the structural systems so that buildings do not collapse in the event of a fire. More specifically, we are interested in the performance of the load-bearing capacity as it relates to the strength, stability, and ductility of the structural system, and the thermal insulation and integrity as it relates to the structural system's ability to contain the spread of fire. By defining these values for a given fire condition, we can predict the safety of the structure.

As a fire within a compartment intensifies, the thermal load on the surrounding structures increases and the residual strength of the member will decrease. The rate of decrease of the structural strength will be a function of the physical characteristics of these structures. For example, given the identical fire scenario, a small, slender steel column would be expected to reach a critical temperature sooner than a larger, heavier column. Under the prescriptive-based code, all structural members must be protected to the same degree. This approach does not allow for the fact that not all of the structural elements within a building are necessarily given the same weight with respect to overall building integrity (i.e., some members may collapse and the building will remain standing).

6.1 ROLE OF THE STRUCTURAL ENGINEER VS. THE FIRE PROTECTION ENGINEER

Typically there is not much interaction between the structural and fire protection engineers retained for a given project. The main reason is that the current building codes dictate required fire resistance ratings (FRRs), thereby minimizing the need for collaboration between the two disciplines. In a performance-based code environment, it will be necessary for this to change.

The structural engineers will be responsible for defining several areas within the building that could be considered sensitive areas containing structural members that are significant to overall building structural stability. These would be areas where, under normal conditions, structural members are at or near their design loads. To determine these areas, a computational analysis of the various loads on all building members under maximum foreseeable load conditions would likely be necessary. Such computations are readily available from current structural engineering design software. The structural engineer would also be responsible for identifying the importance of the isolated areas with respect to overall building stability. This is not to say that the areas identified are necessarily the areas where a critical fire might begin but, rather, serve as a starting point for the overall assessment. Finally, physical characteristics of the supporting structure would have to be provided, such as:

- Member density, thermal conductivity, etc.; and
- Physical size, shape, and proposed construction of the structural element (i.e., protected, unprotected, or partially protected).

6.2 SPECIFIC CALCULATION REQUIREMENTS

Chapter 3 identifies the general format of the proposed approach to the performance-based design of structural members for fire conditions, and identifies the importance of maintaining the current FRRs as the design objective. To this end, a process has been demonstrated that will allow the user to predict a realistically conservative time–temperature curve for a compartment fire based on the specific compartment dimensions, construction, fuel load, and opening sizes. From this information, the goal is to derive the temperature history of the structural element based on the heat input resulting from the compartment fire (Stanzak 1973).

The thermal behavior under fire conditions has been well defined for steel and concrete structures; simple analytical procedures have been developed regarding the steady-state condition; and more complex finite element approximations have been developed for the transient condition.

Although attempts have been made to develop analytical approaches for wood, difficulty remains regarding the calculation of the charring rate of the wood (Pettersson 1985). The significance is that as the fire progresses and the wood structural member burns, a decrease in cross-sectional area occurs, which reduces the ability of the member to withstand an applied load.