PERFORMANCE BASED DESIGN OF STRUCTURAL STEEL FOR FIRE CONDITIONS

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ABSTRACT

As jurisdictions throughout the world progress toward performance based building codes, it is important that the proper tools be made available to the engineering profession in order that they may take full advantage of these new codes. There is currently a large body of work written on the subject of performance based or engineered structural fire safety. Unfortunately, most of this information is scattered throughout technical journals from different countries and organizations, and not easily accessible to the practicing engineer.

Under the current prescriptive code regime there is generally no requirement to undertake an engineering approach to structural fire safety, since the required fire resistance ratings are prescribed and the fire resistance ratings of materials/assemblies are determined through standard tests. However, these methods have been shown to be both unnecessary and expensive in some cases. A method will be developed that can be used to determine required fire resistance ratings for fire exposed structural steel based on a realistic engineering approach.

A procedure is summarized for calculating time-temperature curves from a real fire in a typical compartment. With this time-temperature relationship a realistic time to failure for structural steel members can be determined. The method is summarized. Comments regarding important considerations and a worked example are provided to demonstrate the utility of the method.

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NOMENCLATURE

Alphabetic Symbols	**Description**	**Units**
A_i	Internal surface area per unit length of insulation	m^2/m
A_f	Compartment floor area	m^2
A_h	Area of horizontal compartment vent openings	m^2
A_t	Area of total surface area of compartment	m^2
A_v	Area of vertical compartment vent openings	m^2
A_{vi}	Area of compartment vent opening i	m^2
A_w	Compartment width	m
b	$\sqrt{k\rho c}$ thermal inertia	$J/m^2s^{1/2}K$
c_{ps}	Specific heat of steel	J/kg^0C
c_p	Specific heat	J/kg^0C
C	Constant based on whether a light or heavy building construction material has been used for the compartment boundaries: C=0 for heavy; C=1 for light	--
d_i	Thickness of insulating material	m
F_d	Factor for the distribution characteristics of the fuel loads	--
F_s	Surface area of steel exposed to the fire per unit length	m^2/m
F_v	Ventilation factor	$m^{1/2}$
g	Gravitational constant	m/s^2
h_c	Convective heat transfer coefficient	W/m^2K
h_c”	Combustion enthalpy	kcal/kg
H’	Normalized heat load for a real fire	$s^{1/2}K$
H”	Normalized heat load for the standard fire test	$s^{1/2}K$
H_A	Total area of all compartment openings	m^2
H_c	Height of compartment	m
H_H	Calculated mean opening height for all compartment openings	m
H_i	Height of compartment vent i	m
H_v	Compartment vent height	m
H_{ui}	Lower calorific value of the combustible material	MJ/kg
H_w	Compartment vent width	m
k	Thermal conductivity	W/mK
k_b	Factor applied to account for the insulation properties of the compartment enclosure	--
k_i	Thermal conductivity of thickness being analyzed	W/mK
k_{fs}	Thermal conductivity of the floor slab	W/mK
K_d	Factor applied to the mean fuel load to obtain the 80^{th} or 90^{th} percentile values to be used for design	--
L	Mass of fuel load per unit floor area	kg/m^2
L_{fk}	Average calorific fuel load per unit floor area	MJ/m^2

	Description	Units
L_{tk}	Average calorific fuel load per unit total surface area	MJ/m^2
L_{fd}	Design calorific fuel load per unit floor area	MJ/m^2
L_{td}	Design calorific fuel load per unit total surface area	MJ/m^2
$\dot{m}$	Burning rate	kg/hr
$\dot{m}_{air}$	Mass flowrate of air into the compartment	kg/hr
$\dot{m}_f$	Mass flowrate of hot gases	kg/hr
$\dot{m}_p$	Mass flowrate of combustion gases	kg/hr
m_i	Combustion factor	---
M_i	Mass of product of combustion i	kg
q	Heat per unit length	J/m
q''	Heat flux	W/m^2
q''_c	Convective heat flux	W/m^2
q''_r	Radiative heat flux	W/m^2
$\dot{q}_C$	Rate of heat release due to combustion	W
$\dot{q}_L$	Rate of convective heat loss due to outflow of hot gases	W
$\dot{q}_W$	Rate of heat loss through compartment boundaries	W
$\dot{q}_R$	Rate of heat loss by radiation through compartment openings	W
$\dot{q}_B$	Rate of heat storage in the gas volume	W
t	time	hr
t_e	Equivalent time for identical fire severity as standard fire test	hr
Δt	Time step	hr
T_0	Ambient temperature	^0C
T_1	Temperature as a function of combustion gas temperature T_t	^0C
T_{co}	Temperature of the plenum side of the floor slab	^0C
T_{ci}	Temperature of the plenum side of the suspended ceiling	^0C
T_{fs}	Temperature of the floor slab	^0C
T_{fi}	Temperature of the middle of the lowest strip of the floor slab	^0C
T_i	Temperature of internal surface i	^0C
T_{max}	Maximum compartment temperature	^0C
T_t	Compartment temperature at time t	^0C
T_s	Steel temperature at time t	^0C
T_τ	Temperature at time τ (start of compartment fire decay)	hr
T_w	Wall surface temperature	^0C
ΔT	Change in temperature	^0C
ΔT_S	Change in steel temperature over time Δt	^0C
V_s	Volume per unit length of the steel section	m^3/m
Δx_1	Thickness of layer being assessed	m

Greek Symbols **Units**

		Units
α	Convective heat transfer coefficient	$W/m^2\ {}^0C$
α_1	Surface coefficient of heat transfer in the boundary layer between the combustion gases and suspended ceiling	$W/m^2\ {}^0C$
α_2	Surface coefficient of heat transfer in the boundary layer between the suspended ceiling and floor slab	$W/m^2\ {}^0C$
α_i	Heat transfer coefficient of the inner surface exposed to fire	$W/m^2\ {}^0C$
ε	Emissivity	--
ε_w	Emissivity of the compartment walls	--
ε_r	Resultant emissivity based on combining emissivity of fire gases and steel	--
ε_i	Emissivity of the i^{th} inner compartment surface	--
ε_f	Emissivity of the gases in the compartment	--
ρ	density	kg/m^3
ρ_a	Air density	kg/m^3
ρ_s	Steel density	kg/m^3
σ	Steffan-Boltzman constant	kW/m^2K^4
γ_{q1}	factor of consequence of structural failure based on type of fire compartment and overall building height	--
γ_{q2}	factor to account for probability of occurrence of a fire based on fires reported to fire service	--
γ_n	factor to account for the influence of sprinklers	--
Γ	Fictitious time	hr
τ	Duration of burning period of fire	hr
Φ	Ventilation parameter	kg/s

1.0 Introduction

As jurisdictions throughout the world progress towards performance based building codes, it is important that the proper tools be made available to the engineering profession in order that they may take full advantage of these new codes. There is currently a large body of work written on the subject of performance based or engineered structural fire safety. Unfortunately, most of this information is scattered throughout technical journals from different countries and organizations, and not easily accessible to the practicing engineer.

Under the current prescriptive code regime such as that prescribed by the National Building Code of Canada (NBCC) [4] or the BOCA National Building Code [20] there is generally no requirement to undertake an engineering approach to structural fire safety, since the required fire resistance ratings are prescribed and the fire resistance ratings of materials/assemblies are determined through standard tests. However, there is growing criticism that these standard tests may not be relevant based on current construction practices/materials, and that they do not accurately reflect a real compartment fire scenario given the difference in the time-temperature curves between standard vs. real fires. This document will develop a method that can be used to determine required fire resistance ratings based on a realistic engineering approach.

The method will be described by detailing fire scenario development approaches and limitations. A discussion is presented regarding the relative importance of various components. A procedure is summarized for calculating compartment time-temperature curves for the defined fire scenario and the corresponding thermal behavior of fire-exposed structural steel within the compartment. A procedure is also summarized for calculating the response of non-load bearing partitions in a compartment fire. Based on the time to failure, as described by established criteria, the required fire resistance rating (FRR) can be determined based on established methods. The limitations and scenarios for which these techniques are best suited are discussed to provide the reader with some confidence regarding the applicability of this method in determining actual fire resistance ratings based on the fire scenario developed.

Since the current prescriptive code regime has been dominant for many years it will be important to quantify the relative “safety” of using a performance based design method relative to the current methods. A discussion is presented to demonstrate the limitations of the method relative to the related variables.

A worked example describes in detail the utility of the method for both structural steel and non-load bearing partitions exposed to realistic compartment fire scenarios.

2.0 Weakness of the Current Design Approach

Current building code requirements for determining the fire resistance of structural systems are based on the reaction of specimens to a standard fire exposure such as defined by test standards ASTM E119, ISO 834, and NFPA 251. These standards have been the fundamental basis for determining FRR's in building code applications since the 1920's. Although these standards have resulted in a reasonable level of safety given the lack of frequent building failures, there is nevertheless a growing body of evidence, which suggests that the entire testing procedure used by these standards is not realistic. Specifically, the time-temperature curves used by the standards do not compare well to the time-temperature curve of a real compartment fire. The result is that building construction may be needlessly costly. Some of the criticisms are:

- The standards are based on a specified time-temperature exposure that is constantly increasing, whereas the time-temperature relationship of a real fire has defined components consisting of growth, fully developed, and decay periods. Figure 1 indicates the typical difference between the test curve and a more realistic curve [32] ;
- Load bearing structural members are tested at a load corresponding to the maximum permissible stress of the member being tested. This is significant since the load bearing structural members in a building are not typically designed to carry a load at the maximum permissible stress, nor is the building load distributed evenly throughout the structural members [33] ;
- Only a single component of the overall building structural system is tested. By only performing a single element test it is not possible to account for the load distribution that

will likely occur throughout the remainder of the supporting assembly when a single member of the system fails[42] ; and

- The fire resistance rating of the member is defined by the length of time it can withstand the standard fire exposure while satisfying specific performance criteria. The success of the test is in part a function of the gas temperature within the furnace. The gas temperature is a function of the convective heat from the heat source and radiant heat from the furnace walls. Radiant energy is the dominant component of the total heat release rate incident upon the structural member, and since the magnitude of the radiant flux is proportional to the temperature to the fourth power, the impact of the radiation component can be significant. The type of furnace wall construction directly impacts the magnitude of the radiant energy. Therefore, if the wall construction from one furnace to another varies then the impact of radiation may also vary [2].

It should be pointed out that these examples that identify the weakness of the current test standards do not reflect a comprehensive critique of the standards.

It is also worth noting that ASTM E-119 [5] states the following:

> *This standard should be used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions and should not be used to describe or appraise the fire-hazard or fire-risk of materials, products, or assemblies under actual fire conditions. However, results of the test may be used as elements of a fire-hazard assessment or a fire-risk assessment which takes into account all of the factors which are pertinent to an assessment of the fire hazard or fire risk of a particular end use.*

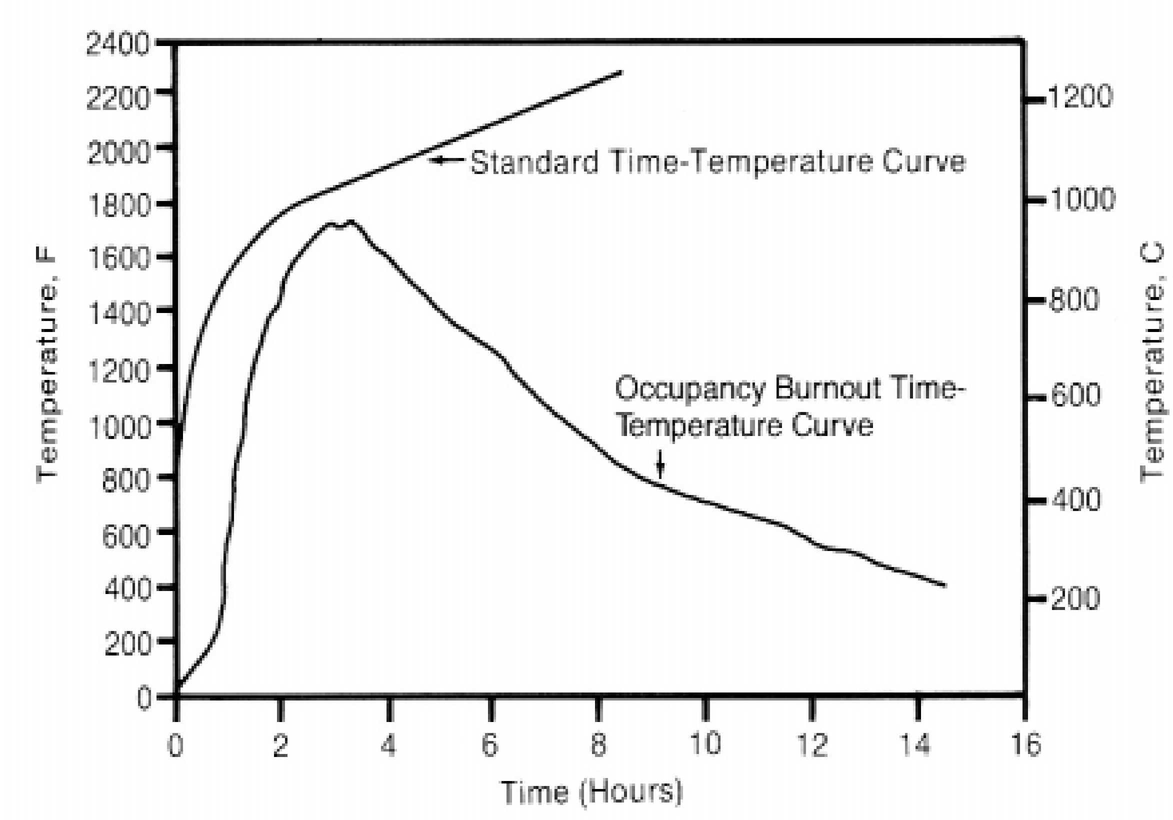


Figure 1 Standard vs Realistic Compartment Fire Time-Temperature Curve [32]

Based on the criticisms summarized above and this statement from ASTM E-119 it is clear that the issue of establishing FRR based on standard fire testing warrants closer examination.

This section will provide further details identifying the significance of the issues described above. However, it is first important to understand the origin of the standard test method.

2.1 History of the Standard Test Methods and Related Fire Resistance Ratings

In 1908 the American Society for Testing Materials (ASTM) published a standard test method based on the need to develop a common approach to evaluating the fire safety of building construction materials. In 1918 a time-temperature curve was established as part of the standard based on the maximum temperatures experienced in real fires at the time. The curve was not based on the response of building components to a real fire but rather what the authors have described as a worst case time-temperature relationship to be expected during a fire.

This curve has remained essentially unchanged and has been adopted by numerous countries around the world with only minor variations. Figure 2 shows a comparison between the time-temperature curves of the standards of various countries.

For ASTM E-119 the standard time-temperature curve may be represented by the following equation:[2]

$$T_t = T_0 + 345 \log(0.133t + 1) \qquad (1)$$

This standard time-temperature curve allowed the construction industry to determine the fire resistance rating for a given structural member or assembly based on the time to failure in the furnace. The difficulty came when trying to relate this time to failure to the building code requirements. To address this, the “Fire Load Concept” was proposed by Ingberg in 1928. This concept proposed that the total heat release rate over the time required for a real fire to consume all combustible contents within a fire compartment could be considered the fire severity, with the fire severity being equal to the area under the real fire curve. This fire severity would vary depending upon the fire load within the fire compartment. For example,

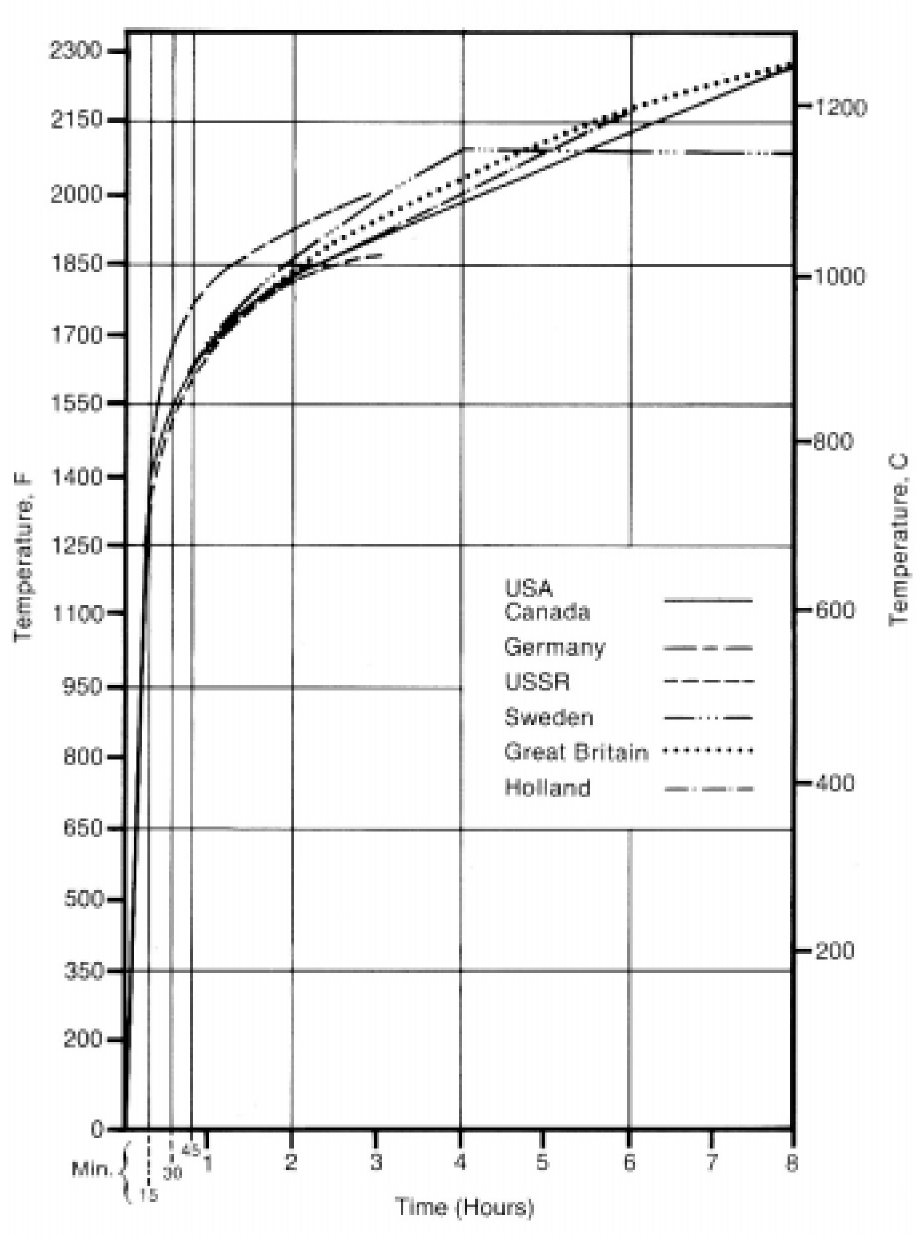


Figure 2 Standard Test Curves for Various Countries [32]

the fire severity in a typical office (area under the curve represented by a real fire in an office) would be expected to be less than the fire severity in an industrial plant (area under the curve represented by a real fire in a plant). It was proposed that the fire severity for a typical compartment fire could be related to the fire resistance determined by the standard fire test by equating the area under the real fire curve above a base-line temperature to the area under the standard fire curve. That is, the point at which the area under the standard fire curve is equal to the area under the real fire curve would provide the equivalent fire resistance for the fire severity being considered. From this, the fire resistance required for a particular compartment could be determined if the compartment fire load was known. Figure 3 indicates this concept.

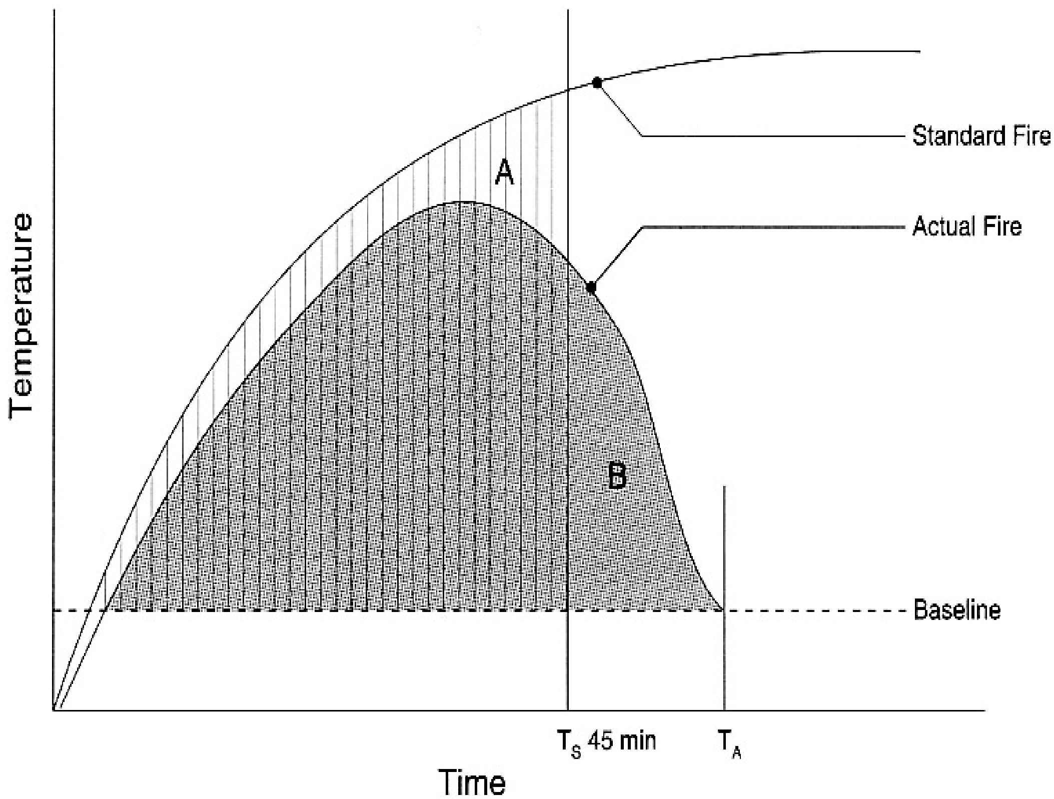


Figure 3 Ingberg's Fire Load Concept [1]

To represent this relationship Ingberg performed a number of tests and generated a table of data shown below:

TABLE 1 ***[1, 2]***

Summary of Ingberg's Fuel Load vs. FRR

Fire Load Of Occupancy[1]		Fuel Load[2]		Fire Resistance[3]
kg/m²	lb/ft²	MJ/m²	BTU/ft²	minutes
24.4	5	456	40,000	30
48.8	10	912	80,000	60
73.2	15	1,368	120,000	90
97.6	20	1,824	160,000	120
146.5	30	2,736	240,000	180
195	40	3,590	320,000	270

Note: (1) ratio of combustible fuel load per unit floor area.
(2) ratio of energy content of combustibles per unit area.
(3) FRR required for structures exposed to fire in room with fire load shown.

In addition to other data such as provisions for fire fighting, exiting requirements, and building size, Table 1 above was used to form the minimum fire resistance requirements for the NBCC [1], and is the basis for the fire resistance requirements of other building codes and for some government agencies [6].

Typically most building codes require that the fire resistance requirements for load bearing elements be equivalent to the fire resistance ratings of the floor/ceiling assemblies being supported[4] [20]. These ratings typically range from 45 min. to 60 minutes for light fire hazard occupancies such as businesses, schools, hospitals, etc. For medium fire hazards occupancies such as department stores and light manufacturing facilities the ratings are typically between 60 minutes and 120 minutes. For high fire hazard occupancies such as for textile mills, pulp and paper plants, and chemical processing factories the fire resistance ratings typically range between 120 minutes and 240 minutes. Table 2 compares the fuel load of typical occupancies with the fire resistance requirements from Table 1 and those of the National Building Code of Canada[4], [5].

Table 2
Comparison of Ingberg's FRR vs. NBCC FRR

Fire Hazard	**Type**	**Fuel Load [3] (MJ/m²)**	**FRR from Ingberg[2] (minutes)**	**FRR from NBC [4] (minutes)**
Light	Office	600 - 800	60	45 - 60
	School	300	30	45 - 60
	Hospital	300	30	60 - 120
	Bank	800	60	45 - 60
Medium	Packaging Plant	1600 - 1800	120	60 - 90
	Wax Plant	1300	90	60 - 90
	Storage Room	1200 - 1400	90	60 - 90
High	Wood Preserving	3000	180	90 - 120
	Synthetics Plant	3400	240	90 - 120
	Paint Plant	4200	>240	90 - 120

Although by no means an exhaustive summary comparing the typical building code requirements to Ingberg's theory, the table above nevertheless demonstrates a general relationship between the National Building Code of Canada requirements and Ingberg's theory. Specifically, as the compartment fuel load increases so does the related FRR.

The North American construction industry relies on the FRR as tested and catalogued by testing laboratories such as Underwriters Laboratories in both the US and Canada. The building code in turn reference these standard tests for use when selecting building components required to meet prescribed FRR. This places a significant amount of importance on the results of the test. That is, the building codes stipulate that a designer merely needs to select a construction component from the catalogue that has a listed FRR that is equal to or greater than the required rating to ensure code compliance, with the assumption that code compliance ensures building fire safety. The significance of this reliance on the catalogued data is described in the following sections.

2.2 Influence of Standard Fire Test Time-Temperature Curve on Test Specimen

Ingberg's "Fire Load Concept" was an attempt to address the difference in the time-temperature relationships of the standard test curve vs. the realistic curve. However, the empirical data on which the simplification was based were obtained from full scale fire tests of buildings from almost 100 years ago, which may not reflect the characteristics of a fire in a modern building. The modern building contains a higher level of plastic materials, which when burned result in a higher heat release rate fire than wood based products [3]. Also, buildings constructed at the time the empirical data was obtained were typically heavy timber construction compared with lighter construction techniques used in modern buildings.

Furthermore, it has been found in some cases that the difference between the real gas temperature in the test furnace and the temperature measured from the thermocouples placed within the test chamber can be as high as 100^0C depending upon the construction of the furnace walls[19]. This is significant because the thermocouples control the fuel supply required to maintain the standard test curve. If these thermocouples do not reflect accurate temperature readings and more fuel is supplied the influence on the radiative component of the energy transfer can be significant. In addition, the testing of structural members that contain combustible materials can directly influence the temperature readings from the thermocouples as they may be surrounded by flames from the burning test specimen, and not measuring only the furnace temperature prescribed by the standard [19]. These characteristics were reported to have led to a 30% difference in the assigned FRR of an identical test specimen based on tests from two different furnaces in the UK [41].

2.3 Influence of Loading & Restraint of the Structural Member in the Test Chamber

Typically standard tests require that structural elements being tested be loaded to the maximum allowable stress of the member. The allowable stress is a combination of the dead load and the live load to be expected by the structural component during the life of the building. However, with modern design philosophy, structural components are normally sized larger than required for service load[21]. The significance is that the actual load on a member during a fire may be different than that used for the standard test to determine FRR. Therefore, the actual member may not perform as expected from the test during a real fire due to different loadings. This is further complicated by the fact that building codes require that all structural members in a given building be given the same FRR regardless of the actual service load. Also neither building codes nor the standard test, which analyzes a single building element, account for the load re-distribution that takes place when a single structural element fails [42].

Standard tests also require that the structural member be restrained at the ends or sides in a manner that is similar in nature to the actual service condition. This is important as the end restraints play a key role in the performance of the structural member in the standard test. For example it has been shown that a beam with rotation and displacement end restraints has a greater FRR than unrestrained beams [34]. The criticism here is that the type of end restraint is difficult to control from one furnace test to another with few laboratories having the ability to define the real degree of end restraint[22].

This is of further concern given the inability to properly regulate the end restraint construction actually applied in the field when utilizing a furnace tested design solution, since in the case of ASTM E119 requirements for restrained and unrestrained conditions are not well defined [34]. As an example, different connecting bolts may be used in the field than were used in the test, or welding techniques may not be the same. This is also a concern since the tested assembly is only for one end restraint condition, which does not account for a variation in assembly techniques that might be experienced in the field. Therefore there is no way to accurately predict the impact of slight variations on the field installed component to the overall FRR.

Although beyond the scope of this document, another factor worth noting is based on the findings of the Cardington Fire Tests and a fire at the Broadgate Development in the UK [42]. In the Broadgate example a fire started in a partially complete 14-storey building consisting of exposed steel frame and concrete floor construction. In the Cardington tests an 8-storey building was constructed with similar characteristics and a series of fire tests conducted. Although deformation and buckling of some of the steel structure occurred, in neither case did the building collapse. The investigation into the Broadgate fire and results of the Cardington tests confirmed that the steel frame for a multi-storey building acted as a system and not as a series of single elements. In fact, as some structures were weakened due to elevated temperatures, the load carried by the weakened members was transferred to other portions of the structural system.

2.4 Influence of Material Properties

Standard fire resistant tests are performed on a sample of structural element/assemblies. Typically this sample is tested once or twice. It is implied that the structural element/assembly tested reasonably represents the field installed components. This is not normally the case as a wide variation in material properties usually exists. For example, a steel beam made from Fe E 240 has a characteristic yield stress of 240 MPa at room temperature, whereas the yield stress can be as high as 300 MPa [22] in practice. The increased strength results in a greater FRR (i.e. time to failure in the standard test, in this example at a temperature 75^{0}C higher)[22].

It should be pointed out that in the above example the difference in material properties is beneficial. However, such a difference of ≥ 20% is cause for concern since it demonstrates a lack of consistency between performance in the standard test and what might reasonably be expected in practice, and therefore should cast doubt over the results of the standard test.

2.5 Influence of Furnace Construction

It has been stated previously that the heat being absorbed by the structural member is a function of the convective and radiative heat release rates in the furnace. The fundamental expressions for these components are as follows [35]:

<u>Convective</u>

$$q_c'' = h_c \Delta T \tag{2}$$

<u>Radiative</u>

$$q_r'' = \varepsilon \sigma \Delta T^4 \tag{3}$$

Clearly the impact of radiation on the overall heat input to the structural member is significant compared with the convective heat due to the T^4 component. Given that the difference in the actual furnace temperature compared with that measured by the thermocouples can be as high as 100^0C, significant differences can occur. In this case, assuming that the actual temperature in the furnace was 500^0C but that the measured temperature was 600^0C, the radiant heat flux actually incident upon the member would be 60% of what would be predicted based on the measured temperatures.

The preceding sections serve to illustrate the variability in the standard fire test, and that indiscriminately relying on the data of these tests as prescribed by the building codes warrants reconsideration. In fact, others have performed a limited review of available experimental data and discovered that a variation in the results of up to 27% for steel columns and 39% for concrete columns for like structural members tested using ASTM E119 or equivalent test procedures in different furnaces[21]. Coupled with the fact that it would be difficult to exactly duplicate in the field the actual workmanship and construction of the furnace tested member, the use of and analytical method may eliminate some of these concerns.

3.0 Performance-Based Design Philosophy

Currently, draft performance based standards are either in use or are being written as first generation documents. In North America these documents consist of:

1. Objective-Based Codes: A Consultation on the Proposed Objectives, Structure and Cycle of the National Building Code of Canada[23];
2. Final Draft ICC Performance Code for Buildings and Facilities, International Code Council[24];
3. The SFPE Engineering Guide to Performance-Based Fire Protection Analysis and Design, Society of Fire Protection Engineers[25].

The NBC and ICC Codes address performance-based objectives for all aspects of buildings including safety, health, accessibility and protection, whereas the SFPE document is specific to the performance-based approach in the design and assessment of building fire safety. The general format of the NBC and ICC codes is as follows:

1. A stated main objective identifying the broad design principal;
2. A stated sub-objective or functional objective which states specific design philosophies for a particular aspect of the building; and
3. A statement of performance requirements identifying specific design considerations.

In both of the NBC and ICC documents the performance requirements related to fire safety are similar as follows:

1. ensure that the structure will remain standing long enough to allow occupants to escape; and
2. ensure that the structure will remain standing long enough for emergency personnel to perform their duties.

Similarly, for structural safety the requirement is to reduce the probability of structural failure, and design the structure in a way that will ensure that the entire structural system will remain stable when a localized collapse occurs.

As stated previously, current prescriptive building codes specify the required fire resistance ratings (FRR) for floor and wall assemblies, and structural members based on occupancy, building height and building construction. Typically these start at a minimum 45 min FRR, followed by 1 hr, 1-1/2 hr, 2 hr and 4 hr ratings. These ratings have a long history and have been developed based on consensus, experience, and past fire losses. As with the standard fire test, these ratings are potentially conservative since they are applied indiscriminately. For example, a two story educational facility will require that structural members supporting the first floor be protected by a 1 hr FRR[4] regardless of whether or not this rating was adequate based on actual fire load, risk etc.. To offer a justifiable alternative to this approach that will satisfy the objectives stated above, a performance-based design should be based on the following:

1. A fire scenario must be characterized by predicting fire load, fire size, fire severity and fire duration, and a time-temperature relationship for the fire scenario must be calculated;
2. The fire must be modeled in a location that represents a worst-case design for the building. That is, consideration must be given to both structural and fuel load to ensure the modeled compartment is representative of the building. To do this, multiple compartments should be assessed as the worst case fire location is not necessarily a structurally critical region in the building; and
3. The time-temperature relationship of the fire exposed steel must be calculated and the thermal properties determined relative to the known failure criteria of the member under consideration. Time to failure values must be predicted based on this analysis.

The purpose of utilizing a performance-based design is to engineer a solution to a technical problem that stands on technical merit instead of depending upon past practice. Although it can be argued that "if it ain't broke, don't fix it"; it has also been demonstrated in Chapter 2 that reliance on the current prescriptive approach may not represent an accurate assessment of expected performance in a real fire. Also, it is difficult to quantify the limitations of the current approach relative to their impact on overall building fire/structural safety given that no calculations are performed.

It may appear self-evident that to proceed on the basis of an engineering approach will yield more realistic results. However, there are several concerns relative to the performance-based approach:

1. In most jurisdictions, National Codes are consensus based documents that are continually updated to reflect an improved understanding of the impact of fire in buildings and the reality of current building construction practices. Inherent in these documents is an implied level of safety, albeit not necessarily based on sound analytical models. Although the existing prescriptive approach to the determination of fire resistance ratings can be criticized, it is difficult to argue that this approach has not served the public safety well, given the lack of frequent large loss fires in countries that adopt such codes. Therefore the use of performance-based codes should ensure an “equivalent level” of safety. This approach will ensure the public’s perception of the safety of the building environment is not eroded. Therefore it is important to be able to quantify this equivalency, which may not be possible in black and white terms;
2. One of the benefits of performance-based designs as they concern building fire safety is that the approach provides the designer with the ability to evaluate the fire safety of buildings that would otherwise not lend themselves to assessment under the prescriptive code regime. However, one of the drawbacks is that performance-based codes may inadvertently result in a lowering of the minimum fire safety levels[26] that would not be permitted with the book-of-rules approach of the prescriptive code;
3. The prescriptive code approach has redundancies, in that minimum fire safety measures are often prescribed exclusive of other measures. However, trade-offs are permitted in some cases, as with automatic sprinkler protection. Under the performance-based regime these trade-offs could be eliminated. It could be argued that the operation of the sprinkler system would reduce the time-temperature curve to a point below which a structural member will fail, therefore minimizing the need for structural fire protection. Although

the failure rate of sprinkler systems is low, it would be unreasonable to assume that they will never fail. Unfortunately, the rationalization for these trade-offs is not well defined in the prescriptive codes, so that understanding the implications of the trade-offs is not always easy;

4. Development of the fire scenario can be difficult given the many possible combinations of events that may take place to result in a fire. Furthermore, human interference often directly affects the outcome of a fire. Such interference is often difficult if not impossible to predict or control; and
5. Performance-based designs are based on fire dynamics, which is not a precise science. There is still experimentation required on which to base and refine the underlying physics[27]. As a result engineering judgment is required. Although not a new concept for the engineering community, this judgment is not necessarily complete and will continue to mature [34].

In order to address these concerns the performance-based design should include the following:

1. A definition of the thermal failure characteristics of the structural member to be assessed so that a minimum set of values can be used to define a pass/fail criteria;
2. Use of the "inherent" or implied safety of the prescriptive code as the minimum level of safety to achieve. This can be done by utilizing the FRR's defined by the prescriptive code for use as a benchmark for the performance-based code. That is, use the prescriptive code as the fire safety goal but use the performance-based approach to define

the level of protection required to achieve these goals. This can be achieved by ensuring that the time to reach the pass/fail criteria is greater than the prescribed FRR. The use of the prescriptive solution as the benchmark makes sense as it offers a definable level of safety arguably accepted by both the public and Authorities Having Jurisdiction. This is the approach that is being proposed for Canada's Objective Based Building Code process[23]; and

3. Not taking the potential beneficial affects of redundant systems such as sprinkler systems into consideration.

It is proposed that the method to be used should provide for improved prediction of structural fire performance based on fundamental physics available. However, the method should be limited to single element analysis and not involve the analysis of the structural system as a whole as the underlying physics has not yet matured. Figure 4 provides a graphical representation of the type of model proposed, specifically model H3/S1.

A flowchart representing the generic performance-based design process is shown in Figure 5. A detailed description of the steps will follow in subsequent sections of this document.

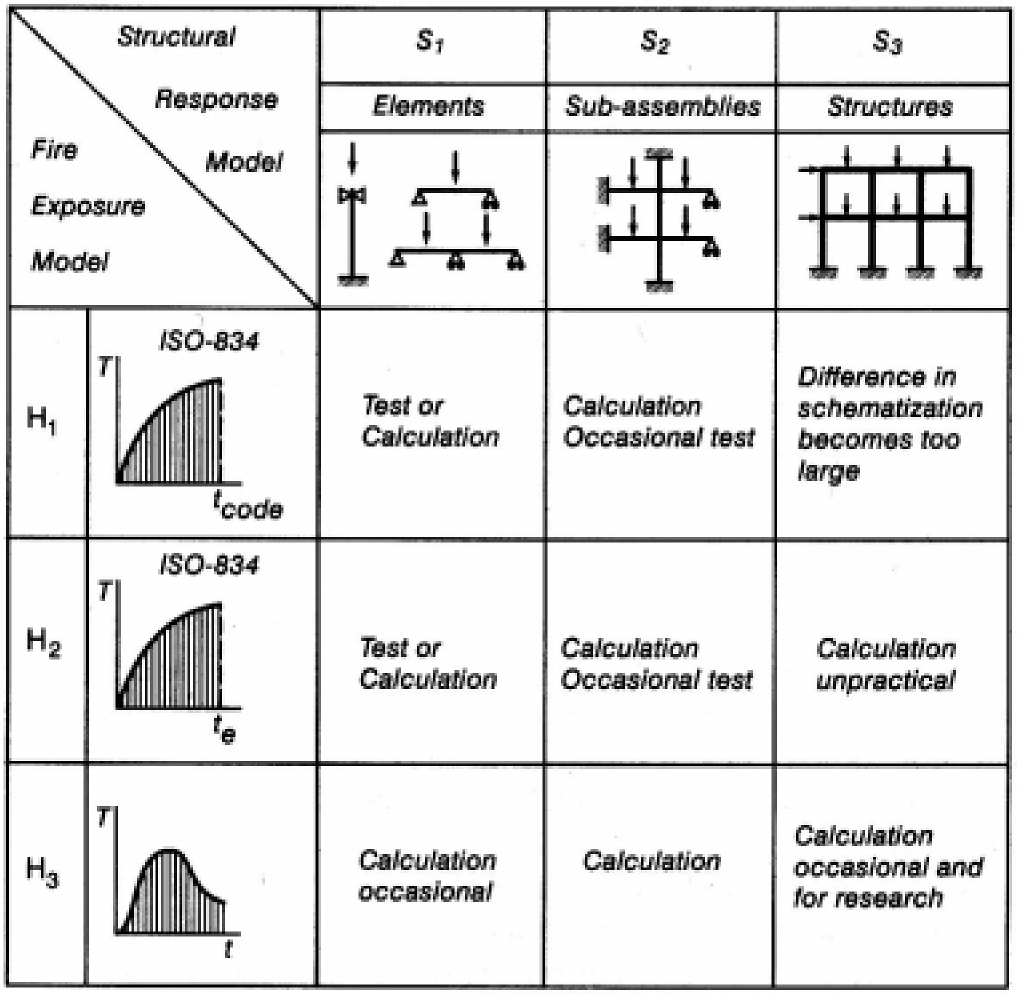


Figure 4 Matrix of Fire and Structural Response Models [34]

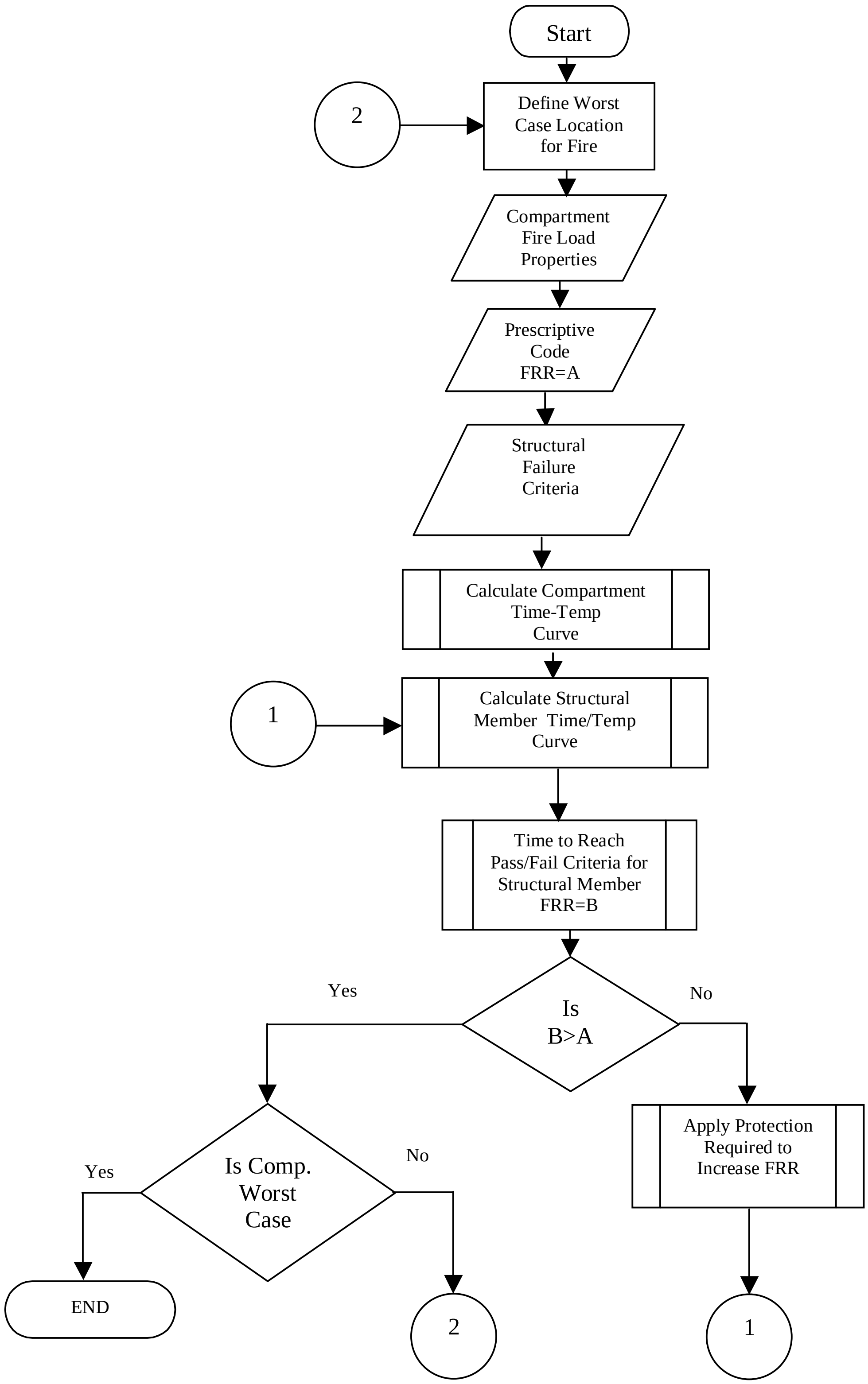


Figure 5 Conceptual Framework for Performance-Based Approach

4.0 Fire Scenario Development

In order to provide credibility to this design method, proper fire scenario development will be critical to achieving realistic results. Much has been written on methods for predicting fire development within a compartment. There are simplistic hand calculations that assume the temperature in the compartment is uniform throughout and can provide a first cut as to the likely fire severity. There are also more complicated computer programs that use computational fluid dynamics to more accurately predict variations in temperatures throughout the fire compartment based on an assumed fuel arrangement. As the purpose of this document is to develop a manual of practice for professionals, the use of more simplistic hand calculation procedures will be used. Although these calculation procedures are less complicated, they have been compared with experimental data to provide a level of comfort with respect to their limitations. In time, as the more sophisticated models are refined and made more user-friendly, they may be used instead of the simpler methods. This chapter will define in detail the steps that must be followed to predict a fire scenario and related temperature/time curve for use in the design method.

4.1 Compartment Fires

Typically a fire in a residential, commercial, or institutional building starts in a single compartment. This single compartment may be a bedroom in a home, an office in a commercial building, or classroom in an institutional building. The compartments within these occupancies are typically rectangular in shape and not overly large with small aspect ratios. Also needing consideration are corridors, which are long and narrow, and large lecture halls or conference rooms, which can be quite voluminous relative to a standard office or classroom. Although a window to the exterior may not always be present in one of these compartments, there is always a door, which may or may not be open at the time of the fire. The significance of the compartment geometry and number and location of openings has a direct impact on the behavior and severity of the fire.

For a typical compartment as described above with either a door or window open, hot gases from the fire rise to the ceiling and spread across the ceiling until stopped by the surrounding walls. As the hot gases reach the boundary of the room in a common scenario, a hot gas layer forms at the ceiling and starts to descend towards the floor. As this happens, the temperature of the hot gas layer increases. Over time the hot gas layer will have descended below the top of the door or open window of the compartment. Hot gases will then leave the room through the opening(s), and air from the surrounding spaces will rush into the compartment. This in-rush of air will make up for the air leaving the hot gas layer and continue to feed the fire. This scenario is illustrated in Figure 6.

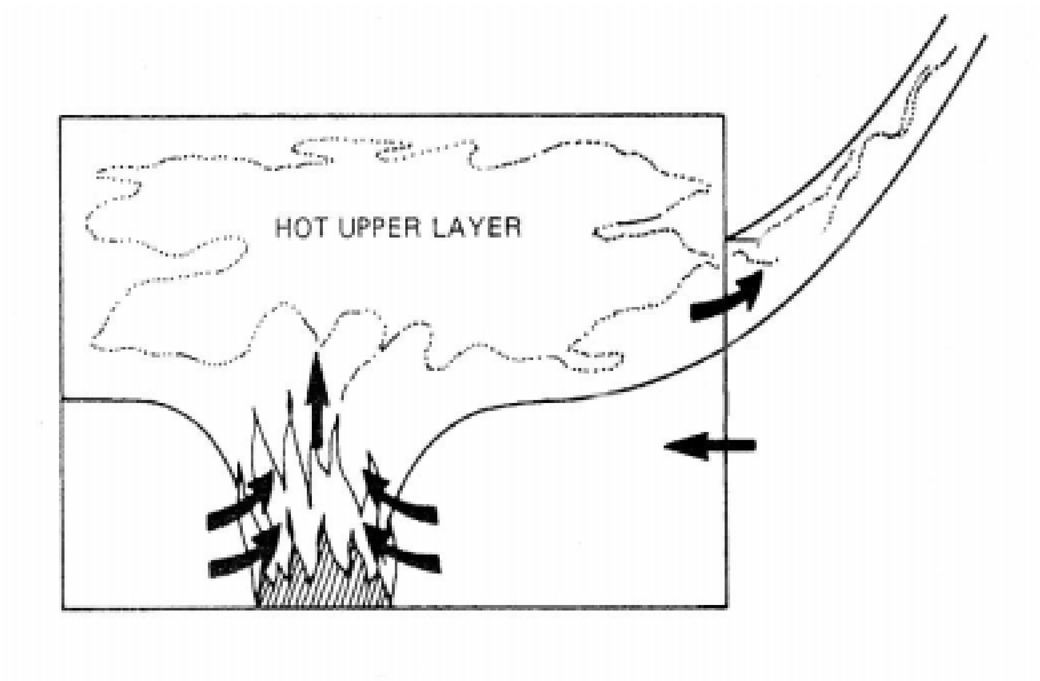
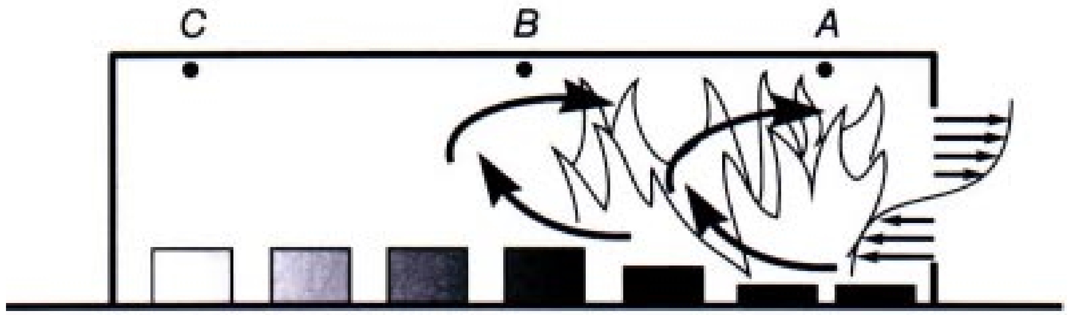


Figure 6   Typical Compartment Fire Phenomena [8]

This figure represents the characteristics of a fire in a typical room. In a typical compartment with no openings the fire will burn more slowly and with less intensity and may self-extinguish as a result of the reduced oxygen supply to the room. In a long narrow room such as a corridor the fire tends to always start to burn available combustibles at the end of the compartment closest to the compartment opening as shown in Figure 7. This movement of flame and heat is drastically affected by the size of and location of openings [37]. As well, if a compartment is large enough relative to the fire size the fire will act as if in the open. The significance of these geometric considerations will be addressed in the sections that follow.



Progressive burning in a deep room with one window

Figure 7   Corridor Fire Phenomena [34]

A fire in a compartment will typically have three distinct phases as follows:

1. Growth Phase: the fire is starting to grow from its point of origin and the temperature within the compartment is beginning to rise;
2. Fully Developed Phase: flashover has likely occurred and the compartment and all of its contents are engulfed in flame; and
3. Decay Phase: the period during which the compartment temperature starts to decrease as the fire consumes all available fuel and begins to loose energy.

These phases are represented graphically in Figure 8.

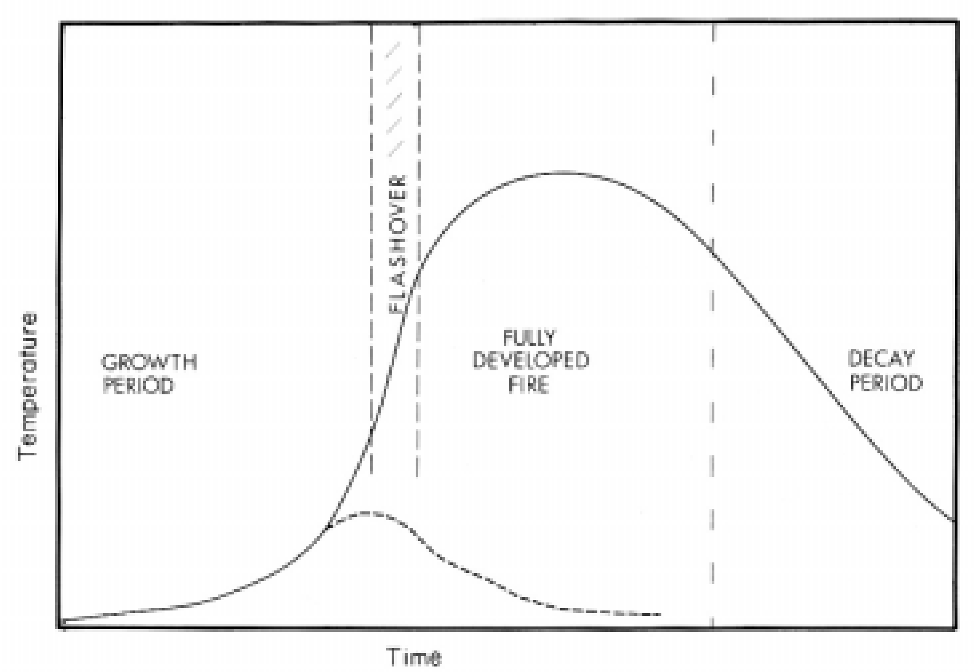


Figure 8 Typical Compartment Fire Time-temperature Curve [8]

4.1.1 Growth Phase

During this phase the fire begins as either a smoldering or flaming fire. The rate of growth of the fire is related to the type and quantity of combustible content within the compartment, and point of origin of the fire relative to room geometry. For example, a fire started in a waste paper basket next to a couch or draperies will likely spread faster and therefore grow in intensity more quickly than a fire started in the middle of a room by a dropped cigarette in a carpet that complies with current fire resistant standards. It has been demonstrated through experimentation that the influence of walls relative to fire location has a dramatic effect on room temperature. That is, fires started adjacent to walls will produce hotter, more rapid fires relative to fires started away from walls. This effect is further enhanced when fires occur in corners [38].

The rate of growth of the fire will be related to the amount of fuel within the compartment available for burning and the number and location of openings. The fuel load typically includes all surfaces and related finishes, and combustible contents. In the worst case, the total potential energy to be released will be due to the burning of all the contents in a compartment. This typically occurs during the fully developed phase of the fire.

4.1.2 Fully Developed Phase

During the growth phase the room temperature increases as described previously. As this happens the surfaces and contents of the room begin to undergo thermal decomposition, and the combustible solids begin to produce volatile gases. This process is known as pyrolysis. For a typically shaped compartment the temperature increases as the fire continues to grow, and the rate of pyrolysis and the concentration of volatile gases in the room increase. When the concentration of volatile gases, oxygen and temperature are sufficient for ignition the compartment will experience flashover, as most combustible materials will ignite.

A common definition of flashover is the point at which the radiant energy incident upon the floor of the compartment is 20 kW/m^2, and the temperature at the ceiling is 600 ^0C [2]. The possibility that a compartment fire will achieve flashover is of great importance as it is during the fully developed phase that room temperatures may be as high as 1100 ^0C [2]. The length of time these temperatures can be maintained will have a direct impact upon the structural integrity of the compartment, since the potential for structural damage is greatest when the temperatures are highest.

4.1.3 Decay Phase

Eventually the production rate of volatile gases will decrease as the fuel content in the compartment is depleted, and the decay period of the fire will begin. During this phase the temperature in the room decreases as the fire intensity decreases. Ultimately the decay rate will be a function of the: quantity and physical arrangement of combustible contents within the compartment; size and shape of openings; and thermal properties of the room boundaries. Typically as fires enter the decay period they begin to change from a ventilation controlled fire to a fuel controlled fire.

A ventilation controlled fire is a fire that is limited in size by the quantity of fresh air supplied to the fire through openings in the compartment boundary. This type of fire usually exists up to and after flashover occurs. However, once flashover has occurred and the fire is in the fully developed phase all of the fuel available will be consumed by the fire, and over time the fire severity will begin to be controlled by the dwindling quantity of fuel available to burn even thought there may be sufficient new air supplied for combustion.

4.2 Ventilation vs. Fuel Controlled Fires

The type of mathematical relationship that can be used to develop a time-temperature curve for the actual design fire is dependant upon whether the fire can be defined as ventilation or fuel controlled. As described previously, a fire can be described as ventilation controlled when the burning rate is controlled by the available supply of oxygen necessary for combustion. A fire can be described as fuel controlled when the burning rate is controlled by the availability of fuel, under a fully ventilated condition.

The Fire Protection Engineering Handbook [8] contains a chapter on time-temperature relationships for compartment fire conditions. In this chapter the issue of fuel vs. ventilation-controlled fires is briefly discussed regarding the need to determine which type may govern a fire. Although the chapter does indicate that this is not a predictable matter, it does point out that based upon experimentation compartments with fuel loads ranging between 40 kg/m^2 to 100 kg/m^2 usually experience ventilation controlled fires. Furthermore, it states that a ventilation controlled fire is usually the most severe fire when analyzing a fire in a single compartment [10]. This is the case because in a fuel-controlled fire the excess air entering the compartment is likely to have a cooling effect on the room temperature[2].

4.3 Room Fuel Load

As described previously one of the factors affecting the duration and intensity of the fire will be a function of the room fuel load. Therefore the first step in establishing the compartment fire time-temperature curve is to determine the room fuel load.

The fuel load in a room is primarily made up of both fixed and moveable loads. The definition of each is described below:

- Fixed Fuel Load – consists of built-in combustible material such as floor and wall finishes, and permanently installed equipment such as lights, receptacles, ventilation diffusers, etc. Typically this potential fuel is rarely moved or changed unless building renovations are undertaken.

- Moveable Fuel Load – this is the fuel load, which may vary during the life of the compartment under consideration as it generally consists of chairs, desks, books, wall hangings, etc.

To a lesser extent the impact of both protected and unprotected materials may contribute to the fuel load. Protected fuel loads are combustible materials that are protected by some type of non-combustible cladding. The contribution of this load to the fire is a function of the probability that the protection will fail. Currently there is no accurate value that is available to describe this probability of failure [3]. Un-protected fuel loads are those loads that lack cladding or use combustible cladding. As with the definition for protected fire loads, the contribution of this load is a function of the probability that the protection will fail. A conservative estimate is to assume this type of cladding will always fail.

It has been proposed that the average fuel load per unit floor area within a compartment may be given by[3]:

$$L_{fk} = \frac{1}{A_f} \sum M_i H_{ui} (m_i) \qquad (4)$$

Although somewhat time consuming to carry out this calculation for the various loads in a compartment, extensive surveys have been carried out which are summarized [3] in Appendix A. This data makes the overall calculation process manageable. It should be pointed out that the tables [3] are primarily survey results for variable (moveable) fire loads. Furthermore, this data is provided in terms of average, 80th, 90th and 95th percentile values.

The combustion factor m_i is a function of the spatial properties of the fuel and location of the fuel relative to the fire's ignition source and is a measure of the influenced of the compartment on the "burnability" of the fuel source. Clearly a conservative value would be $m_i = 1$. However, a more conventional value is $m_i = 0.8$[3] assuming all contents in the room are involved in the fire, which is a conservative approach. Some data suggests that the value could actually be much lower than $m_i = 0.7$ [29].

A table to be used for estimating the weight of fuel in a room (M_i) has been proposed [39] and is repeated as Table 3. In this table there is a differentiation made between cellulosic and petrochemical based products because the calorific value of the material (H_{ui}) is different with a value of 18 MJ/kg for cellulose based materials and between ~ 20 MJ/kg to 45 MJ/kg, [39] for petroleum based materials.

The data in this table can be subdivided into cellulosic based and petroleum based materials. The significance being that when converting to a wood equivalent the mass of the petroleum based materials should be adjusted by a factor of 2 [39] to account for the higher energy content of petroleum based materials. It is necessary to convert the fuels to a wood equivalent since the models that are described in the sections that follow are based on experimental data that has been undertaken with the use of wood as the primary fuel source.

Table 3

Estimating Compartment Fuel Load [39]

Description	Cellulosic (kg)	Petro-Chemical (kg)
Building Fuels		
Structural Fuels	________	________
Service Fuels	________	________
Non-Structural Fuels		
• Non-load bearing	________	________
• Interior Finish & Trim	________	________
Contents Fuels		
Furnishings		
• Furniture	________	________
• Decorations	________	________
• Other	________	________
Occupant Related Goods		
Sub-total (kg)	________	________
Conversion to Wood (kg)	________	________
Wood Equivalent (based on 18 MJ/kg)	________	________
Fuel Load (MJ)	________	

Note: (1) The mass of petro-chemical based materials is adjusted by a factor of 2.

Once the total (fixed + moveable) fuel load has been determined, consideration should be given to the probability that all of the contents of the compartment will be involved in the fire. This probability is based on the distribution of the contents within the room so that the design fuel load may be modified as follows:

$L_{fd} = F_d \, x \, K_d \, x \, L_{fk}$ *(5)*

Table 4 provides suggestions for the factors in equation 5 as follows: [3]

Table 4

Design Distribution Factors for Fuel Loads[3]

Occupancy (1)	Precision Design Value (2)	Fire Load Distribution Factors (F_d) Assuming Uniform Distribution	Fire Load Distribution Factors (F_d) Assuming Non-uniform Distribution	K_d Values
Well Defined	90th	1.0	1.20	1.35 – 1.65
	80th	1.0	1.15	1.25 – 1.50
	Peak			2
Variable	90th	1.0	1.20	1.65 – 2.0
	80th	1.0	1.15	1.45 – 1.75
	Peak			2.25

Notes: (1) Well defined – hotels, hospitals, offices, residences and schools.
Variable – retail and industrial occupancies
(2) Percentile values based on an assumed normal distribution

Therefore a modified form of equation 5 would be:

$$L_{fd} = \frac{1.58}{A_f} \sum M_i H_{ui} \qquad (5a)$$

based on factors $m_i = 0.8$, $F_d = 1.2$, and $K_d = 1.65$.

Buchanan [34] suggests a factor of 2 for design purposes.

A report carried out by the Building Research Association of New Zealand[7] compared the fuel load survey from a small sample of New Zealand Life Insurance Offices to the CIB W14 study. The table below has combined the results of the New Zealand report with data from the CIB W14 study.

Table 5

Summary of Variable Fuel Loads (per unit floor area) [7]

	Variable Fuel Load (MJ/m^2)				
Occupancy	*New Zealand*	*Swiss*	*European*	*Swedish*	*USA*
Hospital – patient Room	-	330	230		
Hotel - bedroom	-	330	310	310	
General Office		750	380-420	417	415
Office – Average All	475	-	330-420	411	555
Schools	-	250	240	285	-

Although it is not recommended that these values be used explicitly in the development of compartment fire load as part of an engineering design, the values nevertheless provide a range that could be considered as typical for design purposes. The New Zealand building code suggests the following [34]:

Residential Occupancy: 400 MJ/m^2 floor area

Office Occupancy: 800 MJ/m^2 floor area

Retail Occupancy: 1,200 MJ/m^2 floor area

In comparison, the National Application Document for the UK suggests 500 MJ/m^2 floor area for Office Occupancies[40]. As well, values ranging from 250 to 2,000 MJ/m^2 unit compartment surface area are recommended for use in the Eurocodes [43].

Based on the summary results above, the variable fuel load in a typical office ranges from 330 MJ/m^2 to 800 MJ/m^2 per unit floor area. If these fuel loads are converted to a wood equivalent using an average heat of combustion of 18 MJ/kg for most woods, the fuel load can be converted to a range from between 18 kg/m^2 – 45kg/m^2. Although little data exists on the range of total fuel loads to be expected (variable plus fixed), the CIB W14 Study [3] does contain limited information which suggests that the total fuel load in a typical office could range anywhere from 635 MJ/m^2 to 3900MJ/m^2 per unit floor area, which converts to 35kg/m^2 to 217 kg/m^2 per unit floor area. These values generally correspond to the range of values suggested [8] as being more than likely to produce a ventilation controlled fire, which is significant as the majority of mathematical relationships that have been developed for use by the practicing engineer are based on the assumption that the fire is ventilation controlled, as will be detailed in the following section.

When using these models care must be taken to ensure that the fuel load is referenced to the compartment floor area or total surface area as is appropriate for the model.

5.0 Fully Developed Fire Modeling

It has been described previously that the post-flashover, or fully developed fire, possesses the greatest risk to building structures due to the high temperatures generated during this stage of the fire. A number of methods have been developed over the past 30 years in an attempt to model a fully developed fire with respect to assisting in the determination of structural fire protection requirements. The first generation of models was developed in the 1970's and early 1980's. Since this time additional research has been performed to modify some of the weaknesses of these models resulting in a second generation of models that are currently under development. In the sections that follow the first generation models will be discussed in detail and a brief description of the direction taken for the second generation of models will be provided.

5.1 T – Equivalent Concept

The primary focus of fire protection within a building is to compartmentalize the fire. Creating boundaries that will resist the spread of both heat and the products of combustion meets this objective. If these boundaries are constructed adequately relative to the expected fire characteristics, then the probability of successful fire containment is high. Ingberg's work that was used for the development of current fire resistance ratings provides the "necessary" fire resistance ratings, although it has been argued that these ratings are misdirected [44].

As described by Law [46] *"the term t-equivalent is usually taken to be the exposure time in the standard fire resistance test which gives the same heating effect on a structure as a given* *compartment fire*". The sections that follow describe the available models that can be used for protected steel and other compartment boundaries, how they work, and their weaknesses and strengths.

5.1.1 Normalized Heat Load Concept

To address the destructive impact of a fire on the compartment boundaries, Harmathy proposed that the total heat load incident upon the enclosure surfaces per unit area was a measure of the maximum temperature that a load-bearing element would be expected to obtain during the duration of the fire. Recognizing that not all compartments are the same by virtue of the construction of the boundaries, it was necessary that an approach be developed that could compare fires in dissimilar enclosures. This approach is referred to as the normalized heat load concept and is defined as follows [44]:

$$H' = \frac{1}{\sqrt{k\rho c_p}} \int_0^{\tau} q'' dt \qquad (6)$$

Harmathy further goes on to describe the most important factors in a fire as follows:

A_f	floor area of the compartment (m^2)
A_t	total area of compartment boundaries (m^2)
H_c	height of compartment (m)
$\sqrt{k\rho c_p}$	surface averaged thermal inertia of compartment boundaries ($J/m^2\ s^{1/2}\ K^1$)
Φ	ventilation parameter (kg/s)
L	specific fuel load per unit floor area (kg/m^2)

With regards to calculating the normalized heat load the only factors that are variable are the ventilation and fuel load factors. The other factors are a function of the compartment geometry being analyzed. Harmathy proposes that the fuel load should be calculated based on the 80th or 95th percentile, similar to what has been proposed previously. The effective multiplier to the mean value ranges from 1.25 for the 80th percentile value to 1.6 for the 95th percentile value depending upon occupancy.

For the ventilation factor Harmathy proposes the following:

$$\Phi_{\min} = \rho_a A_v \sqrt{g H_v} \tag{7}$$

based on the fact that the minimum value for ventilation factor yields the highest value for normalized heat load and is therefore conservative. The premise is that the minimum value is represented by air flow introduced to the compartment through the openings in the absence of drafts or winds.

To provide a more user-friendly equation Harmathy presents a modified form of (6) based on room-burn experiments for compartments with cellulosic fire loads and vertical openings only as follows:

$$H' = 10^6 \frac{11.0\delta + 1.6}{A_t \sqrt{k\rho c_p} + 935\sqrt{\Phi L A_f}} (L A_f) \tag{8}$$

where:

$$\delta = \begin{cases} 0.79\sqrt{H_c^3 / \Phi} \\ 1 \end{cases} \text{, whichever is less} \tag{9}$$

and where δ which is dimensionless is a fraction of the fuel energy released inside the compartment.

Harmathy further proposes a relationship between the normalized heat load in the standard test and the duration of the test (fire resistance rating) as follows:

$$\tau = 0.11 + 0.16\, x\, 10^{-4} H'' + 0.13\, x\, 10^{-9} (H'')^2 \qquad (10)$$

Using (7) through (9) the normalized heat load H' for the compartment being analyzed is determined and then substituted into (10) instead of the normalized heat load for the standard test H''. This provides the ability to determine the fire duration τ resulting from the same normalized heat load that would be expected from the standard test, and therefore the required fire resistance rating for the compartment.

Some of the drawbacks of the approach are; that it is not directly applicable to materials with high thermal inertia such as unprotected steel, and that it relies on a comparison with the standard test results, which have been previously demonstrated as being questionable.

Harmathy, however, argues that the method is more appropriate for the modeling of compartment fires as it does not solely rely on the temperature relationship of the fire gases in the compartment. This is said to be significant since in a real fire these gases are involved in a complex reaction with the compartment boundaries [45]. As well, the model has built in safety factors, which offset the effect of variability on the model inputs [44].

Law [46] compared a series of typical room full-scale compartment fires (less than $30m^2$ in area and 3m in height) and deep well-insulated compartment fires ($128m^2$ in area, < 3 m high and 23m long) experimental data with various t-equivalent models. From this comparison it was determined that Harmathy's normalized heat load model compared well with experimental data for typical compartment fire data.

5.1.2 Eurocode t-equivalent Model

The Eurocodes provide for both parametric and t-equivalent fire models. The parametric model will be discussed in the following sections. Specifically the t-equivalent method is described in ENV 1991-2-2:1995 as follows:[40]

$$t_{e,d} = L_{t,d}.\gamma_{q1}.\gamma_{q2}.\gamma_n.k_b.w_f \qquad (11)$$

where

$$w_f = \text{ventilation factor} = (6/H_c)^{0.3}\left[0.62 + 90(0.4-\alpha_v)^4/(1+b_v\alpha_h)\right] \qquad (12)$$

$\alpha_v = A_v/A_f$ area of vertical openings in the compartment

$\alpha_h = A_h/A_f$ area of horizontal openings in the compartment

$b_v = 12.5(1+10\alpha_v - \alpha_v^2) \geq 10.0$

$k_b = 0.7$ when there are no horizontal openings and bounding surfaces are unknown or when the bounding surfaces have known construction:

$\sqrt{k\rho c}$	k_b
>2500 $J/m^2s^{1/2}K$	0.04
≥ 720 to ≤ 2500 $J/m^2s^{1/2}K$	0.055
< 720 $J/m^2s^{1/2}K$	0.07

The model is specifically defined as being applicable to fire compartments with cellulosic fuel loads and for comparison against FRR assigned through standard fire tests.

One aspect regarding this model that is unique is that it offers that some allowance for factors of consequence addressing fire fighting issues, fire probability and influence of sprinklers. These are clearly values that are open to some interpretation.

The review by Law, which was based on the model without utilizing the factors of consequence, suggests that the model does not provide a good correlation for either typical compartments or deep compartments.

5.1.3 Other t-equivalent Models

There are other t-equivalent models proposed by Law and Pettersson as follows:

$$t_e = L/\left[A_v(A_t - A_v)\right]^{1/2} \quad \text{Law} \quad (13)$$

$$t_e = 1.21L/\left[A_v\sqrt{H_v}A_t\right]^{1/2} \quad \text{Pettersson} \quad (14)$$

Law's review [46] demonstrated that both of these models also correlated well with typical compartments but did not for deep compartments.

Law's general conclusion from the review of the t-equivalent formula is that the models may not be the most appropriate design parameter when the importance of fire temperature and duration are to be assessed. The concern is that t-equivalent formula provide a general "feel" for the total heating effect but do not allow for the difference between short, hot fires and longer cooler fires with the same value for t-equivalent. This concern is supported by Buchanan, [34] who suggests that t-equivalent models provide only a crude approximation of real fire behavior, and that first principals, such as those used to develop parametric design fires, are more appropriate for estimating the effects of post flashover fires.

5.2 Parametric Fire Curves

In 1958[2] Kawagoe set out to develop a theoretical time-temperature relationship for a compartment fire based on a series of full and small scale compartment fire experiments. The model was further refined in 1963[12] and 1967[11].

This theoretical model is based on the fundamental heat balance of a compartment fire as indicated in the following equation:

$$\dot{q}_C = \dot{q}_L + \dot{q}_W + \dot{q}_R + \dot{q}_B \qquad (15)$$

In the sections that follow, the various compartment time-temperature curves models are described and it is demonstrated that it is possible from an engineering design standpoint to utilize these curves. In all models described several fundamental simplifying assumptions were necessary as follows [10]:

- that combustion is complete and takes place exclusively inside the compartment;
- that the compartment is well stirred so that the temperature is uniform throughout;
- that the heat transfer coefficient of the compartment surfaces is a constant and uniform throughout the compartment; and
- that the heat loss through the compartment boundaries is uniformly distributed.

In order to examine the key variables in the fundamental heat balance equation and their related significance, each of the terms will be looked at separately.

5.2.1 $\dot{q}_L$ – Rate of Radiative Heat Loss Through the Ventilation Opening

The general form of this term, which is a direct derivation from the Steffan-Boltzman Law,[2] is as follows:

$$\dot{q}_L = A_v \varepsilon_f \sigma (T_t^{\,4} - T_0^{\,4}) \tag{16}$$

The only variable is the gas emissivity, which is typically taken as 0.7, and is usually in the range of 0.6 to 0.9[2] [10].

5.2.2 $\dot{q}_W$ – Rate of Heat Loss Through Compartment Boundaries

Determination of the rate of heat transfer through the compartment boundaries is fairly complicated. The general calculation technique requires that the boundary surface be broken down into multiple layers, and that a numerical technique be used to determine the conduction as a function of time from one layer to the next. The more layers that are assumed the more accurate the resulting calculation. A real world problem often involves a compartment constructed of different wall, ceiling and floor types. This potentially complicates the calculation, as each surface must be treated separately.

The general form of this term to be used is as follows:

$$\dot{q}_W = (A_t - A_v)\left[\frac{1}{\dfrac{1}{\alpha_i} + \dfrac{\Delta x_1}{2k}}\right](T_t - T_1) \tag{17}$$

Kawagoe [11] performed analyses to demonstrate that this level of calculation, although technically accurate, was not necessary from an engineering design standpoint. The first analysis investigates the impact on the time-temperature curve by comparing “heavy” vs.

“light” boundary materials for varying opening factors. Some literature [9] defines normal weight concretes as heavy (ρ ≥ 1700 kg/m^2) , and light weight concretes and plasterboard as light (ρ ≤ 1700 kg/m^2). In this comparison it was found that the use of a “light” material produced a time-temperature curve with higher temperatures than did a curve based on “heavy” material, as can be seen in Figure 9. However, it should be noted that the temperature difference becomes smaller for larger opening factors.

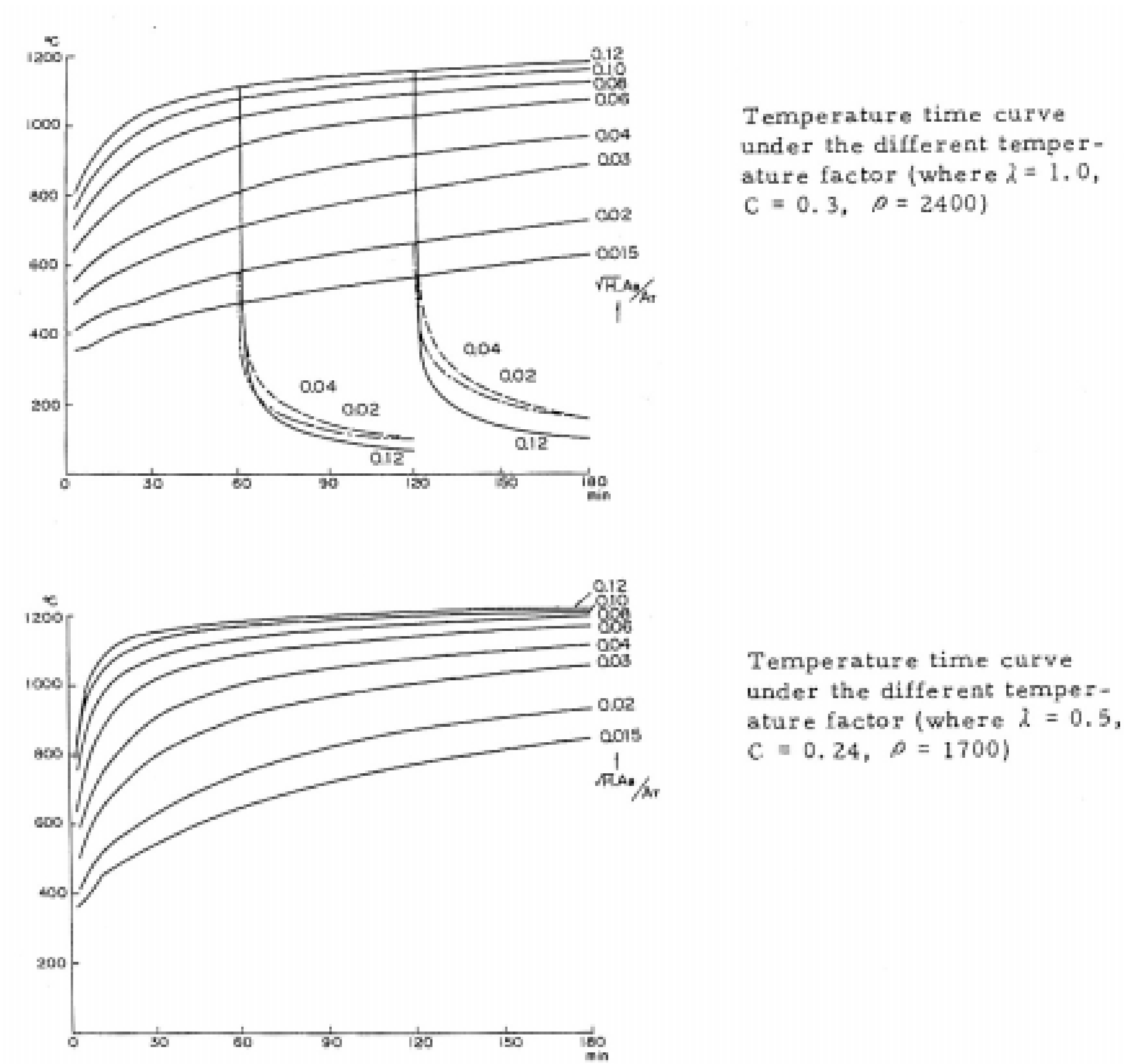


Figure 9 Time-Temperature Curves for Compartments with Different Bounding Surfaces[11]

The second analysis compares the difference in the time-temperature curve obtained by performing the conduction loss calculation for all different bounding surfaces, vs. the time-temperature curve based on using the average of the thermal properties of the bounding surfaces. The graphs are reproduced in Figures 10 (a) and (b). The first three graphs maintain the same bounding surface thermal conductivities while varying the densities for three different opening factors. The last three curves maintain the same density while varying the thermal conductivity for the same three opening factors. A comparison of the 1st and 4th , 2nd and 5th , and 3rd and 6th graphs indicates that there is virtually no difference in the overall room time-temperature curve. It should be noted that there is a difference noted at a plane 3 cm within the ventilation opening. This is of little concern for the real world problem as the overall room temperature is of primary concern.

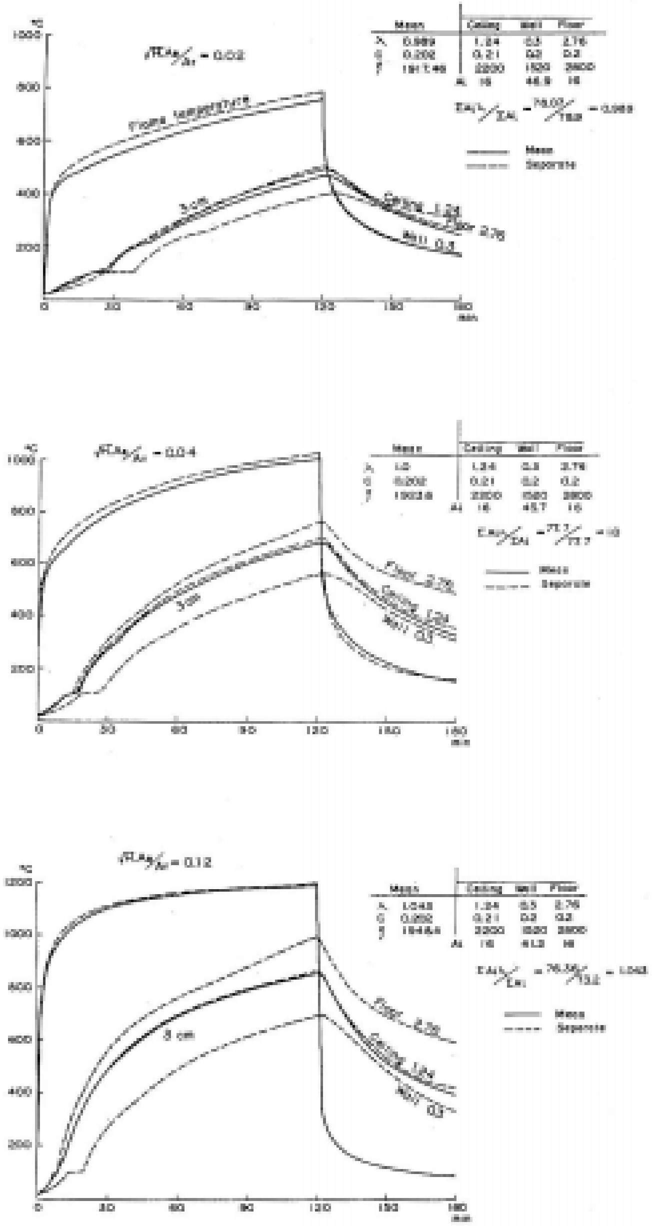


Figure 10(a) Comparison Between Actual Heat Transmission Calculation for each Surface vs. Calculation Based on Weighted Average for All Surfaces [11]

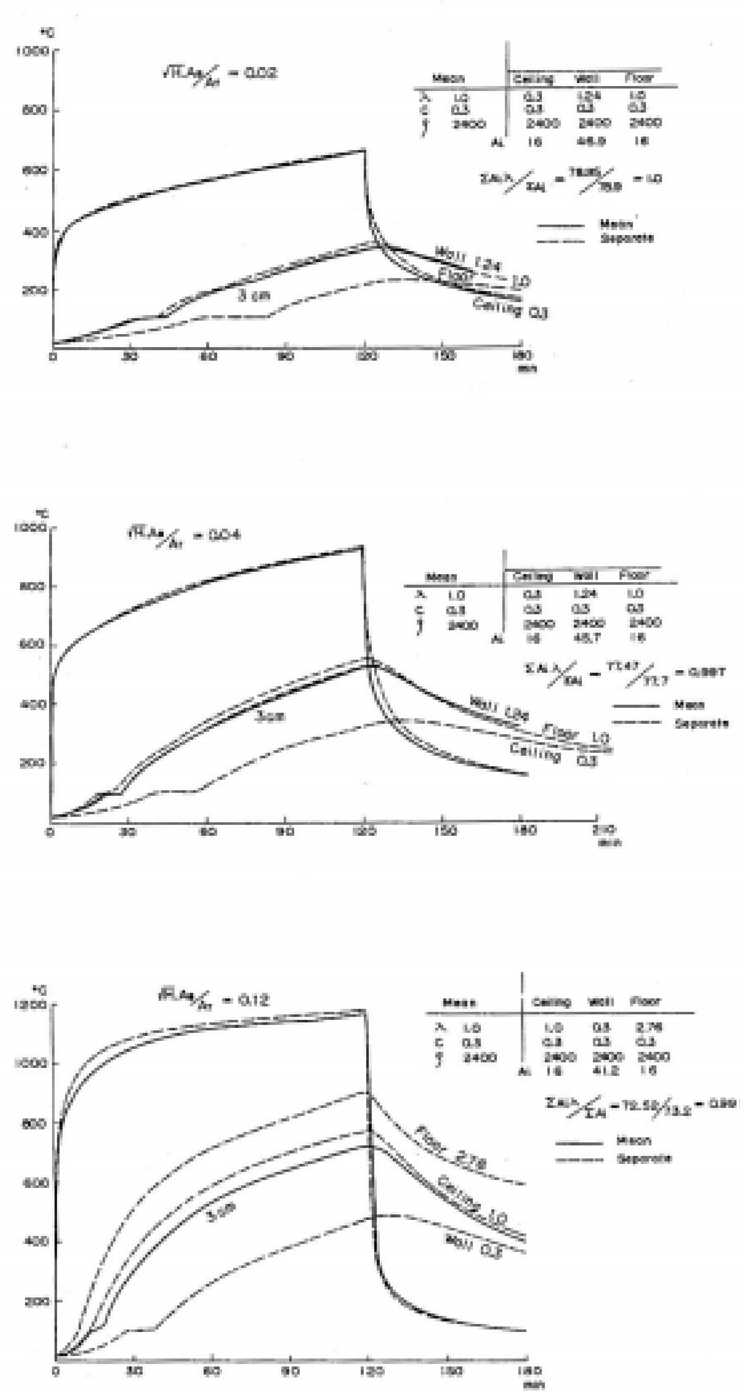


Figure 10(b) Comparison Between Actual Heat Transmission Calculation for each Surface vs. Calculation Based on Weighted Average for All Surfaces [11]

5.2.3 $\dot{q}_L$ – Rate of Convective Heat Loss Out Opening

The general form of the equation is as follows:

$$\dot{q}_L = \dot{m}_f c_p (T_t - T_0) \qquad (18)$$

One of the more significant outcomes of Kawagoe's research was the development of a term for the mass burning rate in a compartment fire, which is:

$$\dot{m} = 5.5 A_v H_v^{1/2} \, kg/min \qquad (19)$$

which is often presented in the form:

$$\dot{m} = 330 A_v H_v^{1/2} \, kg/hr \qquad (20)$$

This term is significant because it represents the rate at which the fuel in the compartment is releasing volatile gases into the compartment atmosphere, which are then burned as fuel by the fire.

Numerous other experiments have followed the original work by Kawagoe to refine the relationship with the following concerns:

1. The burning rate can only be predicted by this expression over a limited range[2];
2. The expression implies that the burning rate is only influenced by the ventilation rate, when the radiative contribution to the burning rate in a compartment is known to be significant since the radiative influence is a function of T^4 [2];

3. The relationship developed by Kawagoe, which "couples" the burning rate with the ventilation rate, is based on wood crib fires as the fuel source[2]. There is some concern that the wood crib shields the fire from radiative effects and thereby results in a lower burning rate than might be expected in a "real fire". As well it has been found that the burning rate is independent of the ventilation factor for fuel controlled fires. In relation to the task at hand this is not important, as the assumption has been made that the fire will be ventilation controlled, which was the assumption on which this expression was determined; and
4. The relationship is based on the results of over 400 experiments carried out using wood cribs as the fuel source during the 1960's, and that Kawagoe's relationship was found not to hold true [2]. In fact it was found that the burning rate was a function of the compartment shape and scale [2].

Notwithstanding the above, the time-temperature relationships that have been developed do rely on Kawagoe's burning rate equations (19) and (20).

5.2.4 $\dot{q}_C$ – Rate of Combustion Heat Release

The fundamental form is:

$$\dot{q}_C = \dot{m}H_{ui} \qquad (21)$$

To develop the mass burning rate correlations Kawagoe assumed a calorific value for wood of 2,575 kcal/kg [12]. This value was used to account for the combustion efficiency of the fire that, based on the experimental data, was assumed to be 0.6 [12]. Babrauskas and Williamson [29] suggest that the ideal value of ~ 4,600 kcal/kg should be used, as the accuracy of assuming a combustion efficiency of 0.6 is not justified, given the lack of direct knowledge regarding the efficiency that might reasonably be expected in a real fire. Pettersson assumed a value of 4,500 kcal/kg [10].

5.2.5 Pettersson et. al

The most often cited time-temperature curves for compartment fires are the Swedish Curves that are described in detail [10] by Pettersson et. al. Based on the fundamental heat balance equation and Kawagoe's burning rate equation, a series of time-temperature curves have been developed for different ventilation and fuel load values. These curves are shown in Figure 11. Shown in Figure 12 is a plot of a theoretical curve based on this model vs. the time-temperature curves for experimental data from short duration fire tests. Although based on a limited data set a review of this figure demonstrates that there is good correlation with the experimental data.

The applicable mathematical model is:

$$T_t = \frac{\dot{q}_c + 0.09 c_p A_v H_v^{1/2} T_0 + (A_t - A_v)\left[\frac{1}{\alpha_i} + \frac{\Delta x}{2k}\right]^{-1}(T_t - T_1) - \dot{q}_L}{0.09 c_p A_v H_v^{1/2} + (A_t - A_v)\left[\frac{1}{\alpha_i} + \frac{\Delta x}{2k}\right]^{-1}} \qquad (22)$$

where

$$\alpha_i = \frac{\varepsilon_r \sigma}{T_t - T_i}\left(T_t^4 - T_i^4\right) + 0.023 \ \text{(kW/m}^2\text{K)} \qquad (23)$$

$$\varepsilon_r = \left(\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_i} - 1\right)^{-1} \qquad (24)$$

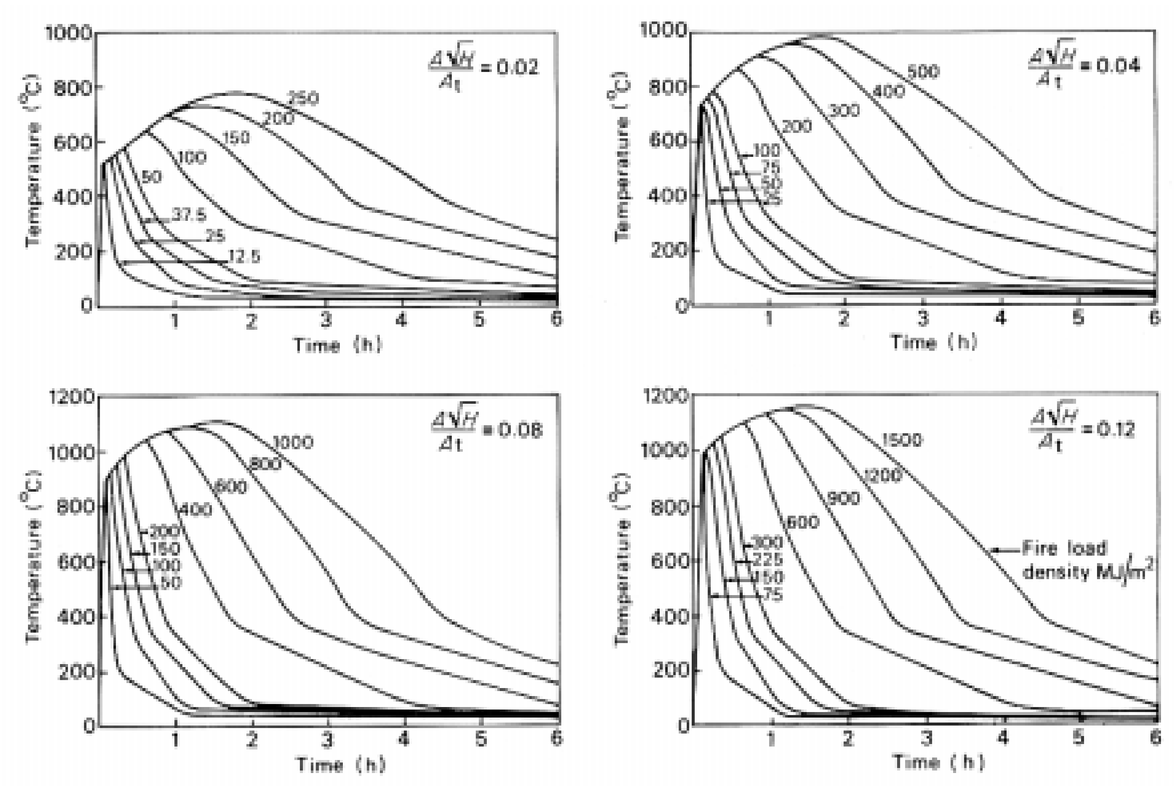


Figure 11 Analytical Time-Temperature Curves – Swedish Method [2]

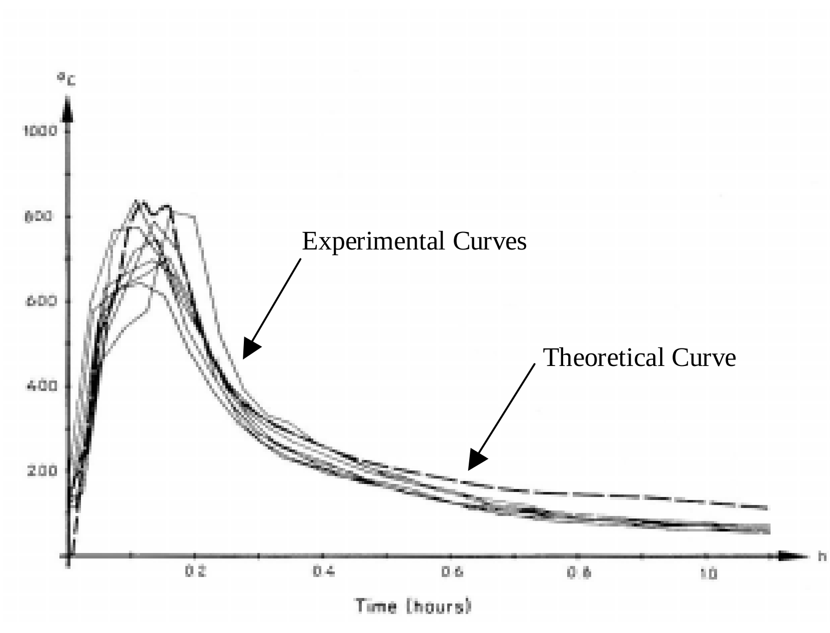


Figure 12 Theoretical vs. Experimental Time-Temperature Curves – Swedish Method [2]

$$\dot{q}_L = A_v \varepsilon_f \sigma \left(T_f^4 - T_0^4\right) \text{ (kW)} \quad (25)$$

$$\dot{q}_c = 0.09 A_v H_v^{1/2} H_{ui} \text{ (kW-based on combustion of wood = 18.8 MJ/kg)} \quad (26)$$

The solution is complicated and requires numerical integration that does not easily lend itself to hand calculations. For this reason, the series of curves shown in Figure 9 has been developed for designers in Sweden. The designer simply has to match the physical characteristics of the actual compartment to be modeled with the closest curve to establish a fire time-temperature curve.

The curves shown in Figure 11 are currently the basis for design of fire resistance requirements in Sweden and form the basis for the Eurocode time-temperature curves.

Some of the assumptions of the model are as follows[10]:

- the mass burning rate is $330A\sqrt{h}$ kg/hr
- the curves are based on wood crib fires with the energy content of wood =18,800 kJ/kg
- the decay phase assumes a rate of cooling of 10^0C/min
- the fire is assumed to be ventilation controlled.

Furthermore, the curves shown in Figure 11 are based on a predefined Type A compartment, which is a compartment with surrounding structures that have thermal properties similar to concrete, brick and lightweight concrete,[10] where the thermal conductivity

$\sqrt{k\rho c_p}$ =1160 J/m^{2}s$^{1/2}$K. Multipliers are provided [10] for other compartment types that might normally be found in buildings.

5.2.6 Babrauskas and Williamson

This theoretical model is also based on the heat balance equation for the compartment and some of the original assumptions developed by Kawagoe [11] [12]. It diverges from Kawagoe's work in that it treats the burning rate in a theoretical manner rather than an empirical manner, as done by Kawagoe and Pettersson et al., presenting a final heat balance equation:

$$h_c'' - \left(\dot{m}_{air} + \dot{m}_p\right)\int_{298}^{T_t} c_p\, dT = A_t \sigma \left[\frac{T_t^4 - T_w^4}{\frac{1}{\varepsilon_f} + \frac{1}{\varepsilon_w} - 1}\right] + A_t h_c (T_t - T_w) + A_v \sigma (T_t^4 - T_0^4) \qquad (27)$$

where the combustion enthalpy $\dot{h}_c$, infiltration air flow rate $\dot{m}_{air}$, and mass flow rate of the products of combustion $\dot{m}_p$ defined [29].

Specifically the model discusses the difficulty in defining the actual combustion efficiency of the compartment fire, and proposes that the enthalpy release rate is the lesser of the potential enthalpy of gas released from the fuel or the enthalpy release rate from perfect burning. This is different from Kawagoe's suggestion, which coupled the mass burning rate with the ventilation factor as shown in (19) and (20).

Furthermore, the model offers a comparison of the pyrolysis rates of plastic fuels compared with wood fuels, and the difference is significant. Given the proliferation of plastics in the typical residential, commercial, or institutional occupancy, this is cause for concern.

Unfortunately, the model does not specifically address the actual impact of these issues on the results of calculated time-temperature curves based on Kawagoe's burning rate.

5.2.7 Eurocode

In the early 1990's draft Eurocodes addressing design issues related to structural steel for fire conditions were developed as follows:

- Eurocode 1: Basis of Design and Actions on Structures, Part 2.2: Actions on Structures Exposed to Fire; and
- Eurocode 3: Design of Steel Structures, Part 1.2 Structural Fire Design

Subsequently the European Convention for Constructional Steel (ECCS) Model Code on Fire Engineering [47] has been prepared by ECCS – Technical Committee 3 to act as a follow-up to the Eurocodes. This document provides improvements to the approaches identified in the Eurocodes to reflect the improved understanding from research that has taken place since the introduction of the original Eurocodes. The time-temperature curve proposed is:

$$T_t = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \qquad (28)$$

where

$$t^* = t \times \Gamma \qquad (29)$$

$$\Gamma = \frac{(F_v/0.04)^2}{(b/\ 1160)^2} \qquad (30)$$

the decay rates are:

$$T_t = T_{max} - 625(t^* - t^*_{max} \cdot x) \text{ for } t^*_{max} \leq 0.5 \quad (31a)$$

$$T_t = T_{max} - 250(3 - t^*_{max})(t^* - t^*_{max} \cdot x) \text{ for } 0.5 \leq t^*_{max} \leq 2.0 \quad (31b)$$

$$T_t = T_{max} - 250(t^* - t^*_{max} \cdot x) \text{ for } t^*_{max} \geq 2.0 \quad (31c)$$

where

$$t^*_{max} = (0.2 \times 10^{-3} \cdot \left(L_{t,d} / F_v\right) \cdot \Gamma \text{ and}$$

$$x = 1.0 \; if \; t_{max} > t_{lim}, or \; x = t_{lim} \cdot \Gamma / t^*_{max} \; if \; t_{max} = t_{lim}$$

where:

t_{lim} = 25 min for a slow growth fire

t_{lim} = 20 min for a medium growth fire

t_{lim} = 15 min for a fast growth fire

The model is applicable for the following conditions:

- Fire compartment floor areas are <500 m^2;
- Openings are only present in the vertical plane;
- Limited to fire compartments with mainly cellulosic type fire loads;
- Thermal inertia: 400 ≤ b ≤ 2000 J/m^{2}s$^{1/2}$K;
- Opening factor: 0.02 ≤ F_v ≤ 0.2; and
- The compartment boundaries are constructed of one material.

The ECCS Model Code [47] does provide for a method to account for different layers of materials within the compartment that is an improvement over the original Eurocodes [34].

Some work has been done to calibrate the COMPF2 [18] computer program to realistic compartment fires with respect to developing modifications to the Eurocode design fire curve described [36]. Figure 13 represents the comparison of the existing Eurocode formulation as described in ENV 1991-2-2 [42] with the output form the COMPF2 program.

There are two primary recommendations that have been proposed to address the discrepancy identified in Figure 13 as follows:

That (30) be modified as below:

$$\Gamma = \frac{(F_v/0.04)^2}{(b/\ 1900)^2} \tag{32}$$

This change is proposed since it provides for a calculated curve that more closely correlates to the experimental data; and

That the decay phase of the fire indicted in equations (31a), (31b), and (31c) should be modified by the following:

$$\Gamma = \frac{\sqrt{(F_v/0.04)}}{\sqrt{(b/1900)}} \tag{33}$$

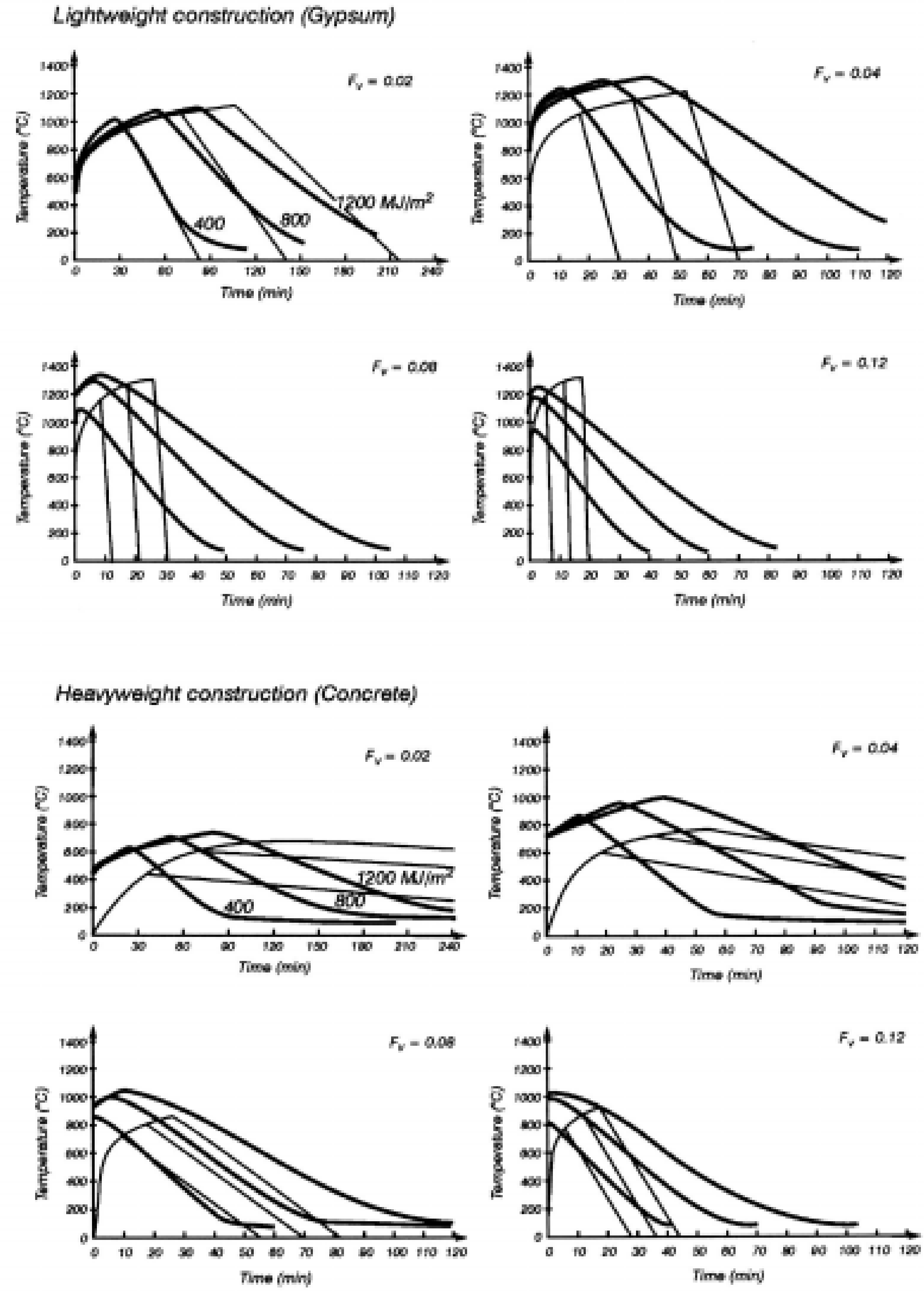


Figure 13 Comparison of Existing Eurocode Time-Temperature Curves with COMPF2 Output [36]

This change is proposed since the model has not justified the use of the fictitious time Γ for calculation of the decay phase. The effect of these changes on the Eurocode Curves is shown in Figure 14.

5.2.8 Lie

Lie proposed that "*a characteristic temperature-time curve that, with reasonable likelihood, will not be exceeded during the lifetime of the building*"[9] should be developed. This proposal was made due to concerns that the typical heat balance approach requires that the designer define the certain parameters which are difficult to define accurately for design purposes, such as:

- the quantity of gases which burn outside the room, which impacts upon the amount of gases available to directly affect the time-temperature curve of the room;
- the degree of temperature difference within the room, which impacts on the time it takes to reach flashover;
- the orientation and quantity of combustible materials within the compartment;
- velocity and wind direction at the time of the fire; and
- outside air temperature.

In addition to the above concerns, the models developed by Pettersson et. al., and Babrauskas and Williamson are very involved mathematically and do not lend themselves to reasonable computation times required for professional practice. Drysdale [2] suggests that due to the uncertainties associated with compartment fires Lie's approach may be used to obtain a "rough sketch" of the compartment fire time-temperature curve.

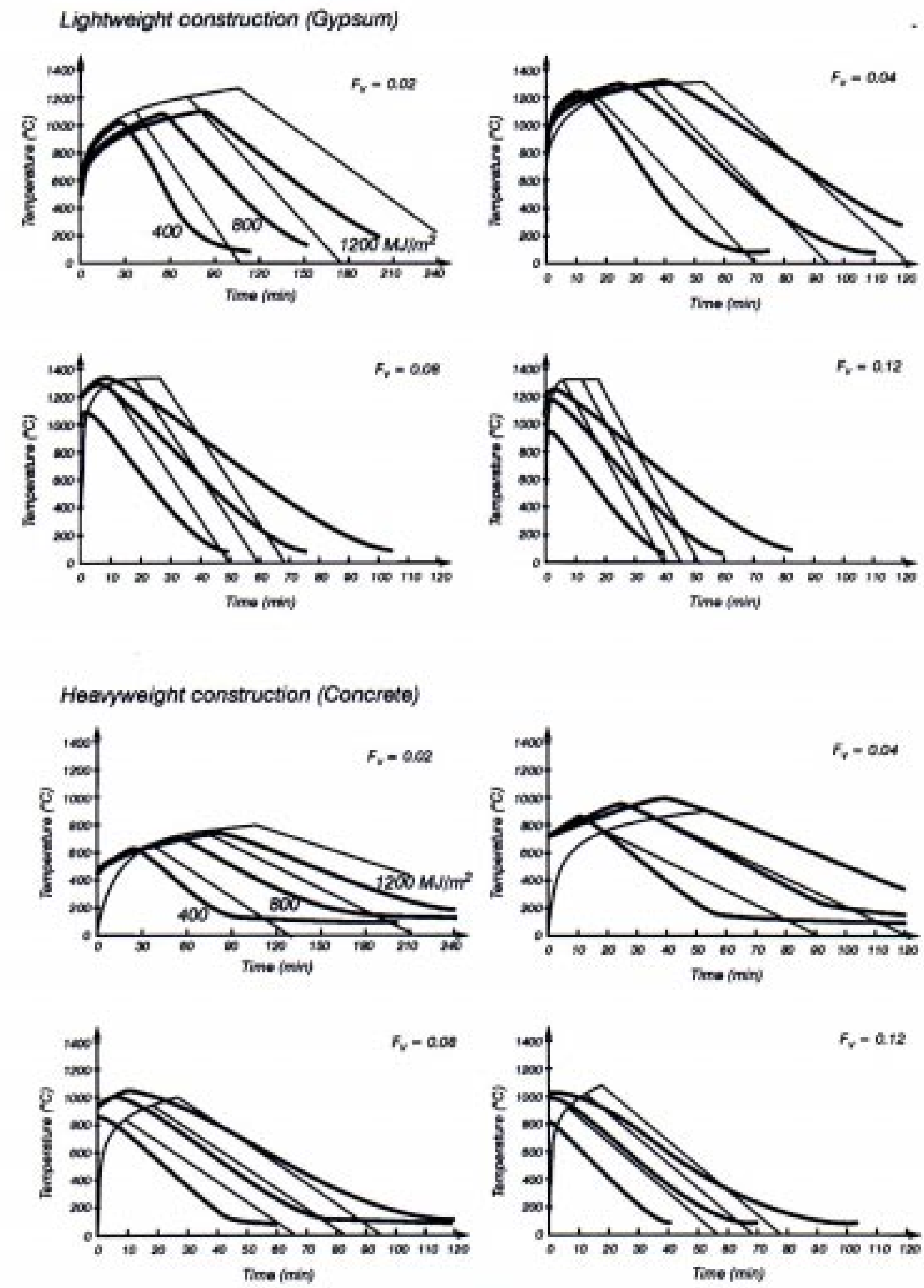


Fig. 11. Comparison of modified parametric fires with COMPF2 output.

Figure 14 Comparison of Modified Eurocode Time-Temperature Curves with COMPF2 Output [36]

In both of the models described previously it is necessary to define some of these parameters. Lie's approach is to eliminate the need to determine these parameters, suggesting that it is not important to predict a time-temperature curve that is representative of the fire scenario, but rather a time-temperature curve that with reasonable probability will not be exceeded. Lie also suggests that the importance of correctly modeling the decay period of the fire is minor as the impact of the decay phase on the maximum room temperatures is small, as determined by Kawagoe.

Based on the theoretical approach developed by Kawagoe[11] [12], Lie developed an expression that approximately described the theoretical curves for any value of opening factors. This development was based on two distinct compartment types: those constructed from light materials; and those constructed from heavy materials. The defining density is 1600 kg/m^3. Lie argues that due to the lack of sensitivity of the heat balance model to small changes in this variable, it represents a reasonable simplification. The expression that Lie proposes is the following:

$$T_t = 250(10F_v)^{\frac{0.1}{F_v^{0.3}}} e^{-F_v^2 t}\left[3\left(1-e^{-0.6t}\right)-\left(1-e^{-3t}\right)+4\left(1-e^{-12t}\right)\right]+C\left(\frac{600}{F_v}\right)^{0.5} \qquad (34)$$

where:

$$F_v = \frac{A_v (H_v)^{\frac{1}{2}}}{A_t} \qquad (35)$$

Figures 15 & 16 compare this expression to Kawagoe's theoretical model for various opening factors.

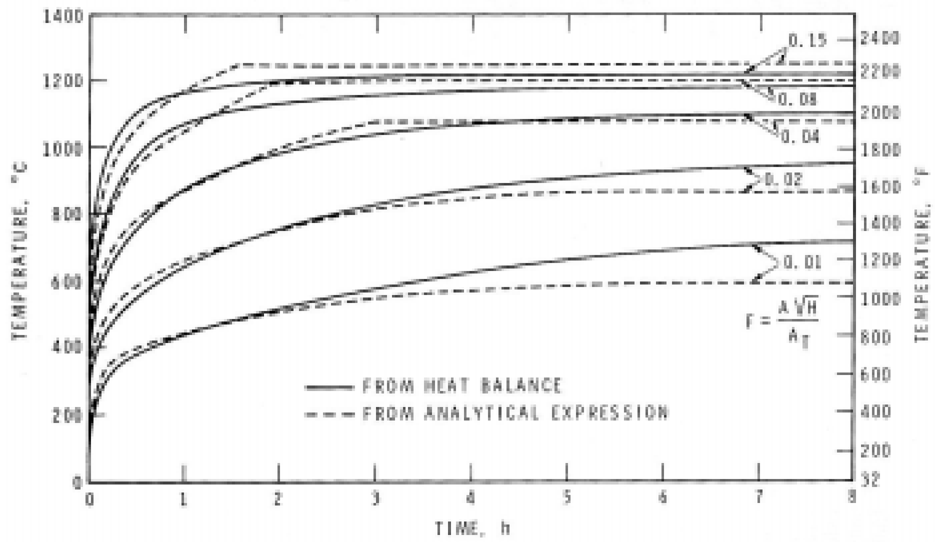


Figure 15 Theoretical vs. Experimental Time-Temperature Curves – Heavy Weight Construction (Lie) [9]

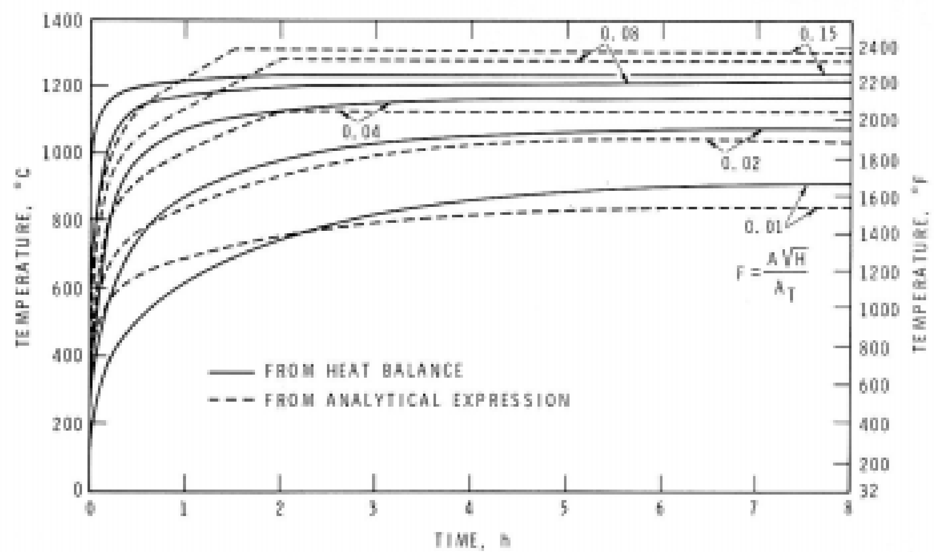


Figure 16 Theoretical vs. Experimental Time-Temperature Curves – Light Weight Construction (Lie) [9]

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

$$T_t = -600\left(\frac{t}{\tau} - 1\right) + T_\tau \qquad (36)$$

where

$$\tau = \frac{L_t A_t}{330 A_v (H_v)^{1/2}} \qquad (37)$$

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 Figure 17 and with the results of Pettersson et. al shown in Figure 18.

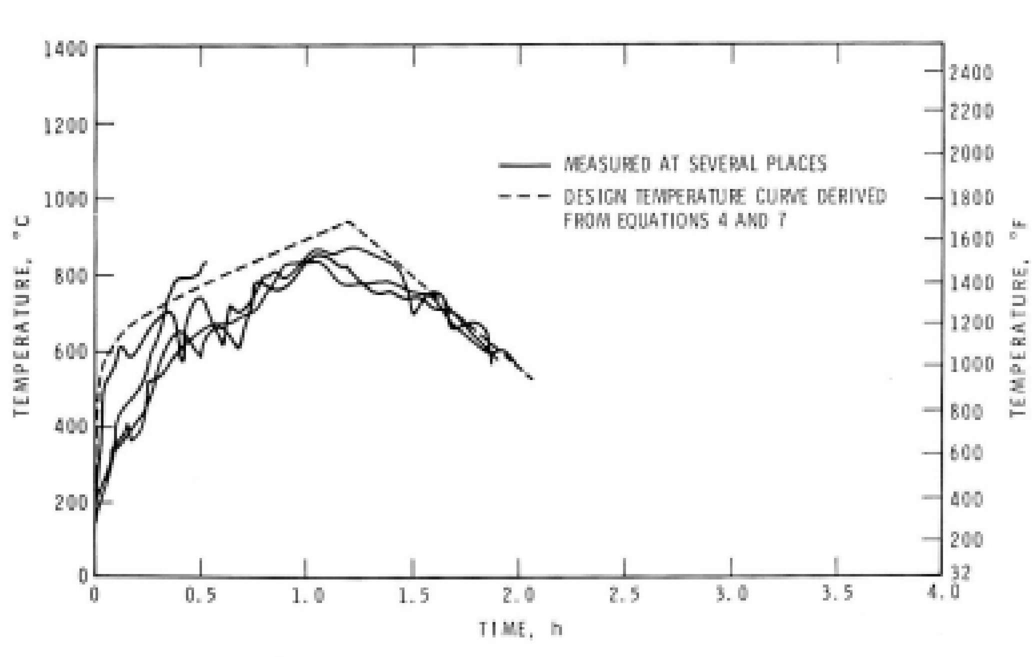


Figure 17   Comparison of Theoretical vs. Experimental Time-Temperature Curves – Lie[16]

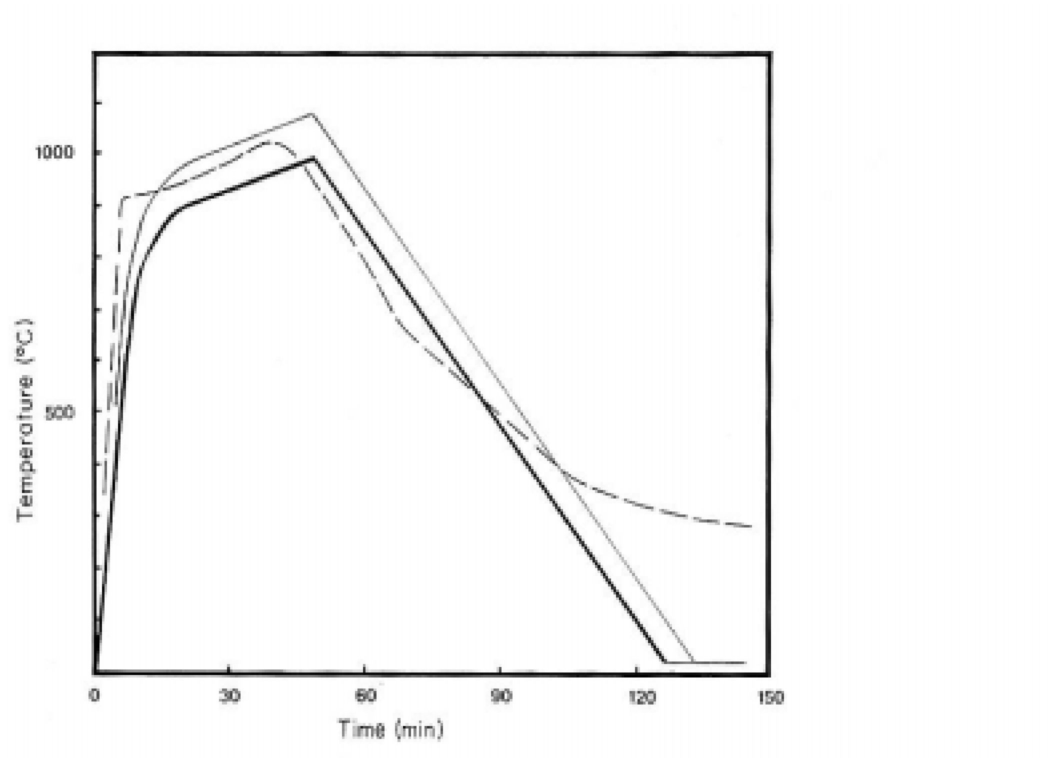


Figure 18   Comparison of Theoretical Time-Temperature Curves – Lie & Pettersson [2]

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 [34] 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.

5.2.9 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 comparison of the curves would be helpful in determining which model produces the more conservative results. In the following table the variables used in the comparison of Pettersson's, Lie's, Original Eurocode [43] and Modified Eurocode [36] are summarized.

For this comparison a typical 5m wide by 5m long by 3m high compartment was selected in addition to the tabulated values in Table 6. For these comparisons the tabulate values from Pettersson [19] 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 the figures that follow:

Table 6

Summary of Data for Comparison of Time-Temperature Models

Variable	**Comparison**					
	1	**2**	**3**	**4**	**5**	**6**
$\sqrt{k\rho c_p}$ (1)	1160	1160	1160	1160	1160	1160
F_v	0.02	0.02	0.06	0.06	0.12	0.12
L_{td} (2)	25	251	75	753	75	1507

Notes: (1) 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.

(2) fuel loads shown are from Pettersson's tables [19] and represent the range of fuel loads used for the opening factors indicated.

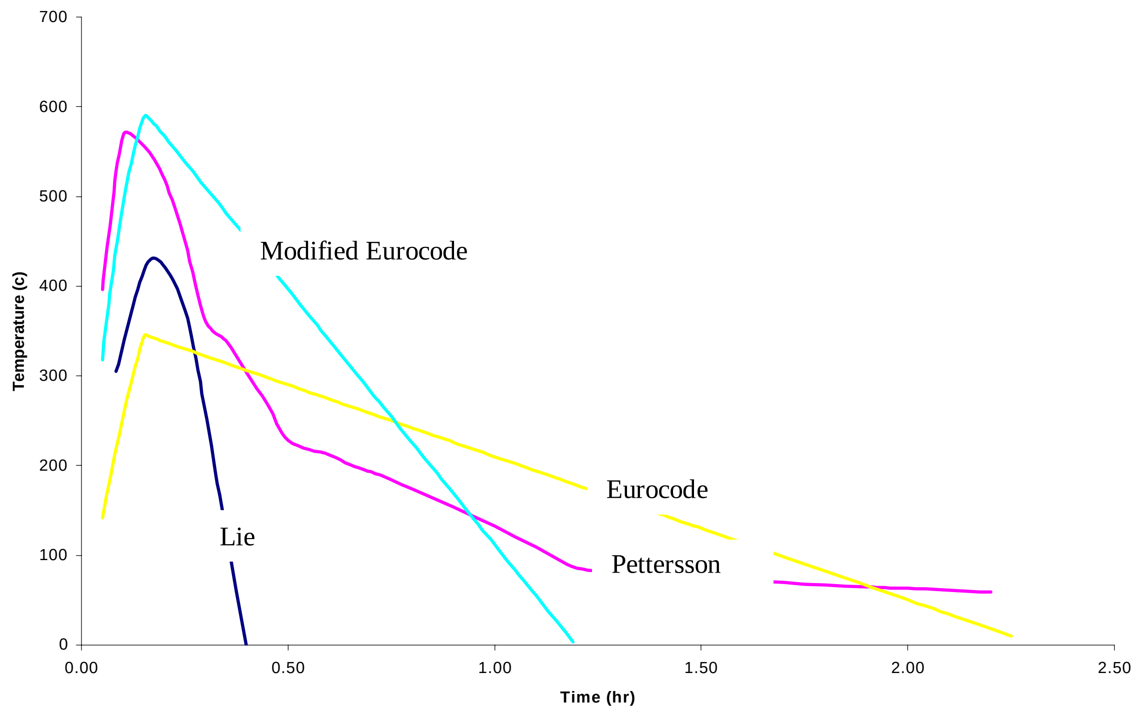


Figure 19 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #1 from Table 6

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. As well the Modified Eurocode curve represents a more severe fire (area under the curve) up to a temperature of about 150^{0}C. Both the Eurocode and Lie curves under-predict compartment temperatures relative to the other two curves.

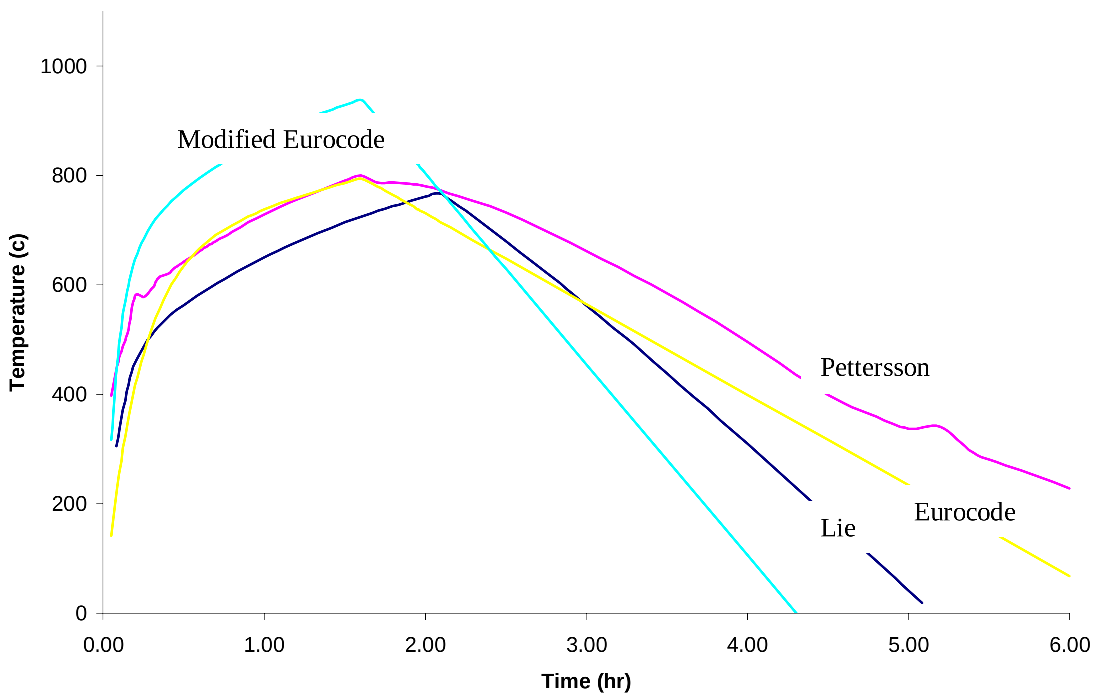


Figure 20 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #2 from Table 6

As with Figure 19 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 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.

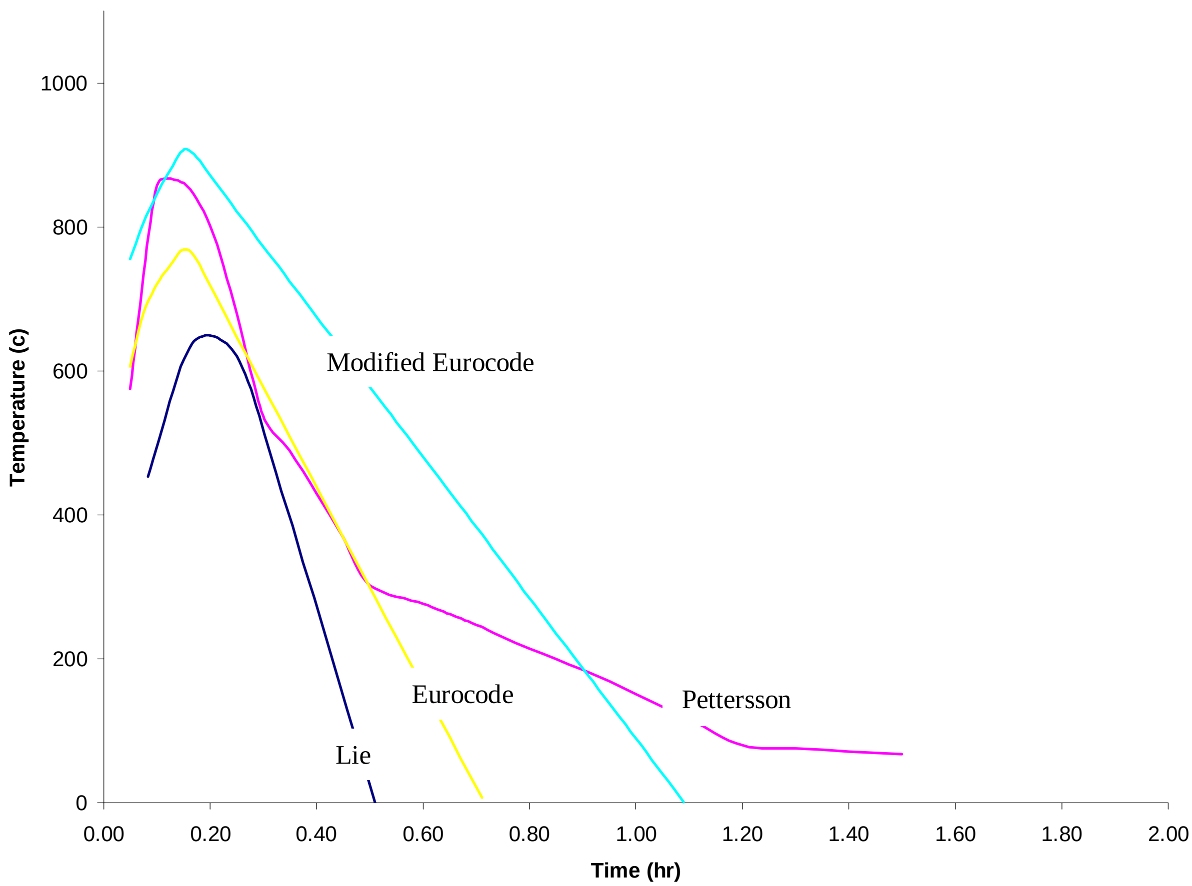


Figure 21 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #3 from Table 6

As with Figures 19 & 20 the Modified Eurocode curve represents the most conservative prediction of both compartment temperatures and fire severity.

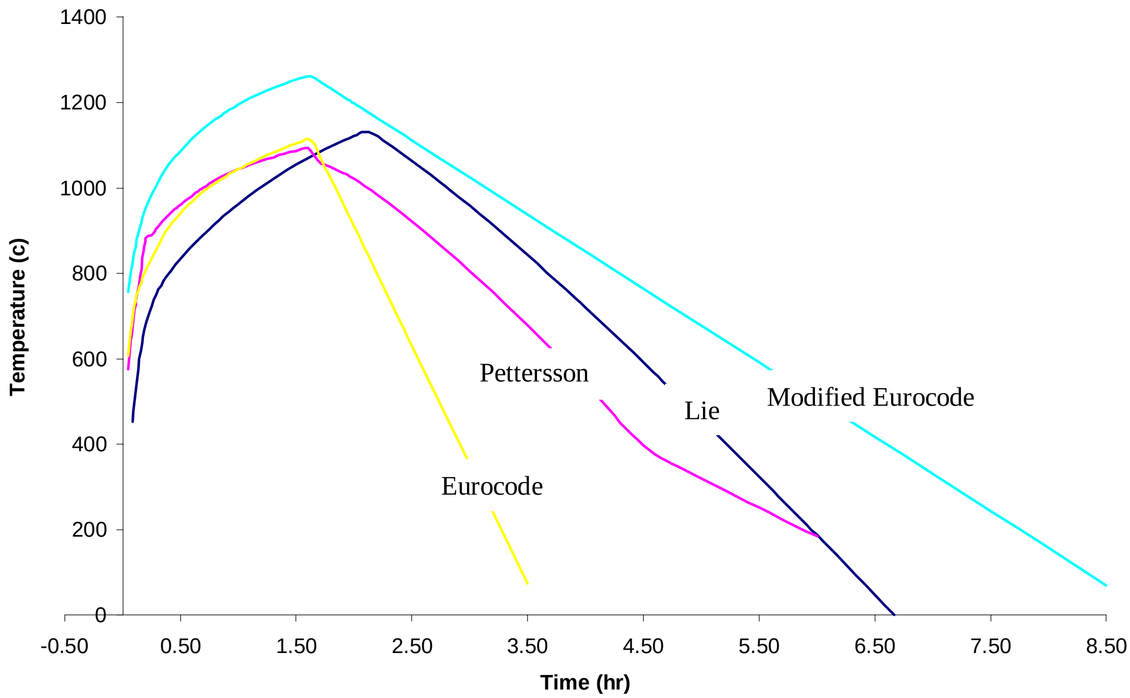


Figure 22 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #4 from Table 6

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 (31b). However, use of this equation resulted in a continuing increase in temperature. As a result the decay rate was generated from (31c) 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 the highest point on the curve.

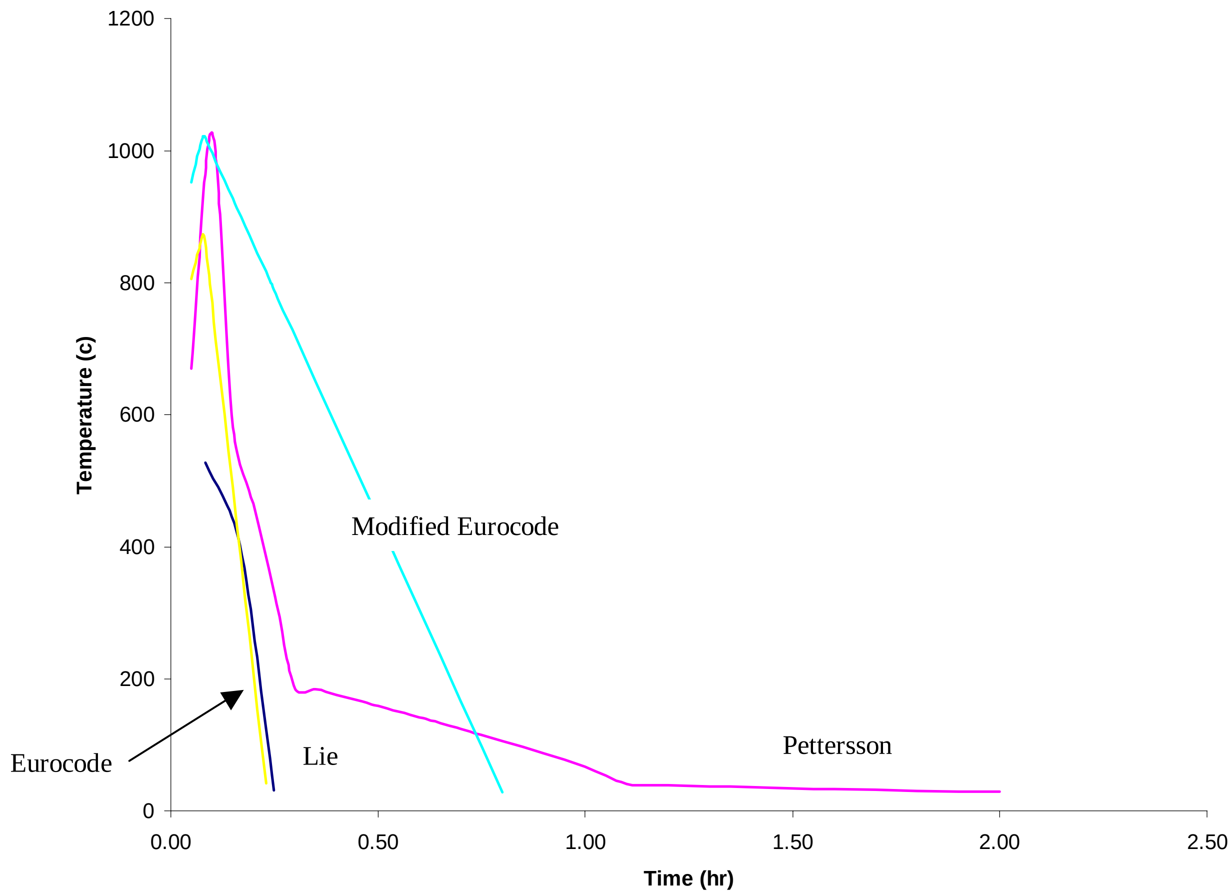


Figure 23 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #5 from Table 6

One thing that can be seen from Figures 19, 21 & 23 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 ~ ½ of that typically expected in a typical office.

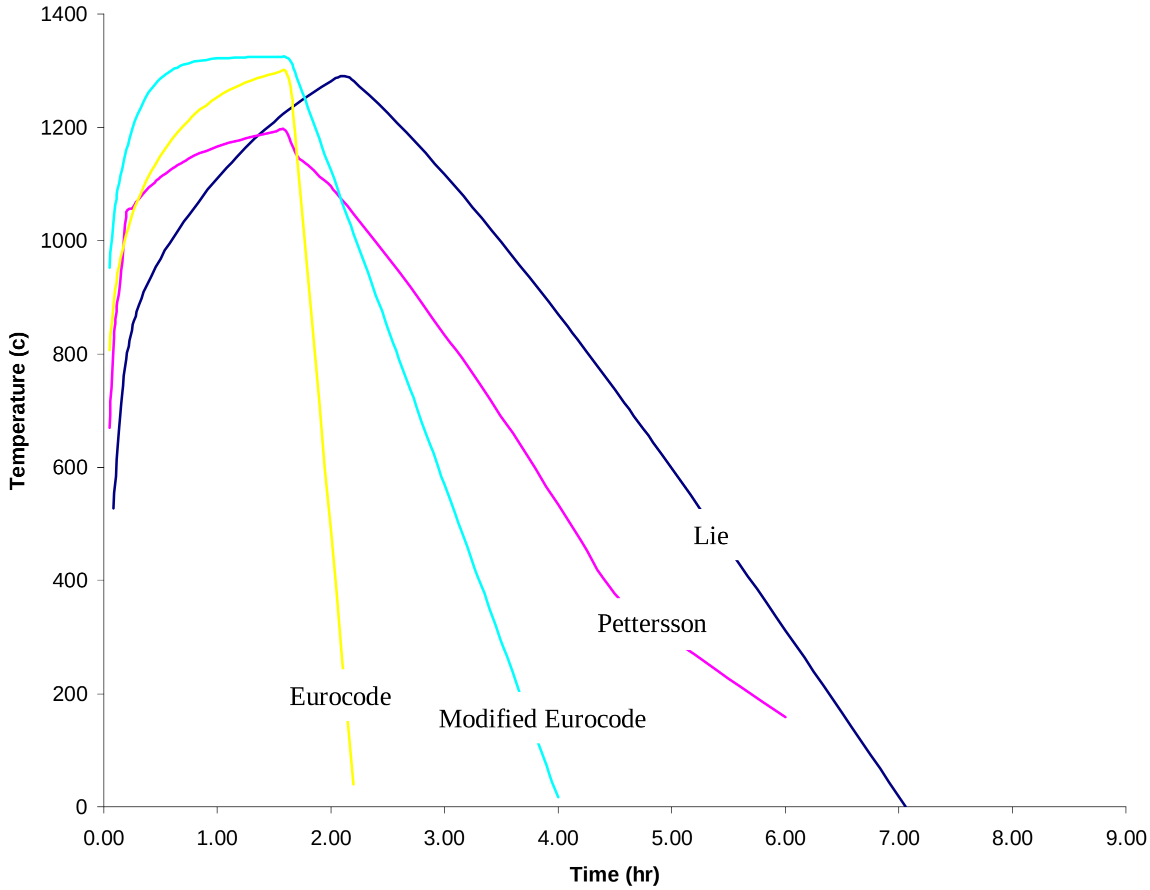


Figure 24 Comparisons of Lie's, Pettersson's, Eurocode & Modified Eurocode Based on Comparison #6 from Table 6

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 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.

5.3 Other Influencing Factors

In a draft paper by Thomas, [13] the author re-analyzes data from previous compartment fire experiments. The purpose of the analysis is to confirm the dependency of the burning rate on the vent width and height as proposed by Kawagoe, which is the basis of time-temperature curves developed by others. In the analysis Thomas has found that more appropriate correlations for the burning rate are as follows:

$$\dot{m} = 0.435\, H_w^{1.17} H_v^{1.69} \text{ (MW) for } H_w/A_w = 1 \quad (38)$$

$$\dot{m} = 3.39\, H_w^{0.543} H_v^{1.31} \text{ (MW) for } H_w/A_w < 1 \quad (39)$$

Kawagoe's expression suggests that the burning rate is proportional to the ventilation factor A√h. that can be re-written as $H_w^{1.0}\ H_v^{1.5}$. It can be seen that the correlation proposed by Thomas is similar but not quite the same.

As a way to evaluate the sensitivity of the time-temperature models to this revised burning rate expression, the ventilation factor can be modified as follows:

$$F_v = \frac{H_w^{1.17}\ H_v^{1.69}}{A_t} \text{ for } H_w/A_w = 1 \quad (40)$$

$$F_v = \frac{H_w^{\ 0.543}\ H_v^{\ 1.31}}{A_t} \quad \text{for } H_w/A_w < 1 \tag{41}$$

It should be recognized that time-temperature models described previously are essentially curve fits of experimental compartment fire data. As a result, the straight substitution proposed may not be completely accurate. The most accurate way to examine the sensitivity would be to re-plot respective compartment fire data and develop new equations based on the revised burning rate equation. Nevertheless, the substitution will be carried out for the Modified Eurocode curves for comparison purposes.

For this comparison purposes the following data will be used:

- compartment 5m x 5m x 3m high;
- light compartment boundaries with a thermal inertia of 700 $J/m^2s^{1/2}K$;
- two opening conditions with one opening being a door where H_w= 0.76m and the other opening being a large garage type door the full width of one wall; and
- a fuel load of 500 MJ/m^2 floor area based on wood equivalent value of 18 MJ/kg

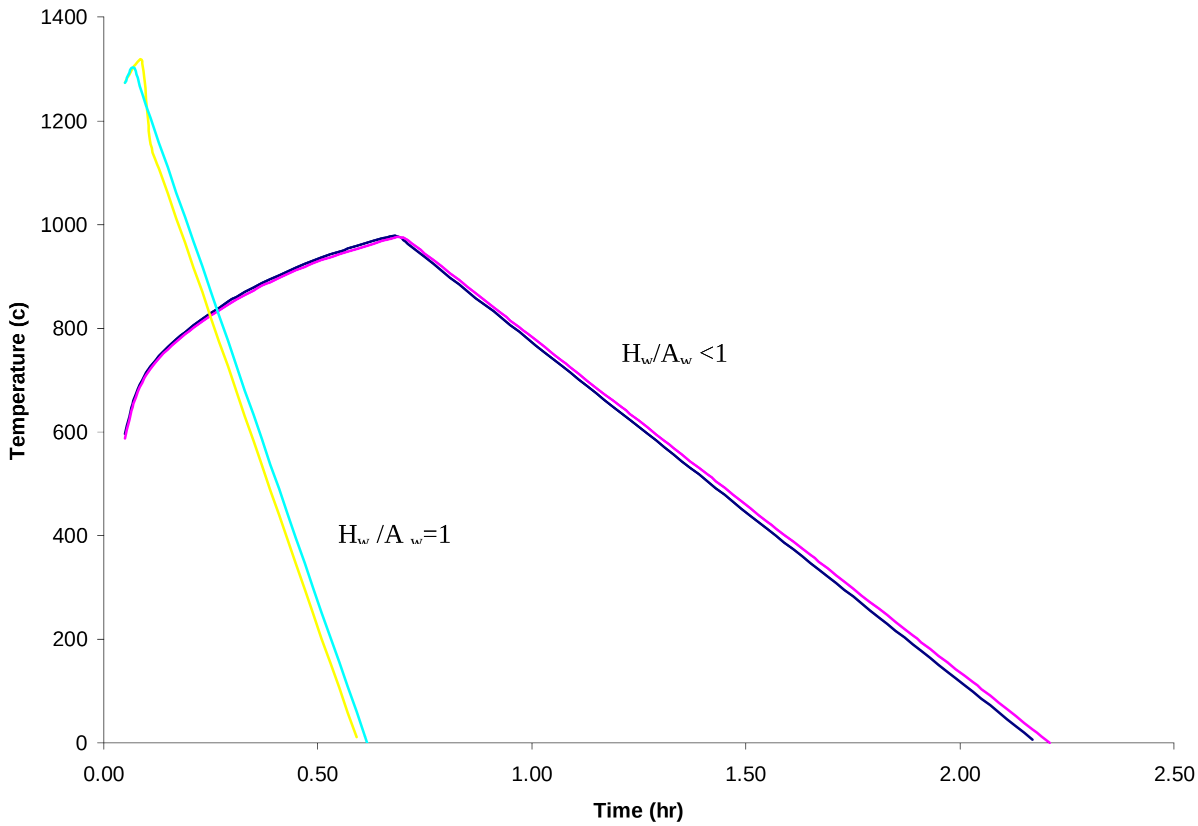


Figure 25 Comparison Modified Eurocode Time-Temperature Curve using Kawagoe's vs. Thomas's Ventilation Factor Correlation

From Figure 25 there appears to be little influence on the overall prediction from this modification to the ventilation factor.

In the case of multiple vertical openings the opening factor F_v may be modified as follows[47]:

$$F_v = A_v \sqrt{H_v} / A_t \tag{42}$$

where

$$A_v = \sum A_{vi} \tag{43}$$

$$H_v = \left[\frac{\sum \left(A_{vi} \sqrt{H_i} \right)}{\sum A_{vi}} \right]^2 \qquad (44)$$

Other factors that have been investigated but not extensively researched include the impact of openings in the roof of the compartment [19] and the impact of cross ventilation caused by openings on opposite walls [48]. Under these conditions it has been demonstrated that fires do not follow the same behavior patterns as the fires researched in “typical compartments”. As a result the time-temperature curves described are not necessarily valid for these scenarios, and until further research is available to allow the proper prediction for these conditions alternate approaches should be utilized.

Another compartment configuration common to most buildings are long narrow compartments such as corridors. Again the models presented do not predict the behavior in corridors well. Fires in these spaces tend to grow from the point adjacent an opening, regardless of the point of ignition, and progressively burn back through the available fuel.

What this does is caution the reader to the fact that there are still some areas of concern that are not adequately addressed by the current models. Nevertheless, for the majority of “typical” compartment configurations the models such as the Modified Eurocode will provide reasonable estimates of temperatures to be expected.

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6.0 Basic Concepts of Structural Fire Design

The reason 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 systems 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 Structural Engineer vs. 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, and therefore minimize the need for collaboration between the two disciplines. Under 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 structural members at normal conditions 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 FRR's 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 [14] the temperature history of the structural element based on the heat input resulting from the compartment fire.

The thermal behavior under fire conditions has been well defined for steel and concrete structures, but not so well defined for timber[15]. Specifically, simple analytical procedures have been developed for steel and concrete 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. 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.

Most modern buildings constructed today and in the past century use structural steel as the primary load bearing elements. Although composite assemblies such as floor/ceiling assemblies consisting of supporting steel, metal pan, and concrete floor are used, the supporting steel is the primary structural component. As a result, the focus will turn to simplified analytical solutions for structural steel. It should be pointed out that this does not preclude the reader from applying the approach described to other structural components within a building such as concrete or timber structures with the appropriate substitution of applicable equations.

The intent of developing this procedure is to define a simplified process that the practicing engineer can apply to evaluate the need, or lack thereof, for structural fire protection. This will improve the utility of the process for the practicing engineer while not necessarily involving significantly increased resources to determine a realistic answer to a structural fire protection problem. As more complex methods become available to the profession at large, the method proposed may become useful in the form of providing a first cut at a particular project's structural fire protection requirements.

6.3 Behavior of Steel Under Fire Conditions

During a fire, steel, whether in the form of a column, beam, or truss will be exposed to hot gases from the fire, and the exposure will depend upon the configuration of the structural member. For example, an unprotected column will likely be exposed on all four sides whereas a beam supporting a floor may only be exposed on the bottom flange and/or sides depending upon whether it is buried in the supported floor assembly. The basic premise of the compartment fire as stated previously, is that the temperature within the compartment is uniform. Given the high thermal conductivity of steel it is usually assumed that steel will be heated uniformly [16]. Therefore, if a compartment experiences uniform temperature distribution during a fire and any steel affected by the fire uniformly distributes the heat, it is reasonable to assume that the steel will experience a uniform temperature increase.

As the structural member is heated, the mechanical properties such as tensile and yield strength, and modulus of elasticity, decrease. If the yield stress decreases to the working stress, the element will fail. The steel temperature at this moment is usually taken as the critical temperature [17]. The critical temperature of steel is often taken as ~540 ^{0}C, but varies depending upon the type and size of the steel member. This form of failure is known as the instantaneous deformation concept with limitations as follows[14]:

1. The model provides a general indication of when the failure in the structural member is likely to occur but not the degree to which the member will deform during this failure process; and
2. The model does not provide insight into the condition of a structural member that is heated to just at or below the critical temperature maintained at this temperature and then cooled.

To account for these unknowns a process known as the creep concept has been described that allows for the entire deflection history of the member to be calculated during the course of the fire. This deflection history is determined by calculating the strain-time history based on the compartment time-temperature relationship. The total strain consists of three components which are:

1. Thermal strain, which is a measurement of the thermal expansion due to elevated temperatures;
2. Instantaneous stress related strain, based on the stress-strain relationship under the fires thermal environment; and
3. Creep strain, which is the plastic deformation of the structural member as a function of time.

Relationships for these values are available based on experimental data but are different depending upon the type of structural member being considered, and configuration of the structural member (i.e. simply supported at both ends, fixed and one end simply supported at the other, etc). This approach, although capable of providing accurate results, is analytically complex and requires significant calculations. As has been discussed earlier, the intent is to develop a model that is simplistic yet sufficiently accurate for engineering calculations.

Lie & Stanzak [31] suggest that the approach described above presents an enormous engineering challenge that is impractical for an engineering analysis. Furthermore they state that it is only important to determine the time at which collapse of the structural member will occur, and not the degree to which it may deform. This is consistent with the approach being proposed where through engineering methods the inherent fire resistance of a structural member is to be calculated and compared to the prescriptive FRR requirements.

6.4 Critical Temperature

As stated previously, the critical temperature of steel is defined as the temperature at which the material loses much of its strength and can no longer support the design load, that being the maximum load permitted by the structural provisions of the building codes [4]. By maintaining the steel temperature below the critical temperature it is possible to ensure that the yield strength is not reduced to less than 50% of the ambient value [50]. From a design perspective the critical temperature of steel varies depending upon the various types of steel as follows:[50]

Table 7

Critical Temperatures for Various Types of Steel [50]

Steel	Standard/Reference	Temperature
Structural Steel	ASTM	538 ^{0}C
Reinforcing Steel	ASTM	593 ^{0}C
Pre-stressing Steel	ASTM	426 ^{0}C
Light-gauge Steel	Eurocode 3	350 ^{0}C
	Gerlich et al	400 ^{0}C

These values should be used as the pass/fail temperature criteria under the performance-based approach. That is, the time to reach the critical temperature should be compared with the FRR prescribed by the building code. If it is less, then protection of the structural steel is required and if it is greater, protection is not required. Given that the building codes have defined the level of safety via a FRR for various occupancies, building types, construction, etc., this approach will result in maintaining the "implied level of safety" as suggested as being necessary in Section 3. The next step would be to design the structure so that the critical temperatures are never reached in a compartment fire. This would result in protection greater than that required under the current building codes. This will be demonstrated in the worked example in Section 7.5.

6.5 Time-Temperature History of Fire Exposed Members

There are numerous configurations under which structural steel may be found within standard building construction. Although by no means a definitive list, the configurations summarized below represent what might reasonably be found in most instances:

1. Uninsulated steel structures, such as exposed columns, trusses, or beams;
2. Insulated steel structures, such as columns, trusses, or beams with an applied fire protective layer; and
3. Structural steel that is shielded from the fire by for example a suspended ceiling.

The expressions that follow are all taken from “Fire Engineering Design of Steel Structures”[10] and can be considered as accurate simplifications. For a full derivation of these expressions the reader should refer to the source.

6.5.1 Uninsulated Steel Structures

The general heat balance equation has been given that represents the quantity of heat absorbed by a structural member exposed to fire as follows:

$$q = \alpha F_S \left(T_t - T_s\right)\Delta t \quad \text{(J/m)} \tag{45}$$

The quantity of heat required to raise the temperature of the steel by and amount ΔT_S is given by:

$$q = c_{ps} \Delta T_S V_S \rho_S \quad \text{(J/m)} \tag{46}$$

By equating the Eq. #45 and #46 above we get the following expression:

$$T_S = \frac{\alpha}{\rho_S c_{ps}} . \frac{F_S}{V_S} \left(T_t - T_S\right)\Delta t \quad (^0\text{C}) \tag{47}$$

The above expression assumes that:

1. The steel temperature is uniformly distributed over the steel cross section;
2. The flow of heat is in one direction.

This equation (47) forms the basic expression that can be used to determine the temperature of an uninsulated structural steel member exposed to fire. The following sections will describe in more detail methods to determine the various terms of the expression.

6.5.1.1 Heat Transfer Coefficient (α)

The heat transfer coefficient contains both a convective and radiative component. Pettersson et. al. propose that a value of 23 W/m^{2} ^{0}C may be used for the convective portion. This value combined with the expression for the radiative component yields the following:

$$\alpha = 23 + \frac{5.77\varepsilon_r}{T_t - T_s}\left[\left(\frac{T_t + 273}{100}\right)^4 - \left(\frac{T_s + 273}{100}\right)^4\right] \text{ W/m}^{2\,0}\text{C} \qquad (48)$$

The emissivity value is dependant upon both the flame and steel emissivities. A summary of acceptable values is contained in the following table:

Table 8[10]
Resultant Emissivity for Fire Exposed Structural Members

Type of Construction	***Resultant Emissivity***
Column exposed to fire on all sides	0.7
Column outside building façade	0.3
Floor girder with floor slab of concrete, only the underside of the bottom flange being directly exposed to fire.	0.5
Floor girder with floor slab on the top flange	
Girder of I section for which the width-depth ratio is not less than 0.5	0.5
Girder of I section for which the width-depth ratio is not less than 0.5	0.7
Box girder and lattice girder	0.7

6.5.1.2 Thermal Capacity ($\rho_s c_{ps}$)

As steel is heated its specific capacity changes and its density remains essentially unchanged at 7850 kg/m^3. To address this heating effect on specific capacity a temperature dependant calculation is proposed [49] as follows:

for $20 \leq T_s < 600^0$C

$$c_{ps} = 425 + (0.733T_s - 1.69\times10^{-3}T_s{}^2 + 2.22\times10^{-6}T_s{}^3 \text{ (J/kg K)} \qquad (49)$$

for $600^0\text{C} \leq T_s < 735^0$C

$$c_{ps} = 666 + 13002/(738 - T_s) \text{ (J/kg K)} \qquad (50)$$

for $735^0\text{C} \leq T_s < 900^0$C

$$c_{ps} = 545 + 17820/(T_s - 731) \text{ (J/kg K)} \qquad (51)$$

for $900^0\text{C} \leq T_s \leq 1200^0$C

$$c_{ps} = 650 \text{ (J/kg K)} \qquad (52)$$

6.5.1.3 Steel Section Ratio (F_s/V_s)

This term represents a geometric ratio between the total surface area of the fire-exposed portions of the structural member and the volume per unit length. Care should be taken when determining the value of this ratio as it has been shown that it can have significant impact upon the steel temperature calculated as shown in Figure 26. To calculate this ratio the relationships summarized in Figure 27 should be utilized.

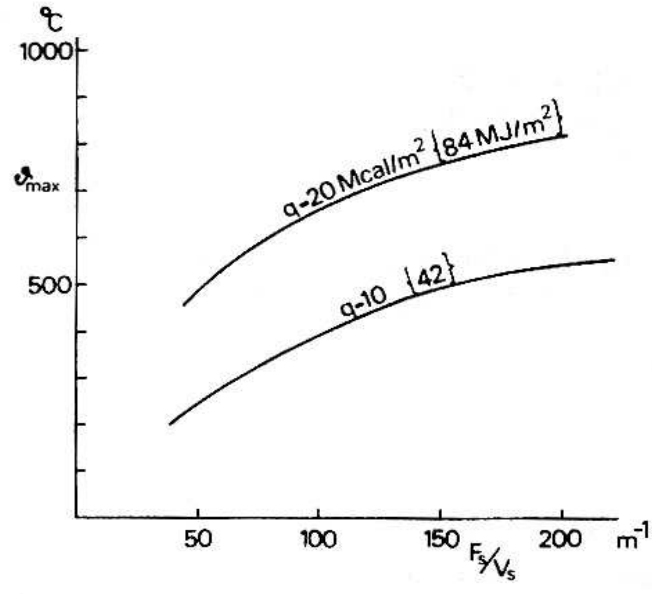


Figure 26 Maximum Steel Temperature as a Function of Emissivity and Opening Factor [10]

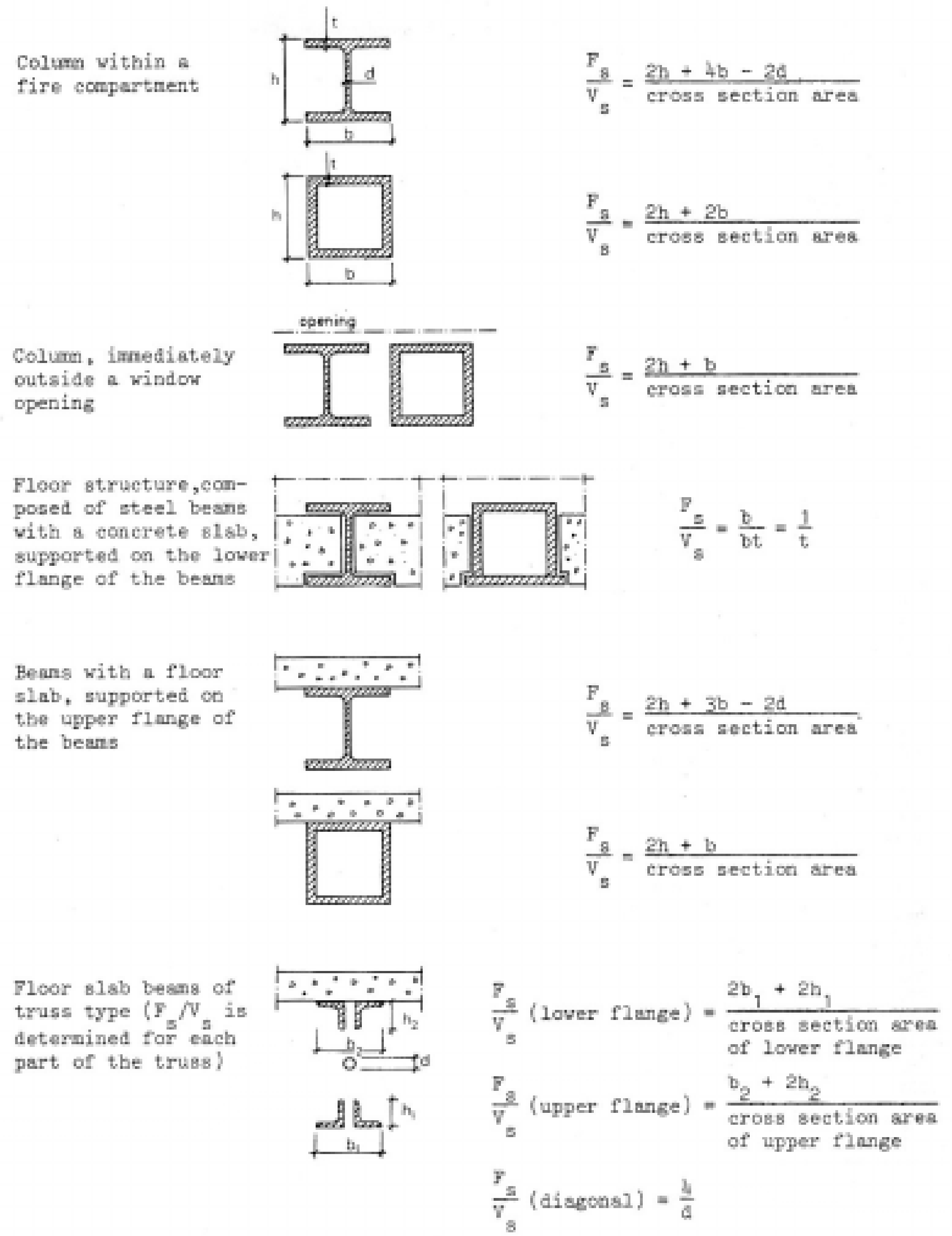


Fig. 5 a. Examples of calculating F_s/V_s (m^{-1}), the ratio of the area per unit length exposed to fire (m^2/m) to the enclosed steel volume per unit length(m^3/m) for different types of construction. See also Table 5 b(Main Section, Subsection 5.2.5)

Figure 27 Example Calculations of F_s/V_s for Uninsulated Steel [10]

6.5.1.4 Time Interval (Δt)

As can be seen from the format of the expression an iterative method will have to be used to solve the problem. The accuracy of the resulting answer will increase with smaller values for the time interval. Use of a spreadsheet will permit use of small time steps, typically 1/10th of the total fire duration and will yield acceptable results [19].

Combining the above relationships into one expression yields the following:

$$T_s = \frac{\left(23 + \frac{5.77\varepsilon_r}{T_t - T_s}\right)\left[\left(\frac{T_t + 273}{100}\right)^4 - \left(\frac{T_s + 273}{100}\right)^4\right]\left(\frac{F_s}{V_s}\right)}{\rho_s c_{ps}} \Delta t \quad (^0\text{C}) \qquad (53)$$

This equation can be easily run with a spreadsheet to obtain the time-temperature distribution for the exposed steel member based on the Modified Eurocode formulation. For example, using the following design criteria:

- Small three story office building having a FRR of 45 min. for structural/separating assemblies;
- Typical office with dimensions 5m x 5m x 2.75m high having one fully exposed steel column in the room with a surface area to volume ratio of 50 m^{-1};
- light compartment boundaries (gypsum wall board steel stud demising walls and lightweight concrete slab with OWSJ and beam supporting structure) with a thermal inertia of 700 J/m^{2}s$^{1/2}$K;
- one opening consisting of a standard door at 2.13m x 0.76m; and

- a fuel load of 700 MJ/m^2 floor area based on wood equivalent value of 18 MJ/kg.

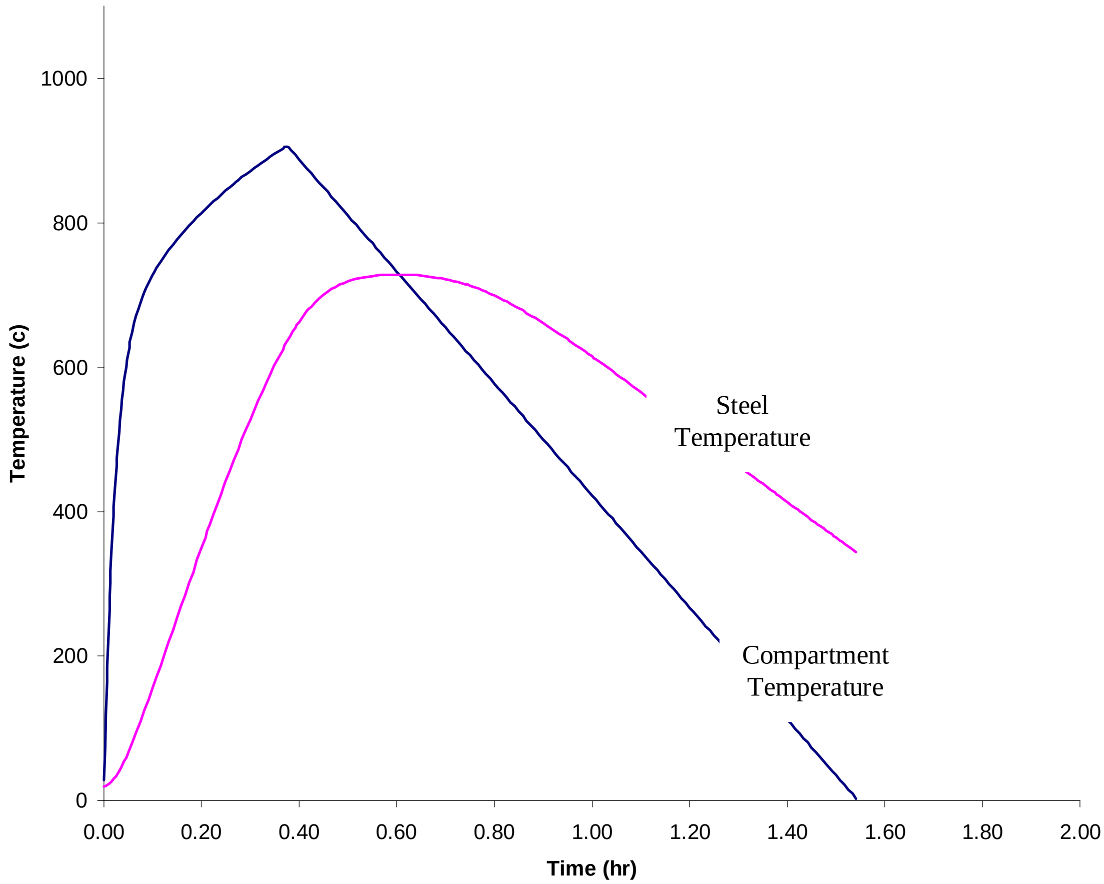


Figure 28 Predicted Time-Temperature Curve for Exposed Steel Column using the Modified Eurocode Model

From this graph it is clear that the steel column will reach the critical temperature of 538 ^{0}C at ~ 18 minutes, long before the required FRR is achieved, and as a result, protection is required.

6.5.2 Insulated Steel Structures

The general heat balance equation that represents the quantity of heat absorbed by a protected structural member exposed to fire has been given as follows:

$$q = \frac{1}{1/\alpha + d_i/k_i} A_i (T_t - T_s) \Delta t \quad \text{(J/m)} \tag{54}$$

The quantity of heat required to raise the temperature of the steel by an amount ΔT_S is the same as for the uninsulated case (46).

By combining (55) and (46) we get the following expression:

$$T_S = \frac{1}{(1/\alpha + d_i/k_i)\rho_S c_{ps}} \cdot \frac{A_i}{V_S} (T_t - T_S) \Delta t \quad ({}^0\text{C}) \tag{55}$$

The above expression assumes that:

1. The temperature gradient in the insulation is linear;
2. The temperature on the inside surface of the insulation is the same as the steel and no energy is stored in the insulating material;
3. That the flow of heat is in one direction.

Equation (55) can be further modified by assuming that the thermal surface resistance at the temperatures experienced during a fire will be negligible in comparison to the thermal resistance of the insulation. Therefore (55) can be reduced to:

$$T_S = \frac{k_i}{d_i \rho_S c_{ps}} \cdot \frac{A_i}{V_S} (T_t - T_S) \Delta t \quad ({}^0\text{C}) \tag{56}$$

There are methods available to account for the potential storage of heat in insulating materials with higher heat capacity. However, it is more conservative to assume that all heat energy is transferred to the steel by ignoring this possibility.

With the exception of the ratio of the internal surface area of the protecting insulation to the sectional volume of the structural component (A_i/V_s), all other variables have been addressed in Section 6.5.1. Calculation of this term is shown in Figure 29.

The thermal conductivity of materials typically used for the protection of structural steel are summarized in the following table:

Table 9 [16]
Summary of Thermal Conductivity of Insulating Materials

Material	**Thermal Conductivity (W/m^{0}C)**
Sprayed Mineral Fibre	0.1
Cementitious Mixture	0.1
Perlite or Vermiculite Plates	0.15
Fibre Silicate Sheets	0.15
Wood	0.2
Gypsum Wall Board	0.2
Mineral Wool Slabs	0.25
Cellular Concrete (600 kg/m^2)	0.30
Cellular Concrete (1000 kg/m^2)	0.45
Cellular Concrete (1300 kg/m^2)	0.65
Light Weight Concrete	0.80
Clay Brick and Lime Brick	1.2
Normal Weight Concrete	1.3 – 1.7
Steel	35

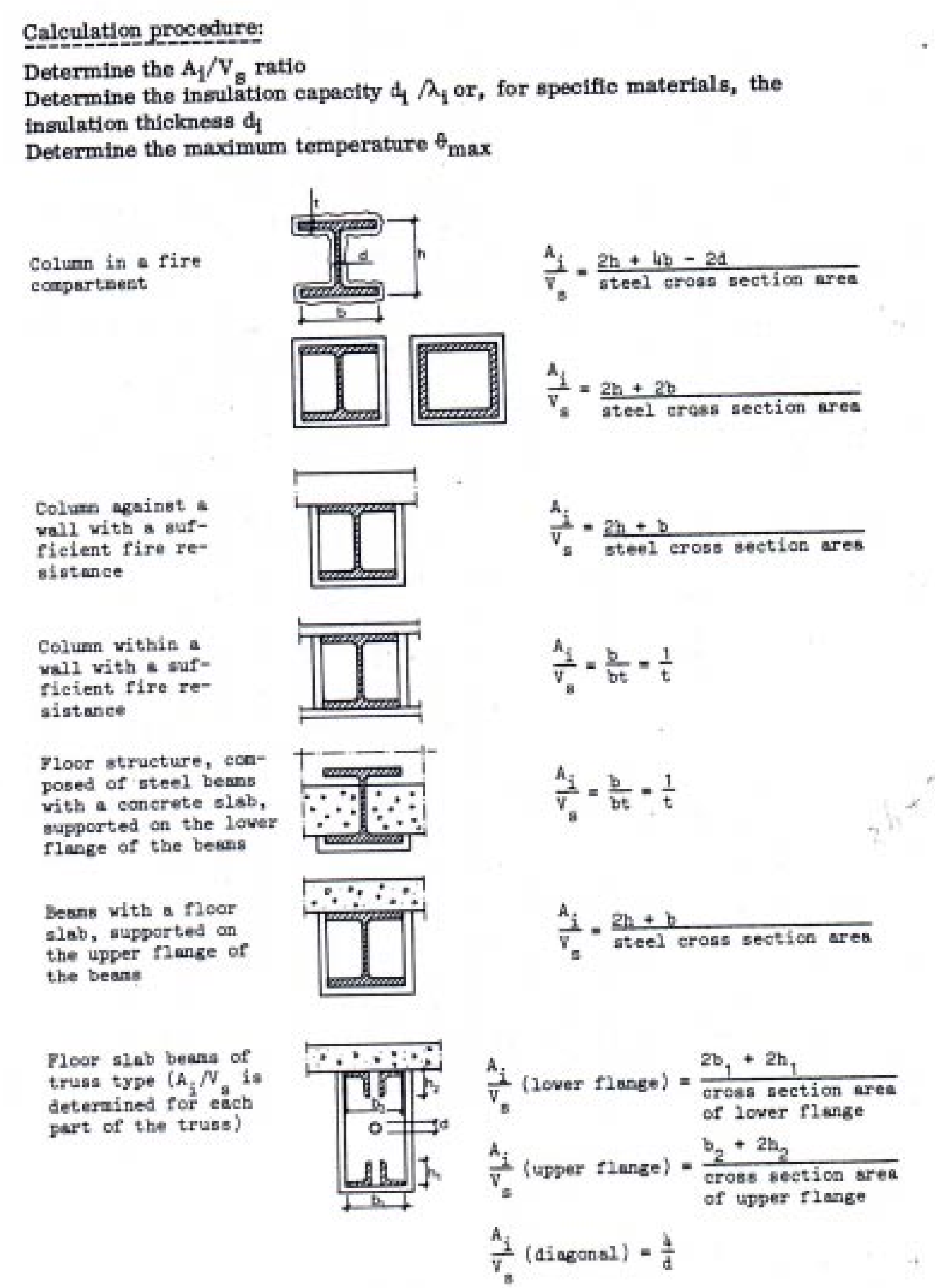


Figure 29 Example Calculations of A_i/V_s for Insulated Steel (Pettersson) [10]

Continuing with the example for uninsulated steel from the previous section, a spreadsheet can be used to predict the type and thickness of the protection required to ensure the critical temperature is not exceeded before the prescribed FRR. In this case, one 13 mm layer of gwb will provide a time to reach the critical temperature of 1 hour and 20 minutes.

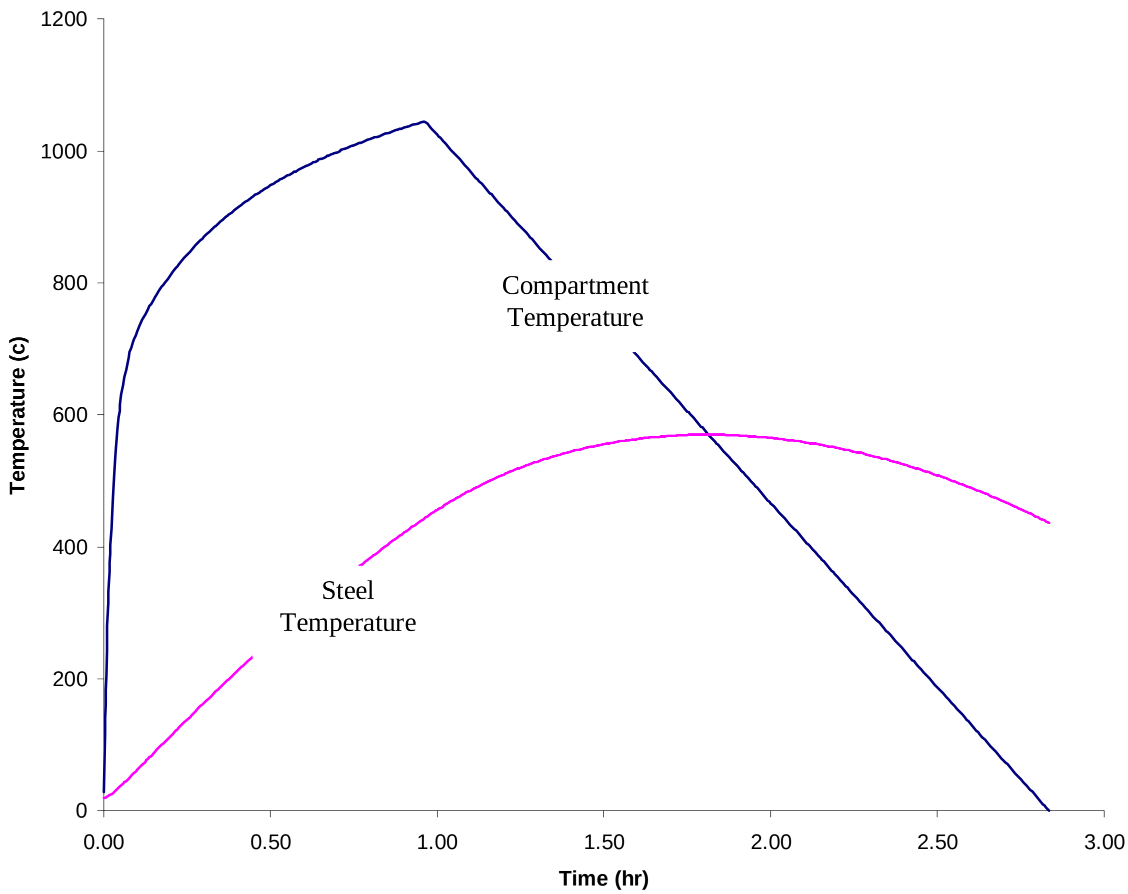


Figure 30 Predicted Time-Temperature Curve for Insulated Steel Column using the Modified Eurocode Model

The user of these equations should realize that the temperatures in a fire will have an impact on the integrity of the protecting material. The significant used of gwb in typical building construction is of particular concern, since at high temperatures the moisture is driven from the gwb, which tends to lead to cracking of the gwb. If this occurs the structural element could be directly exposed to the fire [34]. Therefore, care must be taken in the construction of these protective membranes to ensure cracks do not appear sooner than would otherwise be expected due to poor construction techniques. Type X gwb, which constructed with glass fibers for reinforcement, is more stable at elevated temperatures.

6.5.3 Steel Structures Insulated with a Suspended Ceiling

The analysis to determine the temperature of steel that is supporting a floor assembly and insulated from the fire with a suspended ceiling is more complicated than the previous two sections. In this scenario the temperature in the ceiling plenum between the suspended ceiling and supported floor assembly must be determined as this is the environment that will result in the heating of the steel. In order to determine the temperature profile in the plenum the plenum side temperature of both the suspended ceiling and supported floor assembly must be calculated. Generally speaking these temperatures are not the temperature of the fire in the compartment on account of the insulating capacity of the suspended ceiling and the ability of the floor assembly to conduct heat away form the plenum.

6.5.3.1 Calculation of Plenum Temperatures

For the calculation of the inner surface temperature of the supported floor and suspended ceiling the influence of the thermal capacity of the steel, air gap and suspended ceiling can be ignored to simplify the process. This results in a conservative analysis, since the heat capacity of the floor assembly will be the limiting factor controlling the temperature in the plenum. From this there are three expressions provided:

$$T_{co} = T_t - K\frac{1}{\alpha_1}(T_t - T_{fi})$$ Temp. fire exposed side of suspended ceiling (57)

$$T_{ci} = T_t - K\left(\frac{1}{\alpha_1} + \frac{d_i}{k_i}\right)(T_t - T_{fi})$$ Temp. plenum side of suspended ceiling (58)

$$T_{fs} = T_t - K\left(\frac{1}{\alpha_1} + \frac{d_i}{k_i} + \frac{1}{\alpha_2}\right)(T_t - T_{fi})$$ Temp. plenum side of floor assembly (59)

where

$$K = \frac{1}{\frac{1}{\alpha_1} + \frac{d_i}{k_i} + \frac{1}{\alpha_2} + \frac{\Delta x}{k_{fs}}} \qquad (60)$$

$$\alpha_1 = 23 + \frac{5.77\varepsilon_r}{T_t - T_{co}}\left[\left(\frac{T_t + 273}{100}\right)^4 - \left(\frac{T_{co} + 273}{100}\right)^4\right] \text{ W/m}^2\,{}^0\text{C}$$ repeated (48)

$$\alpha_2 = 8.7 + \frac{5.77\varepsilon_r}{T_{ci} - T_{fi}}\left[\left(\frac{T_{ci} + 273}{100}\right)^4 - \left(\frac{T_{fi} + 273}{100}\right)^4\right] \text{ W/m}^2\,{}^0\text{C}$$ Eq. #61

To calculate the various temperature from (58), (59), and (60) the floor slab must be divided into segments and an iterative procedure performed. With these three temperatures known the time-temperature relationship for the structural steel can be determined based on the following:

$$T_s = \frac{F_s}{V_s \rho_s c_{ps}}\left[\left(\frac{\alpha_k}{2} + \alpha_{s2}\right)(T_{ci} - T_s) + \left(\frac{\alpha_k}{2} + \alpha_{s3}\right)(T_{fs} - T_s)\right] \qquad (62)$$

where

$$\alpha_{s2} = \frac{5.77\varepsilon_r}{T_{ci} - T_s}\left[\left(\frac{T_{ci} + 273}{100}\right)^4 - \left(\frac{T_s + 273}{100}\right)^4\right] \text{ W/m}^{2\,0}\text{C} \quad (63)$$

$$\alpha_{s3} = \frac{5.77\varepsilon_r}{T_{co} - T_s}\left[\left(\frac{T_{co} + 273}{100}\right)^4 - \left(\frac{T_s + 273}{100}\right)^4\right] \text{ W/m}^{2\,0}\text{C} \quad (64)$$

α_k = the surface coefficient of heat transfer due to convection for layer k W/m$^{2\,0}$C

The results of this analysis are tabulated [10] for various opening factors, fuel loads and steel geometry using the Pettersson compartment fire time-temperature model. Unfortunately, this model does not lend itself to hand calculations and a program is required for a worked solution. The tabulated data provides maximum suspended ceiling and steel temperatures for given fuel load, opening factor and steel geometry, but does not cover all scenarios that might be encountered. As well the tabulated values do not provide for the times that these maximum temperatures are expected to occur. Therefore, it is not possible to directly determine the time required to reach the critical temperature for comparison with the prescribed FRR. Nevertheless, this model can be used to compare the calculated maximum temperature of the suspended ceiling to the critical temperature values for the suspended ceiling types that are also tabulated. This is of significance, since at temperatures above these critical values the suspended ceiling would be expected to disintegrate and expose unprotected steel directly to the compartment fire. Therefore, this model provides a simple method to ensure the compartment fire expected will not result in the failure of the suspended ceiling system protecting the floor assembly supporting structure. Further information and a detailed explanation may be found in the sections summarized in the reference [10] cited.

6.5.4 Load bearing and Non-Load bearing Partitions

Up to this point the methods that can be used to determine the time-temperature relationship of structural steel exposed to fire have been addressed. This includes both exposed and protected beams, columns and other structural components, and the structural steel typically forming part of a composite floor/ceiling assembly that is protected with a suspended ceiling. However, the part of building structural system not yet addressed that plays a key role in the protection of the building through containment of the fire are partitions. In modern building design partitions consisting of both load and non-load bearing and wood and metal framed construction are typical.

Standard test criteria such as found in ASTM E119 and ISO 834 consider a failure when the average temperature rise on the unexposed surface exceeds 140^0C or the peak temperature rise at any point exceeds 180^0C. Typically, a two dimensional heat balance equation is required to predict temperature rise on the unexposed side of the assembly. The equations are different for wood-framed vs. steel-framed as the wood in wood-framed assemblies tends to add to the fuel load and increase temperatures within the wall cavity. However, a one dimensional heat transfer model has been developed [51] that can be used to predict the surface temperatures on the unexposed side of the assembly for uninsulated non-load-bearing steel stud assemblies. Although an effective model that compares well with experimental data it is not yet in a form that is useful from a practical engineering design standpoint. Others have developed finite element methods to predict the temperature rise on the unexposed side of the assembly, but these methods are complicated and more suitable for research purposes at this time [34].

As a result of these complications Buchanan [34] suggests that a simple approach is to calculate the temperature of the steel studs for load bearing assemblies using the normal temperature design methods to ensure the steel temperature does not exceed 350^{0}C to 400^{0}C (reference Table 7). The other approach that may be more straightforward from an engineering design standpoint is the use of t-equivalents summarized in Section 4. Keep in mind that Law's review of these methods [46] indicates that the models proposed by Harmathy, Law and Pettersson produce the most realistic results.

7.0 Summary

The preceding sections have identified the weaknesses with the current approach to the assignment of FRR for building components. As well, details have been given describing the various options available for predicting realistic fire protection requirements for structural steel. The sections that follow provide a general summary of the approach with notation regarding the points to keep in mind when using the approach, followed by a worked example.

7.1 Selection of Compartments or Areas to Design

For a proposed or existing building the Structural and Fire Protection Engineers must collaborate to develop a list of possible locations where the start of a fire could lead to significant impact on the structural integrity of the building. To do this, the Structural Engineer must describe the structural system design approach to identify particular structural components that may be critical to the building stability. At the same time the Fire Protection Engineer must, with an understanding of the expected occupancy, determine the areas where fuel loads may be high.

It is not likely to be the case that the area with the most critical structural nature will be the same as the area with the highest fuel load. As a result, multiple compartments should be analyzed with a view to predict the range of fire scenarios that might reasonably be expected at any point through the building. By doing this the designers can be assured that when the analysis is complete, the structural system has been adequately designed.

7.2 Determination of Compartment Fuel Loads

Once various compartments have been selected, the expected fuel load has to be determined. This can be accomplished by using Table 3 to make estimates of the mass of various fuel loads available within the compartments. This includes moveable fuel loads such as furniture and book shelves, fixed fuel loads such as doors and window frames if combustible, and protected fuel loads such as wood framing in walls. For non-combustible construction the fuel load will likely be limited to the furnishings in the room. Care must be taken to properly account for the fuel content of non-cellulosic materials such as plastic containers, binders, etc.

Once the mass of the contents in the room is totaled, it is converted to an energy value based on 18 MJ/kg for cellulosic products, keeping in mind that the petroleum based materials are to be adjusted by a factor of two prior to adding the mass to the cellulosic based materials to account for the higher heat energy content of these materials. This total fuel load is then divided by either the compartment floor area or total surface area to yield a per unit area. Care should be taken to ensure the fuel load (MJ/m^2) is calculated correctly for the model chosen.

This value should be considered the average fuel load to be expected. Assuming a normal statistical distribution the mean should be converted to a 90^{th} percentile value using (5a). The user may wish to use a factor of 2 instead of 1.58 to account for the expected peak value.

7.3 Predicted Compartment Fire Time-Temperature Relationship

Based on the Modified Eurocode time-temperature curve the expected room temperatures for the duration of the fire can be predicted. Before this can be completed the compartment geometry must be defined, including:

1. Compartment dimensions;
2. Thermal inertia of bounding surfaces;
3. Fuel load defined in MJ/m^2 total surface area of the compartment which is given by:

   $L_{td} = L_{fd} \text{ x } A_f/A_t$; and

4. Ventilation factor as modified to account for multiple openings in the compartment walls by (42), (43), & (44).

Keeping in mind that the model is not applicable to large compartments such as those found in department stores, or compartments with high aspect ratios such as corridors. The applicable equations are (28), (29), (30), (31a), (31b), (31c). (32), & (33).

7.4 Predicted Steel Time-Temperature Relationship

Within each compartment to be analyzed various structural components should have been selected to include any or all of the following:

1. Exposed structural steel either in the form of beams, columns, or trusses;
2. Protected structural steel such as columns protected by a wall assembly, beam or truss protected by a suspended ceiling, or load bearing or non-load bearing partitions.

It would be prudent to assess all structural components within the compartment potentially affected by the fire.

Depending upon the type of element selected for analysis different equations would be used as follows:

1. Exposed unprotected structural steel – Equations, Tables and Figures in Subsection 6.5.1;
2. Protected structural steel – Equations, Tables and Figures in Subsection 6.6.1
3. Steel protected by a suspended ceiling – Section 6.7.1 and Tables from Fire Engineering Design of Steel Structures [10] Section 7 of the Design portion of the document; and
4. Load and Non-load Bearing partitions – Harmathy's Normalized Heat Load Concept (7),(8), (9), & (10), Law's t-equivalent method (13) or Pettersson's t-equivalent method (14).

With respect to the use of methods for Items 1 & 2 above, the critical temperature of the type of steel being assessed must be used as the pass/fail criteria as defined in Table 7 in order to establish the level of protection required to meet the prescribed FRR from the building codes.

Ideally a computer program would be written for Item 3 to fully utilize the model. However, until such a program is available to the practicing engineer, it is possible to use the model to verify that the suspended ceiling will stay intact for the duration of the compartment fire predicted.

For Item 4, Harmathy's method essentially compares the expected fire severity with the time taken to achieve the same fire severity with the standard test such as described by ASTM E119. Until some of the research completed to date for estimating the impact of the fire on the partitions by first principles has been translated to practical hand calculation techniques, this approach will yield a reasonable determination of the required FRR.

7.5 Worked Example

The description that follows will demonstrate how the method is to be applied to a real building application.

7.5.1 Building Description

- Five story justice center consisting of both private and general offices, file storage areas, court rooms, libraries, and meeting rooms, with a floor area of ~ 1,250m^2;
- Non-combustible construction steel-framed building containing column and beam primary supporting steel and open web steel joist construction supporting a composite floor-ceiling assembly consisting of metal lathe and 100mm poured concrete;
- Exterior wall construction consisting of spandrel panels and fixed glazing;
- Interior wall construction consisting of steel stud framing and 13 mm gwb on either side of the studs;
- Exit stair and other shaft walls of 150mm thick poured concrete;
- Combination of suspended ceiling and gypsum wall board ceiling throughout;
- Fully sprinklered c/w fire alarm system that shuts down the air handling system upon alarm initiation at the fire alarm panel; and

- Mixture of wood and metal furnishings throughout. There are limited quantities of plastic furniture.

Figures 31 through 35 show the floor plans for each of the fuel levels of the building.

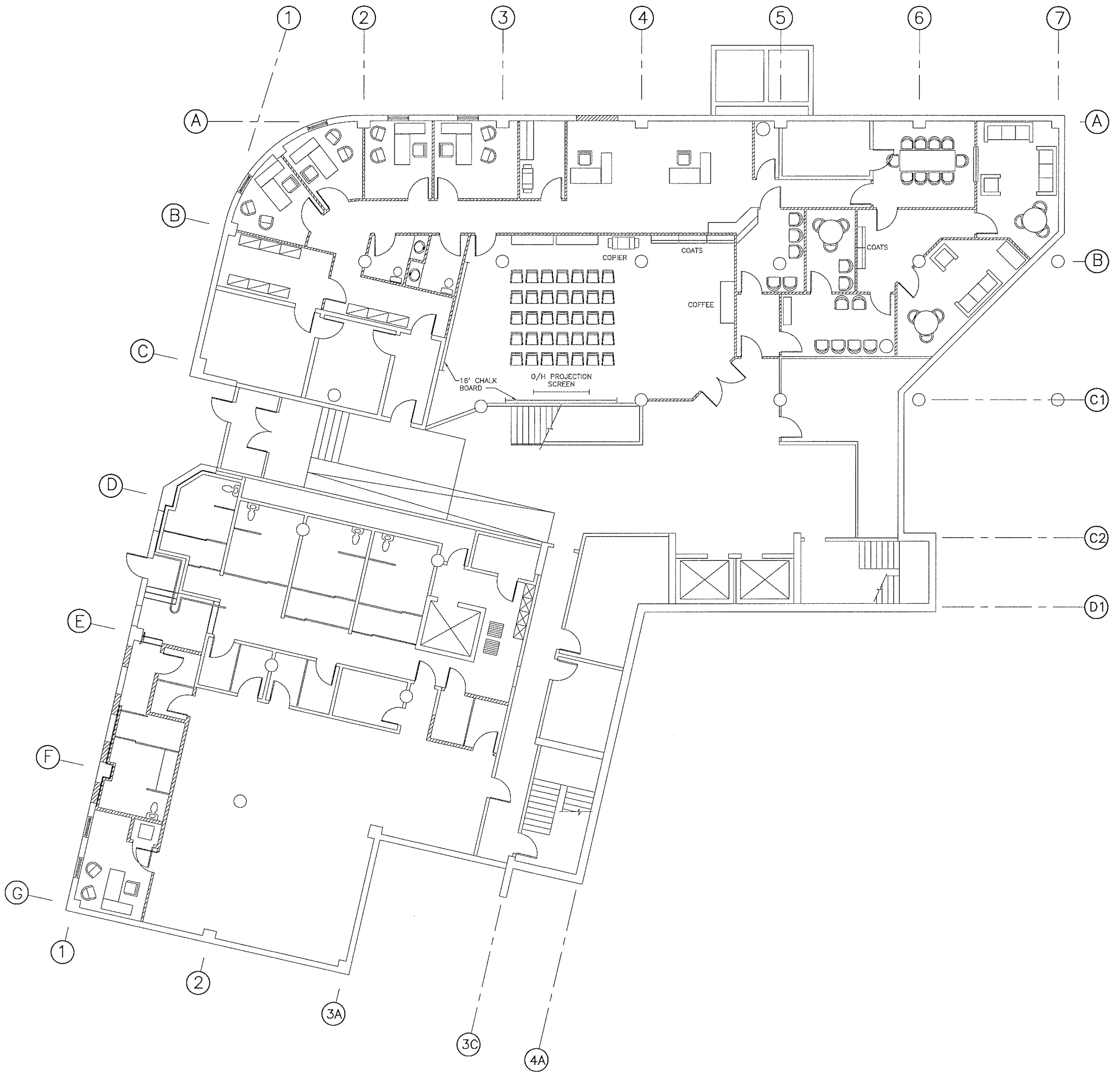


Figure 31 Work Example: Level 1 Floor Plan

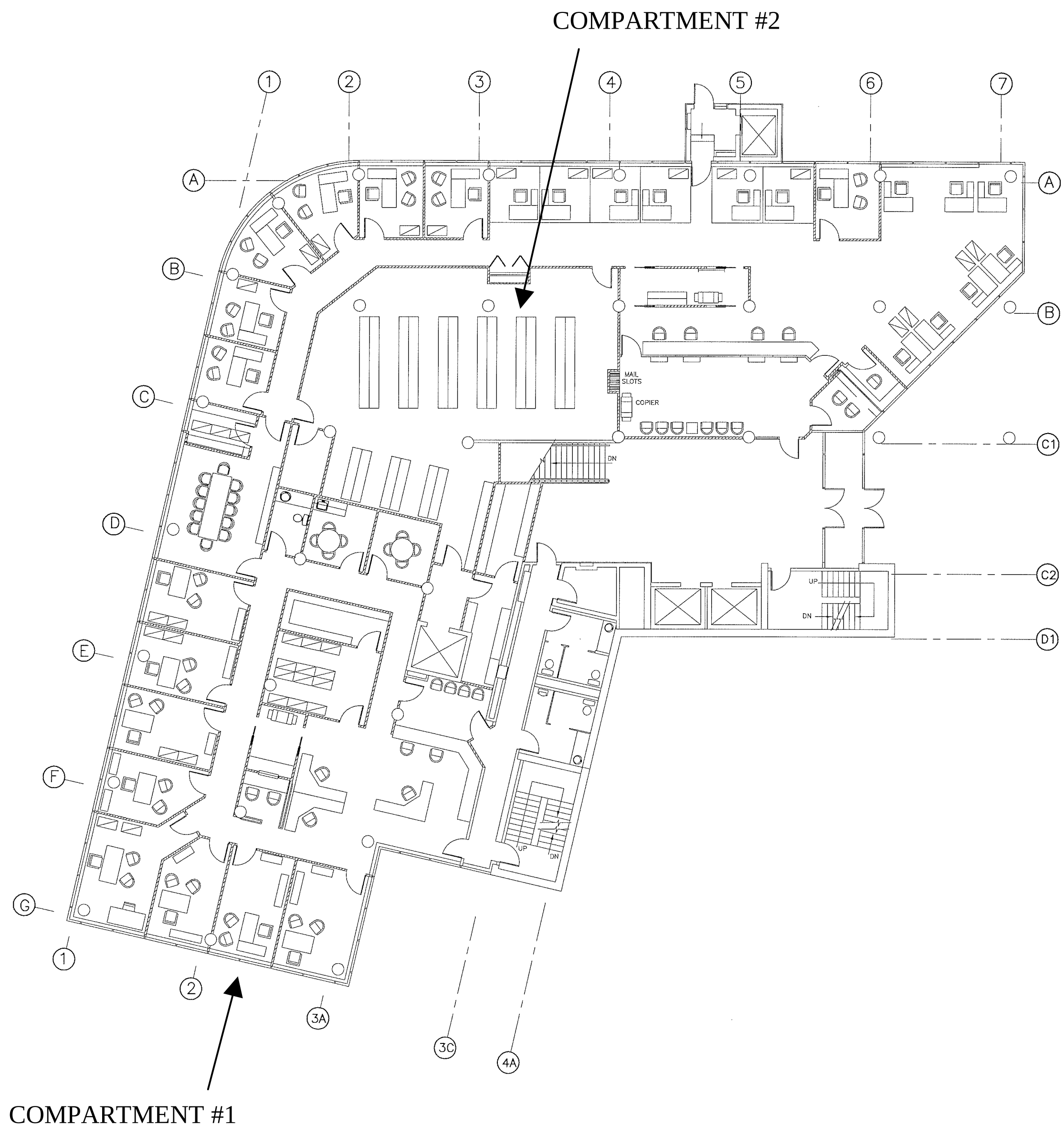
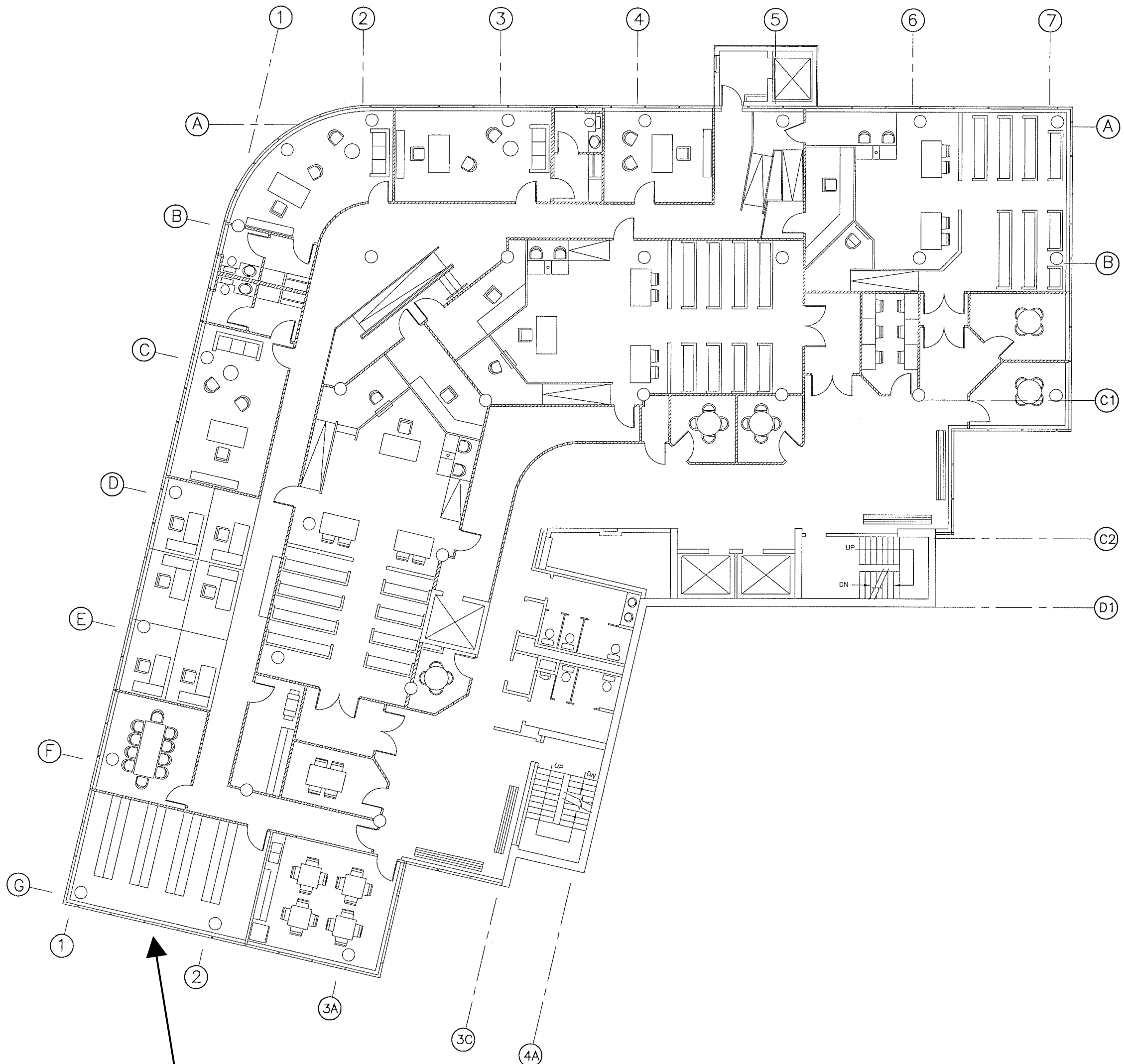


Figure 32 Work Example: Level 2 Floor Plan



COMPARTMENT #3

Figure 33 Work Example: Level 3 Floor Plan

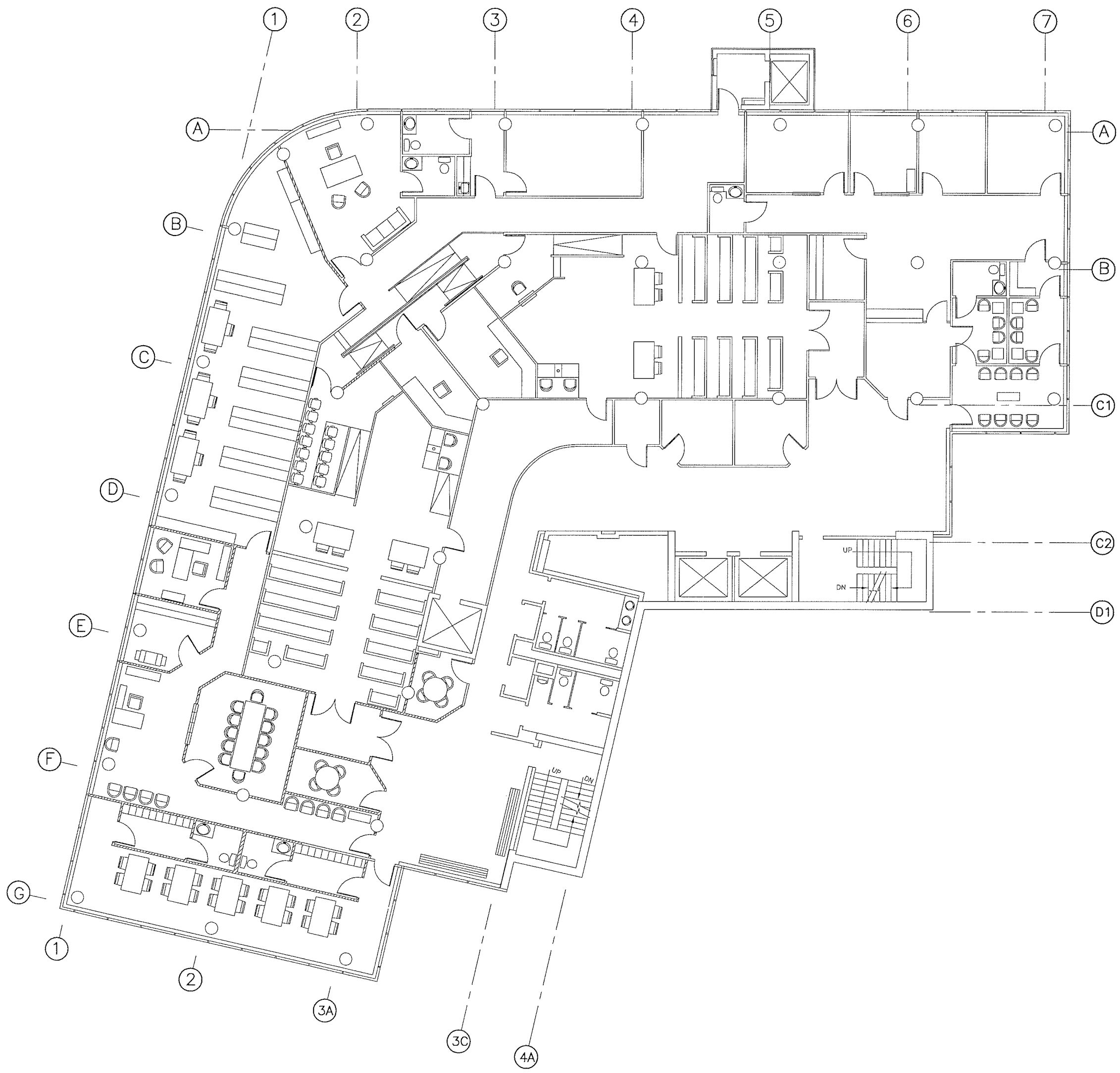


Figure 34 Work Example: Level 4 Floor Plan

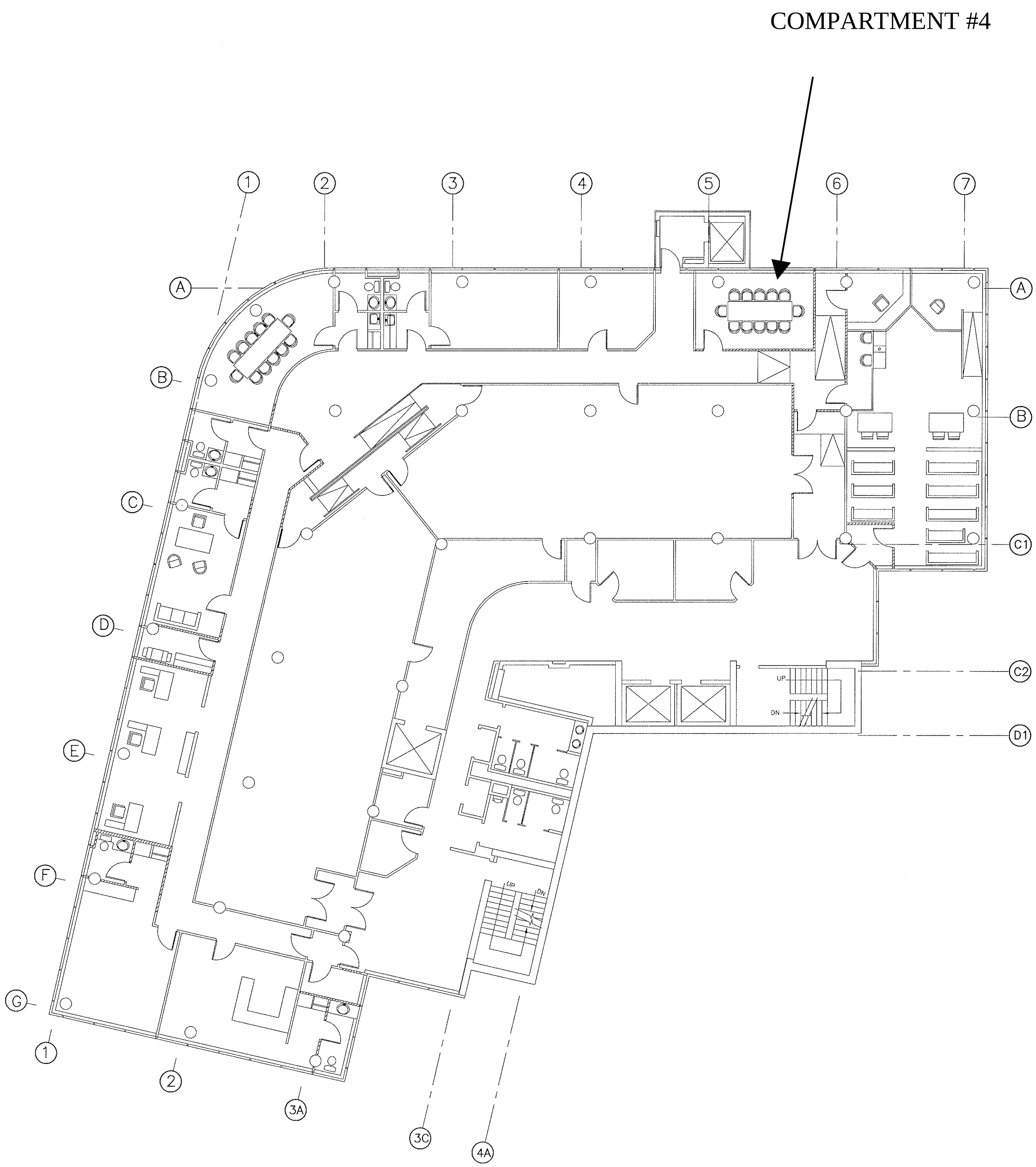


Figure 35 Work Example: Level 5 Floor Plan

7.5.2 Existing Building Code Requirements

Table 10
Summary of Prescriptive Fire Resistance Ratings for a 5-storey Commercial Building

Building Element	**National Building Code of Canada –1995 edition [4]**	**BOCA National Building Code – 1996 edition [20]**
Reference	3.2.2.50	Table 602
Floor/ceiling assembly	1 hr	1 hr
Load bearing walls	1 hr	1 hr
Supporting Structural Elements	1 hr	1 hr
Exit and other shafts	1 hr	2hr
Corridors	1 hr	0 hr

7.5.3 Description of Structural System

There is no portion of the structural assembly that dominates in terms of significance to overall building structural integrity. All columns and beams are designed to support loads as specified by the prescriptive code for maximum expected combination of live and dead load. As a result, the selection of the compartments to be analyzed is to be based on fuel load & geometry considerations.

7.5.4 Description of Compartments to be Analyzed

There are a large number of possible compartments from which to select. However, the intent is to select a number of compartments that reasonably represents the range of possible fire scenarios that might be expected within the building in order to determine the required fire resistance ratings.

7.5.4.1 Compartment #1

Typical private office as indicated on Figure 32, consisting of:

- One wooden desk;
- Three fabric covered upholstered chairs;

- Two wooden book/file storage units that have and open front;
- Miscellaneous plastic storage vessels such as waste baskets, desk-top file holders, etc.; and
- Gypsum wallboard steel stud walls and suspended acoustic tile ceiling.

7.5.4.2 Compartment #2

Large file storage area as indicated on Figure 32 used for archived file storage, consisting of:

- Nine rows of back-to-back metal shelving units used for storage of paper files in bankers boxes c/w lids; and
- Gypsum wallboard steel stud walls and suspended gwb ceiling.

7.5.4.3 Compartment #3

Small file storage area as indicated on Figure 33 used for active file storage, consisting of:

- Four rows of back-to-back metal shelving units used for storage of paper files in bankers boxes c/w lids; and
- Gypsum wallboard steel stud walls and suspended gwb ceiling.

7.5.4.3 Compartment #4

Small conference room as indicated on Figure 35, consisting of:

- One large wooden conference table and 12 upholstered metal chairs; and
- Gypsum wallboard steel stud walls and suspended acoustic tile ceiling.

A summary of required geometric variables for each compartment are summarized in the following table.

Table 11
Summary of Geometric Variables for Compartments 1 through 4 of the Worked Example

	Compartment			
Variable	**1**	**2**	**3**	**4**
Room Width (m)	3	12.2	8.3	5.5
Room Length (m)	4.9	9.8	4.9	3.7
Room Height (m)	2.8	3	3	2.7
Room Floor Area (m^2)	14.7	119.6	40.7	20.4
Room Total Surface Area (m^2)	73.6	371.2	160.6	90.5
Vent Height (m)	2.1	2.1	2.1	2.1
Vent Width (m)	0.9	0.9	0.9	0.9
Vent Area (m^2)	1.9	5.7	1.9	1.9
Number of Ventilation Openings	1	3	1	1

7.5.5 Fuel Load of Compartments to be Analyzed

Using Table 3, an estimate of the compartment fuel loads are calculated and summarized in Table 12. The fuel loads in this table are representative of the existing conditions and should only be taken as average values. To use these values for design purposes, the 90% fractile should be used as demonstrated in (5a). Table 13 summarizes the fuel load per unit floor and surface area for the fuel load data summarized in Table 12 and compares this data to design values suggested [3] in Appendix A.

Table 12
Summary of Compartments 1 through 4 Fuel Loads

Fuel	Compartment #1 Cellulosic (kg)	Compartment #1 Plastic (kg)	Compartment #2 Cellulosic (kg)	Compartment #2 Plastic (kg)	Compartment #3 Cellulosic (kg)	Compartment #3 Plastic (kg)	Compartment #4 Cellulosic (kg)	Compartment #4 Plastic (kg)
Structural	-	-	-	-	-	-	-	-
Service	-	-	-	-	-	-	-	-
Non- structural								
Non-load bearing	-	-	-	-	-	-	-	-
Finish & trim	-	-	-	-	-	-	-	-
Furnishings								
Furniture	300	30(1)	-	-	-	-	363	36(1)
Decorations	12	2	-	-	-	-	12	2
Other	-	-	3,636	-	1,818	-	-	-
Occupant Goods	25	10		-		-	-	-
Sub-total (kg)	337	42	3,636	-	1,818	-	375	38
Conv. to wood (kg) (factor of 2 for plastic)	337	84	3,636	-	1,818	-	375	76
Wood equivalent (based on 18 MJ/kg)	6,066	1512	65,454	-	32,727	-	6,750	1,168
Fuel Load (MJ)	**7,578**		**65,454**		**32,727**		**8,118**	

Note: (1) assumed that plastics make up 10% of the weight of the furniture.

Table 13
Compartment Fuel Load per unit area – MJ/m²

	Compartment			
	1	2	3	4
Fuel Load (MJ)	7,578	65,454	32,727	8,118
Fuel Load/Floor Area (MJ/m^2)	515	547	804	398
Fuel Load/Total Surface Area (MJ/m^2)	103	176	204	90
Reference Fuel Load/Floor Area (MJ/m^2)	1,264^(1)	3,160^(2)	3,160^(2)	1,240^(3)

Note: (1) Taken from Table A-11 for Business Office and adjusted by a factor of 1.58
(2) Taken from Table A-11 for Libraries and adjusted by a factor of 1.58
(3) Taken from Table A-5 for USA Government for conference Rooms and adjusted by a factor of 1.58

To be conservative, the referenced fuel load data will be used for the calculations after conversion to a value per total compartment surface area value.

7.5.6 Impact of Fire on Structural Columns

With reference to Figures 31 through 35 there are protected columns within each compartment, as indicated by the small circles shown on the floor plans. For the purposes of the example the following will be assumed:

- The columns are W310x33 sections with $A_i/V_s = 200\ m^{-1}$ assuming fire exposure on all four sides of the column (ref. Figure 29);
- The thermal inertia of the bounding surfaces for the compartment will be assumed to be 1100 W/m^0C for a combination of lightweight concrete construction;
- The density of steel will be 7,850 kg/m^3; and
- That the critical steel temperature will be 538^0C as indicated in Table 7

Using the geometric information from Table 11, the referenced compartment fuel load from Table 13 is adjusted to a per unit total surface area value. The above information, the compartment time-temperature curves using the Modified Eurocode Equations, and the related steel time-temperature curves using Pettersson's equations for insulated steel were calculated to determine the required protection to maintain the steel temperature below 538^{0}C for the prescribed FRR from Table 10. The table that follows summarizes the calculated vs. prescribed protection requirements for the fire exposed steel column.

Table 14
Summary of Steel Column Protection Requirements Calculated vs. Prescribed

	Thickness of Protection Required				NBBC[4]
Description of Protection(1)	Comp. #1	Comp. #2	Comp. #3	Comp. #4	Requirements for 1 hr FRR
Mineral Wool Slabs (2)	50 mm	44 mm	38 mm	50 mm	62.5 mm
15.9 mm Type X gwb	3 layers	2 layers	2 layers	3 layers	2 layers
Sprayed Mineral Fibre (3)	25 mm	25 mm	13 mm	25 mm	--(4)

Note: (1) Type of protection is as per Table 9.
(2) Mineral wool slabs would be required to be protected by some form of barrier such as metal cladding or gwb, which has not been accounted for in the calculations.
(3) Sprayed on mineral fibre would be required to be protected by some form of barrier such as metal cladding or gwb, which has not been accounted for in the calculations.
(4) Data not available in the National Building Code of Canada.

As can be seen from this table the protection requirements are generally less than required by a typical prescriptive code such as the NBCC, with the exception of the gwb protection that is required to be protected with one additional layer. Clearly this demonstrates the more rational approach to design of fire protection requirements for structural steel. In the table that follows the protection defined will ensure that the critical temperature is not reached during the duration of the fire.

Table 15
Summary of Steel Column Protection Requirements Calculated vs. Prescribed to Ensure the Critical Temperature is not Exceeded

Description of Protection[1]	Thickness of Protection Required Comp. #1	Comp. #2	Comp. #3	Comp. #4	NBBC[4] Requirements for 1 hr FRR
Mineral Wool Slabs [2]	75 mm	-- [3]	-- [3]	100 mm	62.5 mm
15.9 mm Type X gwb	4 layers	-- [3]	-- [3]	5 layers	2 layers
Sprayed Mineral Fibre [4]	32 mm	-- [3]	-- [3]	38 mm	--[5]

Note:
(1) Type of protection is as per Table 9.
(2) Mineral wool slabs would be required to be protected by some form of barrier such as metal cladding or gwb, which has not been accounted for in the calculations.
(3) Could not provide a practical level of protection that would ensure the critical temperature of 538^{0}C was not exceeded.
(4) Sprayed on mineral fibre would be required to be protected by some form of barrier such as metal cladding or gwb, which has not been accounted for in the calculations.
(5) Data not available in the National Building Code of Canada.

What is worth noting is that the results of the calculations summarized in the table require a greater thickness of protection than that prescribed in the NBCC. Of specific concern is that the steel cannot be adequately protected in the file storage. As discussed in previous sections this level of protection would not be practical and is not provided for under the current prescriptive building codes.

7.5.7 Impact of Fire on Steel Protected by Suspended Ceiling

The procedure for determining the impact of the fire on steel protected by a suspended ceiling is described by Pettersson [10]. The portion of this model that is applicable to the method proposed is the determination of the maximum ceiling temperature expected for suspended ceilings for comparison with the known critical temperatures.

For the purposes of the calculations it is assumed that the suspended ceilings are as follows:

- Typical 13 mm suspended ceiling tiles for Compartments #1, & #4: Critical Temperature 550^{0}C; and
- 1-layer of 13mm Type X gwb for Compartments #2, & #3: Critical Temperature 650^{0}C.

The table below summarizes the calculated suspended ceiling temperature and structural steel temperature resulting from the compartment fire for each compartment based on the following additional variables:

- the beams are W360x33 supporting the floor assembly above and are exposed to fire on three sides with F_s/V_s = 256
- the OWSJ's are 610mm deep, 100mm wide at both top and bottom flanges and the cross bracing is 12mm diameter with F_s/V_s = 240 for the flanges and F_s/V_s = 333 for the diagonal bracing

Table 16
Summary of Calculated Maximum Suspended Ceiling Temperatures

	Calculated Temperatures (^{0}C)$^{(1)}$			
Building Element	Comp. #1	Comp. #2	Comp. #3	Comp.#4
Maximum Suspended Ceiling Temp.	440	--$^{(2)}$	--$^{(2)}$	450
Critical Suspended Ceiling Temp.	550	--$^{(2)}$	--$^{(2)}$	550

Note: (1) Interpolation was necessary to obtain the data, which is not technically accurate as the relationships are not linear. However, the values nevertheless are reasonable.
(2) Fuel load was beyond the range of tabulated data.

For Compartments 1 and 2 the suspended ceiling would be expected to stay intact for the duration of the fire. For Compartments 2 and 3 insufficient data is available. The reader should be careful not to interpolate beyond the tabulated results as the relationships are not linear. This clearly provides further support for the creation of a program to fully utilize this model

7.5.8 Impact of Fire on Load and Non-load Bearing Partitions

The calculation of the impact of the fire on non-load bearing partitions will be calculated using Harmathy's Heat Load Concept. This approach is a global approach that is not based on the fire impact in an individual compartment but on the impact in an average compartment within the building. Typically this involves dividing the total floor area by the number of compartments on the floor. For the building being analyzed, there are two general types of compartments: smaller office; and larger courtroom or storage space. The average values for floor area and total surface area for each type of compartment will be assumed to be:

- smaller office type compartments: A_f=20 m^2 and A_t=90 m^2 ; and
- larger courtroom and storage compartments: A_f= 120 m^2 and A_t=370 m^2.

Using (7) the minimum ventilation factor Φ_{min} = 10.5 kg s^{-1} assuming one door is open in each compartment.

Using the fuel load values from Table 13, a value of 18 MJ/kg for wood, the average floor area values above, and adjusting the value by 1.58 (5a) the design mass of fuel per unit floor area can be calculated for each type of compartment:

- smaller office type compartments: L = 36 kg/m^2; and
- large courtroom and storage spaces: L = 48 kg/m^2.

The above values are then substituted into (8) to produce the following:

- smaller office type compartments: H’= 50,394 $s^{1/2}K$
- large courtroom and storage spaces: H’= 114,083 $s^{1/2}K$

These are then substituted into (10) to produce the fire duration. The results are:

- smaller office type compartments: τ = 1.25 hr
- large courtroom and storage spaces: τ = 3.63 hr

The result is that the non-load bearing partitions for the smaller office type compartments will require a fire resistance rating of 1.5 hours, and for the large courtroom and storage spaces 4 hours.

In some cases the calculated protection requirements are greater and in some cases lower that those prescribed by the NBBC, which is typical of prescriptive codes used throughout North America. At first glance it might appear that no significant progress in building fire protection has been advanced by this approach. However, it is important to consider that the method does represent a rational engineering approach to the determination of fire resistance requirements, and is therefore justifiable. Furthermore, the method proposed does not provide a manner through which the beneficial effects of automatic sprinkler protection are taken into account relative to limiting compartment fire temperatures. As well, the method analyzes a single building element in isolation and does not account for the structural system as a whole. Therefore the results should be considered as conservative.

8.0 Future Work

The methods that have been summarized represent the first generation of design methods originating with work done by Kawagoe in the 1960's, and provide a single element analysis for fire protection purposes. There is, however, considerable effort currently under way to produce a second generation of design methods. Some of this research is investigating the impact of the structural system from a holistic approach either in the form of sub-assemblies (Structural Response Model S2 from Figure 5) or for the entire structure (Structural Response Model S3 from Figure 5).

Fore example the Steel Construction Institute in the UK has prepared a design manual [42] specifically for multi-storey steel framed buildings made from composite construction. In this design manual the critical temperature of the composite assembly is coupled to the load ratio (actual load at fire temperatures to load at ambient temperatures). This represents a level of refinement beyond that provided in this document.

As well, research is underway to more accurately account for the impact of end restraint conditions on the structural steel assembly, such as work done by Neves [52, 53], who found that the critical temperature of steel columns can be influenced by the axial restraint and stiffness of the structure with reductions of ~ 20% for slender columns. Franssen [54] concluded the same physical characteristics but determined that even though the column might fail earlier in the fire (i.e. at a lower temperature) the assembly as a whole will not necessarily collapse due to load transfer from the column to the supporting structure. Others looking at rotational restraint of columns [55] have found that failure temperatures are higher under these conditions.

There are others still who are researching the impact of performance-based codes and our understanding of risk associated with building fire safety. Specifically, some have expressed concern that the technically driven performance-based approach is taking decision-making out of the hands of the public and placing it the control of the private sector [56]. Others are proposing methods to address perceptions of risk to ensure that technical decision making does not proceed without due consideration for risk and the public perception of risk.

It has been demonstrated that the models available are in fact reasonably accurate and conservative to some degree. The research currently underway tends to support this claim. However, it is important that the design community does not simply assume that by being technically correct the design objectives have been supported.

9.0 Conclusions

In order to address concerns regarding the technical merit of the current approach used throughout North America to determine the fire resistance ratings of structural assemblies in buildings, a rational engineering approach has been summarized. The mathematical models presented are not new and date back to the 1960's, but do offer a simple engineering approach to building structural fire safety. The approaches have been shown in the past to correlate well to experimental data. A method has been proposed that allows the designer to predict the time-temperature relationship expected in a compartment fire with a reasonable level of conservatism. Based on the compartment fire time-temperature relationship, the time for structural steel to reach the critical temperature can be calculated for comparison to the FRR from the building codes. This, in turn, is used to determine the required level of protection so that the time taken to reach the critical temperature is greater that the prescribed FRR. As well, the method is presented that will allow the user to predict the maximum suspended ceiling temperature expected to verify that the ceiling will remain intact of the duration for the fire. Finally, a method is presented to calculate the required FRR for non-load bearing partitions.

It has also been demonstrated that the models available are reasonably accurate and conservative within the defined limits, and that research currently underway tends to support this claim.

The methods summarized do not address the mechanical load response of the structure to fire conditions. Although a great deal has been written on this subject, especially as it relates to the current design approach in Europe, there is still some reluctance to move forward with performance-based designs in North America. The use of a method that predicts performance on the basis of limiting temperature alone will ensure that attempts to predict the likelihood of failure through more complicated mechanical actions will not unnecessarily complicate the process at this initial stage in the transformation to a performance-based regime in North America. In time these matters may be incorporated into the approach as they become more acceptable.

APPENDIX A

Summary of Various Fuel Load Data

Table A-1
Variable Fuel Loads in Residential Occupancies

Description	Average	Fuel Load (MJ/m^2) per unit floor area Standard Deviation	Percentile 80%	90%	95%	Comments
Swedish Data						
3 rooms	750	104	770			
2 rooms	780	128	870			
European Data						
6 rooms	500	180				
5 rooms	540	125				
3 rooms	670	133	760	780	830	
2 rooms	780	129	870	1020	950	
1 room	720	104	760	780	890	
Swiss Risk Evaluation	330					
USA Data						
Living Room	350	104				
Family Room	250	58				
Bedroom	390	104				
Dining Room	330	92				
Kitchen	290	71				
All Rooms	320	88				
USA Data						Total fuel load including
Residence	750					permanent fuel load
Max. for Linen Closet	4440					
Range of Max. Values	730-1270					

Table A-2
Variable Fuel Loads in Hospital Occupancies

Description	Average	Fuel Load (MJ/m^2) per unit floor area Standard Deviation	Percentile 80%	90%	95%	Comments
Swedish Data						
Patient room			80			
European Data						
Hospitals	230		350		670	
Swiss Risk Evaluation						
Hospitals	330					
USA Data						
Patient room	108	33				
USA Data						Total fuel load including
Hospitals	250					permanent fuel load
Max. for Service Store	1720					
Max. for laundry	2090					
Range of Max values for single patient room	270-1990					

Table A-3
Variable Fuel Loads in Hotel Occupancies

Description	Average	Standard Deviation	Percentile 80%	90%	95%	Comments
	Fuel Load (MJ/m^2) per unit floor area					
Swedish Data						
Hotels	310	92	380			
Bedrooms			420			
European Data						
Bedrooms	310	104	400	470	510	
European Data						
Bedrooms	182					Single value bathroom included
Swiss Risk Evaluation						
Hotels	330					

Table A-4
Variable Fuel Loads in Department Store Occupancies

Description	Average	Standard Deviation	Percentile 80%	90%	95%	Comments
	Fuel Load (MJ/m^2) per unit floor area					
European Data - Shopping Centre (3000 m^2 floor area)						Sales Area = 20 to 25% of total floor area
Articles of daily use	420					
Foods	585					
Textiles	380	535				
Perfumery, toys, stationary store, household items	420	560				
Furniture, carpet	585	960				
European Data						Single Value with permanent fuel load of 200
Furniture store	970					
Little supermarket	750					
Swiss risk evaluation						
Food store	665					
Clothing store	585					
Perfumery	420					
Stationary store	665					
Furniture store	420					
Toy store	500					
Carpet store	835					
Dept. store	420					
USA Data						Total fuel load including permanent fuel load
Mercantile (Dept. store)	935					
Max. for paint Dept.	4260					
Warehouse						
- General	2270					
- Printing	15800					
- Max Value	23200					

Table A-5
Variable Fuel Loads in Office Occupancies

Description	Average	Standard Deviation	Percentile 80%	90%	95%	Comments
Fuel Load (MJ/m^2) per unit floor area						
Swedish Data						Characteristic Value
Company Management	272	126				(0.8 Fractile)
Production Management	355	168				- technical office 720
Officials	441	250				- admin. office 640
Office Staff	417	210				- All Offices Investigated 675
Special Rooms	1172	798				
Technical Rooms	278	109				
Communication Rooms	168	240				
All Rooms	411	334				
European Data						
Company Management	270	125				
Production Management	360	170				
Officials	450	260				
Office Staff	380	46				
Special Rooms	1330	890				
Technical Rooms	330	67				
Communication Rooms	170	220				
All Rooms	420	370	570	740	950	
Swiss risk evaluation						
Technical Offices	250					Single Value
Administration Offices	750					
USA Data – Government						
General	555	285				
Clerical	415	425				
Lobby	115	92				
Conference	270	515				
File	1420	1025				
Storage	950	1700				
Library	2650	695				
All Rooms	555	625				
USA Data – Private						
General	525	355				
Clerical	465	315				
Lobby	300	325				
Conference	370	380				
File	1300	1110				
Storage	1040	980				
Library	1980	940				
All Rooms	580	535				
USA Data						Total fuel load
Offices	1670					
exclu. heavy files	960					
Max. for heavy files	7860					
Range of Max. for single occupied rooms	635-3900					

Table A-6
Variable Fuel Loads in Industrial Occupancies

Description	Average	Standard Deviation	80%	90%	95%	Comments
	Fuel Load (MJ/m^2) per unit floor area		Percentile			
German Data						
Storage of Combustibles						
Goods in amounts						
<150 kg/m^2	1780	1260	2560	3490	4490	Fractile values calculated
>150 kg/m^2	15360	10600	23190	33110	44330	For a lognormal dist.
Manufacturing and Storage of combustible goods in amounts						
<150 kg/m^2	1180	855	1820	2640	3590	
>150 kg/m^2	9920	8530	14180	19810	26040	
Storage of principally non-combustible goods	130	100	190	260	350	
Vehicle Manufacturing	145	105	220	310	420	
Processing of metal goods	140	120	210	330	470	
Processing of timber or plastic goods	305	175	420	550	670	
Manufacturing of metal goods	240	170	420	680	1010	
Manufacturing of electrical devices	235	115	330	430	530	
Garaging, maintenance of vehicles	190	105	270	340	420	
Manufacturing, processing, supply of ceramics and glassware	280	225	470	720	1010	

Table A-7
Variable Fuel Loads in Educational Occupancies

Description	Average	Standard Deviation	80%	90%	95%	Comments
	Fuel Load (MJ/m^2) per unit floor area		Percentile			
Swedish Data						
Junior Level	295	50	345			
Middle Level	340	71	415			
Senior Level	215	67	250			
All Schools	285	83	340			
European Data						
Junior Level	295	58	340	395	400	
Middle Level	340	58	425	445	450	
Senior Level	220	67	275	300	450	
All Schools	285	79	360	415	440	
Classrooms	245					
Cardboard Room	235					
Collection Room	435					
Corridors	63					
Average	240					

Table A-7 cont'd
Variable Fuel Loads in Educational Occupancies

Description	Average	Standard Deviation	Percentile 80%	Percentile 90%	Percentile 95%	Comments
	Fuel Load (MJ/m^2) per unit floor area					
The Netherlands						
All schools	215		365		550	
Swiss Risk Evaluation						
Schools	250					
USA Data						
School	1420					Total fuel load
Max. for textbook storage	20670					
Range of max. values for Single occupied room	635-3540					

Table A-8
Fuel Loads within Individual Rooms in Educational Occupancies

Description	Permanent Fuel Load (MJ/m^2) Mean Value	Permanent Fuel Load (MJ/m^2) 90% Fractile	Variable Fuel Load (MJ/m^2) Mean Value	Variable Fuel Load (MJ/m^2) 90% Fractile	Total Fuel Load (MJ/m^2) Mean Value	Total Fuel Load (MJ/m^2) 90% Fractile
Classrooms	250	360	165	165	360	495
Staff Rooms	435	900	375	720	815	1050
Special Rooms	280	470	190	290	470	685
Material Rooms	265	480	705	1330	965	1666
Lecture Rooms	345	660	80	165	425	720
Administration Rooms	365	625	450	760	815	1260
Libraries	230	325	1510	2550	1750	2690
Storerooms	175	245	440	885	615	1060
Other	345	575	190	465	535	1030

Table A-9
Geometric Properties of the Groups of Rooms in Table A-8

Description	Floor Base (m^2) Mean Value	Floor Base (m^2) 90% Fractile	Total Surface Area (m^2) Mean Value	Total Surface Area (m^2) 90% Fractile	Volume (m^2) Mean Value	Volume (m^2) 90% Fractile	Height of Room (m^2) Mean Value	Height of Room (m^2) 90% Fractile
Classrooms	69.2	79.4	250.9	281.1	231.3	273.5	3.37	3.74
Staff Rooms	32.2	47.5	142.3	187.5	111.9	137.5	3.41	3.85
Special Rooms	87.2	133.7	308.5	438.8	307.8	476.0	3.53	3.86
Material Rooms	47.2	122.0	190.2	448.1	165.9	471.2	3.42	3.85
Lecture Rooms	131.3	275.0	420.5	750.0	490.6	900	3.59	4.00
Admin. Rooms	43.6	92.5	174.7	325.0	149.0	312.5	3.33	3.84
Libraries	35.3	56.2	157.3	275.0	130.7	225	3.56	3.75
Storerooms	69.9	172.5	260.4	597.5	246.0	645	3.44	3.62
Other	84.0	135	280.3	422.5	314.5	445	3.64	3.85

Table A-10
Fuel Load Densities per Total Bounding Surface Area (MJ/m^2)

Type of Compartment	Average (MJ/m^2)	Standard Deviation (MJ/m^2)	Characteristic Value (0.8 Fractile) (MJ/m^2)
Dwellings			
Two rooms with a kitchen	150	24.7	168
Three rooms and a kitchen	139	20.1	149
Offices			
Technical offices	124	31.4	145
Administrative offices	102	32.2	132
All offices	114	39.4	138
Schools			
Junior Level	84.2	14.2	98.4
Middle Level	96.7	20.5	117
Senior Level	61.1	18.4	71.2
All schools	80.4	23.4	76.3
Hospitals	116	36	147
Hotels	67	19.3	81.6

Table A-11
Average Variable Fuel Load Densities per unit Floor Area (MJ/m^2)

Type of Occupancies	Fuel Load (MJ/m^2)	Storage	Type of Occupancies	Fuel Load (MJ/m^2)	Storage
Academy	300		Arms mfg.	300	
Accumulator Forwarding	800		Arms Sales	300	
Accumulator mfg.	400	800	Artificial Flower mfg.	300	200
Acetylene Cylinder Storage	700		Artificial Leather mfg.	1000	1700
Acid Paint	80		Artificial Leather Processing	300	
Adhesive mfg.	1000	3400	Artificial Stone mfg.	40	
Administration	800		Asylum	400	
Absorbent Plant for Combustible Vapors	>1700		Authority Office	800	
Aircraft Hanger	200		Awning mfg.	300	1000
Airplane Factory	200		Bag mfg. (jute, paper, plastic)	500	
Aluminum mfg.	40		Bakery	200	
Aluminum Processing	200		Bakery Sales	300	
Ammunition mfg.	Spez.		Ball Bearing mfg.	200	
Animal Food Preparing mfg.	2000	3300	Bandage mfg.	400	
Antique Shop	700		Bank, counters	300	
Apparatus Forwarding	700		Bank, offices	800	
Apparatus mfg.	400		Barrel mfg., wood	1000	800
Apparatus Repair	600		Basement, dwellings	900	
Apparatus Testing	200		Basketware mfg.	300	200

Table A-11 , cont'd
Average Variable Fuel Load Densities per unit Floor Area (MJ/m²)

Type of Occupancies	Fuel Load (MJ/m²)	Storage	Type of Occupancies	Fuel Load (MJ/m²)	Storage
Bed sheeting production	500	1000	Cardboard box mfg.	800	2500
Bedding plant	600		Cardboard mfg.	300	4200
Bedding Shop	500		Cement plant	40	
Beer mfg.	80		Cement products mfg.	80	
Beverage mfg. (non-alcoholic)	80		Cheese factory	120	
Bicycle Assembly	200	400	Cheese mfg. (in boxes)	170	
Biscuit Factories	200		Cheeses store	100	
Biscuit mfg.	200		Chemical plants (rough average)	300	1000
Bitumen Preparation	800	3400	Chemists shop	1000	
Blind mfg. (Venetian)	800	300	Children's home	400	
Blueprinting firm	400		China mfg.	200	
Boarding school	300		Chipboard finishing	800	
Boat Mfg.	600		Chipboard pressing	100	
Boiler house	200		Chocolate factory, int. storage	6000	
Bookbinding	1000		Chocolate factory, packing	500	
Bookstore	1000		Chocolate factory, tumbling	1000	
Box mfg.	1000	600	Chocolate factory, all others	500	
Brick plant, burning	40		Church	200	
Brick plant, clay preparation	40		Cider mfg. (without crate storage)	200	
Brick plant, drying kiln with wooden grates	1000		Cigarette plant	300	
Brick plant, drying room with metal grates	40		Cinema	300	
Brick plant, drying room with wooden grates	400		Clay , preparing	50	
Brick plant, pressing	200		Cloakroom, metal wardrobe	80	
Briquette factories	1600		Cloakroom, wooden wardrobe	400	
Broom mfg.	700	400	Cloth mfg.	400	
Brush mfg.	700	800	Clothing plant	500	
Butter mfg.	700	4000	Clothing store	600	
Cabinet making (without woodyard)	600		Coal bunker	2500	
Cable mfg.	300	600	Coal cellar		10500
Café	400		Cocoa processing	800	
Camera mfg.	300		Coffee-extract mfg.	300	
Candy mfg.	400	1500	Coffee roasting	400	
Candy packaging	800		Cold storage	2000	
Candy shop	400		Composing room	400	
Cane products mfg.	400	200	Concrete products mfg.	100	
Canteen	300		Condiment mfg.	50	
Car accessory sales	300		Congress hall	600	
Car assembly plant	300		Contractors		500
Car body repairing	150		Cooking stove mfg.	600	
Car paint shop	500		Coopering	600	
Car seat cover shop	700		Cordage plant	300	

Table A-11 , cont'd
Average Variable Fuel Load Densities per unit Floor Area (MJ/m²)

Type of Occupancies	Fuel Load (MJ/m²)	Storage	Type of Occupancies	Fuel Load (MJ/m²)	Storage
Cordage store	500	800	Filling plant/barrels liquid filled and/or non-combustible	<200	
Cork products mfg.	500		Filling plant/barrels liquid filled and/or combustible		
Cotton mills	1200		Class I	>3400	
Cotton wool mfg.	300		Class II	>3400	
Cover mfg.	500		Class III	>3400	
Cutlery mfg. (household)	200		Class IV	>3400	
Cutting-up shop (leather)	300		Class V	>1700	
Cutting-up shop (textiles)	500		Filling plant/casks liquid filled and/or non-combustible	<200	
Cutting-shop, wood	700		Filling plant/casks liquid filled and/or combustible		
Dairy	200		Class I	<500	
Data processing	400		Class II	<500	
Decoration studio	1200	2000	Class III	<500	
Dental surgeons laboratory	300		Class IV	<500	
Dentists office	200		Class V	<500	
Department store	400		Finishing plane, paper	500	
Distilling plant, comb.	200		Finishing plant, textile	300	
Distilling plant, non-comb. Mat.	50		Fire works mfg.	Spez.	2000
Doctors office	200		Flat	300	
Door mfg. Wood	800	1800	Floor covering mfg.	500	
Dressing, textiles	200		Floor covering store	1000	
Dressing, paper	700		Floor plaster mfg.	600	
Dressmaking shop	300		Flour products	800	
Dry-cell battery	400	600	Flower sales	80	
Dry cleaning	300		Fluorescent tube mfg.	300	
Dyeing plant	500		Foamed plastics fabrication	3000	
Edible fat forwarding	900	18900	Foamed plastics processing	600	
Edible fat mfg.	1000		Food forwarding	1000	
Electrical appliance mfg.	400		Food store	700	
Electric appliance repair	500		Forge	80	
Electric motor mfg.	300		Forwarding, appliances	700	
Electrical supply storage (h< 3m)	1200		Forwarding, beverage	300	
Electronic industry	600		Forwarding, cardboard goods	600	
Electronic device mfg.	400		Forwarding, furniture	600	
Electronic device repair	500		Forwarding, glassware	700	
Embroidery	300		Forwarding, plastic products	1000	
Etching plant, glass/metal	200		Forwarding, printed matters	1700	
Exhibition hall, cars	200		Forwarding, textiles	600	
Exhibition hall, furniture	500		Forwarding, tinware	200	
Exhibition hall, machines	80		Forwarding, varnish, polish	1300	
Exhibition of paintings	200		Forwarding, woodware	600	
Explosion industry	4000		Foundry (metal)	40	
Fertilizer mfg.	200	200	Fur, sewing	400	

Table A-11 , cont'd
Average Variable Fuel Load Densities per unit Floor Area (MJ/m^2)

Type of Occupancies	Fuel Load (MJ/m^2)	Storage	Type of Occupancies	Fuel Load (MJ/m^2)	Storage
Furniture exhibition	500		Laboratory, chemical	500	
Furniture mfg. (wood)	600		Laboratory, electric, electronic	200	
Furniture polishing	500		Laboratory, metallurgical	200	
Furniture store	400		Laboratory, physics	200	
Furrier	500		Lacquer forwarding	1000	
Galvanic station	200		Lacquer mfg.	500	2500
Gambling place	150		Large metal constructions	80	
Glass blowing plant	200		Lathe shop	600	
Glass factory	100		Laundry	200	
Glass mfg.	100		Leather goods sales	700	
Glassware mfg.	200		Leather product mfg.	500	
Glassware store	200		Leather tanning, dressing	400	
Glazier's workshop	700		Library	2000	2000
Grainmill, without storage	400	13000	Lingerie mfg.	400	
Gravestone carving	50		Liqueur mfg.	400	800
Graphic workshop	1000		Liquor mfg.	500	800
Greengrocer shop	200		Loading ramp including goods	800	
Hairdressing shop	300		Lumber room	500	
Hardening plant	400		Machinery mfg.	200	
Hardware mfg.	200		Match plant	300	800
Hardware store	300		Mattress mfg.	500	500
Hat mfg.	500		Meat shop	50	
Hat store	500		Mechanical workshop	200	
Heating equip. room (wood or coal)	300		Metal goods mfg.	200	
Heat sealing of plastics	800		Metal grinding	80	
High-rise office building	800		Metal working	200	
Homes	500		Milk condensed, evap mfg.	200	9000
Homes for the aged	400		Milk powdered mfg.	200	10500
Hosiery mfg.	300		Milling work, metal	200	
Hospital	300		Mirror mfg.	100	
Hotel	300		Motion-picture studio	300	
Household appliances, mfg.	300	200	Motor cycle assembly	300	
Household appliances, sales	300		Museum	300	
Ice cream plant (incl. Packaging)	100		Musical instrument sales	281	
Incandescent lamp plant	40		Newsstand	1300	
Inj. mouled parts mfg.-metal	80		Nitrocellulose mfg.	Spez.	1100
Inj. mouled parts mfg.-plastic	500		Nuclear research	2100	
Institution building	500		Nursery school	300	
Ironing	500		Office, business	800	
Jewelry mfg.	200		Office, engineering	600	
Jewelry shop	300		Office furniture	700	
Joinery	700		Office, machinery mfg.	300	
Joiner, machine room	500		Office machine sales	300	
Joinery, work bench	700		Oilcloth mfg.	700	1300

Table A-11 , cont'd
Average Variable Fuel Load Densities per unit Floor Area (MJ/m²)

Type of Occupancies	Fuel Load (MJ/m²)	Storage	Type of Occupancies	Fuel Load (MJ/m²)	Storage
Optical instrument mfg.	200	200	Printing ink, mfg.	700	3000
Packing, food	800		Printing machine hall	400	
Packing, non-combustible	400		Printing office	1000	
Packing, material mfg.	1600	3000	Radio & TV mfg.	400	
Packing, printed matters	1700		Radio & TV sales	500	
Packing, all other combustibles	600		Radio studio	300	
Paint & varnish mfg.	4200		Railway car mfg.	200	
Paint & varnish mixing	2000		Railway station	800	
Paint & varnish shop	1000		Railway workshop	800	
Painters workshop	500		Record player mfg.	300	200
Paint shop (cars, machines, etc.)	200		Record repository, documents	4200	
Paint shop (furniture, etc.)	400		Refrigerator mfg.	1000	300
Paper mfg.	200	10000	Relay mfg.	400	
Paper processing	800	1100	Repair shop, general	400	
Parking building	200		Restaurant	300	
Parquetery mfg.	2000	1200	Retouching department	300	
Perambulator mfg.	300	800	Rubber goods mfg.	600	5000
Perambulator shop	300		Rubber goods store	800	
Perfume sale	400		Rubber processing	600	5000
Pharmaceutical packing	300	800	Saddlery mfg.	300	
Pharmaceutical mfg.	300	800	Safe mfg.	80	
Pharmacy (including storage)	800		Salad oil forwarding	900	
Photographic laboratory	100		Salad oil mfg.	1000	18900
Photographic store	300		Sawmill (without woodyard)	400	
Photographic studio	300		Scale mfg.	400	
Picture frame mfg.	300		School	300	
Plaster product mfg.	80		Scrap recovery	800	
Plastic floor tile mfg.	800		Seedstone	600	
Plastic mfg.	2000	5900	Sewing machine mfg.	300	
Plastic processing	600		Sewing machine store	300	
Plastic products fabrication	600		Sheet mfg.	100	
Plumbers workshop	100		Shoe factory, forwarding	600	
Plywood mfg.	800	2900	Shoe factory, mfg.	500	
Polish mfg.	1700		Shoe polish mfg.	800	2100
Post office	400		Shoe repair with mfg.	700	
Potato, flaked, mfg.	200		Shoe store	500	
Pottery plant	200		Shutter mfg.	1000	
Power station	600		Silk spinning (natural)	300	
Precious stone cutting etc.	80		Silk weaving (natural)	300	
Precision instrument mfg.			Silverwares	400	
with plastic parts	200		Ski mfg.	400	1700
without plastic parts	100		Slaughter house	40	
Precision mechanics plant	200		Soap mfg.	200	4200
Pressing, metal	100		Soda mfg.	40	
Pressing, plastics, leather, etc.	200		Soldering	300	
Printing, composing room	300		Solvent distillation	200	

Table A-11 , cont'd
Average Variable Fuel Load Densities per unit Floor Area (MJ/m²)

Type of Occupancies	Fuel Load (MJ/m²)	Storage	Type of Occupancies	Fuel Load (MJ/m²)	Storage
Spinning mill excl. garneting	300		Umbrella store	300	
Sporting goods store	800		Underground garage, private	>200	
Spray painting, metal goods	300		Underground garage, public	<200	
Spray painting, wood products	500		Upholstering plant	500	
Stationary store	700		Vacation home	500	
Steel furniture mfg.	300		Varnishing, appliances	80	
Stereotype plate mfg.	200		Varnishing, paper	80	
Stone masonry	40		Vegetable, dehydrating	1000	400
Storeroom (workshop)	1200		Vehicle mfg. assembly	400	
Synthetic fibre mfg.	400		Veneering	500	2900
Synthetic fibre processing	400		Veneer mfg.	800	4200
Synthetic fibre resin	3400	4200	Vinegar mfg.	80	100
Tar coated paper mfg.	1700		Vulcanizing plant (without stor.)	1000	
Tar preparation	800		Waffle mfg.	300	1700
Telephone apparatus mfg.	400	200	Warping department	250	
Telephone exchange	80		Washing agent mfg.	300	200
Telephone exchange mfg.	100		Washing machine mfg.	300	40
Test room, electric appliances	200		Watch assembling	300	40
Test room, machinery	100		Watch mechanism mfg.	40	
Test room, textiles	300		Watch repair shop	300	
Theatre	300		Watch sales	300	
Tin can mfg.	100		Water closets	0	
Tinned goods mfg.	40		Wax products forwarding	2100	
Tinware mfg.	120		Wax products mfg.	1300	2100
Tire mfg.	700	1800	Weaving mill (without carpets)	300	
Tobacco products mfg.	200	2100	Welding shop	80	
Tobacco shop	500		Winding room	400	
Tool mfg	200		Winding, textile fibers	600	
Toy mfg. (combustible)	100		Window glass mfg.	700	
Toy mfg. (noncombustible)	200		Window mfg (wood)	800	
Toy store	500		Wine cellar	20	
Tractor mfg.	300		Wine merchants shop	200	
Transformer mfg.	300		Wire drawing	80	
Transformer winding	600		Wire factory	800	
Travel agency	400		Wood carving	700	
Turnery (wood working)	500		Wood drying plant	800	
Turning section	200		Wood grinding	200	
TV studio	300		Wood pattern making shop	600	
Twisting shop	250		Wood preserving plant	3000	
Umbrella mfg.	300	400	Youth hostel	300	

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