STUDY REPORT

SR 314 (2014)

The Relationship Between Fire Severity and Time-Equivalence

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Funded by BRANZ
from the Building Research Levy

The work reported here was funded by BRANZ
from the Building Research Levy.

ISSN: 1179-6197

Preface

This report has been prepared as part of a research project on limiting fire spread by design that investigates the basis for determining the required fire resistance ratings in buildings using time-equivalence methods.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for fire engineers, researchers and regulatory authorities.

The Relationship between Fire Severity and Time-Equivalence

BRANZ Study Report SR 314

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Reference

Wade, C. A., Gerlich, J. T. & Abu A., 2014. The Relationship between Fire Severity and Time-Equivalence. BRANZ Study Report 314. BRANZ, Porirua, New Zealand.

Abstract

This study describes various methods for calculating the amount of fire resistance required for parts of buildings to satisfy Building Code objectives for preventing fire spread or maintaining structural stability during and after fire.

Time-equivalence methods seem most useful for determining the fire resistance ratings required when little is known about the specific materials and type of construction to be used. However, the usefulness of time-equivalent methods is limited by the accuracy to which the compartment fire temperatures or heat fluxes can be predicted. Therefore improvements made to post-flashover compartment fire models, together with an appropriate time-equivalence method, will allow the design of fire resistant construction to be optimised.

It is proposed that an energy-based time-equivalent calculation, principally founded on the absorbed heat flux by the compartment boundaries, be used to assess the performance of building elements exposed to compartment fires of different severities. Areas of further research are proposed that, if carried out, would provide a more robust basis for the levels of fire resistance currently specified by engineers and included within regulatory supporting documents. The need for a comprehensive series of fully-developed fire experiments within a compartment is identified.

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1. INTRODUCTION

1.1 General

In April 2012, new Building Code Clauses C1 to C6 and associated compliance documents for protection from fire took effect in New Zealand. This provided a new framework, giving engineers the opportunity to routinely calculate the levels of fire resistance necessary for buildings to comply with the Building Code. However, the current engineering methods typically used (with time-equivalence being the main focus of this report) to determine the fire resistance needed are limited in their application and scope, and lack the level of robustness needed. Consequently there is currently a high degree of uncertainty as to whether buildings are actually delivering the level of safety in relation to fire resistance expected by the Building Code.

The purpose of this report is to:

- Describe and critique current methods used in New Zealand for demonstrating compliance with the Building Code for calculating and prescribing the levels of fire resistance provided to elements of construction, for the purpose of either preventing fire spread or maintaining structural stability during and after fire;
- Highlight alternative approaches that could be considered for further development; and
- Identify a general programme of further research that, if carried out, would provide a more robust basis for the levels of fire resistance currently specified by engineers and included within regulatory supporting documents.

1.2 New Zealand Regulatory Framework for Fire Design

The New Zealand Building Code (New Zealand Government, 2012) has the general objectives of:

(a) Safeguarding people from an unacceptable risk of injury or illness caused by fire;

(b) Protecting other property from damage caused by fire; and

(c) Facilitating firefighting and rescue operations.

The New Zealand Building Code (NZBC) sets out to limit fire spread (both external and internal), in order to provide occupants with adequate time for and means of escape, and to provide access for firefighters to safely carry out firefighting and rescue operations. Although the NZBC is not concerned with the protection of the building under consideration, provisions are included to ensure a low probability of fire spread to other properties under separate ownership (including unit titles) or to places where people sleep.

Although the NZBC contains limited provision for the prevention of fire occurring, relating to fixed appliances only, it does not set out to protect persons in close proximity to or intimate with a fire source.

Compliance with the NZBC provisions can be demonstrated by adopting one of the following three design processes:

- NZBC – Acceptable Solutions C/AS1 to C/AS7;
- NZBC – Verification Method C/VM2; or
- Alternative solution.

To meet the stated objectives of limiting fire spread and preventing collapse, the Acceptable Solutions and some parts of the Verification Method require certain building elements to have a prescribed fire resistance rating (FRR), sometimes referred to as fire resistance level (FRL) in other jurisdictions. The Verification Method also allows fire severity and fire resistance to be calculated. The Acceptable Solutions and Verification Method are captured in the NZBC supporting documents for the Protection from Fire and their FRR requirements are discussed in more detail below.

1.3 Acceptable Solutions

The NZBC Acceptable Solutions follow a prescriptive “cookbook” type process for use by “non-engineer” building designers. Solutions are ordered in defined “risk groups” and two types of FRR are prescribed. A “life rating” is intended to ensure safe evacuation and to facilitate firefighting and rescue operations and a “property rating” is intended to ensure the protection of adjacent “other property” under separate ownership. These ratings are expressed as FRR and the acceptable test standards quoted are: AS 1530 Part 4 (Standards Australia, 2005); and NZS/BS 476 Parts 21 and 22 (1987).

It is important to understand that both FRR and FRL relate directly to results obtained in accordance with the standard furnace test for fire resistance or specific calculation verified by experimental data from standard fire resistance tests. Three numbers give the time in minutes for which each of the criteria structural adequacy/integrity/insulation (in that order and as defined by the test standard), are satisfied.

Life rating requirements in the current Acceptable Solutions are conservatively based on the “F” or “firecell” ratings adopted in the previous version of the NZBC Acceptable Solutions. The prescribed levels of FRR do not directly equate to required safe evacuation times, but are intended to allow for the difference between expected compartment fire time-temperature histories and the time-temperature experienced in the standard fire resistance test. Modifications to the level of FRR required for life safety purposes were made following the work by Nyman (2002) as further described in Section 4.7. Depending on the risk group, the required life rating is commonly 30 or 60 minutes and is applied to achieve firecell or egress separation.

Property rating requirements in the current Acceptable Solutions are again rounded and conservatively based on the “S” or “burnout” ratings adopted in the previous version of the NZBC Acceptable Solutions, based on the time-equivalence formula taken from Eurocode (2002) as described in Section 4.3. The property rating values range from 30 minutes (30/30/30) for simple residential type applications to 180 minutes (180/180/180) for high-risk groups such as warehousing capable of high storage.

1.4 Verification Method

The NZBC Verification Method C/VM2 sets a framework for the specific fire safety design of buildings and is suitable for use by professional fire engineers proficient in the use of fire engineering modelling methods. Available safe egress time (ASET) is compared with required safe egress time (RSET) to determine the ability to evacuate occupants without them suffering ill effects from fire. Different fire scenarios are required to be modelled. Egress times are commonly expressed in minutes representing real elapsed time, such that engineers are required to specify fire resistance levels based on standard fire tests for construction needed to perform for the real period of elapsed time.

The Verification Method provides three options for modelling the full burnout design fire:

(a) Use a time-equivalent formula to calculate the equivalent fire severity and specify building elements with a fire resistance rating not less than the calculated fire severity;

(b) Use a parametric time versus gas temperature analytical equation to calculate the thermal boundary conditions (time/temperature) for input to a structural response model, or

(c) Use a fire model or energy conservation equations to determine suitable thermal boundary conditions (time/temperature/flux) for input to a structural response model.

However, only detailed guidance is provided for option (a) as discussed in Section 4.3.

Design scenario FO (firefighting operations) of C/VM2 requires firefighters to have safe path access to all floors capable of resisting burnout for buildings with escape height > 10 m. For buildings ≤ 10 m the documents require safe paths to have the lesser of “a period of 60 minutes from ignition” or burnout. No guidance is provided on how to relate this period of 60 minutes (or any other period) to a FRR obtained in a standard fire resistance test.

1.5 Alternative Solutions

Instead of designs in accordance with the Acceptable Solutions or Verification Method, an “alternative solution” can also be submitted for consideration by the local Building Control Authority provided substantiated evidence is included showing compliance with the higher level NZBC Clauses C1-C6 Protection from Fire. This latter path is not frequently followed in New Zealand and was intended to apply to exceptional building designs not otherwise captured by the first two options.

1.6 Design to Withstand Burnout

The basis for the property ratings in the Acceptable Solutions and the full burnout design referred to in the Verification Method can be found in the Eurocode (2002) time-equivalence formula. The basis for this formula is found in experimental work on protected steel members exposed to compartment fires with varying ventilation conditions, as discussed in more detail in Section 4.3 of this report. The premise is that a protected steel member can survive a compartment burnout if it can sustain the same maximum temperature in a standard furnace test without structural failure.

Although the empirical basis and applicability of the time-equivalence formula is the subject of research activities described and proposed in this report, it has long been an accepted measure of compartment burnout “survivability” of a fire-rated construction element being part of a compartment with constant ventilation conditions.

Interestingly, in New Zealand the property rating is often applied to single elements of construction only, such as external walls when a building is located “sufficiently close” to a relevant (ownership) boundary.

Given that the time-equivalence formula assumes constant compartment ventilation conditions for the duration of the calculated FRR, it would appear imprecise to apply the equation to only part of a compartment whilst other parts can reasonably be expected to fail before the calculated FRR is reached, thus increasing compartment ventilation conditions and rendering calculations inaccurate and in some cases overly conservative.

A further NZBC structural provision in NZBC B1/VM1 (MBIE, 2014) requires such single-boundary elements to maintain lateral stability against foreseeable imposed post-fire loads or a nominal wind loading of 0.5 kPa in either direction. This leads to the situation where, on the one hand, fire rating requirements are based on the assumption that the compartment has constant ventilation conditions and thus remains substantially intact whilst, on the other hand, structural post-fire stability measures are required assuming substantive compartment failure and lack of lateral support to the fire-rated boundary element.

2. FIRE RESISTANCE RATINGS

Like many standard engineering test procedures, assigning a fire resistance rating to an element of construction involves following a defined laboratory procedure. The fire resistance of a construction element is determined following exposure, in a furnace, to clearly demarcated time-temperature conditions. Although differences exist between different test standards, these are relatively insignificant and generally relate to furnace pressure and the way temperature measurements are conducted.

Most historical fire resistance ratings have been established following exposure to the ISO 834 time-temperature history as defined by the relationship:

$$T_t = T_0 + 345 \log_{10}(8t+1) \quad (1)$$

Where:

T_0 is the ambient temperature at the start of the test;

T_t is the furnace at time *t*; and

t is the elapsed time (minutes).

Historically, reproducibility between different test furnaces has been relatively poor due to differences in the fuel used and the design and properties of the materials used to construct the furnace. This has improved with the introduction of the plate thermometer to measure (and control) the gas temperature in the furnace (Wickström, 1997; Cooke, 1994). Although it is noted that the standard commonly used in New Zealand, AS 1530.4, does not require plate thermometers to be used unlike general practice in Europe, e.g. BS EN 1363-1 (BSI, 2012).

Repeatability within furnaces is also not well understood, given there is no requirement to test more than one assembly, therefore allowing the most favourable result from multiple tests to be used to assign a rating, in the event that multiple tests were carried out.

3. SEVERITY OF COMPARTMENT FIRES

The severity of building or compartment fires is a function of parameters such as fuel load and type, available ventilation and the thermal properties of the compartment boundaries. Compartment fires vary in nature and would only coincidentally resemble the standard furnace test time-temperature history.

With advances in fire engineering science it is now accepted practice to model compartment gas temperatures and species concentrations to predict the effect of specific fire scenarios on the occupants. However, calculating the performance of construction elements exposed to non-standard fires from first principles is still relatively uncommon for a number of reasons, including the ease of instead using a time-equivalence formula along with the relative low levels of fire resistance required for many buildings. Calculation methods could be used in some cases where the materials and structural system are well characterised (e.g. structural steel and reinforced concrete) but in other cases (e.g. fire doors, fire stopping systems) there are no well-developed calculation methods available.

In order to compare compartment and standard furnace test fires, the concept of "fire severity" is often applied in fire engineering analysis. The premise is that by comparing the time-temperature history of a compartment fire with the standard furnace test, an "equivalent fire severity" for the compartment can be determined.

Ideally, equivalent fire severity or the "destructive power of a fire" as described by Harmathy (1987), would enable the performance of a construction element exposed to a compartment fire to be assessed when the fire resistance rating, determined in accordance with standard furnace testing, is known.

Equivalent fire severity has also been used to set minimum requirements for fire resistance ratings, as determined by standard furnace testing, in prescriptive Building Code documentation.

Before discussing time-equivalence methods it is important to identify the two streams that commonly form part of the comparative analysis.

Firstly, fuel load and type, ventilation conditions and thermal properties of the compartment boundaries are essential input parameters for determining the expected compartment gas temperatures in the case of a fire.

Secondly, once the expected time-temperature history has been generated, the impact on structural elements and structural and non-structural fire separations needs to be determined.

Historical methods often lump both streams into a single-step analysis assuming that all construction elements respond similarly when fire severity is changed. However, because different structural elements respond differently to elevated temperatures, it is useful to maintain a distinction between fire severity or compartment gas time-temperature history and the actual response of construction elements.

4. TIME-EQUIVALENCE METHODS

4.1 General

The main reason for the interest in time-equivalence methods is because of the extensive amount of fire test performance data gathered over the years from standard fire resistance tests. This establishes performance to the particular fire severity experienced in the test furnace. While it may be feasible to determine an expected "design" thermal exposure for a given scenario, and reproduce that in a furnace test, it is not a practical solution for commercial testing and rating of building construction because there are a vast number of possible "design fire severities" depending on compartment size, ventilation and thermal properties.

While fire resistance can be calculated for some types of construction or structure, there are many other types of construction where this is not currently possible or practical, and the need remains to have methods that enable standard fire resistance test results to be generalised and able to be used for a range of real compartment fire severities.

4.2 Early Time-Equivalence Methods

Ingberg (1928) was the first to suggest a method for the assessment of equivalent fire severity or equivalent fire exposure (EFE). He burned office furniture in compartments, adjusting ventilation to maximise the severity, and allowed the fuel to burn out. He compared the area under the time-temperature curve above a certain reference temperature to that in the standard fire test. He regarded the EFE (τ_e) simply as a function of the specific compartment fire load (L) and this usually ranged from 150 to 500 °C. Ingberg's formula is:

$$\tau_e = 0.0205L \text{ (hours)} \quad (2)$$

With the restriction that L ≤ 146 kg/m^2.

This approach did not have any real theoretical merit and did not account for ventilation conditions or any variations in the thermal properties of the compartment boundaries.

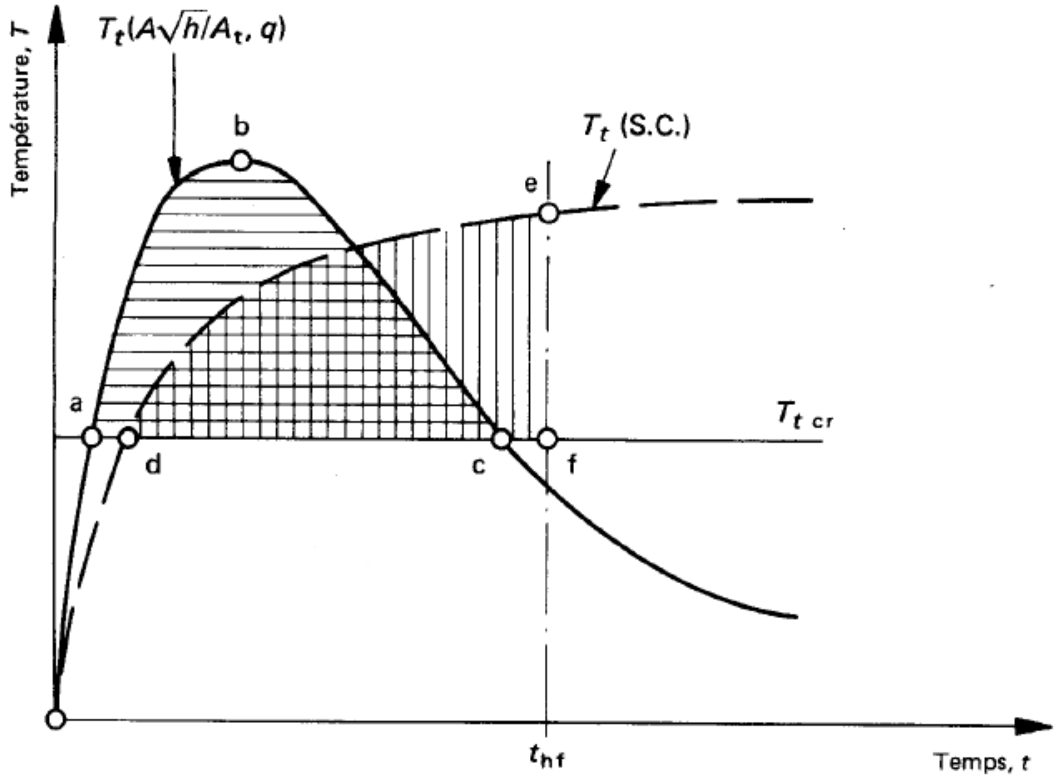


Figure 1 Equivalent fire severity as postulated by Ingberg (1928) based on area under the time-temperature curve (adapted from ISO TR 3956)

Further advances in fire engineering science show that simple linear time-temperature dependence is not representative of the destructive energy imposed by fire on the compartment boundaries.

Harmathy (1972) identified shortcomings of a simple time-temperature dependence and suggested that fire severity can be characterised by the duration of a fully-developed fire and *"... the 'effective heat flux' defined as the heat flux available for penetration into the elements of the compartment averaged over the duration of the fully developed fire ..."*. Harmathy (1982) further postulated that *"… normalised heat load is a suitable parameter for ranking various enclosure fires on a 'potential for destruction scale'."* and that *"… this parameter is convertible to the familiar fire resistance"*. Recognising that heat transfer to enclosure boundaries is mainly radiative and depends on the fourth power of fire gas temperature, he introduced a variable referred to as "heat load". This is discussed in detail later.

Kodur (2010) also agreed that the equal area method of establishing time-equivalency based on time-temperature histories has no rational basis and underestimates heat transfer in a short, hot fire and overestimates heat transfer in a long, cool fire.

Nyman (2002) additionally attempted to fit simple temperature dependence to a range of results for framed drywall specimens exposed to standard fire tests as well as compartment fire exposures and found no reliable correlation for the area under the time-temperature curve.

Kawagoe et al (1963, 1964) extended Ingberg's concept, still assuming burnout of the fuel but adding the effect of ventilation. Their equation for time-equivalence thus became:

$$t_e = k_2 L'' \left(\frac{A_t}{A_v\sqrt{h}}\right)^{0.23} \quad \text{(min)} \tag{3}$$

Where:

k_2 is 1.06;

L'' is the fuel load expressed as "weight of wood" (kg);

A_t is the total internal surface area (wall, ceiling, floor) of the enclosure (m^2);

A_v is the area of vertical openings (m^2); and

h is the height of vertical openings (m).

The equation was considered valid for values of the term $\frac{A_t}{A_v\sqrt{h}}$ between 5 and 30 $m^{-1/2}$.

Thomas (1970) discussed the dependence of fire resistance requirements on fire load in terms of requirements for the structure to survive a burnout and confirmed the fire resistance required was proportional to:

$$\frac{A_F}{\sqrt{A_v(A_t - A_v)}} \tag{4}$$

Law (1971) further developed the t_e concept from results of wood crib fires, allowed to burnout in model compartments. The maximum temperature reached by a protected steel element in the compartment fire was chosen and compared with that reached in the standard furnace test fire. The following empirical t_e equation was developed for brick or concrete compartments approximately 3 m high:

$$t_e = k_4 L'' \frac{A_F}{\sqrt{A_v(A_t - A_v)}} \quad \text{(min)} \tag{5}$$

Where:

k_4 is 1; and

A_F is the floor area of the enclosure (m^2).

As such, Law did not predict the compartment temperature-time history, but simply provided a means for calculating an equivalent time of fire exposure for an enclosure with known fuel load and known dimensions including ventilation parameters.

Magnusson and Thelandersson (1970) developed a method to calculate the temperature-time curve for a burnout compartment fire and Pettersson (1973) then adopted the Law approach and derived a t_e equation for a family of calculated temperature-time curves for standard compartments. Modified to account for the thermal properties of the enclosure this gave:

$$t_e = 1.21\sqrt{k_f L''}\frac{A_F}{\sqrt{A_v\sqrt{h}A_t}}\ \text{(min)} \quad (6)$$

Where:

k_f is a factor to take into account the thermal properties of the enclosure boundaries.

Law (1997) later reviewed the development of the time-equivalent equation from the early days of Ingberg to Eurocode 1. Law compared the various formulae, with experimental data from post flashover fires in full-scale compartments. Although most compartments did not exceed the size of a small room, less than 30 m^2, some results from larger and deeper rooms, up to 128 m^2, were included. Law did not find satisfactory time-equivalence correlations for both the smaller and larger compartments.

Despite the common and continued use of the time-equivalent approach based on empirical data, she concluded that it was not a useful parameter for design purposes.

4.3 Eurocode Formula

The current version of the time-equivalence equation found in the New Zealand Building Code, Protection from Fire Verification Method C/VM2, is based on Eurocode (2002) which was developed after extensive reviews of the previous formulations, but with more conservative estimates of the lining factor as recommended by Kirby et al (1999). Law (1997) reported that the original form of the Eurocode formula was based on correlating results from a heat balance model or computer program called MRFC developed at the University of Kassel.

The C/VM2 form of the equation is given as:

$$t_e = e_f k_b k_m w_f \quad (7)$$

Where:

$$w_f = \left(\frac{6.0}{H}\right)^{0.3}\left[0.62 + \frac{90(0.4-\alpha_v)^4}{1+b_v\alpha_h}\right] \geq 0.5$$

$$\alpha_v = A_v / A_f \qquad 0.025 \leq \alpha_v \leq 0.25$$

$$\alpha_h = A_h / A_f \qquad \alpha_h \leq 0.20$$

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

e_f is the fuel load density (MJ/m^2) on a floor area basis and in C/VM2 is adjusted using the F_m factor as shown in Figure 2;

k_b is a lining materials factor (ranging from 0.04 to 0.10) being a function of the thermal inertia of the compartment boundaries, as shown in Figure 3;

k_m is a structural material factor (which is 1.0 for protected steel, reinforced concrete timber or a mix of protected/unprotected steel);

For unprotected steel, $k_m = 13.7A_v\sqrt{h_v}/A_f$ applicable over the range –

$0.02 \leq A_v\sqrt{h_v}/A_f \leq 0.20$

w_f is a ventilation factor calculated considering horizontal and vertical openings;

A_h is the area of horizontal openings (m^2);

A_v is the area of vertical openings (m^2);

H is the height of the compartment (m); and

A_f is the compartment floor area (m^2).

It is noted that the United Kingdom did not accept the above k_m factor for unprotected steel due to lack of correlation with test data (Kirby, 2004). They also noted that the time-equivalence equation should not be used beyond 60 minutes for unprotected steel.

Table 2.3	F_m factors to be applied to FLED	
	Sprinklered *firecell*	Unsprinklered *firecell*
For calcuations of *fire* duration[1] and for *fire* resistance of all non-structural elements[2] Fire resistance of structural elements not covered by the description in the row below	0.50	1.00
Fire resistance of structural elements in a structural system which is unable to develop dependable deformation capacity under post-*flashover fire* conditions [3]	1.00	1.25

Notes

1. Life safety calculations of the duration of the *fire* (total duration of burning) may use the *FLED* as modified by the F_m factor in the table.
2. This table does not prescribe that all non-structural elements require fire resistance based on fire duration. However, where calculation of *fire* resistance of non-structural elements is based on *fire* duration, this table gives the F_m value to be applied to the *FLED*.
3. This factor accounts for impact of non-uniform *fire load* and/or ventilation and hence local increase in actual structural *fire* severity on a structural system which has less resilience to accommodate variations from the calculated *fire* severity. For this purpose the structural system comprises the individual members and the connections between these members.

Figure 2 F_m factor from C/VM2 used as a multiplier to the fuel load density (extracted from MBIE, 2013)

Table 2.4	Conversion factor k_b for various lining materials	
Typical values for $\sqrt{kpc}$ $J/m^2s^{0.5}K$	*Construction* materials	K_b
400	Very light highly insulating materials	0.10
700	Plasterboard ceilings and walls, timber floors	0.09
1100	Light weight concrete ceilings and floors	0.08
1700	Normal weight concrete ceilings and floors	0.065
>2500	Thin sheet steel roof and wall systems	0.04

NOTE:

k=thermal conductivity (W/m K)

ρ=density (kg/m^3)

c=specific heat (J/kg K)

Figure 3 k_b factor from C/VM2 (extracted from MBIE, 2013)

4.4 Time-Equivalence Based on Maximum Temperature of Protected Steel

It is important to remember that the Eurocode formula given in the previous section has resulted from a twofold historical development involving the estimation of equivalent fire exposure of building elements when exposed to non-standard fires, later combined with the generation of compartment temperature-time histories.

The assessment of equivalent exposure is mainly empirically based and compares the maximum temperature of a protected steel member achieved during compartment burnout with that same temperature achieved in the standard fire test.

The time-equivalence concept using correlations is only valid when comparison is made following compartment burnout and cannot be applied to temperature of the protected steel member other than that achieved at burnout.

Time-equivalence is thus a variable with dependence on the peak steel temperature reached in the compartment fire test. If any other temperature, below the peak temperature, were selected for comparison then the result for a given protected steel member exposed to the standard furnace test would simply become a constant with no relevance to the performance in a compartment fire.

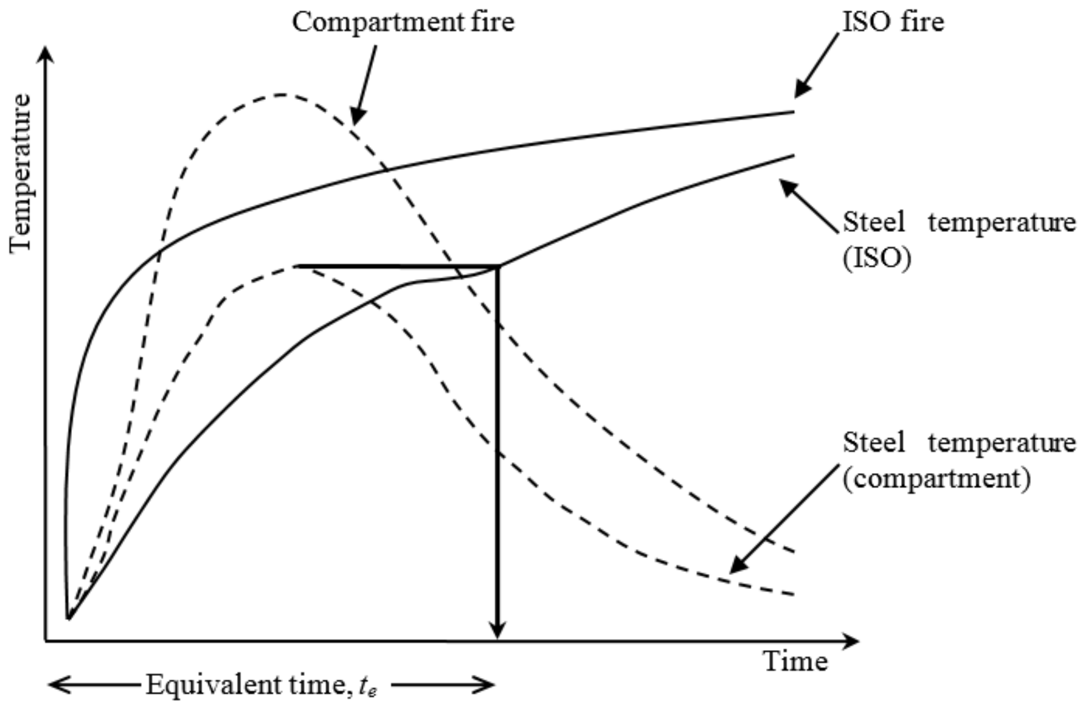


Figure 4 Graphical time-equivalence

Although time-equivalence is often associated with structural performance, specifically the performance of protected steel members, the concept has been developed based on temperature measurement of a narrow range of unloaded protected steel members. The temperature reached is not necessarily indicative of structural performance but is simply a vehicle for comparison with temperature recorded during the standard furnace test fire. The premise is that burnout can occur without structural failure if equivalent exposure to the standard furnace test, or greater value, is specified.

Although this may hold for structural members sensitive to critical temperature, bearing in mind the relatively narrow range of protected steel members validated, it is unlikely to be valid for structural or construction elements that continue to decay during the cooling phase of a fire. Such elements include heavy timber columns and beams and framed “drywall” elements lined with gypsum plasterboard where decay following char and dehydration is expected to continue beyond the point of maximum temperature. A long and cooler fire may also not raise the temperature of protected steel to the same level as a shorter but hotter fire; however, the impact on gradually degrading elements could be similar.

There is therefore a risk of over-simplification inherent in the time-equivalence approach as it does not take variations of the properties of the structure into account. This was also identified by Hertz (1983) who concluded that the equivalent time concept can be justified only for very small, well defined groups of concrete structures, if any. This is due to variations in failure mode and aspects such as dimension of the cross section, cover thickness and thermal properties of the concrete used.

Cooke (1999) also investigated time equivalence and its applicability to deep, well insulated compartments and found there was large variation in the measured time equivalence depending on the position in the compartment. He also commented that for columns, the load ratio needs to be considered to make a connection between time equivalence and fire resistance.

4.5 Harmathy’s Normalised Heat Load Method

Harmathy proposed that the destructive potential of a fully-developed fire can be quantified using a parameter called the normalised heat load (Harmathy, 1980 and 1987; Harmathy and Mehaffey, 1983 and 1985). Harmathy (1980) demonstrated this based on an analytical solution for the maximum temperature reached at a given depth below the surface of a semi-infinite solid, noting its applicability to many reinforced or prestressed concrete elements where the critical element is located at some depth and its structural performance depends on the maximum temperature reached (e.g. the steel reinforcing in this case). The concept therefore does not apply when the critical element is located at the surface, i.e. not embedded within or protected by a material that can be represented by a semi-infinite solid such as unprotected steel for example.

The heat load parameter therefore is useful to describe the relative fire severity in a given fire enclosure with given thermal properties, but not for comparing different fires in unlike enclosures. In the latter case, to compare fires in unlike compartments, a normalised heat load parameter is instead required.

The heat absorbed by a test furnace or by compartment surfaces exposed to fire depends on the thermal inertia ($\sqrt{k\rho c}$) of the boundaries. For boundary surfaces comprising different materials the thermal inertia can be represented by a weighted average of the thermal inertia of the individual boundary elements. Typical values for thermal inertia are given in Table 1 (Harmathy, 1981).

Table 1 Typical values of the thermal properties of common construction materials (in moistureless condition) for the appropriate temperature intervals (extracted from Harmathy, 1981)

Table 1. Typical values of the thermal properties of common construction materials (in moistureless condition) for the appropriate temperature intervals

Material	Thermal conductivity, k ($W\ m^{-1}\ K^{-1}$)	Density, ρ ($kg\ m^{-3}$)	Specific heat, c ($J\ kg^{-1}\ K^{-1}$)	Thermal inertia, $\sqrt{k\rho c}$ ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)
Steel	42.0	7800	530	13177
Marble	2.0	2650	975	2273
Normal weight concrete	1.68	2200	1300	2192
Fireclay brick	1.15	2600	900	1640
Brick	1.10	2100	1000	1520
Lightweight concrete	0.46	1450	1300	931
Plaster board	0.27	680	3000	742
Vermiculite plaster	0.25	660	2700	667
Wood	0.15	550	2300	436
Insulating firebrick	0.25	722	1000	425
Mineral wool (Fiberfrax)	0.04	160	1150	86

The normalised heat load (with units $s^{1/2}K$) is the heat absorbed per unit area divided by the thermal inertia of the enclosure boundaries and is defined as:

$$H = \frac{1}{\sqrt{k\rho c}} \int_0^{\tau} q dt \tag{8}$$

Where:

q is the instantaneous heat flux penetrating the boundaries of the fire enclosure;

τ is the duration of the fire exposure;

t is time; and

$\sqrt{k\rho c}$ is the thermal inertia of the boundaries of the enclosure.

The instantaneous heat flux is a weighted average of the heat flux penetrating each surface and the area of that surface as follows:

$$q = \frac{1}{A_t} \sum_{i=1}^{n} A_i(q_i) \tag{9}$$

The normalised heat load can be calculated from a compartment energy balance from which the penetrating heat flux can be estimated or measured experimentally, based on the following equation for the maximum temperature rise $(T_m - T_o)$ at depth a within a boundary element of thermal diffusivity κ (Harmathy and Mehaffey, 1987):

$$H \approx 2.3 \frac{a}{\sqrt{\kappa}} (T_m - T_o) \tag{10}$$

Provided that $0.8 < \frac{a}{\sqrt{\kappa\tau}} \leq 1.2$ (within this range the maximum temperature reached is more or less independent of the rate of cooling after heat penetration has ceased). The heat absorbed (penetrating) the compartment boundaries is stated to typically be in the range of 15-40% of the chemical energy contained in the combustibles (Harmathy, 1981).

When an energy balance calculation for a fire compartment is undertaken the heat losses and penetrating heat flux to the compartment boundaries can be determined. However, this limits the application and a simplified form of the concept is also useful. Accordingly Harmathy and Mehaffey (1983) provide a simplified empirical form of the maximum normalised head load H absorbed by the compartment boundaries during the fire, assuming all the energy from volatile combustibles are released within the compartment, as:

$$H = \frac{1260G}{A_t\sqrt{k\rho c} + 935\sqrt{\Phi G}} \times 10^4 \quad (11)$$

Where:

G is the wood equivalent fire load in kg;

A_t is the total surface area of the compartment boundaries (walls, ceiling and floor); and

Φ is the ventilation parameter defined as –

$$\Phi = \rho_a A_v \sqrt{g h_v} \quad (12)$$

Where:

ρ_a is the ambient air density (1.2 kg/m^3);

A_v is the area of the ventilation opening;

g is the acceleration due to gravity (9.8 m/s^2); and

h_v is the height of the ventilation opening.

A compartment fire and a standard fire resistance test are considered to have equal fire severity when the total normalised heat load is the same. Therefore if a building element can successfully withstand a certain normalised heat in the standard fire resistance test it is expected it will be able to withstand the same normalised heat load in the compartment fire. Harmathy (1981) gave an expression for the (equivalent) time of exposure τ (in hours) to the standard fire resistance test for a floor furnace at the National Research Council of Canada as:

$$\tau = 0.11 + 0.16 \times 10^{-4} H + 0.13 \times 10^{-9} H^2 \quad (13)$$

For $0 < H < 9 \times 10^4$ s$^{1/2}$K where τ, the length of exposure to the standard fire resistance test, is given in hours. If the normalised heat load from the compartment fire is substituted for H into the above equation, the equivalent time of exposure to the standard fire test can be calculated. In theory the normalised heat load in a test furnace should vary slightly depending on the thermal properties of the test specimen, which is ignored in equation (13) where it is only dependent on the heating duration. Harmathy found that the value did not change significantly for thermal inertia in the range applicable for common compartment boundaries.

Harmathy (1987) compared the time-equivalent value determined from five different methods (Ingberg,1928; Law, 1971; Pettersson [CIB W14], 1986; DIN, 1978; and Harmathy, 1987), applying them to a series of compartment burnout tests and concluded that the normalised heat load method was more accurate than the other four.

The key concept embodied in Harmathy's method is that the destructive potential of the fire exposure is a function of the heat absorbed and therefore of the thermal properties of the boundary, given more highly-insulating boundaries result in higher gas temperatures but less heat conducted into the compartment boundaries and therefore a lower destructive potential of fire severity.

Yung and Mehaffey (1991) provided an example of a practical application using this method to determine the fire resistance requirements of rubber tyre warehouses.

4.6 Harada's Time Heat Flux Method

Harada et al (2000) proposed a simple formula for equivalent fire duration based on an equivalent time-heat flux area. The heat absorbed by the compartment boundaries are described by an analytical expression for heat conduction in a semi-infinite solid. The time for the same amount of heat to be absorbed under the standard fire resistance test is also determined and this is considered to be the equivalent fire duration, assuming the behaviour of the construction is the same if the total amount of heat is equivalent.

The formula was checked against numerical calculations of the heat flux history for both thermally thick and thermally thin walls. He concluded that the formula gave reasonable results for the heating phase and conservative results for the cooling period.

Harada's procedure requires the standard fire and the compartment fire to be given as functions of time raised to the one-sixth power.

For example, the standard ISO 834 time-temperature can be approximated by:

$$T_{f,ISO} - T_\infty = 345 \log_{10}\left(\frac{8t}{60} + 1\right) \approx 230t^{1/6} \tag{14}$$

And for a ventilation-controlled fire, the fire temperature and duration were given as:

$$T_f - T_\infty = 3.0T_\infty\left(A_w\sqrt{H_w}/A_T\sqrt{k\rho c}\right)^{1/3} t^{1/6} \tag{15}$$

$$t_D = wA_F/0.1A_w\sqrt{H_w} \tag{16}$$

If the building elements can be approximated by a semi-infinite body with respect to heat conduction and if the heat flux is assumed constant over some time interval, an analytical expression can be given for the surface temperature rise:

$$T_s - T_\infty = \frac{2q}{\sqrt{\pi}}\sqrt{\frac{t}{k\rho c}} \tag{17}$$

Rearranging for q:

$$q = \frac{\sqrt{\pi}}{2}\sqrt{\frac{k\rho c}{t}}(T_s - T_\infty) \tag{18}$$

If we assume that the surface temperature can be approximated by the gas temperature, we have:

$$q \approx \frac{\sqrt{\pi}}{2}\sqrt{\frac{\lambda\rho c}{t}}\beta t^{1/6} \tag{19}$$

Where:

$\beta = 230$ for the standard time-temperature curve; and

$\beta = 3.0T_\infty\left(A_w\sqrt{H_w}/A_T\sqrt{\lambda\rho c}\right)^{1/3}$ for a ventilation-controlled time-temperature curve.

Integrating the above equation with respect to time gives an analytical expression for the total absorbed energy allowing the energy absorbed in the compartment fire to be compared with the energy absorbed in the standard fire resistance test.

$$E(t) = \int_0^{t_D} q(t)dt = \frac{3\sqrt{\pi}}{4}\sqrt{\lambda\rho c}\,\beta\, t^{2/3} \tag{20}$$

In order to use Harada's analytical method we would need to represent both the standard fire and the compartment fire temperature as a simple function of t, which makes it difficult to use other parametric time-temperature relationships.

4.7 Nyman's Method Based on Emissive Power of Fire Gases

Nyman (2002) conducted three full-scale tests using compartments constructed to enable simultaneous testing of various lightweight timber and steel-framed walls and ceiling/floor systems, including a fire door. The compartments were constructed so that the assemblies formed an integral structure with realistic connections between them. All three test compartments had internal dimensions of 3.6 m long x 2.4 m wide x 2.4 m high, with a single opening in one of the shorter walls as shown in Figure 5. Wall and ceiling systems were constructed of materials previously subjected to standard furnace testing. The three tests and construction elements are presented in Tables 2 and 3.

The fires were intended to simulate rapid growth associated with upholstered furniture, followed by a period of ventilation-controlled burning. Design fire load energy density values of 800 MJ/m^2 and 1200 MJ/m^2 were selected to ensure failure of the assemblies, enabling comparison with furnace test failure times. Polyurethane foam cushions with a synthetic fibre covering mounted on a steel chair-shaped frame were used to provide the initial fire growth with untreated "rough sawn" radiata pine wood cribs used for the balance of the fuel load. The width of the opening varied from 0.8 to 1.2 m.

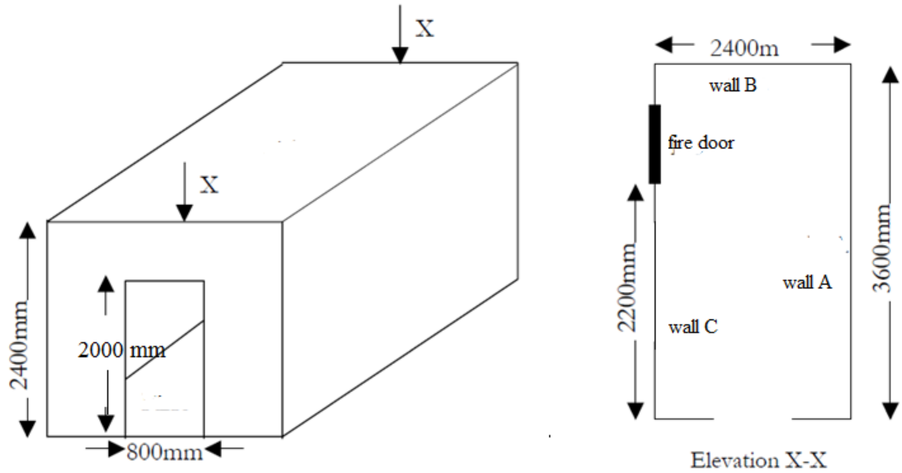


Figure 5 Compartment geometry (adapted from Nyman, 2002)

Nyman found that the time to failure of non-load-bearing drywall assemblies exposed to compartment fires can be predicted with reasonable accuracy by comparing the cumulative radiant energies to which the assembly is exposed as illustrated in Figure 6. Nyman considered this appropriate because the prime mode of heat transfer in compartment fires is radiant and a function of the absolute temperature T_f (K) to the fourth power. Nyman simply considered the emissive power of fire gases, independent of the thermal inertia of the compartment boundary:

$$E = \int_0^t \dot{Q}''dt = \varepsilon\sigma \int_0^t \left({T_f}^4\right)dt \text{ (J/m}^2\text{)} \quad (21)$$

Where:

- E is the cumulative radiant energy on the assembly over a period of time (Jm^{-2});
- $\dot{Q}''$ is the radiant heat flux incident upon the assembly at any point in time (Wm^{-2});

ε is the emissivity of the compartment gases (=1);

σ is the Stefan Boltzmann constant (5.67 $\times 10^{-8}$ $Wm^{-2}K^{-4}$);

t is the time (s); and

T_f is the compartment gas temperature (K).

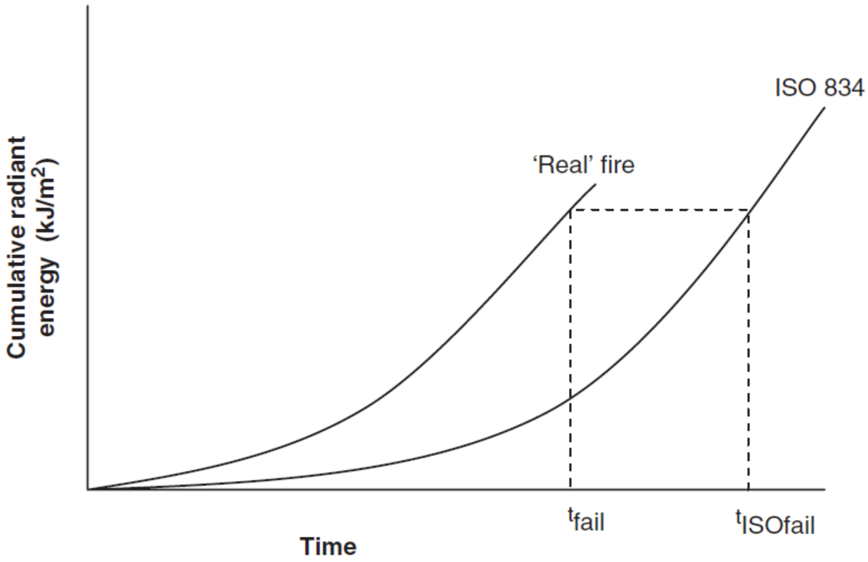


Figure 6 Cumulative radiant energy approach for fire severity (extracted from Nyman et al, 2008)

Figure 7 compares furnace test results with the predicted times to failure for nine different assemblies in the three full-scale experiments. Using the cumulative radiant energy method, time to insulation failure predictions were generally underestimated (above the diagonal line) whilst time to structural or integrity failures were generally overestimated.

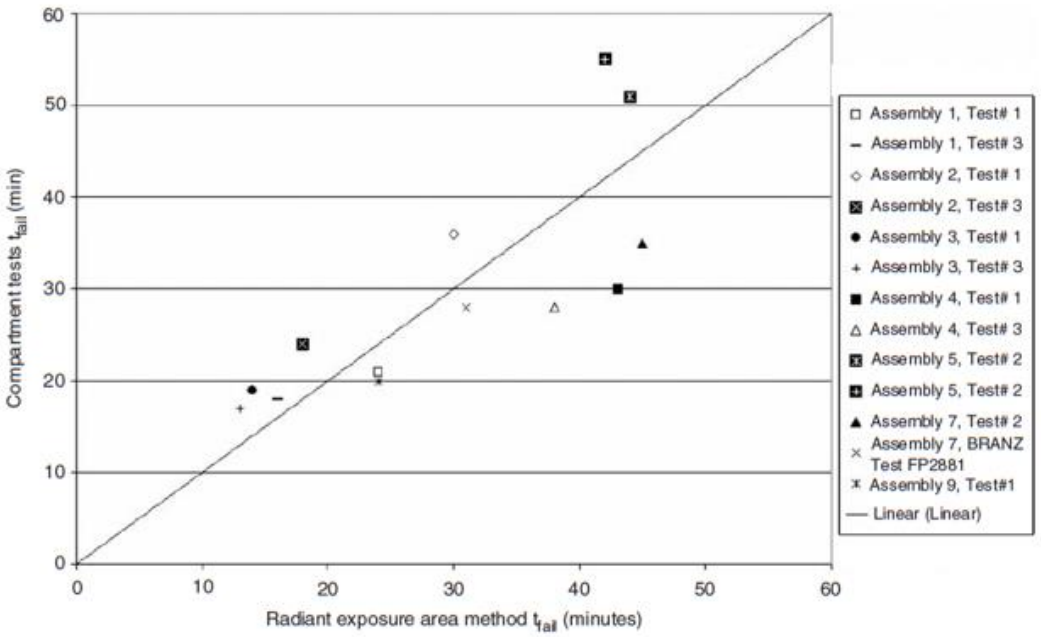


Figure 7 Predicted failure time using cumulative radiant energy (extracted from Nyman et al, 2008)

The cumulative radiant heat energy approach of Nyman (Nyman, 2002; Nyman et al, 2008) was then applied by Gerlich et al (2004) using the time-temperature histories generated from the parametric fire equations given in Annex A of Eurocode 1 (Third Draft). Examples of the temperature-time histories and matching cumulative radiant energy histories are given in Figures 8 and 9.

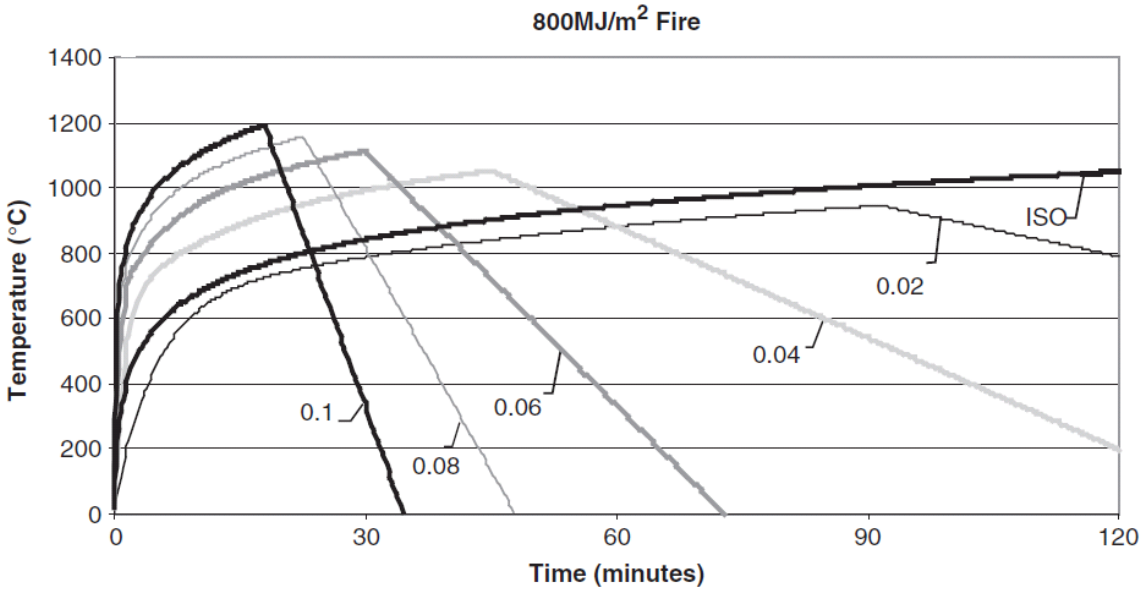


Figure 8 ISO 834 temperatures compared with compartment time-temperature histories generated using Eurocode equations for b = 700 $J/m^2s^{1/2}K$ and opening factors from 0.02 to 0.1 (extracted from Nyman et al, 2008)

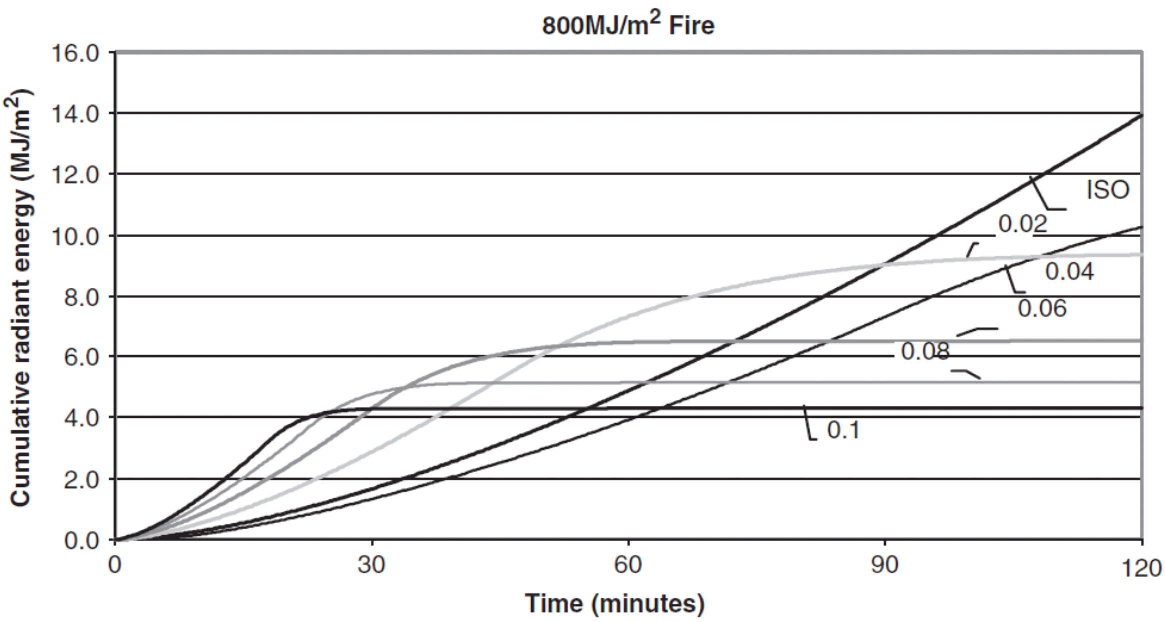


Figure 9 ISO 834 cumulative radiant heat energy compared with energy histories generated from Figure 8 (extracted from Nyman et al, 2008)

A design procedure was developed to predict the time to failure in a compartment fire for an assembly with a known furnace test result, requiring:

- Compute the predicted time-temperature history for the compartment;
- Obtain the time-temperature history for the standard ISO 834 furnace test curve (or other test curve which was used for furnace testing of the assembly);
- Calculate the cumulative radiant heat energy with time for each curve; and then
- Determine the predicted failure time for equal amounts of cumulative radiant energy from each curve.

For assemblies with a given furnace test result (FRR), predictions of times to failure (t_{fail}) were determined as presented in Table 2 where the opening factor F_v is defined as:

$$F_v = \frac{A_v\sqrt{H_v}}{A_t} \quad (m^{0.5}) \tag{22}$$

Where:

A_v is the area of vent openings;

H_v is the height of vent openings; and

A_t is the total area of internal bounding surfaces (including openings).

It can be seen from Table 2 that the times to failure are much less than the specified FRR, for opening factors of 0.02 or more.

Table 2 Predicted times to failure (t_{fail}) in minutes for assemblies with a fire resistance rating (FRR) from a standard fire test

Opening factor	Fire load											
	400 MJ/m²				800 MJ/m²				1200 MJ/m²			
	FRR				FRR				FRR			
	15	30	45	60	15	30	45	60	15	30	45	60
0.01	22	41	59	nf	22	40	60	80	22	40	60	80
0.02	12	24	38	nf	12	24	36	49	12	24	37	50
0.03	9	18	31	nf	9	19	28	38	9	18	28	37
0.04	7	15	28	nf	7	15	23	32	7	15	23	31
0.05	6	13	26	nf	7	13	20	28	6	13	20	27
0.06	5	12	25	nf	6	12	18	26	6	12	18	24
0.07	5	11	23	nf	5	11	16	24	5	11	16	22
0.08	5	10	23	nf	5	10	15	22	5	10	15	21
0.09	4	9	23	nf	4	9	14	22	4	9	14	19
0.1	4	9	14	22	4	9	14	22	4	9	13	18

nf = no failure. Fuel will be depleted before failure occurs

Conversely, and to assist setting Building Code requirements, the cumulative radiant heat energy concept was applied to determine the minimum standard furnace test result required to ensure that a safe evacuation or intervention time is achieved. These values are presented in Table 3. It can be seen that the FRR values are nearly all much larger than the required evacuation times. This work was used to set life safety requirements for the New Zealand Building Code Acceptable Solutions relating to Protection from Fire.

To test the cumulative radiant energy method, a finite difference heat transfer model was used (Collier, 1996; Collier, 2000) to calculate the fire resistance (insulation failure) of two timber-framed wall systems, lined with either 10 or 13 mm gypsum plasterboard each side. Each wall system was assessed against five parametric design fire curves and the ISO 834 standard test time-temperature exposure. Results are presented in Tables 4 and 5.

Table 3 Required FRR in minutes to ensure that safe evacuation times are achieved

Opening factor	400 MJ/m²				800 MJ/m²				1200 MJ/m²			
	Evacuation times				Evacuation times				Evacuation times			
	15	30	45	60	15	30	45	60	15	30	45	60
0.01	10	22	34	45	10	22	34	45	10	22	34	45
0.02	19	38	50	55	19	38	56	75	19	37	55	73
0.03	25	44	52	55	25	49	71	83	25	49	72	95
0.04	30	47	52	54	30	58	75	83	30	58	85	103
0.05	33	48	52	52	35	64	76	81	35	66	92	104
0.06	35	48	52	52	38	66	76	80	39	74	94	102
0.07	37	48	52	52	42	68	75	76	42	78	93	98
0.08	38	48	50	50	48	68	74	75	45	80	92	96
0.09	39	48	50	50	48	68	73	73	48	80	92	93
0.1	40	48	49	49	50	68	72	72	51	80	88	90

Table 4 Predicted performance of 10 mm fire-rated plasterboard assembly, finite difference model compared with the cumulative radiant energy method

Design fire type	Fire load (MJ/m²)	Opening factor	Time to insulation failure	
			FireBarrier (Collier, 1996)	Cumulative radiant energy method
ISO834	-	-	44.0	-
Eurocode	400	0.05	25.0	nf*
Eurocode	800	0.02	49.0	50.7
Eurocode	800	0.05	25.0	26.7
Eurocode	800	0.08	18.0	19.7
Eurocode	1200	0.05	25.0	26.7

* reached end of decay phase without failure

Table 5 Predicted performance of 13 mm fire-rated plasterboard assembly, finite difference model compared with the cumulative radiant energy method

Design fire type	Fire load (MJ/m²)	Opening factor	Time to insulation failure	
			FireBarrier (Collier, 1996)	Cumulative radiant energy method
ISO834	-	-	69.0	-
Eurocode	400	0.05	nf*	nf*
Eurocode	800	0.02	77.0	79.5
Eurocode	800	0.05	44.0	44.7
Eurocode	800	0.08	32.0	nf*
Eurocode	1200	0.05	44.0	43.0

* reached end of decay phase without failure

Considering the "insulation" failure criterion, close agreement is achieved between the results of the cumulative energy method and the finite difference modelling, with some exceptions. Where there is a marked difference these are indicated by an asterisk in the tables above. It is noted that the discrepancies occurred in the decay phase of the two Eurocode fires with FLED/opening factors of 400/0.05 and 800/0.08. In these cases the relatively low FLED to large opening factor ensures the fires burn out rapidly and enter the decay phase sooner than for smaller opening factors.

Barnett (2007a) quoted Nyman's work and also applied the cumulative radiant energy (CRE) method to fire door tests by Joyeux (2002) who found that a fire door with a standard furnace test result of 37 minutes failed in 16 minutes when exposed to a high-temperature fire curve. Application of the CRE method resulted in a failure prediction of 21 minutes. Barnett suggested that the combustible contribution of the door itself might explain the difference.

Barnett further applied the CRE method to a number of case studies where he generated compartment temperature-time histories and compared the CRE with ISO 834 furnace conditions to find an equivalent time of fire exposure to the standard furnace test. He concluded that the CRE method can be applied to different construction assemblies but may have limitations for ceilings and combustible assemblies.

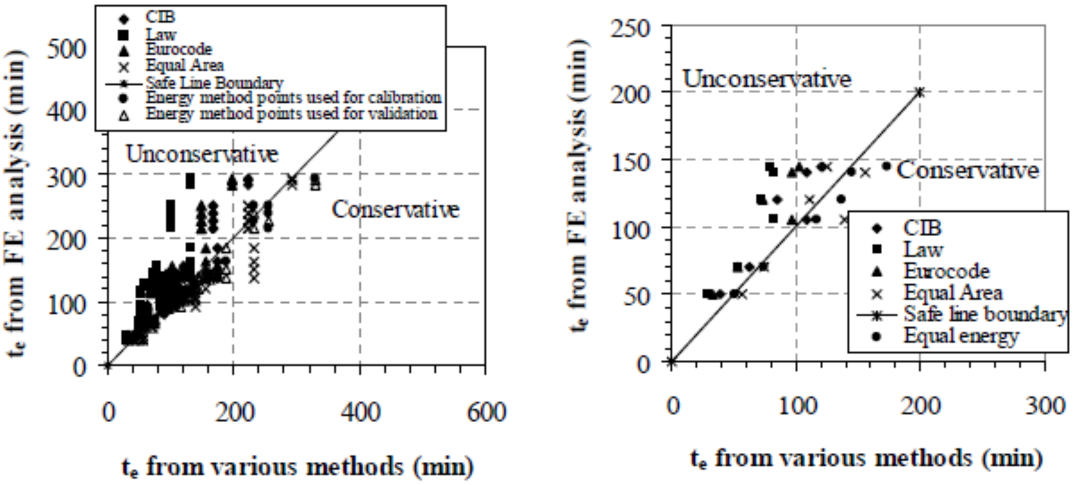
The main flaw in using the emissive power of the fire gases as representing the destructive potential of the fire on a given construction element (as measured by the temperature rise at some depth beneath the surface) is that the proportion of heat penetrating the element (the more appropriate parameter to use according to Harmathy [1987]) will be dependent on the thermal inertia of the element.

4.8 Kodur's Equivalent Absorbed Energy Method

Researchers at the University of Michigan (Kodur et al, 2010; Kodur and Pakala, 2010) developed an energy-based approach to calculating the fire resistance founded on equivalent time of exposure and with reference to reinforced concrete beams.

They used numerical heat transfer and finite element (FE) structural response calculations to generate fire resistance data based on maximum deflection criteria for a range of reinforced concrete beams and for a range of compartment fires. The compartment fires were based on the parametric fire time-temperature curve from the Eurocode (CEN, 2002) with modifications to the rate of decay as proposed by Feasey and Buchanan (2002).

They compared the fire resistance calculated from the FE numerical simulations of the deflection response of reinforced concrete rectangular, T and I beams with estimated time-equivalent using various simple formula (CIB W14, 1986; Law, 1971; CEN, 2002) and plotted these as given in Figure 10. This showed unconservative predictions by the simple formula in many cases.



(a) Comparison of time equivalent values for rectangular beam

(b) Comparison of time equivalent values for T beam

Figure 10 Comparison of time-equivalent computed, based on FE analysis with that of other methods for reinforced concrete rectangular and T beams (extracted from Kodur and Pakula, 2010)

Assuming that two fires will have the same fire severity if they transfer the same amount of energy to the concrete beam, their method involved calculating the convection and radiation heat flux on the compartment boundary with:

$$q_c = h_c(T_f - T_c) \tag{23}$$

$$q_r = \sigma\epsilon(T_f^4 - T_c^4) \tag{24}$$

Where:

q_c is the convective heat flux (W/m^2);

q_r is the radiative heat flux (W/m^2);

h_c is the convective heat transfer coefficient (W/m^{2}K);

T_f is the fire temperature (K);

T_c is the temperature on the surface of boundary element (K);

σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W/m^{2}K^4); and

ϵ is emissivity.

Assuming T_c can be approximated with T_f, the radiation heat flux could be rewritten as:

$$\begin{aligned} q_r &= \sigma\epsilon(T_f^4 - T_c^4) \\ &= \sigma\epsilon(T_f^2 + T_c^2)(T_f^2 - T_c^2) \\ &= \sigma\epsilon(T_f^2 + T_c^2)(T_f + T_c)(T_f - T_c) \\ &\approx \sigma\epsilon(T_f^2 + T_c^2)(T_f + T_f)(T_f - T_c) \\ &\approx 4\sigma\epsilon T_f^3(T_f - T_c) \end{aligned} \tag{25}$$

Thus the total heat flux can be given as:

$$q = q_r + q_c \approx 4\sigma\epsilon T_f^3(T_f - T_c) + h_c(T_f - T_c) \tag{26}$$

If we assume that the temperature difference between the fire gases and the compartment surface is a fixed ratio (α) of the fire gas temperature, i.e.$(T_f - T_c) = \alpha T_f$, we can now write the total heat flux as:

$$q \approx \alpha\left(4\sigma\epsilon T_f^4 + h_c T_f\right) \quad (27)$$

Accordingly, the total amount of energy transferred to the element is given by:

$$E = \int qAdt \approx \int \alpha\left(4\sigma\epsilon T_f^4 + h_c T_f\right)Adt \approx \alpha A \int \left(4\sigma\epsilon T_f^4 + h_c T_f\right)dt \quad (28)$$

or $E \approx \alpha A$ × area under the heat flux (q/α) curve

This estimate of the total energy assumes that the fire gas temperature can be represented as a single value for the compartment at any point in time and that the convective heat transfer coefficient is a constant. Kodur et al (2010) used a value of $h_c = 25$ W/m^{2}K and $\epsilon = 0.5$ in their study.

Using this equation, the total energy for the design fire (E_d) and for the standard fire (E_s) can be calculated, and the time at which the E_s=E_d is the equivalent time of exposure.

If α can be assumed to be the same in the furnace test as in the real fire compartment, then its actual value need not be known for determining the equivalent time of exposure. This is probably a reasonable assumption when considering the material of the test specimen or construction element is the same in both cases.

Kodur et al (2010) compared the energy-based time-equivalent value with the predicted failure time, based on deflection criteria for the reinforced concrete beam elements calculated using the FE numerical methods, and found a trend for the energy-based time-equivalent (t-e) to be non-conservative for lower compartment temperatures and conservative for higher compartment temperatures. They proposed using the following equation as a means of adjusting or calibrating the energy t-e in order to provide a conservative prediction of the t-e derived from the FE method for reinforced concrete beam elements. The equation is shown in Figure 11 giving a conservative approximation for the data points:

$$\frac{t_{e,\,\mathrm{FE}}}{t_{e,\,\mathrm{energy}}} = 1.6 - 0.0004 T_{f,max} \quad (29)$$

This approach might be useful by separately estimating fire severity and fire resistance (failure time) and applying a safety factor or calibration depending on the construction elements, i.e. a more conservative safety factor would be used for prescriptive requirements when the actual construction type is unknown and can be refined as more becomes known about the construction. The appropriate safety factors would be determined by comparison between a fire severity (energy dose) estimate and more detailed calculations of fire resistance.

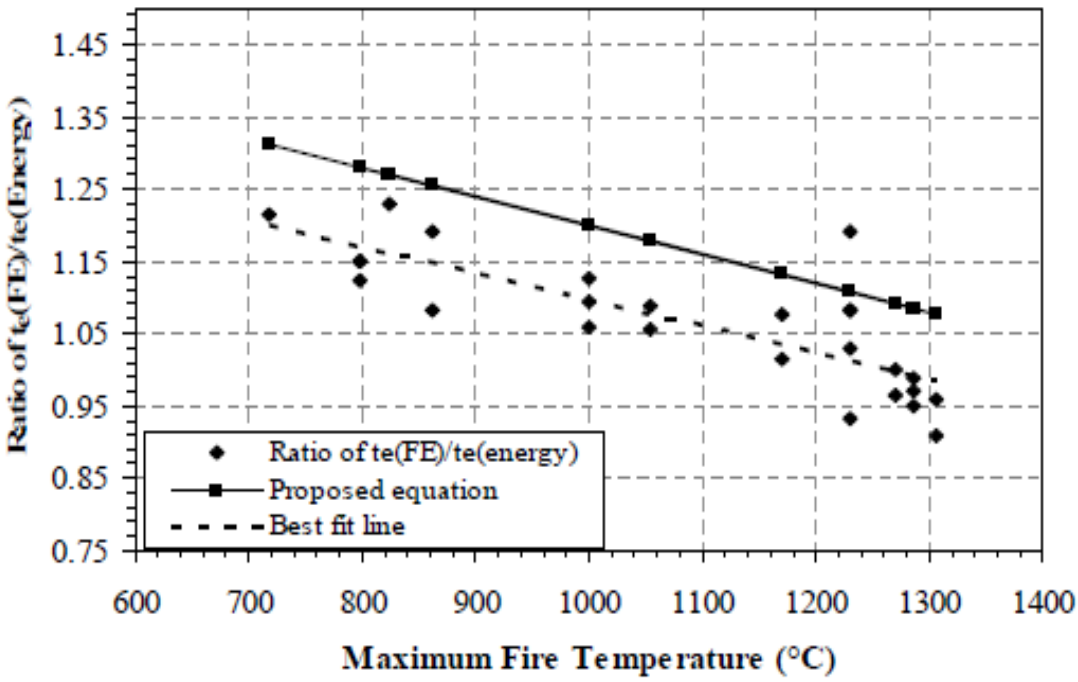


Figure 11 Variation of $t_{e,\,\mathrm{FE}}/t_{e,\,\mathrm{energy}}$ with maximum fire temperature (extracted from Kodur and Pakala, 2010)

5. GAS TEMPERATURES IN COMPARTMENT FIRES

Several of the time-equivalent approaches discussed in Section 4 require the time-dependent compartment gas temperature to be known. This can either be obtained from a fire model based on a full mass and energy balance for the compartment fire or instead an analytical equation (parametric fire) can be used. It is clear that the accuracy of the energy-based time-equivalence methods will in turn be dependent on the accuracy of the compartment time-temperature histories used in the calculations.

The parametric fires from EC1-1-2 originally based on research by Wickstrom (1985) were used by Kodur et al (2010) in the methodology described in Section 4.8 but with a modification to the rate of decay as proposed by Feasey and Buchanan (2002) to more closely match temperatures they obtained using the post-flashover fire model COMPF2 (Babrauskas, 1979).

Kirby (2004) also stated that the CEN (2002) parametric curves had been validated against a background of real fires carried out over the previous 20 years by Corus and BRE, and that in general they provided good agreement between predicted and measured temperatures, and where they did not agree the predicted temperatures were more onerous (conservative).

Other parametric curves have been developed by Lie (1974), Barnett (2002, 2007b), and Hertz (2012).

Hunt et al (2010) as part of an SFPE study assessed the performance of 23 methods for computing the time-temperature profile in an enclosure, with all methods having been published in the literature and not requiring the use of computer simulation. The methods included simplistic approaches such as a constant temperature exposure, correlations of particular data sets, generalised parametric approaches and correlations of computer-generated data. The selection process involved assessing the performance of all 23 methods against a database containing 146 fully-developed single-compartment fire tests. They identified two methods that were almost always conservative acknowledging that in some cases they may be considered to be over-conservative. Overall, the method that provided the greatest number of predictions that exceeded those derived from the test data was the 1200 °C constant temperature exposure. Of the correlations that were evaluated, the Tanaka (refined, 1996) method provided the greatest number of predictions that were equal to or greater than that derived from the test data. The recommendations from this study were incorporated into the SFPE Engineering Standard on Calculating Fire Exposures to Structures (SFPE, 2011).

It is not the intention of this report to describe in detail the different models and parametric equations for predicting the gas time-temperature histories of the compartment fires other than to note that the accuracy of the curves, both during the heating and decay periods, are important where energy-based time-equivalence is proposed and readers are referred to the literature for details of specific equations and methods.

6. DISCUSSION AND COMPARISON OF TIME-EQUIVALENCE METHODS

Time-equivalence calculations are intended to determine the length of exposure in a standard fire resistance test that results in the same fire severity as experienced in a given compartment fire. More specifically, fire severity has most commonly been treated as the length of exposure in the standard fire resistance test that results in the same maximum temperature in a protected steel element as occurs when that same protected steel element is exposed to the compartment fire.

The time-equivalent value can be determined in this way by conducting experiments or by calculations using an iterative energy balance (or fire model) to determine the time-temperature history and combined with a heat transfer calculation to determine the maximum temperature of a protected steel element.

The Eurocode formula as described in Section 4.3 is a simple empirical equation that has been developed based on comparisons with energy balance and heat transfer calculations for a protected steel element, and with measured temperatures from compartment fire experiments.

For construction elements with fire performance closely related to the maximum temperature reached by a critical element embedded within the boundary surfaces (e.g. reinforced or prestressed concrete) or steel protected with a layer of insulation, the time-equivalent calculation may provide a reasonable estimate of the expected failure time based on insulation or thermal transmission criteria in the compartment fire. However, it should not be expected to predict failure times for construction elements that fail fire resistance criteria by different mechanisms, e.g. buckling, excessive deflection or by erosion/destruction of material.

There have been other time-equivalent methods developed, mostly energy based, starting with the normalised heat load method of Harmathy in the 1980s followed by Harada et al (2000), Nyman (2002) and more recently Kodur et al (2010). Table 6 summarises some of the pros and cons of the different methods.

Table 6 Comparison of time-equivalence methods

Method	Pros	Cons	Comments
Eurocode formula (ENV 1991-1-2:2002 Annex F)	Simple empirical equation, widely used, validated	Empirical	Uses thermal inertia, FLED, vent area, floor area and enclosure height
Maximum temperature rise in protected steel section	Easy to do in spreadsheet Commonly accepted method with theoretical basis	Designed for protected steel	Basis of BS 9999 prescriptive requirements used with ENV parametric fire
Equal energy dose based on emissive power (i.e. Nyman, 2002)	Easy to calculate Can be applied at times earlier than "burnout"	Limited validation May not truly represent the destructive potential for the boundary element Ignores convective contribution	Independent of the structural element, requires only knowledge of the time-temperature gas history
Normalised heat load based on penetrating heat flux (i.e. Harmathy)	Can be applied at times earlier than "burnout"	More easily used within a model calculating energy balance and heat loss terms, unless simplifying assumptions are made to estimate the penetrating heat flux	Concept based on maximum temperature rise at a depth within a slab, assuming a semi-infinite solid A theoretically founded method
Normalised heat load (simplified method)	Easy to use	Empirical Only applies to full fire duration (burnout)	Concept based on max temp rise at a depth within a slab, assuming a semi-infinite solid
Calibrated energy dose (i.e. Kodur)	Easy to do on spreadsheet	Calibration done for reinforced concrete beams Assumes surface temperature is proportional to gas temperature and proportionality constant same in furnace and real fire	Compared and calibrated using finite-element calculations to predict failure time

7. PROPOSED ALTERNATIVE TIME-EQUIVALENCE METHOD

Time-equivalence methods have a useful role as described in Sections 4 and 6 of this report. It is helpful to list some of the ideal characteristics of such a method in order to identify the optimal approach.

Ideal characteristics of a time-equivalence method include the following:

- Theoretical basis;

- Simple to apply, i.e. able to be easily done and no more complicated than using iterative spreadsheet calculations;
- Able to be used to evaluate the destructive potential of the fire for time periods up to and including burnout;
- Able to account for ventilation, thermal properties of the compartment and the fire load;
- Be independent of the specific characteristics of the structural system (i.e. steel properties, maximum temperature reached, insulation thickness and thermal properties etc.);
- Able to be applied using a specified time-temperature history for the fire gases, as well as when using a first principles energy balance; and
- Of known accuracy with reference to common materials and systems.

An energy-based time-equivalence method using the absorbed heat flux satisfies all of the above attributes with the exception of the last. Experimental investigation will be required to better assess the accuracy and limitations of the approach with respect to specific types of materials and assemblies.

The absorbed heat flux is considered more relevant than the incident flux alone (at least for fire separations and protected structural elements), or the emissive power of the fire gases (as proposed by Nyman, 2002), because it determines the flow of heat into the boundary elements which affects the subsequent rise in temperature within that boundary element. The implicit assumption here is that ability of the construction to survive the fire is closely associated with the temperature reached within the depth of the assembly.

There are various expressions that could be used to estimate the penetrating heat, including equations derived from heat transfer to a semi-infinite solid due to a constant heat flux at the surface such as those presented by Harmathy (1987) and Harada et al (2000). However, it is proposed here to use the general expression for the total heat flux as presented by Kodur et al (2010) based on a heat balance at the surface of the bounding construction.

The proposed methodology for estimating the FRR would result in the compartment boundary being exposed to the same destructive potential in the furnace test as it would in the compartment fire after a specified period of time, as follows:

1. Determine a time-temperature history for the gas temperature in the compartment fire from a parametric equation or fire model; and
2. Using a timestep of say one minute, calculate the heat flux q (W/m^2) absorbed at the surface of the construction element concerned in the compartment at each timestep. The net heat transfer to the surface can be estimated using equation (27 (Kodur and Pakala 2010) –

$$q = q_r + q_c \approx 4\sigma\epsilon T_f^3\left(T_f - T_c\right) + h_c\left(T_f - T_c\right) \approx \alpha\left(4\sigma\epsilon T_f^4 + h_c T_f\right)$$

Where:

q_c is the convective heat flux (W/m^2);

q_r is the radiative heat flux (W/m^2);

h_c is the convective heat transfer coefficient (≈25 W/m^{2}K);

T_f is the fire temperature (K);

T_c is the temperature on the surface of boundary element (K);

σ is the Stefan-Boltzmann constant (5.67 x 10-8 $Wm^{-2}K^{-4}$); and

ϵ is emissivity (≈0.5).

Assume that the temperature difference between the fire gases and the compartment surface is proportional to the fire gas temperature, i.e. $(T_f - T_c) = \alpha T_f$ where α is a constant.

As an approximation, assume that the value of α is the same, when the same element is exposed to the compartment fire and to the standard fire resistance test, such that its actual value need not be known.

3. Calculate the total absorbed heat (with units J/m^2) by integration over the time period of interest τ using equation (28. This can be easily done in a spreadsheet using a simple trapezoidal technique –

$$Q = \int_0^\tau q dt$$

$$\frac{Q}{\alpha} = \int_0^\tau \left(4\sigma\epsilon T_f^4 + h_c T_f\right) dt$$

4. Repeat the calculation (step 2 and 3) using the time-temperature curve for the standard fire resistance test, where the gas temperature can be described by –

$$T_f = T_0 + 345 \log_{10}(8t + 1)$$

Where:

T_0 is the ambient temperature at the start of the test;

T_f is the furnace at time t; and

t is the elapsed time (minutes).

5. Determine the time when the total absorbed heat for the compartment fire is reached under the standard fire resistance test. This time is the equivalent time of exposure.

Note that this method compares the calculated result, using the standard time-temperature history, with that using a known time-temperature history for a compartment fire, assuming the fire gases behave as a gray body radiator, i.e. $\varepsilon < 1$. Any influence of the compartment thermal properties (where they are different from the test specimen) is only accounted for as part of determining the compartment time-temperature history.

While the equivalent time of exposure could be used as a basis for quantifying the destructive potential of the fire on a given construction element and as a basis for setting fire resistance requirements, it cannot be relied upon to provide an accurate prediction of the expected failure time in a compartment fire.

8. TIME-EQUIVALENCE AND COMBUSTIBLE CONSTRUCTION

Existing time-equivalent methods do not explicitly allow for materials that burn or char during or following consumption of the primary fuel load within the compartment.

It is hypothesised that the current methods may not be appropriate for evaluating the performance of assemblies with combustible materials because once these materials burn or char they may continue to be consumed after the fire intensity decays. This continued self-sustaining degradation of the fire-rated elements may be significant and result in eventual failure of the element or assembly, even after the contents of the compartment have been consumed. Thus, applying the concept of “withstanding burnout” may not be appropriate unless it can be assured that either the degrading material does not get involved or else continued degradation of the material ceases at some point and the residual structure continues to maintain stability or prevent fire spread depending on the design objective. For example, for gypsum plaster-lined and timber-framed assemblies, a temperature-based time-equivalence method could be based on preventing the onset of char.

The specification of fire resistance ratings for combustible construction to ensure structural adequacy or prevent fire spread requires much additional research.

9. REGULATORY APPLICATION OF TIME-EQUIVALENCE

A task group of the BSI Committee FSH/14/-/2 carried out an investigation intended to develop a new set of tables for BS 9999 (BSI, 2008) setting out required fire resistance ratings. The task group’s approach was based upon a combination of engineering calculations of time-equivalence and risk assessment (Kirby et al, 2008).

A graphical approach was adopted by the task group that related the maximum temperature of a protected steel element in a compartment fire to the time taken to reach the same temperature in a standard fire resistance test. The basic calculation model used the EC1-1-2 parametric time-temperature equation (CEN, 2002) with fire load, ventilation opening factor, compartment size and thermal inertia as the main inputs to generate the fire gas temperature. This became the thermal boundary condition used to calculate the maximum temperature reached in protected steel members (with steel Hp/A, load ratio and insulation thickness and thermal properties as inputs). The final part of the calculation was to determine the time in the standard fire resistance test when this same maximum steel temperature would be reached and this was the time-equivalent value.

A Monte Carlo analysis was carried out involving up to 200,000 simulations for each occupancy with inputs randomly chosen within specific ranges considered applicable for that occupancy, except for the thermal properties of the compartment which were fixed to represent a well-insulated building. The output from the Monte Carlo analysis provided a plot of the cumulative percentage fractile time-equivalent. A typical example is shown in Figure 12.

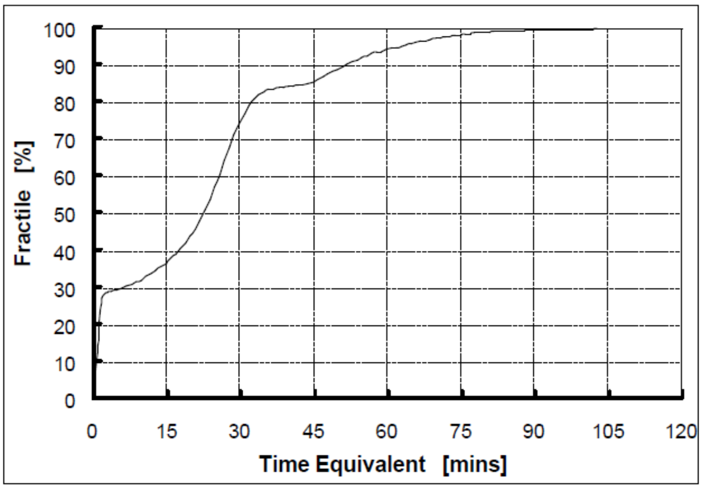


Figure 12 Typical plot of cumulative fractile versus time-equivalent (extracted from Kirby et al, 2008)

The task group argued that the overall risk in a multi-storey building could be treated as proportional to the square of the height, given both the frequency of fire and the consequence of fire could be related to building height. They also proposed that an 80% fractile design value could be treated as acceptable for an 18 m high building and this could be treated as the relative risk measure, against which other building heights could then be assessed. Table 7 shows the fractile percentage values selected as the basis for specifying the appropriate fire resistance level for different building heights. Table 8 shows the fire resistance levels proposed by the task group for different unsprinklered occupancies and different height ranges. Further details regarding the investigation and the results obtained can be found in the task group report (Kirby et al, 2008).

Table 7 Consequence rating versus building height

Height m	Fractile %	Consequence rating
0-5	20.0	1
5-11	46.4	2
11-18	80.0	3
18-30	92.8	4
30-60	98.2	5
>60	99.6	6
****	100.0	7

Table 8 Non-sprinklered buildings: proposed fire resistance periods (extracted from Kirby et al, [2008])

Occupancy	Building Height m					
	0 - 5	5-11	11-18	18-30	30-60	>60
Dwelling $	60#	90	105	120	135	150
	30	60	60	90	N/P	N/P
Hospital	30*	60	75	90	120	120
	30*	60	60	90	120	120
Hotel	30	45	60	75	90	105
	30	60	60	90	120	120
Office	30+	30	60	90	120	150
	30	60	60	90	N/P	N/P
Retail	30	45	75	105	135	180
	60	60	60	90	N/P	N/P
Assembly (low)	30	30	60	75	90	105
	60	60	60	90	N/P	N/P
Assembly (med)	30	45	75	105	135	180
	60	60	60	90	N/P	N/P
Assembly (high)	30	45	90	120	180	240
	60	60	60	90	N/P	N/P
Manufacturing (low)	30+	30	75	90	120	150
	60	90	90	120	N/P	N/P
Manufacturing (high)	60	105	180	240	300	300
	60	90	90	120	N/P	N/P

Notes:
+ Reduced to 15minutes when maximum ground floor area is limited to 1000m^2
$ 15 minutes reduction when compartment size is limited to 10% of floor area on each floor
# Reduced to 30 minutes for single owner occupancy
* Increased to 60 minutes in accordance with NHS Code
Shaded background - not permitted without sprinklers
AD-B values in blue font
Comparison with AD-B (**Red font: increase in FR**, **Green font: decrease in FR**, **Black font: no change**)

10. CONCLUSIONS

For determining fire resistance rating requirements, time-equivalence as a concept should be considered to be the length of time exposed in a standard fire resistance test that results in the same destructive potential (or severity) experienced in the compartment fire. This approach has utility since the vast amount of fire performance data previously gathered from standard fire resistance tests can still be used in the analysis of compartment fires even though the gas temperature history may differ from that in a standard fire resistance test.

This definition of time-equivalence is however subtly different from equating the times of failure in a standard fire resistance test with the time of failure in a compartment fire, although there is likely to a strong link between the destructive potential of a fire and the time to failure for many construction elements. This means that the use of time-equivalence methods such as those discussed in this report may at best be considered to provide only first-order estimates of time to failure in compartment fires. They are best not used as part of a performance-based structural fire design for key load-bearing structural elements, without thorough understanding of the limits of application and extent of validation of those methods against more accurate calculations or measurements of the fire behaviour of specific types of building elements.

Time-equivalence methods seem most useful for determining the fire resistance ratings required when little is known about the specific materials and type of construction to be used, e.g. to inform prescriptive Building Code compliance documents. They might also be used for building elements for which the consequence of failure is considered less critical (e.g. ratings of external wall elements designed to limit radiation received at a site boundary in contrast to columns supporting a high-rise building).

The concept of withstanding burnout is liberally used within the New Zealand Building Code Protection from Fire Clauses and Verification Method, and can be taken to mean the construction continues to perform its function as a barrier or load-bearing structure following exposure to a compartment fire for its full duration including any decay period. Using time-equivalence methods to specify a fire resistance rating sufficient to withstand burnout does not provide certainty that the functional requirements of the Building Code will be achieved (i.e. no collapse or fire spread prevented).

The usefulness of time-equivalent methods are limited by the accuracy to which the compartment fire temperatures or heat fluxes can be predicted. Therefore improvements made to post-flashover compartment fire models, together with an appropriate time-equivalence method, will allow the design of fire resistant construction to be optimised.

The suggested way ahead is to use an energy-based time-equivalent calculation principally founded on the absorbed heat flux by the compartment boundaries to quantify the fire severity of the compartment fire. A series of calibration or correction factors could then be developed which when applied to the energy time-equivalent value would allow conservative estimates to be made of the actual expected failure times in the compartment fire, similar to Kodur's approach. These correction factors no doubt will be different for different types of construction and failure mechanisms and an upper-bound generic value could be identified for use when the actual construction elements were unknown, with one application being to inform prescriptive code requirements.

11. FUTURE WORK RECOMMENDATIONS

In light of the material discussed in this report and the conclusions stated above, the following recommendations are made for further research on this topic.

- Extend spreadsheet methods using graphical time-equivalence methods to include simplified formula for predicting temperature of unprotected steel, reinforced steel in concrete slab and depth of char in heavy timber construction as alternative graphical time-equivalent approaches based on parametric time-temperature equations;
- Construct Monte Carlo models from the spreadsheet methods developed for sensitivity analysis and to construct cumulative density functions for time-equivalence;
- Extend the functionality of existing zone models, such as B-RISK, to include the calculation of Harmathy's normalised heat load parameter within a zone model for fully-developed fire (B-RISK) for the room of origin, using the thermal inertia of enclosure boundaries and the calculated heat flux penetrating the ceiling, upper/lower wall and floor. This provides a single scalar measure of the destructive potential of the fire and provides a comparison with the length of the exposure to a standard fire resistance test producing the same value of normalised heat load;
- Investigate a new simplified time-equivalent method based on absorbed energy dose and parametric time-temperature curves;

- Investigate the accuracy of parametric time-temperature curves;
- Investigate whether a time-equivalent method based on emissive power of the fire gases is more suitable for unprotected steel or other critical elements which are directly exposed to the fire;
- Investigate the relationships between equivalent fire severity or destructive potential of the fire and the failure time for specific types of construction in compartment fires;
- Determine the normalised heat load parameter applicable to the BRANZ fire resistance furnaces;
- Develop and carry out an experimental programme using a fire resistance test furnace to expose test specimens to standard and non-standard fire temperature curves; and
- Develop and carry out an experimental programme using real compartment fires to expose test specimens of known performance in standard fire resistance tests.

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