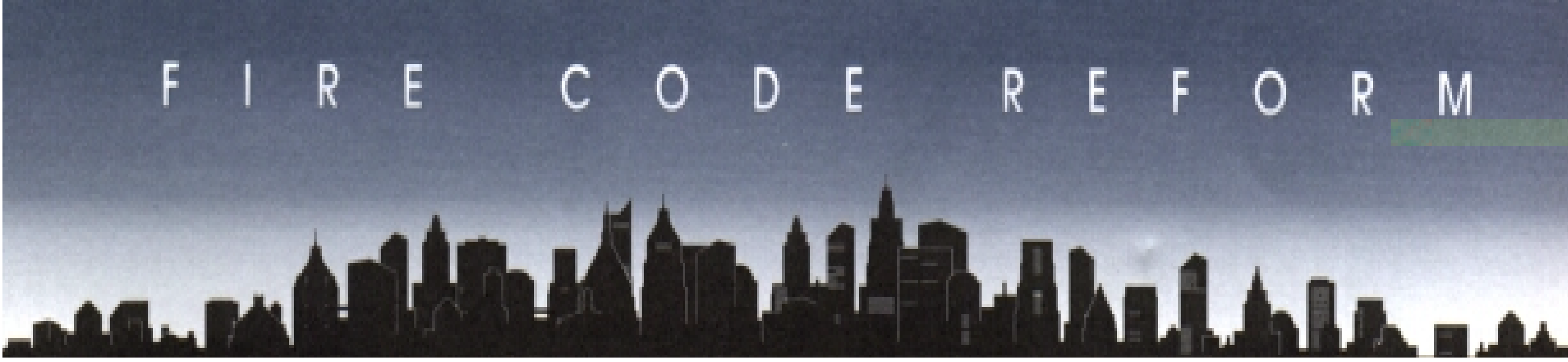


Project Report
FCRC-PR 99-03

Fire Resistance And Non-Combustibility

Evaluation of Fire Resistance Levels: Techniques, Data and Results

FCRC Project 3 Part 2
Fire Resistance and Non-Combustibility

Fire Code Research Reform Program
December 1999

Acknowledgements

Since inception of the Fire Code Reform Research Program in 1994 the Australian Building Codes Board has been its principal financial contributor. Substantial funds have also been provided by Forest and Wood Products Research and Development Corporation and generous contributions have been received from a number of industrial and financial entities and individual donors.

The Board and management of Fire Code Reform Centre Limited acknowledge with sincere thanks receipt of all these financial contributions. The company also acknowledges the kind permission of the three major research organisations involved in this work for permission to re-produce and publish this document.

Comments

Comments on the content or other aspects of this document are always welcome and should be addressed to:- Fire Code Reform Centre Ltd, Suite 1201, 12th Floor, 66 King St, Sydney, NSW 2000, Australia. Tel. No: +61 (2) 9262 4358. Fax No: +61 (2) 9260 4255.

Fire Code Reform Centre

PROJECT 3

FIRE RESISTANCE AND NON-COMBUSTIBILITY

PART 2

EVALUATION OF FIRE RESISTANCE LEVELS: TECHNIQUES, DATA AND RESULTS

November 1999

Level 4 Rockliffs Chambers
50 King street, Sydney 2000
NSW AUSTRALIA

FIRE CODE REFORM RESEARCH PROGRAM

PROJECT 3

REQUIREMENTS FOR FIRE RESISTANCE AND NON-COMBUSTIBILITY

PART 2
EVALUATION OF FIRE RESISTANCE LEVELS:
TECHNIQUES, DATA AND RESULTS

DECEMBER 1999

EXECUTIVE SUMMARY TO REPORT

This document sets out the techniques, data used and results of FCRC Project 3.

Estimates of the fire resistance required for the range of buildings covered by the BCA have been developed, based on limited data. The data is inadequate to cover the range of situations that the BCA is expected to cover.

Tables in Appendix J provide a rational estimate of the FRLs required for many of the enclosures in buildings covered by the BCA. Many of the estimated FRLs are similar to those currently required by the BCA. However, many are also greater than those required by the BCA.

It is not recommended that FRLs in the BCA be increased as there is no indication in the fire record that the current FRLs are unsatisfactory.

Many factors that affect estimates of the severity of fires in enclosures. The FRLs in the BCA are necessarily conservative for the majority of situations. They are only appropriate for the more extreme situations on which that are based. Therefore determination of reduced FRLs by designers using appropriate estimation techniques should be facilitated. To not do so is equivalent to saying all structural members in each class of building shall be of a certain (very large) size, and that the normal method of structural design cannot be used.

Attention of readers is particularly drawn to the Appendices where detailed summaries of work undertaken in many areas are given.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THIS REPORT

The purpose of Fire Code Reform Centre Project 3 was to develop a rational methodology for the calculation of fire resistance levels, to apply it to the elements which require an FRL within the BCA, and on the basis of the results to make recommendations to ABCB as to how the BCA should be modified. The Part 1 report for this project outlined a methodology for the calculations to be carried out, which was developed starting from several assumed objectives for the role of fire resistance requirements within the BCA. This Part 2 report develops the methodology in detail, presents the calculation techniques used and gives the data which was been gathered for input to the calculations together with the calculations and resulting recommendations.

Because many of the terms used in discussing fire resistance are not well understood, or are used loosely, and some new ones have been defined for this project, a list of definitions which will be used throughout this report is given in Appendix A, together with the notation which is used. Defined terms are highlighted in the text where first used in **bold** typeface.

1.2 SUMMARY OF PART 1

The objectives of Project 3, as outlined in the Part 1 report, were:

- To examine the basis of existing requirements for non-combustibility and fire resistance in the BCA[1].
- By considering likely fire severities, to establish the basis on which fire resistance levels should be specified to achieve the regulatory intent and objectives of the BCA.
- To establish the levels of performance required for different methods of construction and occupancy categories.
- To establish the role of non-combustibility in delivering the fire-safety objectives.

Part 1 examined the basis for requirements for fire resistance identified on the basis of the existing BCA, the perceptions of the industry and the statistical evidence, that there was a case for review of fire resistance and how it is determined. In the process of rationalising these tasks a set of **performance levels** was defined that can be applied to all building elements that are currently required to have a fire resistance level. In this process the Part 1 report introduced a number of important concepts which it is worthwhile to review here.

Fire resistance requirements relate to construction that is required to function either as a barrier to smoke and/or fire, or as a structural element. The performance required of a barrier or structure is the maintenance of necessary attributes while exposed to a fire of a certain

[1] For the purposes of this project, the term "BCA" refers to the Building Code of Australia 1990 Amendment No 9, without state variations

intensity for a specified time. For barriers, the necessary attribute is their ability to resist the passage of smoke or fire, which is ultimately reflected in the FRL criteria for integrity and insulation. For structure the necessary attribute is stability under load, which is reflected in the FRL criterion for structural adequacy.

For the purposes of this report, a **fire compartment** has been defined as given in Appendix A.

The early work on providing solutions to the tasks posed by Project 3 involved the identification of a set of performance levels which barriers and structure must achieve.

For barriers, the performance levels described below apply to internal and to external barriers and will influence FRL criteria for integrity and insulation. The barrier system is composed of elements that provide protection from the effects of fire and would typically include walls, doors, floors/ceilings, roofs and windows.

> **Level 1**: relates to barriers in place to limit the passage of smoke early in a fire. The duration for performance is the expected period of time in which people will reach a place of safety.
>
> **Level 2**: relates to barriers which must survive exposure to fire to provide protection for escape routes. The duration for performance is the expected time in which people will reach a place of safety.
>
> **Level 3**: relates to barriers which must survive exposure to fire to provide access for firefighters. The duration for performance is the expected time of arrival of the fire brigade plus the expected time for them to set up firefighting and rescue operations and stop the fire growth.
>
> **Level 4**: relates to barriers which limit fire spread to a fire compartment. The duration for performance is the expected time of arrival of the fire brigade plus the expected time for them to set up firefighting and rescue operations and stop the fire growth.
>
> **Level 5**: relates to barriers which are there to prevent fire spread where firefighting operations are significantly delayed or unsuccessful. The barriers are therefore required to survive burnout. Barriers requiring this level of performance are those which must survive even in the very unlikely event of no or ineffective fire brigade intervention.

In considering the Performance Levels proposed above, it is assumed that a barrier includes all of the structure required to maintain its effectiveness. A barrier also includes all openings through it. Therefore windows, doors, shafts, and shutters must achieve at least the same function as the barrier in which they are located, unless it can be shown that the barrier performance is not adversely affected by alternative arrangements.

The different functions and Performance Levels are indicated in Table 1.1.

In undertaking a similar study on performance of the structure expressed in terms of real fire response, it needs to be noted that fire does not simultaneously attack all structural elements, even when it may be said that the whole building became (eventually) involved in fire. Local failure of part of the structure may not lead to significant collapse, as loads may be redistributed through other elements not affected by the fire. Buildings have been seen to perform better than expected judged by simple single-element analysis. Therefore it is necessary to distinguish between **critical structure** and **non-critical structure** as defined in Appendix A.

Although the necessary attributes of barriers and load-bearing structures are different, performance is defined in terms of the same fire intensities and durations. It is assumed that smoke will have no impact on structure, and Level 1 may therefore be ignored.

> **Level 2**: relates to the stability required of structure contributing to the proper functioning of escape routes, which will include all floors. The duration for performance is the expected time in which people will reach a place of safety.
>
> **Level 3**: relates to the structural stability of structure required to provide access for firefighting. The duration for performance is the expected time of arrival of the fire brigade plus the expected time for them to set up firefighting and rescue operations and stop the fire growth.
>
> (Level 4 is not relevant, since it deals with barriers exclusively.)
>
> **Level 5**: relates to the behaviour and structural stability of critical elements to prevent collapse in the case of burnout.

From the above, it can be seen that performance levels can be found for any building element that is required to resist fire. It should not be assumed however, that the FRL for an element that is required to perform to Level 5 will be greater than that of an element that is required to perform to Level 3. The quantification of the FRL from the performance level will depend on the severity of the fire **and** on the time during which the element must continue to perform its intended function. Thus, for example, barriers protecting an escape path in a large building with long escape times might require higher FRLs than barriers in another part of the same building or in a different building that are required to perform to Level 4.

The severity of a fire (**fire severity**) may be thought of as a combination of the temperatures reached and the duration of those temperatures. Thus fire severity is can be thought of as a maximum temperature and the duration of high temperatures. This is dependent only on the fire. Fire severity is discussed further in Sections 3 and 9 and in Appendices H and I.

However, because of the levels of performance defined above for elements with different purposes, depending on the purpose (and thus level) a **duration** of exposure less than the duration of high temperatures might be appropriate. Thus the required duration of performance depends on the purpose (Level) of the element. (Determination of the durations is discussed further in Section 7.)

TABLE 1.1- Fires which challenge fire resistant barriers and structures

		Critical Structure	Non-critical structure	Internal fire barriers	Boundary fire barriers
Protect people in escape routes	from smoke			1	
	from fire			2	
	from collapse	2	2		
Limit fire spread				3	
Protect fire fighters	from smoke				
	from fire			4	
	from collapse	3	3		
Protect neighbours	from fire				5
	from collapse	5			

hot smoke for escape duration	1
room fire for escape duration	2
compartment fire for fire access duration	3
compartment fire for fire access duration	4
burnout	5

2 CALCULATION OF REQUIRED FRLS

2.1 GENERAL

This section outlines the calculation steps that have been used in deducing the necessary fire resistance levels of barriers and elements of structure. As will become apparent in the report, a number of alternative approaches have been considered through the life of the project, and work has been undertaken to establish the data required as input to the various stages. The identification of relevant input data to the calculations and the gathering of such data has been an important part of this phase of the project.

The calculations have been undertaken for each occupancy in the BCA.

2.2 CALCULATION STEPS

The following steps were used for each occupancy:

- establish enclosure size(s), ventilation and fire load
- derive fire severities (maximum temperature and duration) based on enclosure size, ventilation and fire load
- for each fire severity determine the FRL required to ensure no failure for the duration required (for each of evacuation time, fire brigade control time and duration of high temperatures)

2.3 COMMENT

The above steps form the core of the approach outlined in this report. The calculations outlined represent a deterministic approach to the problem.

3 DETERMINATION OF FIRE SEVERITY

3.1 GENERAL

For the purposes of this project, it will be necessary to quantify fire severity, on an occupancy by occupancy basis, in order to be able to calculate the FRL values necessary to meet the performance Levels. In practice, fire severity is most usefully expressed in terms of a temperature-time curve to which an element will be exposed. Under the effects of this fire severity the element will required to survive for a time which is determined by the its role in the building. Clearly the greater the temperature reached in the fire, and the longer the period for which high temperatures are sustained, the more severe will be the fire.

3.2 PARAMETERS GOVERNING FIRE SEVERITY

The most important factors governing fire severity have been shown in the past to be fire load and ventilation in the enclosure of fire origin. Fire load is usually expressed in terms of the quantity of material available to burn. Most fires which pass flashover and enter the fully developed phase become ventilation controlled. In other words, the ventilation determines the amount of air that can reach the fire, thereby limiting its peak heat release rate. In addition to ventilation, **enclosure** size is important, particularly for large enclosures. How these aspects can be incorporated into a general fire severity model remains to be discussed in this document. The nature and quantity of the combustibles obviously vary with occupancy, as do the characteristic enclosure shape and ventilation characteristics (if such characteristic values exist). Assuming that they can be meaningfully defined these provide parameters for determining how FRL requirements should vary between different building uses.

It will be noted above that use is made of the term 'enclosure' rather than the 'compartment' of fire origin. A compartment is by definition bounded by fire resisting barriers; an enclosure simply represents the room in which the fire arises, which may, or in many instances may not, be a fire compartment. However, it is the influence of the enclosure which determines to some extent the early growth and development of the fire, and it is only when the immediate enclosure barriers fail that it becomes necessary to start to think in terms of the fire compartment. Many enclosures, whilst possibly not required to have fire resisting walls by regulation, may indeed have walls with inherent fire resisting properties for structural, insulation or acoustic reasons. The statistical surveys reported in Part 1 of this report suggested that a large proportion of fires are confined to the room of fire origin, but a very small proportion of those that have spread beyond the room of origin are confined to the compartment of fire origin.

It has become apparent that the total enclosed area serviced by a vent or opening is the important area, not simply the area of the individual rooms. The barriers and structure near the vent(s) (particularly at the upper level of the room) "see" the fire throughout the fire in the whole area, not just when it is in the enclosure nearest the vent.

3.3 APPROACHES CONSIDERED

Two approaches were considered in detail in the early stages of this project. The first was based on well established correlations which have been used for many years to generate fire temperature-time curves and to provide a means to calculate fire resistance through the intermediary of a concept known as the t-equivalent. These correlations are generally based on fire load per unit area of the compartment, dimensions of the compartment and factors relating to the ventilation. However, it became apparent at an early stage that these correlations could not predict the results of recent experiments carried out by British Steel in the UK. These have demonstrated significant unforeseen effects, in particular non-uniformity of burning in the enclosure and extended times of burning in deep compartments.

The concept of t-equivalent was also considered but rejected. This concept is possibly useful in calculating the response of exposed steel to fire, where failure may be characterised by a critical temperature. But it is of less use with insulated steel, and other materials that require an extended period of exposure before failure. The usefulness of the t-equivalent concept has also been questioned by Law, who recommends that survival periods are calculated directly.

The review of existing calculation methods for fire severity fire resistance is given in Appendix B. Also included in Appendix B is a comprehensive review of the correlations to be found in the literature with respect to the prediction of enclosure temperature. Once again, these were not thought to be comprehensive enough for use in the present study.

The second approach considered was the adoption of a fire model to generate temperature-time curves to characterise fire severity. The purpose was to generate automatically a set of temperature-time curves for use in the project on the basis of enclosure characteristics and fire load. Early progress involving the use of the model CFAST gave very promising results. However, later comparison with large-scale test data produced very poor agreement and results that were highly questionable physically in terms of the fire temperatures particularly those generated for high fire load fires. It was essential that a model should be able to generate the fire curves automatically: post optimisation of the results on a case by case basis was considered to be unsatisfactory. Similar problems occurred with other models tested.

3.4 CURRENT APPROACH

In the absence, as discussed above, of any certain way forward using simple correlations based on equivalent fire resistance, nor the possibility of using a fire model to generate the post-flashover fire severity, a decision was taken to review as much as possible of the available literature on large scale fully developed fires. The aim was to see whether or not it would be feasible to generate correlations that would give fairly simple but conservative techniques for the generation of fire temperature and duration. The literature survey revealed that there is not a great deal of data relating to fire experiments in large enclosures, and in most of these the fire load density was not high. There is a concentration of tests in enclosures about 3 to 4 m (roughly) square and about 2.4 to 3 m high. There are tests in larger enclosures but very few in large enclosures. The largest we are aware of were the British Steel tests in enclosures about 22 m deep by 6 m wide and 2.7 m high.

The results in the latter tests were of great interest in that the pattern of temperature-time curves generated within the enclosure showed clearly that though the combustible material was evenly spread throughout the compartment, and though it was all ignited simultaneously, the pattern of burning was far from even. It was apparent that burning in the early stages was concentrated at the end of the enclosure nearest the opening and that, as the fuel was consumed, the burning front moved back into the enclosure. The structural member closest to the opening were exposed to the greatest level of fire severity, as they were receiving hot gases flowing towards the opening throughout the fire duration. In contrast those members furthest from the opening were exposed to the least level of fire severity in terms of the temperature and duration of the fire at that point.

It should be noted however that even these enclosures are not large compared with the dimensions of many of the enclosures considered to be relevant for many of the BCA building classes.

The data given in the literature was analysed to establish fire duration. It was observed that the fires exhibited growth periods that were highly variable, and decay periods also that changed from fire to fire, neither of which were thought to be of great significance in terms of the required fire resistance for barriers and structure. Therefore, a decision was taken to limit the measured duration of the fire to the time for which the maximum compartment temperature remained above 500ºC. Whilst being somewhat arbitrary, it was thought that structural materials would not be affected significantly below this temperature, either in the growth phase or the decay phase of the fire. It is of course perfectly possible to analyse the results with a different cutoff, so the approach does not lose its generality as a result of this choice. All of the variables recorded in the literature for the fires under consideration were noted.

An extensive search was conducted for a regression expression that accurately predicts the fire duration. The best fit that was obtained related fire duration to the total fire load, the opening width and the opening height. This is an interesting result. Conventionally it has been found or assumed that the duration of burnout is related to the fire load density, not to the total fire load as was found here.

As with all correlations, great care has to be exercised in their use. As noted above there is little data on deep compartments apart from the work conducted by British Steel, and there is no data on wide compartments (where the enclosure wall containing the opening is long in relation to the depth of the compartment). It seems entirely reasonable to assume (as in fact British Steel did) that a wide compartment behaves in a similar manner to a row of cube-shaped enclosures, this has not been demonstrated experimentally. In order to investigate qualitatively the behaviour of fires in enclosures that are far from cubic, a small-scale experimental programme has been set up, to be described below. It should be noted that, though initially included in the regression analysis, there was little effect of enclosure insulation on the enclosure temperatures (although there was some effect on the duration of high temperatures in some cases), even though this was varied in some of the experiments considered. This conclusion is in line with the analysis of Law, who also failed to see any affect in the comparison of a set of large-scale test data (some of which was the same data used in the current analysis).

A similar approach based on regression analysis of the temperature data obtained from the fire curves is currently being adopted. Clearly, it would be unduly conservative to describe a fire by its absolute maximum temperature, and a “average” maximum temperature for the fully developed phase is being used to characterise the measured results, which will be used to predict characteristic temperatures for the fire severities under consideration.

The British Steel data, though compelling, is limited. A decision was taken therefore to undertake a very large set of small scale experiments the results of which could be included with the large scale experiments in deriving temperature-time correlations. These experiments were conducted mainly on enclosures of 300mm and 600 mm wide x 300mm high, and of varying depth up to 1500mm. Some experiments were also conducted on wider enclosures 300mm and 600 mm deep. The ventilation factor has been varied: the fire load (alcohol burning in trays) was maintained throughout. In addition several experiments in similar enclosure have been conducted with wood cribs as the fuel. These experiments are reported in more detail in Appendix H Calculation of Burnout Times.

The results of this small-scale programme have confirmed the results of the British Steel experiments. The burning zone progresses from the opening to the rear of the enclosure. The results suggest that it is correct to assume that a wide enclosure behaves like a row of narrower enclosures side-by-side. A regression study has been conducted using all of the available data. In the end though, although there is a very large number of small scale tests the large scale data dominate the final regression relationship.

3.5 CALCULATION OF FIRE RESISTANCE

To determine Fire Resistance Level, the period of survival in a test furnace is determined subject to a standard temperature-time curve. In Australia, the construction of the furnace and the shape of the temperature curve is determined by AS1530.4-1990. This Standard is identical to ISO 834:1975, which has been widely adopted throughout the world. There is a vast body of test data available from around the world that relates to the performance of building elements when subjected to these standard conditions. It is the purpose of the work of this project to ensure that these test results can still be used and to define the required performance of building elements ultimately in terms of these test results.

In a real fire situation the temperature history to which a building element is subjected is not the same as the standard curve and depends on the fire severity and duration of exposure. Fire severity of a post-flashover fire is related to the ventilation and thermal properties of the building. The time of exposure is related to the time for which the element must perform. In real fire situations, the temperature-time history which a building component is required to withstand depends on the building and occupant characteristics. The temperature in the standard furnace rises slowly in comparison to the rate of temperature rise achieved in real fire conditions. The furnace temperature is programmed to reach about 900ºC in an hour. A rapidly developing fire in a small room could peak at temperatures in excess of 1000ºC in less than 10 minutes from ignition, and could have burnt out in 20 minutes.

However unrepresentative the standard furnace may be, the range of data which has been derived from it over the years suggests that for the foreseeable future it will be highly desirable to rely upon its results for the regulation of barrier and structural performance in fire. The challenge of Part 2 of Project 3 is therefore two-fold. It is necessary on the one hand to generate fire severities which are representative of real fires. In the second place it is necessary to translate these fire severities into fire resistance levels as measured in the standard test.

The challenge of translating real fire performance into performance in a furnace test has been become known as the calculation of "equivalent fire resistance" for the elements so exposed, and has received much attention in the literature. The following provides a review of the methods that have been developed. Some of these methods have been reviewed in more detail by Harmathy (1987).

3.6 EXISTING METHODS

Equivalent fire exposure is defined as that length of the heating period in a standard furnace test which gives the same critical effect on a structural element with respect to failure as the complete process of the compartment fire (Pettersson (1985)). A number of different methods have been used to assess equivalent fire exposure:

- equal temperature-time areas,
- equal temperature rises,
- normalised heat load concept, and
- equal strength criteria

Each of these techniques is discussed in detail in Appendix B of this report. These are all simplified techniques and each has its drawbacks in terms of failing to reflect the actual correspondence between performance as measured in a test and performance as observed in a fire. Ideally, the goal is to derive a correlation which when applied to an element of known fire resistance as measured in a furnace will generate the performance which will be expected under exposure to a real temperature-time curve. This is in many ways an unrealistic goal, and the fact that many researchers have resorted to the above simplified techniques is evidence in itself that no simple correlation is likely to emerge. There are a number of reasons why this is likely to be so. In the first instance, the measured fire resistance in a test and the performance in a fire are functions of complex interactions of heat transfer, both to and within the element, and physical properties of materials that change with temperature. There are affects of history in the sense that the properties of a material, or a composite, heated slowly to a given temperature (as in a test) will not necessarily be the same as those for the same material or composite heated rapidly (as in some fires). It is perhaps unrealistic, though for the present we will continue to do it, to expect that all elements giving 1 hour FRL will perform in the same way (or with the same degree of satisfaction) when exposed to real fires.

For the reasons outlined above, in the present project we have therefore abandoned the simplified methods available to us.

3.7 OUTLINE OF PROPOSED PROCEDURE

In this project use was made of the Barrier Model described in Section 8 which was developed for use in FCRC Project 4. This model permits building elements to be exposed to the fire severities generated by the method described above, for the durations specified in Section 8. Either the element will survive or it will fail. By varying the element parameters, elements that are predicted to just have the specified FRL can be developed for each type of element covered by the barrier models. The response of such elements to a range of idealised but non-standard fires can be predicted. The response of sets of elements with FRL of 30, 45, 60, 90, 120 and 180 minutes is tabulated and discussed further in Section 8.

3.8 DERIVING FRLS FROM PERFORMANCE LEVELS

Apart from the statistical review carried out and described in Part 1 of this report, further work on the Australian statistics has been carried out and is summarised in Appendix F.

4 CHARACTERISTIC FIRE ENCLOSURES

4.1 CLASSIFICATION OF OCCUPANCIES

The BCA requires that certain occupancies are divided into compartments by fire resisting walls. The BCA requirements are outlined below.

Table 4.1 Floor Area and Volume Limitations - BCA 1990/1996

1. Buildings that are not isolated

Area (m^2)
Volume (m^3)

Type of construction

Rise in storeys	1	2	3	4 and more	Notes
Class 2	C	B or C (C1.5)	A	A	1, 2, 4
Class 3	C	B or C (C1.5)	A	A	
Class 4					
Class 5	3000 C 18000	3000 C 18000	5500 B 33000	8000 A 48000	4
	5500 B 33000	5500 B 33000	8000 A 48000		
	8000 A 48000	8000 A 48000			
Class 6	2000 C 12000	2000 C 12000	3500 B 21000	5000 A 30000	4, 5
	3500 B 21000	3500 B 21000	5000 A 30000		
	5000 A 30000	5000 A 30000			
Class 7 Carpark	C	C	B	A	3, 11
Class 7 Other than carpark	2000 C 12000	2000 C 12000	3500 B 21000	5000 A 30000	3, 4
	2000 C 12000	3500 B 21000	5000 A 30000		
	5000 A 30000	5000 A 30000			
Class 8 purpose-built					3, 4
Class 8 general purpose	2000 C 12000	2000 C 12000	3500 B 21000	5000 A 30000	3, 4
	3500 B 21000	3500 B 21000	5000 A 30000		
	5000 A 30000	5000 A 30000			
Class 9a other than patient-care areas	2000 C 12000	3500 B 21000	5000 A 30000	5000 A 30000	4
	3500 B 21000	5000 A 30000			
	5000 A 30000				
Class 9a patient-care areas	Patient-care areas generally - fire-compartments not to exceed 2000. Ward areas - fire-compartments not to exceed 1000. smoke-compartments not to exceed 500. If patient-care/ward areas are less than 1000, smoke compartments must be also fire-compartments.				
Class 9b school					3, 4, 7
Class 9b disco or nightclub					3, 4, 10
Class 9b exhibition hall					3, 4, 6
Class 9b theatre or public hall with stage					3, 4, 8

Class 9b theatre or public hall without stage					3, 4, 9, 10
Class 9b open spectator stand					3, 12
Class 9b other	3000 C 18000	5500 B 33000	8000 A 48000	8000 A 48000	3, 4, 10
	5500 B 33000	8000 A 48000			
	8000 A 48000				

2. Buildings that are isolated and protected with a sprinkler system and perimeter vehicular access

Area (m^2) Type of construction
Volume (m^3)

Rise in storeys	1	2	3	4 and more	Notes
Class 5	18000 C 108000	18000 C 108000	18000 B 108000	18000 A 108000	4
Class 6	18000 C 108000	18000 C 108000	18000 B 108000	18000 A 108000	4,5
Class 7 Carpark	C	C	B	A	3, 11
Class 7 Other than carpark	18000 C 108000	18000 C 108000	18000 B 108000	18000 A 108000	3, 4
Class 8 purpose-built					3, 4
Class 8 general purpose	18000 C 108000	18000 C 108000	18000 B 108000	18000 A 108000	3, 4
Class 9a other than patient-care areas	18000 C 108000	18000 B 108000	18000 A 108000	18000 A 108000	
Class 9a patient-care areas	Patient-care areas generally - fire-compartments not to exceed 2000. Ward areas - fire-compartments not to exceed 1000. smoke-compartments not to exceed 500. If patient-care/ward areas are less than 1000, smoke compartments must be also fire-compartments.				
Class 9b school					3, 4, 7
Class 9b disco or nightclub					3, 4, 10
Class 9b exhibition hall					3, 4, 6
Class 9b theatre or public hall with stage					3, 4, 8
Class 9b theatre or public hall without stage					3, 4, 9, 10
Class 9b open spectator stand					3, 12
Class 9b other	18000 C 108000	18000 B 108000	18000 A 108000	18000 A 108000	3, 4, 10

3. Buildings of class 7 or 8 that are isolated, of not more than 2 storeys, protected by an open space not less than 18 m wide to C2.4(a) and by the detection and smoke-control systems of C2.3(a)(i)

Area (m^2) Type of construction
Volume (m^3)

Rise in storeys	1	2	Notes
Class 7 Carpark	C	C	3, 11
Class 7 Other than carpark	18000 C 108000	18000 C 108000	3, 4
Class 8 purpose-built			3, 4
Class 8 general purpose	18000 C 108000	18000 C 108000	3, 4

Continues next page.

4. Buildings that are isolated, protected with a sprinkler system and perimeter vehicular access and provided with a smoke-exhaust system or smoke-and-heat vents depending on ceiling height.

Area (m^2) Type of construction

Volume (m^3)

Rise in storeys	1	2	3	4 and more	Notes
Class 2	C	B or C (C1.5)	A	A	1, 2, 4
Class 3	C	B or C (C1.5)	A	A	
Class 4					
Class 5	No limit C	No limit C	No limit B	No limit A	4
Class 6	No limit C	No limit C	No limit B	No limit A	4, 5
Class 7 Carpark	C	C	B	A	3, 11
Class 7 Other than carpark	No limit C	No limit C	No limit B	No limit A	3, 4
Class 8 purpose-built					3, 4
Class 8 general purpose	No limit C	No limit C	No limit B	No limit A	3, 4
Class 9a other than patient-care areas	No limit C	No limit B	No limit A	No limit A	4
Class 9a patient-care areas	Patient-care areas generally - fire-compartments not to exceed 2000. Ward areas - fire-compartments not to exceed 1000. smoke-compartments not to exceed 500. If patient-care/ward areas are less than 1000, smoke compartments must be also fire-compartments.				
Class 9b school					3, 4, 7
Class 9b disco or nightclub					3, 4, 10
Class 9b exhibition hall					3, 4, 6
Class 9b theatre or public hall with stage					3, 4, 8
Class 9b theatre or public hall without stage					3, 4, 9, 10
Class 9b open spectator stand					3, 12
Class 9b other	No limit C	No limit B	No limit A	No limit A	3, 4, 10

NOTES

1. Buildings of classes 2 or 3 are not subject to floor-area or volume limitations.

2. Class-4 parts are not subject to floor-area or volume limitations and derive their FRL requirements via C1.6 from the buildings that contain them.

3. The subdivisions listed in the original task description have been retained although the BCA does not presently discriminate so far as floor-area or volume limitations are concerned. Go to the general classification in each case.

4. Basements that aren't carparks, are of more than 2000 m^2 and that aren't counted in the rise in storeys are subject to Table 2.2a page 13,751.

5. In class-6 buildings, fire-compartments of more than 2000 m^2 are subject to Table 2.2b, pages 13,752 and 13,753.

6. Exhibition halls of more than 2000 m^2 are subject to Table 2.2b, page 13,753. A distinction is made between floors of over 2000 m^2 but less than 3500 m^2 and those over 3500 m^2.

7. A theatre or public hall that is a school-assembly, church or community hall and has a stage and back-stage area of more than 300 m^2 is subject to Table 2.2b, page 13,754.

8. A theatre or public hall that is not a school-assembly, church or community hall and has a stage and back-stage area of more than 200 m^2 is subject to Table 2.2b, page 13,754.

9. In a theatre or public hall, including a lecture theatre and a cinema/auditorium complex but not including those already covered by notes 6, 7 and 8 nor a school lecture theatre, a fire-compartment of more than 2000 m^2 is subject to Table 2.2b, page 13,754.

10. In assembly buildings not already covered by notes 6, 7, 8 or 9 and excluding schools, a fire-compartment of more than 2000 m2 is subject to Table 2.2b, page 13,755.

11. Open-deck carparks and carparks with a Specification-E1.5 sprinkler system are not subject to floor-area or volume limitations.

12. Open spectator stands are not subject to floor-area or volume limitations. See also C1.7 about classification.

4.2 CHARACTERISTIC FIRE ENCLOSURE DIMENSIONS

For the reasons noted earlier, the fire may start in an enclosure which is not, or not intended to be, a fire compartment. Therefore a set of representative enclosures has to be derived for the purposes of carrying out analysis of fire severity which differ markedly from the above compartments dimensions. For each enclosure, the following data will be required:

Characteristic dimensions
Ventilation factor
Fire load

Since fires in large enclosures present more of a threat to barriers and structures than fires in small enclosures, the largest probable enclosure in each category will be taken to represent that category. The regression model proposed in this project can be used for enclosures <(5m x 22m) with low ceilings, since this is the range of the available data. "Small" enclosures will therefore be those within this range of dimensions.

Table 4.2 Assumed Enclosure Sizes for BCA Classes of Buildings

For small, low enclosures (ceiling height 2.5m – 4m) the following characteristic dimensions are assumed:

Class 1b	5m x 5m
Class 2	5m x 20m
Class 3	4m x 8m
Class 4	As Class 2
Class 5	4m x 8m
Class 6	5m x 20m
Class 7 – carpark	5m x 20m
Class 7 – other	5m x 20m
Class 8	5m x 20m
Class 9a (wards)	6m x 20m
Class 9b	5m x 20m

For large rooms with low ceilings, the following characteristic dimensions are assumed:

Class 1b	-
Class 2	-
Class 3 – ballroom	30m x 50m
Class 4	-
Class 5	60m x 60m
Class 6	50m x 100m
Class 7 – carpark	50m x 100m
Class 7 – other	50m x 100m
Class 8	50m x 100m
Class 9a	-
Class 9b	30m x 50m

The enclosure size was expanded to include the additional enclosures that might contain combustible material that could reasonably be expected to be open to the enclosure of fire origin. For example, apartments were assumed to have all rooms open to one another, but not to be open to the corridor beyond. Clearly these choices are somewhat arbitrary and are open to debate.

<< This page is intentionally blank >>

5 FIRE LOADS FOR OCCUPANCIES

5.1 SURVEYS

The fire load (quantity of combustible materials) is one of the main factors that may influence the severity of a fire. A number of surveys of fire load for various occupancies have been conducted based on data collected in various overseas countries. The results are summarised in Appendix C to this report. Proposed fire loads for the building classifications of the Building Code of Australia are tabulated based on these surveys, and are listed below in Table 5.1.

Total fire loads consist of permanent (or fixed) fire loads and variable (or movable) fire loads. Permanent fire loads are those combustible materials which have a negligible variation during the service life of a structure and comprise building materials including the load-bearing structure, linings, finishes, and permanently installed devices. Variable fire loads are all combustible materials that may vary during the service life of a structure, for example, furniture, storage goods, and movable equipment.

In the following data surveyed, the fire load was expressed in terms of fire load density: fire load per unit floor area.

5.2 RECOMMENDED FIRE LOADS FOR BCA CLASSES

Based on the data available the following table was compiled to represent the fire loads that would be applicable to the BCA classes of buildings. In the first draft of this table, the available data were averaged for occupancies which appeared to match those of the BCA classifications. This gave a mean and an estimate of standard deviation for each class. The data were then reviewed by an expert panel, see below, and modified to take into account their views. Table 5.1 is considered to be the best estimate currently available of the fire loads of buildings in Australia. It should be noted that the present project is related only to BCA classes 2-9.

5.3 REVIEW OF FIGURES

A summary of the total data from all sources which were surveyed was distributed to a panel of experts who were asked to rate each data source according to its relevance to the present project. Once the weightings were analysed and taken into account in deriving mean and standard deviation values, the resulting values were found to be only slightly different from those which had been derived before the weighting exercise.

The list of experts who took part in the study and the instructions issued to them are given in Appendix C.

Table 5.1 Fire Loads for BCA Classes of Buildings

Class		Description	Total fire load (MJ / m^2 floor area)		
			Average	Standard deviation	C.O.V
1		One or more buildings which in association constitute -	1000	300	0.3
	1a	(a) a single dwelling being (i) a detached house; or (ii) one or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house or villa unit; or			
	1b	(b) a boarding house, guest house, hostel or the like with a total floor area not exceeding 300 m^2 and in which not more than 12 persons would ordinarily be resident, which is not located above or below another dwelling or another Class of building other than a private garage.			
2		A building containing two or more sole-occupancy units each being a separate dwelling.	1000	300	0.3
3		*A residential building, other than a building of Class 1 or 2, which is a common place of long term or transient living for a number of unrelated persons, including-*	500	150	0.3
		(a) a boarding-house, guest house, hostel, lodging-house or backpackers accommodation; or (b) a residential part of an hotel or motel; or (c) a residential part of a school; or (d) accommodation for the aged, disabled or children; or (e) a residential part of a health-care building which accommodates members of staff.			
4		A dwelling in a building that is Class 5, 6, 7, 8 or 9 if it is the only dwelling in the building.	1000	300	0.3
5		An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.	800	480	0.6
6		*A shop or other building for the sale of goods by retail or the supply of services direct to the public, including-*			
		(a) an eating room, cafe, restaurant, milk or soft-drink bar; or (b) a dining room, bar, shop or kiosk part of a hotel or motel; or (c) a hairdresser's or barber's shop, public laundry, or undertaker's establishment; or (d) market or sale room, showroom, or service station.	1000	500	0.5
7		A building which is-			
		(a) a carpark; or	200	60	0.3
		(b) for storage, or display of goods or produce for sale by wholesale.	5500	3900	0.7
8		A laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.	600	420	0.7
9		A building of a public nature-			
	9a	(a) a health-care building; including those parts of the building set aside as a laboratory; or	350	110	0.3
	9b	(b) an assembly building, including a trade workshop, laboratory or the like in a primary or secondary school, but excluding any other parts of the building that are of another Class.	750	230	0.3
10		*A non-habitable building or structure-*			
	10a	(a) Class 10a - a non-habitable building being a private garage, carport, shed, or the like; or	500	150	0.3
	10b	(b) Class 10b - a structure being a fence, mast, antenna, retaining or free-standing wall, swimming pool, or the like.	-	-	-

VENTILATION FACTORS

6.1 GENERAL

Though there is not a large amount of data on fire loads with which to characterise various occupancies, there is even less data on ventilation characteristics. It is easy to envisage that this parameter may vary even more widely than fire loads between various occupancy types, and that it may not even be feasible to speak of a characteristic ventilation factor. The results of a preliminary ventilation survey based on drawings for some typical buildings and measured values for shops in a shopping centre are presented in Appendix D. Based on this information, the assumed ventilation is listed for each Building Code of Australia class considered in this project (classes 2 to 9 inclusive) in Table 6.1 below.

6.2 SURVEY DATA

A survey of available data was carried out and the results detailed in Appendix D to this report. A summary of the data is given in Table 6.1 below.

Low, medium and high values for ventilation for each BCA class were derived from the data surveyed. Where data was not available for a particular class of building then assumptions were made about the ventilation by comparison with other classes. The ventilation characteristic chosen as a representative parameter is the opening factor $A_v\sqrt{h_v} / A_t$. The medium value was taken to be the average value as taken from the data, the low value is the average minus 1.65 times the standard deviation with a minimum opening factor of 0.02 $m^{1/2}$, and the high value is the average plus 1.65 times the standard deviation. The low and high values correspond to the 5^{th} and 95^{th} percentile values, respectively.

Table 6.1 Ventilation Factors for BCA Classes of Buildings

Class	Description	Opening factor $A_v\sqrt{h_v} / A_t$ ($m^{1/2}$)		
		Low	Medium	High
2	A building containing two or more sole-occupancy units each being a separate dwelling.	0.06	0.10	0.16
3	*A residential building, other than a building of Class 1 or 2, which is a common place of long term or transient living for a number of unrelated persons.*			
3a**	(a) Accommodation for the aged, disabled or children; or	0.04	0.13	0.28
3b**	(b) Others, including • a boarding-house, guest house, hostel, lodging-house or backpackers accommodation; or • a residential part of an hotel or motel; or • a residential part of a school; or • a residential part of a health-care building which accommodates members of staff.	0.02	0.06	0.12

Class	Description	Opening factor $A_v\sqrt{h_v}/A_t$ (m$^{1/2}$)		
		Low	Medium	High
4	A dwelling in a building that is Class 5, 6, 7, 8 or 9 if it is the only dwelling in the building.	0.06	0.10	0.16
5	An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.	0.02	0.08	0.21
6	*A shop or other building for the sale of goods by retail or the supply of services direct to the public, including-* (a) an eating room, cafe, restaurant, milk or soft-drink bar; or (b) a dining room, bar, shop or kiosk part of a hotel or motel; or (c) a hairdresser's or barber's shop, public laundry, or undertaker's establishment; or (e) market or sale room, showroom, or service station.	0.03	0.09	0.20
7	A building which is-			
7a**	(a) a carpark	0.02	0.1	0.3
7b**	(b) for storage, or display of goods or produce for sale by wholesale.	0.03	0.09	0.20
8	A laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.	0.03	0.09	0.20
9	A building of a public nature:			
9a	(a) A health-care building; including those parts of the building set aside as a laboratory; or	0.03	0.09	0.20
9b	(b) An assembly building, but excluding any other parts of the building that are of another Class, including • a primary or secondary school, including a trade workshop, laboratory or the like; or • disco or nightclub; or • exhibition hall; or • theatre or public hall with stage; or • theatre or public hall without stage; or • other assembly buildings	0.03	0.09	0.20

** Not a current BCA class.

6.3 COMMENT

Because of the variations note above, in practice, it may be necessary to consider within occupancy types a range of ventilation factors, to choose the worst case for insertion in the BCA, or to provide tables within the BCA whereby designers can select a value most appropriate to the building under consideration. Whether or not this proves to be a necessary or feasible option depends on how the fire resistance levels deduced appear to depend on the ventilation, and the complexity that it is desirable to introduce into the code.

7 DETERMINATION OF EXPOSURE PERIODS

7.1 INTRODUCTION

In introducing the performance levels in Part 1 of this project report, a characteristic time of exposure for an element was defined, determined by its role in the building. Elements that are there primarily to protect escape routes only have to survive until the building occupants have escaped and elements that are there to protect fire-fighters may be required to survive for a different period of time. In order to calculate the exposure it will therefore be necessary to evaluate these times.

7.2 ESCAPE TIMES

There is a shortage of readily available data in summary form, which will allow confident calculation of escape times for different occupancies. The Fire Engineering Guidelines provides a methodology which in principle would generate the required times for input to the escape duration. However, since the Guidelines document was published in March 1996, it has become apparent to users of the document that the times predicted for escape from many building types are extremely conservative, and suggest that levels of fire protection for life safety should be far higher than the BCA demands. An alternative set of figures was derived for FCRC Project 2, but again these appear to be rather conservative. A proposal is under consideration by FCRC to review the relevant Chapter of the Guidelines document, but it appears likely that this review will not be concluded in time for the planned completion of Project 3.

It was initially proposed that the Guidelines document should be used in Project 3 to generate escape times. A summary of the escape times as calculated from the Guidelines is presented in Appendix E. The Guidelines method suggests that the escape time is made up of a cue time, a response time, a coping time and an evacuation time. The cue time is the time taken for people to have some evidence that there is a fire, such as smell of smoke, seeing flames, hearing an alarm or being informed by another person. The response time is the time taken for people to acknowledge that the cue represents a fire and to decide to do something. The coping time covers the activities undertaken by people following response. Finally the evacuation time is the time required to evacuate, once that activity is undertaken. The time taken for people to respond and to cope is assumed to depend on the type of cue received. The sound of an alarm bell is assumed to elicit a very slow response whereas the sight of flames results in a rapid response. Each of the times calculated is, in the Guidelines method, subject to a weighting factor depending on the occupancy. In cases where people are likely to be asleep, for example, the weighting factor is long. For people awake, alert and familiar with evacuation routes, the weighting should be shorter. However, as can be seen from the results presented in Appendix E, the times obtained are excessively long, and the results do not differentiate clearly between sleeping and non-sleeping occupancies.

Marchant (ref) has pointed out that the methodology developed in the Guidelines appears to be based on the work of Sime, but manipulates the weighting factors differently, obtaining total evacuation times that are much greater than Sime's. In some instances the difference amounts to a factor of 3 or more in total calculated evacuation time. It is not clear whether or not the Guidelines document has additional data to support the alternative method: it seems unlikely that it does. It is therefore proposed here that Sime's method be adopted for the calculation of evacuation time.

Sime does not separate response and coping time, but calculates a time to move. This is founded on a base time which is then multiplied by a weighting factor. The weighting factors are calculated differently from the method used in the Guidelines. These two factors give rise to the difference in the time prior to movement that is calculated by the two methods.

It is worthwhile to consider buildings in two groups, high-rise and low-rise. In the high-rise buildings the time for evacuation is highly dependent on flow down stairs, whereas in low-rise buildings it will depend more on the flow through doors. High-rise buildings would be expected to have much greater evacuation times. Not all buildings would be expected to be high-rise in Australia, and we have just considered only offices, hotels and apartments as being typical of Australian construction.

7.3 FIRE BRIGADE ACCESS TIME

One figure is needed for each occupancy which describes the time for which the fire brigade might need to have access to the building for firefighting purposes, where this is envisaged within the BCA. This last point has been addressed above: it is still not clear how to distinguish buildings which the fire brigade is expected to enter and for whom protective measures are included in the BCA, from those where this is not expected and no provisions are included. Guidance on this point has been sought from ABCB, and the response is that there are no such building specifically envisaged with the BCA, though in principle firefighters could require access to any building for search and rescue purposes. The implication is that buildings do not have features specifically for fire-fighting access. For the purposes of this project, it will be assumed that the required performance from compartment boundaries is as stated previously, that the element should survive until fire-fighters have brought the fire under control. However, where elements for the protection of the fire brigade can be identified, the required duration of survival of such elements is the time for the fire brigade to get the fire under control.

Consideration was given to the use of the recently developed Fire Brigade Intervention Model (FBIM) for calculation of the fire brigade access time. The model sets out to assign probabilities and representative times to the range of activities undertaken by the Fire Brigade from the time they receive a call to an incident to the time that they leave the scene. These activities include response, setup of equipment, assistance with evacuation, search and rescue and direct fire-fighting operations. The model is described in detail in Appendix F. It is sufficiently detailed that the calculation of probable response times and times to certain activities is possible.

On consideration, it was thought that the application of the FBIM to the calculation procedures in Project 3 would be inappropriate because the level of detail is not required. From the NSW fire statistics (paper 27/04/97), it is possible to deduce figures for the time which elapses between the first call to the fire brigade regarding an incident, and the time at which the incident is recorded as being under control. From the statistics, it is not possible to relate this time to the type of building. Though a significant difference may be identified in 'time to arrival' on the basis of 'rural' or 'urban' location, it is debatable whether such distinctions exist in the 'time to control'. In any case the incorporation of such a distinction would not be feasible from a regulatory point of view, since these could be subject to change with time. It is therefore proposed that to address the Project 3 prescriptions, one representative value of the time to get the fire under control must be adopted for all buildings and locations. The statistical data is summarised in Appendix F. From the data presented, it may be seen that in 50% of all incidents, the fire brigade arrive within 7 minutes, and the fire is brought under control within about 15 minutes, ignoring the fire incidents for which this data is unknown. In 90% of cases for which it is recorded, the time to bring the fire under control is within 50 minutes. The data show that these results may be skewed by some very long fire control times.

7.4 FIRE SEVERITY (BURNOUT TIME)

The time to burnout is generated by the fire severity model and is related to the time required to consume all of the fuel. Higher fire loads will give longer burnout times. Lower ventilation will tend to give longer burnout times. In practice, all of the fuel is often not consumed in a fire, and literature searches were undertaken to see whether experimental data concerning the proportion of the fire load which remains unburnt is available. On useful data was found. However, in the tests that are the main sources of the data on which this report is based no mention of unburnt fuel is made.

Appendix H presents the data and basis for the calculation of the duration and temperatures of fires in enclosures for use in the calculation of the severity of the fires in the enclosures suggested for the BCA occupancies. Appendix I provides some general information on the temperature rise in elements in an enclosure subject to an idealised temperature relationship and in the same elements subjected to the temperature rise required in the standard fire test.

Calculation of the estimated time to burnout in the maximum size enclosures for each of the BCA occupancies is covered in Appendix J.

8 BARRIERS AND STRUCTURE

8.1 GENERAL

Where barriers fail in fire, they do so because of the effects of heat or high temperatures on the properties of materials. High temperatures cause loss of strength in steel or timber members within composite barriers, or causes concrete to spall , or plasterboard to crack. The prediction of barrier failure requires the development of a heat transfer model from the fire within the barrier, which can incorporate the effects of moisture, since this is relevant to the failure of plasterboard and concrete. Coupled with time-dependent heat flow models is the necessity to incorporate temperature-dependent predictions of material properties.

The criteria for failure of the barrier need to be established such that the heat flow model can be used for predictive purposes. For the behaviour of barriers, Project 3 has adopted the models developed for Project 4 which include models for the behaviour of concrete and masonry, as well as timber/plasterboard and steel/plasterboard composites.

8.2 MODELS FOR BARRIER FAILURE

Details of the barrier failure models is given in Appendix G. The criteria for failure adopted are the loss of integrity of the barrier or the increase in temperature of the non fire surface being greater than 200°C. Once these criteria have been exceeded it is assumed that there is a high likelihood of fire passing to the far side of the barrier.

The following is an extract from the Barrier failure model report prepared for project 4

> This report describes the models that have been developed for predicting the failure times of barriers exposed to an enclosure fire in a building. Failure times due to failure from structural adequacy, integrity and insulation are considered. Models for the failure times of structural frame elements are also developed to be used in conjunction with barriers which depend upon the stability of the structural elements for support. Models have been developed for the following elements of construction:
>
> - Steel Stud Walls
> - Masonry Walls
> - Concrete Walls and Shafts
> - Concrete Beams and Slabs
> - Concrete Columns
> - Steel Structural embers
> - Metal Shafts and Ducts
>
> The work described in this report was undertaken as part of Fire Code Reform Centre Project 4 entitled "Fire Safety System Model - Residential Buildings". A computer program called BSpread has been written to be used as part of the development of the Fire Safety System Model for residential buildings.
>
> The results of each of the models have been validated against selected published test results, generally only for thermal performance. Where data for checking of structural response is not available the structural performance is implied on the

basis that the models for structural behaviour under elevated temperatures were adopted from established sources. Due to a paucity of tests on elements exposed to real fires, comparisons have only been possible with standard fire tests. However, it is believed that accuracy in the prediction of thermal response is not sensitive to the differences in the shape of the temperature time curves between real and standard fires.

Barriers which are not considered in this report are construction elements made of timber (e.g. timber stud wall, timber flooring) and barriers which have combustible linings. However, in Project 4 barriers with timber studs have been considered and a very sophisticated model used. The failure times in real fires of elements with similar FRLs using this model are similar to those using the BSpread models. Thus it can be assumed that the results produced using BSpread also reasonably represent barriers using timber studs also.

The models can be extended to develop distribution functions of time-dependent failure probabilities of the barriers using a Monte Carlo simulation approach for the purpose of conducting a risk analysis. This is achieved by varying the input values for each barrier according to appropriate distribution functions over a large number of runs. Calculations of this sort are not done in this report.

The models have been developed to be relatively simple such that they will have a fast execution time and yet be sufficiently accurate such that they can be incorporated into a risk assessment analysis. Overall, the models show reasonable predictions despite their relative simplicity.

8.3 MATERIALS

Conventional materials have been assumed for the barrier materials and standard (published) material properties used. However, to achieve reasonably precisely the FRLs required, the thicknesses of materials (plasterboard, concrete cover, etc) used are non-standard. In general, this has been accomplished by adjusting the thickness of the insulating component of the element (for example the plasterboard thickness for steel-stud walls). In some cases minor adjustment has been accomplished by also adjusting the overall member size, etc

8.4 CONSTRUCTION CHARACTERISTICS

An analysis has been carried out to determine the likely properties of building structures as follows. The actual sizes of structural members are dependent on the structural arrangement in any given building and so only general estimates of sizes can be made. Typical sizes probably do not exist except in a limited number of places and so ranges of sizes are required for any given occupancy.

Reinforced Concrete Slabs (Roofs and Floors)

Slabs thicknesses are usually in the range of 120 to 250 mm. The lower end of the range is governed by the need to allow for top and bottom cover, four layers of reinforcement and space between the top and bottom layers. The upper end of the range is governed by economics in that above a certain slab thickness the designer will provide supporting beams (or slab bands) or more closely spaced beams to reduce the slab thickness and overall concrete quantity.

Minimum thickness for given spans of one-way slabs not supporting construction likely to be damaged by large deflections may be estimated from Table 9.5(a) of ACI 318:

Member	Minimum thickness			
	Simply supported	One end continuous	Both ends continuous	Cantilever
Solid one-way slabs	*l* / 20	*l* / 24	*l* / 28	*l* / 10
Beams or ribbed one-way slabs	*l* / 16	*l* / 18.5	*l* / 21	*l* / 8

The cover to the bottom reinforcement mainly governs the structural adequacy fire resistance of slabs. Therefore, for the purpose of generating elements for the FRL calculations of a given occupancy it is probably only necessary to have two or three slab thicknesses to ensure there is no size effect but have a wide range of bottom covers. For a selected reasonable slab thickness the span may be calculated from the above table, then the reinforcement may be estimated based on AS1170.1 loads and strength considerations. The design load for fire situations can be calculated to be consistent with the design ultimate dead and live loads.

Residential slabs (supported on load-bearing walls) are usually 120 to 160 mm thick.

Reinforced Concrete Beams

Base the depths on the tabulated values for beams from ACI 318 and the following estimates of span:

Class 2, 3 and 4 (Residential): 5 m
Class 5 (Offices): 6 – 12 m
Class 6 (Retail): 6 – 12 m
Class 7 (a)(Carpark), (b)(Storage): 6 – 12 m
Class 8 (Industrial): 6 – 12 m
Class 9a (Health), 9b (Assembly): 6 – 12 m

(Most of these span lengths are not based on any evidence.)

Reinforced Concrete Columns

Column sizes are dependent on the total loaded area supported by the column i.e. the sum of the loaded area for each floor above the level under consideration. The smallest column size is 200 mm square but it is unusual to find a column so small. A reasonable size estimate for columns in the lower levels of a 50 storey office tower building is 900 mm square (based on approx. 50 sq. m floor area per column per level). For a similar 10 storey building the column size is of the order of 500 mm square, and 20 storey is 600 mm square. These sizes will be relatively insensitive to occupancy type for the occupancies that occur in high-rise buildings. Internal columns in low-rise buildings may support larger values of floor area per level than the edge columns in towers.

Reinforced Concrete Walls

Typical wall thicknesses are in the range of 150 to 250 mm, although thicker sections will occur in the core walls of tower buildings.

8.5 BARRIER AND STRUCTURAL ELEMENTS PREDICTED PERFORMANCE

In Appendix G appended to the report on the barrier models from Project 4 is a table giving the predicted failure times in idealised (real) fires for FRLs of 30, 45, 60, 90, 120 and 180 minutes for each of the elements considered.

The temperature profile for the design fires are the specified (maximum) temperature (Tmax) at the start of the fire with the temperature falling linearly to 500 °C at the time corresponding to the duration. These temperature profiles are shown in Figure G1.

In Table G1 the duration, in seconds, is given in the column marked t500.

An entry of "Nil" in Table G1 means no failure is predicted.

Examination of Table G1 shows that for each FRL most of the elements fail within a similar time period (generally within ±5 minutes). This is to be expected and comes about because elements designed to just survive a specific period in the standard fire test are likely to have similar sensitivity to other time-temperature histories.

9 CALCULATION OF REQUIRED FRLS

9.1 INTRODUCTION

Appendix A3.1 of the Part 1 Report on Project 3 summarised the BCA requirements for internal compartmentation in buildings of Type A construction. It was not intended that this table should be a comprehensive analysis of the BCA FRL requirements, but rather that it should draw attention to the complexities of the current requirements. It is questionable whether it is the role of Project 3 to prescribe a new FRL to be substituted into the BCA as it stands, where a current requirement appears. Rather, it has been assumed that the task of Project 3 was to derive a sound calculation methodology and, for each building category, to deduce the FRL appropriate to each performance level. The regulators may then be in a position to decide the function of the fire resistance requirement for each case, and hopefully to introduce simplifications to the requirements in the course of that process. Tables 7.3 and 7.4 of the Part 1 Report indicate how this might be achieved.

In the following subsections the actual calculation of fire severity for each BCA class is summarised, as is the calculation of the required fire durations and the FRLs required for each building class.

9.2 ESTIMATION OF FIRE SEVERITY

A detailed discussion of the estimation of fire severity is given in Appendix H and a qualitative discussion of the relationship between the standard fire test temperature-time curve and that if various idealised real fires is given in Appendix I.

The enclosures, fuel loads and ventilation conditions of interest in Project 3 are shown in Table A2 of Appendix H. Many of these enclosures (particularly in relation to size) are considerably different from the enclosures covered by the experimental data.

As the formulae in Appendix H are least squares correlations it is not considered advisable to extrapolate significantly from the conditions represented by the experimental data. Consequently some consideration is required of how to treat the enclosures that require significant extrapolation.

Apart from the enclosure and vent dimensions, the other major departure from the experimental data is the fire load, which in many of the enclosures is considerably greater than used in the tests. Examination of the test results has revealed that for the quite limited range of fire loads covered, the changes in the fire load have little or no effect on the rate of burning. Thus, for a given enclosure size and ventilation condition, the duration of burning is essentially proportional to the fire load. It will be assumed that this remains true throughout the range of fire loads required for Project 3 although it is by no means certain that this is indeed the case for the very high fire loads specified for some occupancies.

It is recommended in Appendix H that a single maximum enclosure temperature of 1100°C be used for all enclosures and ventilation conditions. (It is clear in Appendix H that wide variations in temperature occur for the same enclosures and ventilation conditions. It also appears from Figure 22 of Appendix H that there is no significant difference between the *w/W = 1* and *w/W < 1* cases in regard to temperatures.) With this recommendation, the duration of high temperatures (assumed closely related to the duration of burning) becomes de facto a surrogate for fire severity. As discussed above, small scale testing and the regression formulae developed in Appendix H indicate that for a given vent size a full width vent (*w/W = 1*) results in longer fire durations than partial width vents. In terms of the objectives of Project 3, related to determination of FRLs for deemed to satisfy requirements it is conservative (that is, longer fire durations and thus higher FRLs will result) if it is assumed all vents are full width vents (*w/W = 1*). Thus Equation 4 of Appendix H (for the *w/W = 1* case) is used in preference to Equation 5 of Appendix H (which is for the *w/W < 1* case) for determination of fire duration.

Considering now the enclosure and vent size issues. The enclosure sizes 4 m by 8 m, 8 m by 4 m and 5 and 6 m by 20 m are within the range covered by the data and therefore can be addressed using Equations 4, 5 and 9 of Appendix H. The remaining enclosure sizes 30 m by 50 m, 50 m by 100 m, 60 m by 60 m and 100 m by 50 m (see Table 1 of Appendix H) are outside this range and therefore are not covered and, due to the degree of extrapolation involved no estimates are made of fire duration for these enclosures

Fire duration and temperature results based on Equations 4 and 9 of Appendix H for the range of enclosures considered to be covered by the data are given in Table A3 of Appendix H.

The fire duration is obtained from the following formula:

$$t_{500} = \frac{(Q \times D)}{\left(\frac{R}{1.7}\right) \times 60} \text{ (minutes)} \qquad \text{(Equation 10 of Appendix H)}$$

This relates the total fire load per unit width of enclosure (and vent) divided by the maximum burning rate estimated using Equation 4 of Appendix H to the fire duration (taken as the time for which temperatures are above 500 °C). The 1.7 term adjusts the estimated maximum burning rate back to an average rate.

Before considering how to cover those enclosures requiring extrapolation it is worthwhile considering the results obtained from Equation 4 for the largest enclosures covered by the data. Therefore an enclosure 5 m wide by 20 m deep with a full width vent will be considered. The vent heights required for the large enclosures (Table A2 of Appendix H) include 0.91, 1.13, 1.21, 1.52, 1.70, 2.04, 2.40, 2.89, 3.00, 4.08, 4.34, 4.63, 5.00 and 6.00 m. The only vent height in the data for an enclosure of this approximate size is 2.75 m high. However in the smaller enclosures there are a variety of vent heights less than this, so it is presumed that smaller vents are reasonably covered by relationships based on the data. As pointed out in Attachments 1, 2 and 3 of Appendix H the flows observed in enclosures with full width vents are essentially two-dimensional and thus it is expected that the gas flows and thus burning rate are essentially proportional to the width of the enclosure and vent. A regression has been carried out on the data similar to Equation 4 but with the index for the vent width w constrained to 1.0. The resulting relationship is:

$$w/W = 1 \qquad R = (0.53 \times (w) \times (h)^{1.8} \qquad (r^2 = 0.97) \qquad \text{(Equation 11 of Appendix H)}$$

This relationship (with *w* = *1.0* m) produces the results shown in Table 6 of Appendix H (reproduced below) for unit width vents and the range of vent heights required. Note that vent heights greater than 3 m are a significant extrapolation from the data.

Table 6 of Appendix H Burning Rate and Fire Duration for a Range of Vent Heights

h (m)	R (MW/m)	$t_{<500}$ (minutes) for D = 20 m and Q = 1000 MJ/m^2
0.91	0.45	1267
1.13	0.66	858
1.21	0.75	759
1.52	1.13	503
1.70	1.38	411
2.04	1.91	296
2.40	2.56	221
2.89	3.58	158
3.00	3.83	148
4.08	6.66	85
4.34	7.44	76
4.63	8.36	68
5.00	9.60	59
6.00	13.33	42

The resulting fire durations for an enclosure 20 m deep with the fire load densities relevant for these enclosures are shown in Table 7 of Appendix H (also reproduced below).

Inspection of Table 7 of Appendix H reveals that for all but the lowest fire loads and greatest vent heights the fire durations are very high. Thus, it is expected that for enclosures of greater depth (but having the same vent height) the fire durations will be even greater.

Interpolation within Table 7 of Appendix H reveals that the actual duration for the enclosure that is just over 20 m deep with a 2.75 m high vent is close to the predicted duration. However, the durations for a similar depth enclosure at much smaller vent heights are greater than those actually obtained.

Table 7 of Appendix H Fire Durations

	Fire Duration (minutes) for 20 m deep enclosure and specified fire load density (MJ/m^2)													
	Fire Load Density (MJ/m^2													
h (m)	**121**	**170**	**201**	**309**	**410**	**590**	**600**	**1000**	**1401**	**1600**	**1600**	**1904**	**5508**	**13005**
0.91	153	215	254	392	519	747	760	1266	1775	2027	2027	2412	6979	16477
1.13	104	146	172	265	352	506	515	858	1202	1373	1373	1634	4726	11159
1.21	92	129	152	235	311	448	455	758	1063	1214	1214	1444	4179	9866
1.52	61	86	101	156	206	297	302	503	705	805	805	958	2772	6544
1.7	50	70	83	127	169	243	247	411	576	658	658	783	2266	5350
2.04	36	50	59	92	121	175	178	296	415	474	474	564	1632	3853
2.4	27	38	44	68	91	130	133	221	310	354	354	421	1218	2876
2.89	19	27	32	49	65	93	95	158	222	253	253	301	872	2058
3	18	25	30	46	61	87	89	148	207	237	237	282	815	1925
4.08	10	14	17	26	35	50	51	85	119	136	136	162	469	1107
4.34	9	13	15	24	31	45	46	76	107	122	122	145	419	990
4.63	8	12	14	21	28	40	41	68	95	108	108	129	373	881
5	7	10	12	18	24	35	35	59	83	94	94	112	325	767
6	5	7	9	13	17	25	26	42	60	68	68	81	234	553

The figures in Table 7 of appendix H indicate that for many deeper enclosures with moderate to very high fire load densities the possible fire durations are very great. Possibly in these cases extrapolation is unnecessary, as the fire durations are such that it is obvious that fires of such durations in buildings are simply unacceptable and also that the fire resistance level that would be required to withstand fires of such durations would be well over even the greatest fire resistances normally specified for buildings (180 minutes or 240 minutes). In such cases it might be argued that systems preventing such fires occurring are more appropriate than attempting to physically confine or resist them by specifying a fire resistance level.

Thus estimates of the duration and maximum temperatures that might be experienced in fires in small enclosures have been made and are presented in Table A2 of Appendix H.

Prediction of the duration and maximum temperatures that might be experienced in fires in large enclosures (but with sizes that are quite realistic for many buildings) is subject to great uncertainty as the test data that is available is only for smaller enclosures. Extrapolation based on such data as is available would require assumption of the form of the relationships between the variables. This is not possible at this stage.

9.3 ESTIMATION OF FRLS

A detailed discussion of the estimation of required FRLs is given in Appendix J. In essence the fire durations estimated above and the maximum temperature of 1100°C mentioned above are used to determine the required FRL such that the element would be expected to not fail within the duration required using Table G1 of Appendix G.

The estimates of the FRLs required in the cases considered are highly dependent on the three factors considered in their derivation (fire load density, enclosure area and vent size) and on the temperature assumed to occur. The assumption of an 1100 °C temperature (which it is acknowledged is in the upper range of temperatures measured in realistic fire tests in enclosures) results in a quite severe fire when compared with the standard fire test as the furnace temperature only gets to this level nearly three hours after the commencement of the test. (The fire load density used is the average, and thus does not represent an extreme, although some of the values appear to be very high when it is assumed that this density of fuel is considered to occur throughout the enclosure.)

The three factors considered in the derivation are all important but the size of the enclosure is possibly most important. There are two (possibly three, if the 1100 °C temperature is considered also) extreme factors involved in the calculations on which the FRLs are based: the enclosures are the largest considered likely for the occupancies and the ventilation is the minimum considered likely. Both of these lead to longer durations, and therefore the durations estimated must be towards the upper extreme of those that might occur in practice.

For a specific building design a calculation using the methods used above but with the actual enclosure size and ventilation conditions would lead to considerably lower requirements. This can be accomplished by calculating the fire duration and then using Table 4 of Appendix J.

The following table (Table 5 of Appendix J) is an example of a possible presentation to cover a range of enclosure sizes and ventilation conditions. It is for Classes 2&4 and includes the values in Table 4 of Appendix J.

Table 5 of Appendix J Example Table Covering a Range of Enclosure and Vent Sizes

Enclosure Size	Ventilation	
	Small (10m x 1.2m)	Large (10m x 2.4m)
Large (10 m x 20 m)	771 (FRL)	223 (FRL)
Medium (5 m x 10 m)	386 (FRL)	112 (FRL 120)
Small 3 m x 5 m)	193 (FRL)	56 (FRL 90)

This estimate may also be made slightly more approximately by using the following formulae:

$$t = \frac{FLD \times D}{18.7 \times h^{1.79}} \qquad (1)$$

$$FRL \geq \frac{(t + 1230)}{67} \qquad (2)$$

For the same example as in Table 5 of Appendix J (reproduced above) these formulae would lead to the results in the following table (Table 6 of Appendix J). In this table the FRLs are expressed in the calculated number of minutes rather than in the standard FRL periods (60, 90, 120, etc)

Table 6 of Appendix J Example Covering a Range of Enclosure and Vent Sizes Based on Equations

Enclosure Size	Ventilation	
	Small (10m x 1.2m)	Large (10m x 2.4m)
Large (10 m x 20 m)	770 (FRL 708)	221 (FRL 216)
Medium (5 m x 10 m)	385 (FRL 363)	111 (FRL 117)
Small 3 m x 5 m)	192 (FRL 191)	55 (FRL 68)

(Note in this table that for fire durations up to about 160 minutes the FRL period is slightly greater than the fire duration, but for those above about 200 minutes the FRL period is less than the fire duration. This is because the standard fire test temperature is about 1100 °C at 180 minutes.)

It can be seen that the results in the two tables are very similar.

9.4 COMMENT

It should be noted that many of the FRLs recommended above and in Table 4 of Appendix J are greater than those currently required by the BCA.

It is not recommended that FRLs in the BCA be increased as there is no indication in the fire record that the current FRLs are unsatisfactory. Indeed, the general opinion seems to be that, if anything, FRLs are too high. As the estimates above are highly dependent on the enclosure size, fire load density and ventilation assumed it may be that reduced values of these parameters might be appropriate, and that further consideration of these values by ABCB would be sensible.

It should also be noted that aspects of the estimation of fire severity in enclosures are still under investigation. Consequently, it is likely that the estimates of fire severity developed above will be refined in the near future.

10 CONCLUSIONS

Estimates of the fire resistance required for the range of buildings covered by the BCA have been developed. These are based correlations which are themselves based on limited data. The data is inadequate in that it does not cover the range of enclosure sizes and other important factors that may occur in practice and which the BCA would be expected to cover.

Nevertheless, the tables in Appendix J provide a rational estimate of the FRLs required for many of the enclosures in buildings covered by the BCA. Many of the estimated FRLs are similar to those currently required by the BCA. However, many are also greater than those required by the BCA.

It is reiterated that it is not recommended that FRLs in the BCA be increased as there is no indication in the fire record that the current FRLs are unsatisfactory. As the estimates are highly dependent on the enclosure size, fire load density and ventilation assumed it may be that reduced values of these parameters might be appropriate, and that further consideration of these values by ABCB would be sensible.

Finally, examination of Appendix H shows that there are many factors that affect estimates of the severity of fires in enclosures. It cannot be expected that required FRLs in a document such as the BCA are anything but conservative, and often very conservative, for the majority of situations to which they are applied. They will only be really appropriate for the more extreme situations on which that are based. Consequently, it is appropriate that determination of reduced FRLs by designers using appropriate estimation techniques be made possible, preferably within the BCA, but certainly within the regulatory system. To not do so is equivalent to saying all structural members in each class of building shall be of a certain (very large) size, and that the normal method of structural design cannot be used.

APPENDIX A

DEFINITIONS AND NOTATION

Critical Structure

Critical structure is any system of structural elements in a building where simultaneous failure under fire conditions is foreseeable, and would signal collapse involving the whole or a significant part of the building. (Failure of non-critical structure would cause only local collapse, if any.)

Compartment

A fire compartment is intended to limit the fire size to that which can be controlled by available fire fighting resources. It may contain one or more enclosures. It is bound on all sides by barrier elements with defined Fire Resistance Levels (FRL)

Enclosure

A room or other enclosed space.

Fire Load

The mass of combustible materials in an enclosure, room, compartment or area, usually specified as the equivalent mass of wood having the same total heat of combustion.

Fire Load Density

The fire load per unit area (kg wood equivalent per m^2).

Fire Severity

The temperature-time history of a fire in an enclosure. The severity is greater with higher temperature fires of a given duration and with longer duration fires of a given temperature.

Performance Levels

The five levels of performance of barrier elements (3 of non-barrier structural elements) defined in Section 1.2 of this report. The performance levels define rational objectives that barriers might be intended to achieve.

Survival Times

The time for which barrier or structural elements will perform their intended function under defined fire conditions.

Ventilation Factor

The term $Ah^{0.5}$ where A = area of opening(s) and h = height of the opening(s). It defines the ventilation available in an enclosure.

APPENDIX B

REVIEWS OF TECHNIQUES FOR DETERMINING FIRE SEVERITY

B1 EQUAL TEMPERATURE-TIME AREAS

The concept of equal temperature-time areas was pioneered by Ingberg in the 1920's. The equivalent fire exposure was regarded as solely a function of the fire load density (the amount of combustible material per unit floor area) so that the degree of ventilation and the thermal properties of the compartment were not considered. Ingberg correlated equivalent fire exposure with the fire load density by determining the time at which the area under the time-temperature curve in a standard ASTM fire test (above a certain base line, somewhere between 150° and 300°C) equalled the same value as the area under the time-temperature curve for a real fire (above the same base line). Temperature histories for real fires were based on burnout tests conducted by the US National Bureau of Standards. The tests included two actual buildings that were allowed to burn to destruction and a series of fires in fire resistive test buildings containing contents representative of office, record room, and household occupancies (Campbell (1986)). Although the ventilation in the test buildings was not reported, the windows were equipped with steel shutters that could be adjusted to control ventilation and maximise fire severity. The correlation between equivalent fire exposure and fire load (from AISI (1971)) is:

Fire load density			Equivalent fire exposure
(lb / ft^2)*	(kg / m^2)**	(MJ / m^2)**	(hours)
5	25	450	½
7 ½	37	680	¾
10	50	910	1
15	75	1400	1 ½
20	100	1800	2
30	150	2700	3
40	200	3600	4 ½
50	240	4500	6
60	290	5400	7 ½

* combustibles reduced to wood equivalent of 8000 BTU per pound

** soft conversion based on 1 lb/ ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

Campbell (1986) and Butcher (1991) have slightly different values for equivalent fire exposure at higher fire load densities.

Given estimates of fire load density for different occupancy types then the Fire Resistance Level (FRL) to withstand burnout may be estimated. AISI (1971) relates fire load density and FRL for US occupancy types as:

Occupancy type	Fire load density (lb / ft²)	(kg / m²)*	(MJ / m²)*	Equivalent Fire Exposure (hours)
Residential	5 to 10	25 to 50	450 to 910	½ to 1
Educational	5 to 10	25 to 50	450 to 910	½ to 1
Institutional	5 to 10	25 to 50	450 to 910	½ to 1
Assembly	5 to 10	25 to 50	450 to 910	½ to 1
Business	5 to 10	25 to 50	450 to 910	½ to 1
Mercantile	10 to 15	50 to 75	910 to 1400	1 to 1 ½
Industrial	variable	variable	variable	**
Storage	variable	variable	variable	**
Hazardous	variable	variable	variable	**

* soft conversion based on 1 lb/ft² = 4.88 kg/m² and heat of combustion = 18.6 MJ/kg
** fire severity will depend on the specific occupancy

and Butcher (1991) for British occupancy types as:

Occupancy type	Fire load density (BTU / ft²)	(lb/ ft²)*	(MJ / m²)	Equivalent Fire Exposure** (hours)
Domestic	40 000	5	465	½
Institutional	40 000	5	465	½
Other residential	40 000	5	465	½
Office	40 000 to 80 000	5 to 10	465 to 930	½ to 1
Shop	up to 400 000	up to 50	up to 4650	up to 6
Factory	up to 240 000	up to 30	up to 2790	up to 3
Assembly	40 000 to 80 000	5 to 10	465 to 930	½ to 1
Storage and general	up to 800 000	up to 100	up to 9300	to more than 7

* wood equivalent
** from correlation between Equivalent Fire Exposure and Fire Load Density

Apparently, British post-World War II fire studies (MOW(1946)), where buildings were grouped or graded into three broad categories depending on fire load density, were used as the basis for the Australian building regulations. The following table (after Drysdale (1949)) summarises these gradings and the corresponding fire load densities and equivalent fire exposure:

Occupancy Types	Fire load density (average) (BTU / ft^2)	(lb/ ft^2)*	(kg / m^2)**	(MJ / m^2)**	Equivalent Fire Exposure (hours)
Low fire load (domestic buildings, hotels, offices)	up to 100 000	up to 12.5	up to 60	up to 1100	1
Moderate fire load (trade and factory buildings)	100 000 to 200 000	12.5 to 25	60 to 120	1100 to 2300	2
High fire load (bulk storage buildings)	200 000 to 400 000	25 to 50	120 to 240	2300 to 4500	4

* combustibles reduced to wood equivalent of 8000 BTU per pound
** soft conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

The relationship between fire load density q_f in kg.m^{-2} of floor area and the equivalent fire exposure t_e in minutes is approximately

$$t_e = (q_f$$

ie. the factor of proportionality is unity for the chosen units. The British studies considered the earlier American results as well as the results of the examination of fire damage to structural elements in burnt-out buildings. The equivalent fire severities for low fire loads are similar to the American values, but at higher fire loads are somewhat lower.

Drysdale (1991) demonstrates that a relationship exists between the current fire grade (or equivalent fire exposure) and the minimum design live load (and by implication with fire load density) for different classes of occupancy (or occupancy type) in Australia:

Class of Occupancy	Fire Grade (minutes)	Minimum Design Live Load (kPa)
Houses	not graded in Australia	1.5
Flats	90	2.0
Residential buildings	90	2.0
Office buildings	120	3.0
Shops	180	5.0
Warehouses	240	2.4 per clear metre of height

Kawagoe and Sekine (1963) and Kawagoe (1967) extended the equal temperature-time areas approach to include the compartment ventilation properties and thermal properties as well as the fire load. In its final form, the "equivalent testing time" (same as equivalent fire exposure) was calculated by determining the time at which the area under the time-temperature curve in a standard JIS fire test (above a base line) equalled the same value as the area under the time-temperature curve for a simulated real fire (above the same base line). The base line was 400°C for normal weight concrete and similar constructions, and 500°C for lightweight concrete and similar constructions. A post-flashover compartment fire model was used to simulate the temperature history for the real fire. Nomograms were provided to enable easy computation of the equivalent testing time. The above method was formulated to ensure that the maximum temperature rise which occurs a small distance inside the compartment walls (30mm to 60mm) is approximately the same for the real fire and the test fire.

B2 EQUAL TEMPERATURE RISES

The equal temperature rises concept proposes that equivalence between real and test fires may be obtained by the attainment of a certain temperature level by some important building component in the two fire exposures. From room-burn experiments or from calculation the maximum temperature rises at some locations (usually in steel components) in the boundaries of the room or in columns placed in the room are determined. Then, the temperature rises at the same locations due to the standard test temperature history are determined either by subjecting the elements to standard fire tests or by calculation. The equivalent fire exposure is then taken as the time at which the temperature in the standard test reaches the same maximum value as in the room-burn experiment or fire simulation.
Based on the results of an international experimental program on the behaviour of fully developed fires in compartments, Law (1971,1973) developed the following formula (with slightly different notation)

$$t_e = K \frac{A_f q_f}{\sqrt{A_v (A_t - A_v)}}$$

where t_e is the equivalent fire exposure in minutes, K is a constant of the order of unity, q_f is the fire load in kg.m^{-2} of floor area, A_f is the floor area in m^2, A_v is the ventilation area in m^2, and A_t is the total area of the compartment internal surfaces in m^2. Law's formula does not take account of the thermal properties of the compartment boundaries or the height of the openings. The expression derived from a correlation of the estimated times for equal temperature rises of 550°C in a protected steel column due to experimental compartment fires and furnace tests.
Pettersson (1985) improved Law's formula by including the height of the openings and by taking account of the thermal properties of the compartment boundaries

$$t_e = 0.067 \frac{q_{tf}}{\sqrt{(A_v \sqrt{h_v} / A_t)_f}} \quad \text{(min.)}$$

where $q_{tf} = K_f q_t$ is the effective fire load density per unit area of the bounding surfaces of the compartment (MJ m^{-2}), $(A_v \sqrt{h_v} / A_t)_f = K_f A_v \sqrt{h_v} / A_t$ is the effective opening factor of the fire compartment, h_v is the average opening height (m), q_t is the fire load density per unit area of the bounding surfaces of the compartment (MJ.m^{-2}), K_f is a coefficient which is related to the thermal properties of the compartment bounding surfaces (eg. $K_f = 0.85$ for concrete). The expression resulted from a comparison of the calculated times for equal temperature rises of 500°C in a protected steel column due to simulated compartment fires and ISO834 furnace tests. Pettersson shows that the formula is applicable to both unprotected and protected steel elements with a critical steel temperature of about 500°C, and may also be used for other values of the critical temperature provided that the opening factor of the fire compartment $A_v \sqrt{h_v} / A_t > 0.05 \text{ m}^{\frac{1}{2}}$. An alternative form of Pettersson's formula is

$$t_e = 0.067 \frac{A_f q_{ff}}{A_t \sqrt{(A_v \sqrt{h_v} / A_t)_f}} \quad \text{(min.)}$$

where $q_{ff} = K_f q_f$ is the effective fire load density per unit floor area (MJ.m^{-2}), and q_f is the fire load density per unit floor area (MJ.m^{-2}).

CIB (1986) presented the following form of the equation

$$t_e = c w q_f \qquad \text{(min.)}$$

where c is a conversion factor which accounts for the thermal properties of the boundaries (min./MJ.m^{-2}), w is a ventilation factor, and q_f is the fire load density per unit floor area (MJ.m^{-2}). The conversion factor may be conservatively estimated as $c = 0.1$ min./MJ.m^{-2}, or may be found from the following table:

Thermal absorptivity $\sqrt{k\rho C}$ (W/m^2.K.h$^{1/2}$)	(J/m^2.K.s$^{1/2}$)	Material	Conversion factor c (min./MJ.m^{-2})
< 12	< 720	Aerated concrete, timber	0.09
12 to 42	720 to 2500	Brick, normal and lightweight concrete	0.07
> 42	> 2500	Steel	0.05

where k is the thermal conductivity (W/m.K), and ρC the heat capacity (J/m^3.K) of the compartment boundaries. The ventilation factor is $w = A_f / [A_t \sqrt{(A_v \sqrt{h_v} / A_t)}]$ (note: this expression is not dimensionless), and which is approximated as $w = \sqrt{0.25 A_f / A_v} \leq 1.5$. For excellent ventilation conditions, including roof openings of more than 2% of the floor area, the ventilation factor maybe reduced to 70% of this value.

[***NOTE: FINALISE WHEN EUROCODE OBTAINED,
THE FOLLOWING IS FROM BUCHANAN (1994)]

The Eurocode 1 (1994) expression for equivalent fire duration is similar to the CIB expression but the conversion factor c (min./MJ.m$^{-2.3}$) and ventilation factor w (m$^{-0.3}$) are different. If the properties of the lining materials of the compartment are not known then a value of the conversion factor $c = 0.067$ min./MJ.m$^{-2.3}$ may be used, otherwise

Thermal absorptivity $\sqrt{k\rho C}$ (W/m^2.K.h$^{1/2}$)	(J/m^2.K.s$^{1/2}$)	Material	Conversion factor c (min./MJ.m^{-2})
< 12	< 720	Insulating material	0.090
12 to 42	720 to 2500	Concrete or plasterboard	0.055
> 42	> 2500	Thin steel	0.045

The ventilation factor w is

$$w = \left(\frac{6.0}{h_c}\right)^{0.3} \left[0.62 + \frac{90(0.4 - \alpha_v)^4}{1 + b_v \alpha_h}\right] > \ 0.5 \text{ m}^{-0.3}$$

where $\alpha_v = A_v / A_f$ $\qquad 0.05 \le \alpha_v \le 0.25$

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

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

and A_v is the area of vertical window and door openings (m^2), A_h is the area of horizontal openings in the roof (m^2), and h_c is the ceiling height of the compartment (m). Tabulated values of t_e in Acceptable Solution C3/AS1 of the New Zealand Building Code (BIA(1995)) were calculated using the Eurocode formula with ceiling height $h_c = 3.0$ m and conversion factor $c = 0.067$ min./MJ.m$^{-2.3}$ (Buchanan (1994)).

B3 NORMALISED HEAT LOAD CONCEPT

The normalised heat load concept was developed over a long period and the application of the method to the determination of equivalent fire exposure is summarised in Harmathy (1990-91). Normalised heat load H is the total heat absorbed by a unit area of the boundaries of an enclosure during a fire, divided by the thermal absorptivity of the boundaries, and has three important characteristics

If the boundaries of an enclosure are surfaced with different building materials, H is approximately the same for all surfaces, as well as for the enclosure as a whole. This does not apply to building elements which are made from or coated with metal eg. unprotected steel columns and beams.

For any element of the enclosure, H is approximately a measure of the maximum temperature rise at some critical depth from the surface, and therefore the normalised heat load procedure is also an equal temperature rises method.

The normalised heat load does not depend significantly on the history of the heat flux that penetrates the surface, and therefore two fires in the same enclosure which produce the same H will be of the same severity. This enables the performance of a building element in a real-world fire to be related to its performance in a standard fire test.

The normalised heat load endured without failure by a prototype of a building element in a standard test fire H'' must be equal to or greater than the normalised heat load which is expected to be imposed on it in a real-world fire H'. An expression for the normalised heat load for the standard fire test H'' was determined empirically and is dependent solely on the length of testing. This may be rearranged, substituting H' for H'' (as $H'' \geq H'$), and therefore the equivalent fire exposure is

$$t_e = 0.11 + 0.16 \times 10^{-4} H' + 0.13 \times 10^{-9} (H')^2 \qquad \text{(hours)}$$

$$t_e = 6.6 + 9.6 \times 10^{-4} H' + 7.8 \times 10^{-9} (H')^2 \qquad \text{(min.)}$$

where

$$H' = C_1 \frac{(11.0\delta + 1.6) A_f q_f}{A_t \sqrt{k\rho C} + C_2 \sqrt{\Phi_{\min} A_f q_f}} \qquad (\text{s}^{1/2}\ \text{K})$$

$$\delta = C_3 \sqrt{h_c^3 / \Phi_{\min}} \leq 1$$

$$\Phi_{\min} = 3.78 A_v \sqrt{h_v} \qquad (\text{kg.s}^{-1})$$

q_f is the average fire load density in kg.m^{-2}, $C_1 = 1.06 \times 10^6$ J kg^{-1}, $C_2 = 935$ J kg^{-1} K^{-1} and $C_3 = 0.79\ \text{kg}^{\frac{1}{2}}\ \text{m}^{-\frac{3}{2}}\ \text{s}^{-\frac{1}{2}}$. The formula for H' was obtained from the results of a large number of compartment fire simulations, and does not include random effects. Harmathy (1990-91) presents expressions which allow H' to be factored to include the effects of random variables such as fire load density, ventilation and the imperfect reproducibility of fire test results.

B4 EQUAL STRENGTH CRITERIA

Unlike the methods for estimating the equivalent fire exposure which are described in the previous sections, this method seeks to directly satisfy the requirements of the definition of equivalent fire exposure i.e. it seeks to find the time for which the loadbearing capacity of a given structure (or structural element) is identical to the minimum loadbearing capacity of the same structure subjected to a compartment fire. Schleich (1988, 1993) gives an example of such a determination of equivalent fire exposure for a composite steel-concrete frame from numerical simulations, and notes that this loadbearing equivalence is more generally useful than the temperature equivalence which is inadequate for structures with a non-uniform temperature distribution.

B5 NOTATION

A_f floor area (m^2)

A_t total area of the compartment internal surfaces (m^2)

A_h area of horizontal openings in the roof (m^2)

A_v ventilation area , or area of vertical openings (m^2)

b_v factor related to vertical opening area to floor area ratio

c conversion factor which accounts boundary thermal properties (min./MJ.m^{-2})

H normalised heat load ($s^{1/2}$ K)

H' normalised heat load of a building element in a real-world fire ($s^{1/2}$ K)

H'' normalised heat load of a building element in a standard test fire ($s^{1/2}$ K)

h_c ceiling height of the compartment (m)

k thermal conductivity of the compartment boundaries (W/m.K)

K a constant of the order of unity

K_f compartment boundary thermal properties coefficient

q_f fire load per unit floor area (kg.m^{-2}, MJ m^{-2})

q_{ff} effective fire load per unit floor area (MJ m^{-2})

q_t fire load per unit area of the compartment bounding surfaces (MJ m^{-2})

q_{tf} effective fire load per unit area of the compartment bounding surfaces (MJ m^{-2})

t_e equivalent fire exposure (minutes)

w ventilation factor (dimensionless, or $m^{-1/4}$, or $m^{-0.3}$ depending on definition)

α_v ratio of vertical opening area to floor area

α_h ratio of horizontal roof opening area to floor area

$\delta($ fractional heat evolution within a compartment

ρC heat capacity of the compartment boundaries (J/m^3.K)

Φ_{min} minimum ventilation factor for a compartment (kg.s^{-1})

B6 REFERENCES

AISI (1971). "Fire Protection Through Modern Building Codes", 4th Edition, American Iron and Steel Institute, New York, 347pp.

AS1530, Part 4-1990. "Methods for Fire Tests on Building Materials, Components and Structures : Fire resistance Tests of Elements of Building Construction", Standards Australia.

BIA (1995). "The New Zealand Building Code Handbook and Acceptable Solutions", Second Edition, Building Industry Authority, Wellington, New Zealand.

Buchanan, A.H. (1994), (Editor). "Fire Engineering Design Guide", Centre for Advanced Engineering, University of Canterbury, Christchurch, New Zealand, 203pp..

Butcher, G. (1991). "Fire Resistance of Buildings", Fire Surveyor, Vol. 20, No. 6, Dec. 1991, pp.6-12.

Campbell, J.A. (1986). "Confinement of Fire in Buildings", Fire Protection Handbook, 16th Edition, National Fire Protection Association, Quincy, MA, Section 7, Chapter 9.

CIB W14 (1986). "Design Guide - Structural Fire Safety", Fire Safety Journal, Vol. 10, No. 2, pp.75-137.

Drysdale, J.W. (1949). "Fire Grading of Buildings", Technical Record No. 3, Commonwealth Experimental Building Station.

Drysdale, J.W. (1991). "Fire Protection in Buildings", Technical Report No. 91/1, CSIRO Division of Building, Construction and Engineering (formerly published as Bulletin 9 by the Experimental Building Station, republished with revisions by J.J. Keough).

Eurocode 1 (1994). "Basis of design and actions on structures, Part 2-2: Actions on structures exposed to fire", European Committee for Standardisation, ENV1991-2-2:1994.

Harmathy, T.Z. (1987). "On the Equivalent Fire Exposure", Fire and Materials, Vol.11, No.2, pp.95-104
.
Harmathy, T.Z. (1990-1991). "Design of Buildings Against Fire Spread (A Review)", Journal of Applied Fire Science, Vol.1, No.1, pp.65-81.

Kawagoe, K. and Sekine, T. (1963). "Estimation of Fire Temperature-Time Curve in Rooms", Occasional Report No. 11, Building Research Institute.

Kawagoe, K. (1967). "Estimation of Fire Temperature-Time Curve in Rooms", BRI Research Paper No. 29, Building Research Institute.

Law, M. (1971). "A Relationship between Fire Grading and Building Design and Contents", Fire Research Note No. 877, Joint Fire Research Organisation.

Law, M. (1973). "Prediction of Fire Resistance", Symposium No.5, Fire-Resistance Requirements for Buildings - A New Approach, Proceedings of the Symposium held in London on 28 September 1971, Dept. of the Environment and Fire Offices' Committee / Joint Fire Research Organisation.

MOW (1946). “Fire Grading of Buildings, Part I - General Principles and Structural Precautions”, Post-War Building Studies No.20, by a joint committee of the Building Research Board of the Department of Scientific & Industrial Research and the Fire Offices’ Committee, Ministry of Works.

Pettersson, O. (1985). “Characteristics of Fire Exposure - with Particular Reference to Steel Structures”, Report LUTVDG/(TVBB-3034), Lund University, Sweden (also published as Chapter II and Appendix A in the “Design Manual on the European Recommendations for the Fire Safety of Steel Structures”, Publication No.35, European Convention on Constructional Steelwork, Brussels).

Schleich, J.B. (1988). “Fire Engineering Design of Steel Structures”, Steel Construction Today, 2, pp.39-52.

Schleich, J.B. (1993), (Chairman). “International Fire Engineering Design for Steel Structures: State of the Art”, prepared by a Working Group for the International Iron and Steel Institute, Brussels.

B7 TEMPERATURES OF COMPARTMENT FIRES

B7.1 INTRODUCTION

The fire temperature and fire duration are the main determinants of the severity of compartment fires, and are dependent on the fire load, the ventilation characteristics and the thermal properties of the building. It is proposed that fire severity be defined by a set of fire temperature histories or time-temperature curves which relate to the building fire load, ventilation and thermal properties. Fire time-temperature curves may be computed using either compartment fire models, or from temperature relations derived from correlation with experiment or compartment fire models.

B7.2 COMPARTMENT FIRE MODELS

B7.2.1 General

The following sections give a brief overview of the main features of compartment fire models. Harmathy and Mehaffey (1983) review and classify fourteen post-flashover models on the basis of a number of principal modelling aspects. Friedman (1991) surveyed a large number of models for compartment fires, as well as models for fire endurance of structural members, evacuation, thermal detectors and fire-sprinkler interaction. Janssens (1992) gives a review of deterministic fire modelling which includes post-flashover (one-zone) models and pre-flashover (multiple-zone) models.

B7.2.2 Post-flashover Models

The following brief description of a post-flashover model is based on the work of Pettersson et al. (1976). The gas temperature in the compartment is assumed to be uniform and is determined on the basis of a heat balance. The rate of heat generated by combustion is equal to the sum of the conductive heat losses through the boundaries (walls, floor and ceiling), convective and radiative heat losses through the openings, and the rate of change of heat energy stored in the gas volume. The rate of change of heat energy stored in the gas volume is usually small and is neglected. The radiative heat losses are equal to the radiation from a black gas volume at the gas temperature through an opening into a black environment at the ambient temperature according to the Stefan-Boltzmann law. The convective losses are equal to the enthalpy carried away by the mass flow rate of the hot gases leaving the room through the opening. The mass flow rate is calculated from an approximate solution to the equations of conservation of mass and momentum at the opening. The heat losses through the boundaries consist of a radiative part and a convective part and are dependent on the gas and boundary temperatures. This means that the heat conduction must be calculated through the thickness of the boundary. At the inner boundary surface the convective heat transfer is assumed to be Newtonian, and the radiative heat transfer is according to the Stefan-Boltzmann law with the emissivity assumed to be constant with temperature. At the outer boundary surface a temperature-dependent surface heat transfer coefficient is used. The rate of heat generated by combustion (heat release rate) is equal to the product of the mass loss rate and the effective heat of combustion of the fuel. This means that it is assumed that all of the fuel is burned within the compartment. The calculated gas temperatures are highly dependent on the form and magnitude of the heat release rate curve. Some of the relations for mass loss rates and heat release rates in compartment fires with cellulosic fuels from the literature are listed in the section entitled “Mass Loss Rates And Heat Release Rates”. The equations of the system are nonlinear and consist of an equation for the heat balance of the gas volume which is solved for the gas temperature, plus a number of equations for the temperatures through the thickness of the boundaries. The system equations are solved at discrete time intervals.

Other post-flashover models may be found in the work of Kawagoe and Sekine (1963), Harmathy (1972a,b), and Babrauskas (1979).

B7.2.3 Pre-flashover Models

Pre-flashover models are primarily concerned with predicting fire growth and smoke spread, and divide a room into a number of volumes or zones, each of which is assumed to be either internally uniform or to follow empirical relations of the space coordinates and time. The following brief description of a multi-room zone model is based on CFAST (Peacock et al. (1993)).

The main zones in a room are a lower layer of cold air and an upper layer of hot gases. Conditions in a room can only vary from floor to ceiling and not horizontally. This is based on experimental observations that generally room conditions stratify into two layers in fires. In addition to the two layers there are other zones for the fire plume and door plume. The model solves a set of equations that predict state variables (temperature, pressure, smoke density and gas concentration) at small increments of time. The equations are derived from conservation equations for energy, mass, and momentum, and the ideal gas law.

A fire is a source of fuel which is released at a specified rate and is converted into heat and mass as it burns. Above the fire, a plume forms which acts a pump for heat and mass from the lower layer to the upper layer. Plumes at vents such as windows and doors act to move heat and mass from the room. Flow through vents is governed by the pressure differences across a vent. The amount of mixing in the plumes is defined by empirical correlations. The analysis does not include a pyrolysis model to predict fire growth and therefore the accuracy of the analysis depends on the accuracy of the specified fuel mass loss rate and heat release rate in modelling an actual fire. The model has two types of fires - an unconstrained fire in which all the burning takes place within the fire plume, and a constrained fire in which burning occurs where there is sufficient oxygen. For a constrained fire where insufficient oxygen is entrained into the fire plume, unburned fuel will successively move into and burn in: the upper layer of the fire room, the plume in the doorway to the next room, the upper layer of the next room, and so on until it is consumed or gets to the outside.

Convective heat transfer occurs from the gas layers to the room surfaces in a direction perpendicular to the wall, ceiling or floor surface. Radiative transfer occurs among the fire, the gas layers and the room surfaces and is a function of the temperature differences and the emissivity of the gas layers and the room surfaces. For the gas layers, the emissivity is a function of the concentration of species such as smoke particulates, carbon dioxide and water.

At the start of the simulation, when the layers are initialised, they are set to ambient conditions. As fuel is pyrolysed, the various species are produced in direct relation to the mass of fuel burned (as specified by the user). Hydrogen cyanide and hydrogen chloride are assumed to be products of pyrolysis whereas carbon dioxide, carbon monoxide, water, and soot are products of combustion. The model keeps track of the mass of each species in each layer, as well as the volume of each layer at any time.

B7.2.4 Mass Loss Rates And Heat Release Rates

Mass loss rates (or rate of burning) and corresponding heat release rates are essential data for the compartment fire models. The literature has been surveyed for methods of prediction of mass loss rate and heat release rate in compartment fires. As the notation used by various researchers has not always been the same, then that listed in the section entitled "Notation" will be adopted.

Some existing relations for mass loss rate (or rate of burning) and/or heat release rate in compartment fires with cellulosic fuels such as wood are:

Kawagoe and Sekine (1963)

Rate of burning $R = (5.5 A_v \sqrt{h_v}$ kg / min. (ventilation controlled)

$R = (0.092 A_v \sqrt{h_v}$ kg / s

Heat of combustion $\Delta h =$ 2575 kcal./kg = 10.78 MJ / kg

Heat release rate $Q = R\,\Delta(h = (0.99 A_v \sqrt{h_v}$ MW

Fire duration time $t_f = (M_0 / R$ s

where A_v is the total opening (or vent) area of the fire compartment (m^2), h_v is the mean height of the fire compartment openings (m), and M_0 is the mass of cellulosic fuel in the compartment before the fire (kg).

The rate of burning expression was based on the results of experimental fire tests in model and full-scale rooms (Kawagoe(1958)). The room sizes varied from 0.4m square x 0.2m high for small model rooms to approximately 5m square x 2.6m high for full scale tests. Generally, the test rooms were constructed of concrete or masonry, but the smallest model rooms were made of steel plate. In all cases, the rooms had vertical openings ie. either windows or doors.

Magnusson and Thelandersson (1970), Pettersson et al. (1976)

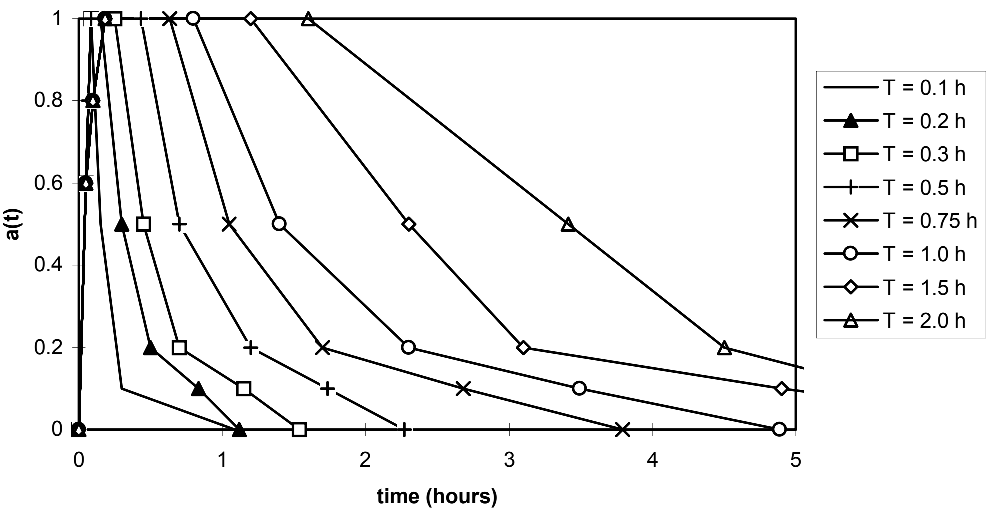
Rate of burning $R = (a(t)\ 330 A_v \sqrt{h_v}$ kg / h. (ventilation controlled)

$R = (a(t)\ 0.092 A_v \sqrt{h_v}$ kg / s

Heat of combustion $\Delta h =$ 2575 kcal./kg $= 10.78$ MJ / kg

Heat release rate $Q = R\,\Delta h = a(t)\ 0.99 A_v \sqrt{h_v}$ MW

A set of dimensionless piecewise linear functions $a(t)$ was determined for a range of fire duration by matching the temperatures output by their compartment model to experimental measurements (see figure below).



The appropriate curve for $a(t)$ depends on the nominal duration of the flame phase defined as

$$T = q_t A_t / (1500 A_v \sqrt{h_v})\ \text{h}.$$

where q_t is the fire load in Mcal. m^{-2} distributed over the total surface area of the compartment A_t (m^2).

The experimental results were from four test series. The first series was carried out in a test house with concrete floors and concrete or lightweight concrete walls. The fire load consisted of ordinary furniture, and the openings were windows or doors. The floor area was either 10.4 m^2, 18.8 m^2 or 29.2 m^2, and the opening factor $A_v \sqrt{h_v} / A_t$ ranged from 0.016 $m^{\frac{1}{2}}$ to 0.068 $m^{\frac{1}{2}}$. The second series of tests consisted of three tests of Kawagoe(1958). These tests were performed on a building with one window, and with walls of hollow concrete blocks and concrete floor and roof structures. The floor area was 9 m^2, room height 2.5m, and the opening factor was 0.0467 $m^{\frac{1}{2}}$. The third series of tests was conducted in a concrete tunnel building of an approximately semi-circular cross-section with total bounding surface area 75 m^2 and total enclosed volume of 46 m^3. As air was supplied by a fan and exhausted by vents in each end wall fictitious opening factors were used for computations based on these tests. The fourth test series was conducted in the lower storey of a three storey steel framed building clad in lightweight concrete elements. The fire room had an external window and a vertical ventilation duct by-passing the upper stories. The ventilation provided by the duct was estimated to be similar in magnitude to that provided by the window.

Harmathy, T.Z. (1993)

The method is a refinement of that in Harmathy (1972a,b) for cellulosic fuels.

The fire is divided into two time periods - the period of primary or fully developed burning and the period of secondary burning. Both periods are assumed to be of equal length τ. The length of the period of fully developed burning is equal to the duration of the pyrolysis process, and the duration of char-oxidation is equal to 2τ. The time τ in seconds is

$$\tau = 39.6\frac{M_0}{\Phi} \qquad \frac{\Phi}{A_f} < 0.263 \quad \text{(ventilation controlled)}$$

$$\tau = \frac{151}{\varphi} \qquad \frac{\Phi}{A_f} \geq 0.263 \quad \text{(fuel-bed controlled)}$$

where $\Phi = \rho_a A_v \sqrt{g h_v}$ is the ventilation parameter, $\rho_a = 1.184 \text{ kg m}^{-3}$ is the air density at $25\,^{\circ}\text{C}$, $g = 9.8 \text{ ms}^{-2}$ is the acceleration due to gravity, $A_f = M_0\varphi$ is the aggregate surface area of the fuel, and $\varphi \approx 0.13 \text{ m}^2\text{kg}^{-1}$ for conventional furniture. The expressions for τ are based on a large number of experimental observations of burning rate. The majority of the tests were for half-scale or smaller model compartments, along with the full-scale tests of Kawagoe(1958), Butcher et al. (1966) and Butcher et al. (1968). The tests of Butcher et al. were conducted in a test room of 7.6m x 3.7m x 2.9m high constructed of brick with a concrete floor and ceiling. The fuel was wood cribs which were evenly distributed on the floor. Ventilation was provided by two openings each 3.05m x 1.83m high in one long wall, and the sizes of the openings could be halved by the addition of panels.

The rate of formation of volatile pyrolysis products is

$$R_c = 0.87 M_0 / \tau \;\; \text{kg/s}$$

and the rate of char-oxidation is

$$R_{ch} = 0.065 M_0 / \tau \;\; \text{kg/s}.$$

Then in the period of primary burning, the burning rate is

$$R = R_c + R_{ch} = 0.935 M_0 / \tau \;\; \text{kg/s}$$

and in the period of secondary burning

$$R = R_{ch} = 0.065 M_0 / \tau \;\; \text{kg/s}.$$

The rate of heat released within the compartment is constant over each period. Within the period of primary burning

$$Q = \left(\frac{M_0}{\tau}\right)(0.87\delta\,\xi_F\,\Delta h_c - \Delta h_p + 0.065\xi_{ch}\,\Delta h_{ch})\ \text{MW}$$

and for the period of secondary burning

$$Q = \left(\frac{M_0}{\tau}\right)0.065\xi_{ch}\,\Delta h_{ch}\ \text{MW}$$

where $\xi_F \approx 0.8$ is a factor quantifying incomplete combustion of volatile pyrolysis products in the flame, $\xi_{ch} \approx 0.8$ is a factor quantifying incomplete oxidation of char, $\Delta h_c \approx 16.7$ MJ kg^{-1} is the heat of combustion of volatile pyrolysis products, $\Delta h_{ch} \approx 33.4$ MJ kg^{-1} is the heat of oxidation of char, $\Delta h_p \approx 1.8$ MJ kg^{-1} is the heat of pyrolysis (heat of converting the virgin fuel into volatiles and char), and δ is the fraction of the heat evolved from flaming combustion inside the compartment. The parameter δ is determined from

$$\delta = 1 \qquad h_F \le h_C$$

$$\delta = \left(\frac{h_C}{h_F}\right)^{3/2} \qquad h_F > h_C$$

where h_C (m) is the height of the compartment and h_F (m) is a hypothetical flame height for compartment fires given by

$$h_F = 1.17\Phi^{\frac{1}{3}} \qquad \frac{\Phi}{A_f} < 0.263$$

$$h_F = 0.75A_f^{\frac{1}{3}} \qquad \frac{\Phi}{A_f} \ge 0.263.$$

Babrauskas and Williamson (1978), Babrauskas (1981,1988)

Rate of burning -

i) ventilation controlled: $R = 0.12A_v\sqrt{h_v}$ kg / s (constant)

ii) fuel-bed controlled: $R = \left(\frac{4v_p}{d}\right)\sqrt{M_0 M}$ kg / s (diminishing)

where $v_p = 2.2\times10^{-6}d^{-0.6}$ ms^{-1} (for $d \le 0.05$ m) is the fuel (wood) surface regression velocity, M is the total mass remaining at any time (kg), and d is the original stick thickness (m) for square sticks.

Heat of combustion $\Delta h =$ 12 MJ / kg

Heat release rate $Q = R\,\Delta h$

Law (1983)

Rate of burning $R = 0.18\sqrt{(W/D)}(1 - e^{-0.036\eta})\, A_v\sqrt{h_v}$ kg / s

Effective fire duration $t_f = M_0 / R$ s

where $\eta = (A_t - A_v) / A_v\sqrt{h_v}$, W is the width of the compartment parallel to the opening (m), and D is the depth of the compartment normal to the opening (m). The equation for rate of burning is for ventilation controlled fires, and is based on a large program of experimental fires carried out by eight laboratories for the Conseil International du Batiment (CIB) (Thomas and Heselden(1972), Heselden(1973)). The fire compartments were small asbestos-lined boxes with heights ranging from 0.5m to 1.5m and plan dimensions ranging from 0.5m x 1m to 6m square. Ventilation was provided by a full-height opening in one wall of either ¼ , ½ or the full area of the wall. Wood cribs of various arrangements were used as fuel.

Thomas, P.H. (1988)

Rate of burning $R = 0.02\sqrt{(A_t - A_v)(W/D) A_v\sqrt{h_v}}$ kg / s

$$R = 0.02\sqrt{\frac{(A_t - A_v)}{A_v\sqrt{h_v}}\left(\frac{W}{D}\right)} A_v\sqrt{h_v} \text{ kg / s}.$$

The rate of burning expression was derived by correlation with the CIB experiments (Thomas and Heselden(1972), Heselden(1973)). Burning rates for two larger compartments (Hagen et al. (1986)) were compared with the extrapolation of the CIB data. The larger compartment (20.4m x 7.2m x 3.6m high) had walls, floor and ceiling of lightweight concrete. The fuel in the experiments was wood cribs with a maximum total mass of 2500 kg. Ventilation was provided by an opening located centrally in the long wall of the form of a window or door with area 1.5 $m^2 \leq A_v \leq$ 7.8 m^2 and ventilation factor 1 $m^{5/2} \leq A_v\sqrt{h_v} \leq$ 13.5 $m^{5/2}$. The smaller compartment (7.8m x 7.2m x 3.6m high) was the same as the larger compartment but reduced in length. The results for the larger compartment supported the expression, while the smaller compartment shows a lesser effect of $(A_t - A_v) / A_v\sqrt{h_v}$ than implied by the expression.

Poon (1995)

The heat release curve has three stages:

i) Growth stage

Heat release rate $Q = \alpha t^2$ MW

where $\alpha = 0.1876 \times 10^{-3}$ MW / s^2 is the fire intensity factor, and t is the time (s).

ii) Uniform stage (ventilation-controlled)

Rate of burning $R = 0.12 A_v \sqrt{h_v}$ kg / s

Heat release rate $Q = R\,\Delta h$

Heat of combustion $\Delta h =$ 10.5 MJ / kg

iii) Decay stage (fuel-bed controlled)

Rate of burning $R = 0.0012 M_0 \left(M / M_0\right)^{\frac{1}{2}}$ kg / s

where M is the mass remaining at any time, M_0 is the initial mass, and the heat release rate is by the same expression as the uniform stage.

B7.2.5 Thermal Feedback

None of the compartment fire models with cellulosic fuels mentioned in the previous sections included the effect on the rate of burning of thermal feedback from the burning gases to the fuel. Thomas (1975) suggested that thermal feedback should be included in compartment fire models. In response to Thomas, Harmathy (1975) states “Experimental facts strongly support the view that, in the case of cellulosic fuel fires, thermal feedback from the flames to the fuel need not be considered in formulating either the compartment temperature (or energy balance for the compartment) or the rate of burning. For liquid fuels and solid fuels decomposing without leaving behind combustible solid pyrolysis products (probably all plastics), thermal feedback does play a significant part in the rate of burning, but its direct effect on the energy balance for the compartment is insignificant”. He argues that thermal feedback is impossible with a burning wood pile as the temperature of the pile is higher than the average temperature of the flames so the flames moderate heat losses from the pile rather than supply heat to it. The lack of thermal feedback is confirmed by the experimental observations that over a wide range of conditions the rate of burning is roughly proportional to the rate of airflow into the compartment, and that the rate of burning depends relatively little on the average compartment temperature.

B8 TEMPERATURE EXPRESSIONS

A number of authors have produced closed-form expressions either for the fire time-temperature curves or the peak fire temperatures.

Lie (1974, 1992) developed temperature curves based on results of the analysis of Kawagoe and Sekine (1963) for ventilation-controlled fires. The expression is

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

where T_f is the fire temperature ($°C$), t is time (h), C is a constant which depends on the boundary material properties ($C = 0$ for heavy materials $\rho \geq 1600 \text{ kg/m}^3$, $C = 1$ for light materials $\rho < 1600 \text{ kg/m}^3$), and $F = A_v \sqrt{h_v} / A_t$ ($\text{m}^{\frac{1}{2}}$) is the opening factor. The expression is valid for $t \leq 1 + 0.08/F$ and $0.01 \leq F < 0.15$. If $t > 1 + 0.08/F$ then a value of $t = 1 + 0.08/F$ should be used, and if $F > 0.15$ then $F = 0.15$ should be used. The temperature during the decay period is

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

where τ is the time at which decay begins (h), T_τ is the temperature ($°C$) at time $t = \tau$, and $t > \tau$ and $T_f \geq 20°C$. The decay period begins at the time given by the nominal fire duration

$$\tau = \frac{q_t A_t}{330 A_v \sqrt{h_v}} = \frac{q_t}{330F}$$

where q_t is the fire load per unit area of the bounding surfaces (kg/m^2).

Babrauskas (1981) expressed the fire temperature T_f as

$$T_f = T_\infty + (T^* - T_\infty) \cdot \theta_1 \cdot \theta_2 \cdot \theta_3 \cdot \theta_4 \cdot \theta_5$$

where T_∞ is the ambient temperature, $T^* = 1725°C$ is an empirical constant associated with adiabatic combustion, and the factors θ_1 to θ_5 have values which can range from 0 to 1 and are associated with burning rate stoichiometry, boundary steady-state losses, boundary transient losses, opening height and combustion efficiency, respectively. Expressions for the factors θ_1 to θ_5 may be found in the reference. Either steady-state or transient solutions may be obtained.

Wickstrom (1981/82, 1985) developed a method which allows the approximate post-flashover fire temperatures to be expressed as a single curve which is then modified by scaling the time to take into consideration ventilation conditions and wall properties of the compartment. The temperature change θ_f is

$$\theta_f = \sum_{i=0}^{3} B_i \exp(-\beta_i t^*)$$

where t^* is the modified time (h), and B_i ($°\mathrm{C}$) and β_i (h^{-1}) are constants. The earlier paper used values of B_i and β_i which gave a good comparison with the computed results of Magnussen and Thelandersson (1970) and Pettersson et. al (1976). The later paper used values of B_i and β_i which gave a good approximation to the ISO834 standard furnace curve and are tabulated below.

i	0	1	2	3
B_i ($°\mathrm{C}$)	1325	-430	-270	-625
β_i (h^{-1})	0	0.2	1.7	19

The modified time is defined as

$$t^* = \gamma^2 t$$

where

$$\gamma = \frac{A_v \sqrt{h_v} / A_t}{\sqrt{k\rho c}} \frac{(\sqrt{k\rho c})_A}{(A_v \sqrt{h_v} / A_t)_{0.04}}$$

and $(A_v \sqrt{h_v} / A_t)_{0.04} = 0.04 \ \mathrm{m}^{\frac{1}{2}}$ is taken to be the standard opening factor and $(\sqrt{k\rho c})_A = 1165 \ \mathrm{Ws}^{\frac{1}{2}}\mathrm{m}^{-2}\mathrm{K}^{-1}$ is the thermal inertia of a standard wall material in a fire compartment. The fire duration can be estimated as for Lie (1974) above and then the modified duration t_d^* calculated according to the modified time expression. Wickstrom (1981/82) suggests that the following linear temperature decreases based on ISO834 may be used in the decay phase (in modified time)

$625 \ °\mathrm{C/h}$	for $t_d^* \le 0.5$ h
$250(3 - t_d^*) \ °\mathrm{C/h}$	for $0.5 < t_d^* < 2$ h
$250 \ °\mathrm{C/h}$	for $t_d^* \ge 2$ h.

Based on many experimental fires (CIB program, Thomas and Heselden(1972), Heselden(1973)), Law (1983) derived a relation between the average temperature during the fully developed period of fires in compartments T_f ($°\mathrm{C}$) and the parameters $\eta = (A_t - A_v) / A_v \sqrt{h_v}$ and $\psi = L / \sqrt{A_v (A_t - A_v)}$ where L is the fire load in kg wood,

$$T_f = T_{f(\max)}(1 - e^{-0.05\psi})$$

and

$$T_{f(\max)} = 6000\frac{(1-e^{-0.1\eta})}{\sqrt{\eta}}.$$

Eurocode 1 (1995) incorporates "parametric" curves for calculating the temperatures of hot gases both for fires within compartments and for fires issuing from the windows of buildings. The temperature development predicted for the fire is normalised against the details of the particular compartment so that it takes the form of the "general natural fire curve" - this is the approach developed by Wickstrom (1981/82, 1985). The "general natural fire curve" is similar to the ISO834 curve but reaches a maximum temperature after a specific duration and includes a cooling part. The curves for temperatures within a compartment are valid for fire compartments up to 100 m^2 of floor area, without openings in the roof, for a maximum compartment height of 4 m, and with mainly cellulosic type fuel loads. The temperature T_f ($°C$) in the heating phase is given by

$$T_f = 1325(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*})$$

where $t^* = t\,\Gamma$ (h), t is time (h), $\Gamma = (O/b)^2/(0.04/1160)^2$, $O = A_v\sqrt{h_v}/A_t$ ($m^{1/2}$) is the opening factor with $0.02 \le O \le 0.20\ m^{1/2}$, and $b = \sqrt{k\rho c}$ ($Jm^{-2}s^{-1/2}K^{-1}$) with $1000 \le b \le 2000\ Jm^{-2}s^{-1/2}K^{-1}$. The temperature given by the above expression should probably be the temperature change from the initial temperature. If the boundary consists of layers of different materials then

$$b = \sqrt{\sum s_i c_i k_i} \Big/ \sqrt{\sum (s_i c_i k_i / b_i^2)}$$

where s_i is the thickness of layer i, c_i is the specific heat of layer i, k_i is the thermal conductivity of layer i, and $b_i = \sqrt{k_i \rho_i c_i}$. To account for different material in walls, ceiling and floor then

$$b = \sum b_j A_{tj} \Big/ \sum A_{tj}$$

where A_{tj} is the area of enclosure including openings with the thermal property b_j. The temperature ($°C$) in the cooling phase is given by

$$T_f = T_{f(\max)} - 625\,(t^* - t_d^*) \qquad \text{for } t_d^* \le 0.5 \text{ h}$$
$$T_f = T_{f(\max)} - 250\,(3 - t_d^*)(t^* - t_d^*) \qquad \text{for } 0.5 < t_d^* < 2 \text{ h}$$
$$T_f = T_{f(\max)} - 250\,(t^* - t_d^*) \qquad \text{for } t_d^* \ge 2 \text{ h}$$

where $T_{f(\max)}$ ($°C$) is the maximum temperature in the heating phase for $t^* = t_d^*$, $t_d^* = 0.13 \times 10^{-3} q_t \Gamma / O$ (h), $q_t = q_f A_f / A_t$ is the fire load density related to the surface area of the enclosure (MJ/m^2), and q_f is the fire load density related to the floor area (MJ/m^2).

B9 NOTATION

A_f aggregate surface area of the fuel (m^2)

A_t total area of the enclosing area surfaces including openings (m^2)

A_v total opening (or vent) area of the fire compartment (m^2)

$a(t)$ piecewise linear function of time t

B_i fire curve constants ($°C$)

b thermal inertia of boundary material ($Jm^{-2}s^{-1/2}K^{-1}$)

C a constant which depends on the boundary material properties

D depth of the compartment normal to the opening (m)

d original stick thickness (m)

F opening factor ($m^{\frac{1}{2}}$)

g acceleration due to gravity (ms^{-2})

h_C height of the compartment (m)

h_F hypothetical flame height for compartment fires (m)

h_v mean height of the fire compartment openings (m)

L fire load (kg wood)

M total mass remaining at any time (kg)

M_0 mass of cellulosic fuel in the compartment before fire (kg)

O opening factor ($m^{\frac{1}{2}}$)

q_f fire load density related to the floor area of the compartment (MJ/m^2)

q_t fire load density related to the surface area of the compartment (MJ/m^2, kg/m^2, $Mcal./m^2$)

R mean rate of burning (kg/h , $kg/min.$, kg/s)

R_c rate of formation of volatile pyrolysis products (kg/s)

R_{ch} rate of char-oxidation (kg/s)

T nominal duration of the flame phase of the fire (h)

T_f fire temperature ($°C$)

$T_{f(max)}$ maximum fire temperature for a given compartment geometry ($°C$)

T_τ temperature at the start of the decay stage ($°C$)

T_∞ ambient temperature ($°C$)

T^* an empirical constant associated with adiabatic combustion ($°C$)

t time (s, min., h).

t_f fire duration time (s)

t^* modified time (h)

t_d^* modified duration (h)

v_p fuel (wood) surface regression velocity (ms^{-1})

W width of the compartment parallel to the opening (m)

α fire intensity factor (MW/s^2)

β_i fire curve constants (h^{-1})

γ	time scaling or modifying parameter
Δh	calorific value or heat of combustion of fuel (kcal./kg, MJ / kg)
Δh_c	heat of combustion of volatile pyrolysis products ($MJ\ kg^{-1}$)
Δh_{ch}	heat of oxidation of char ($MJ\ kg^{-1}$)
Δh_p	heat of pyrolysis ($MJ\ kg^{-1}$)
δ	fraction of the heat evolved from flaming combustion inside the compartment
η	parameter, similar to inverse of opening factor ($m^{-\frac{1}{2}}$)
θ_f	temperature change ($^\circ C$)
$\theta_1 - \theta_5$	reduction factors
Γ	time scaling or modifying parameter
ξ_{ch}	factor quantifying incomplete oxidation of char
ξ_F	factor quantifying incomplete combustion of volatile pyrolysis products in the flame
ρ	compartment boundary material density ($kg\ m^{-3}$)
ρ_a	air density at $25\,^\circ C$ ($kg\ m^{-3}$)
τ	duration of either primary or secondary burning phase (s)
τ	time at which decay begins (h)
Φ	ventilation parameter (kg / s)
φ	fuel surface area per unit mass ($m^2 kg^{-1}$)
ψ	fire load parameter ($kg\ m^{-2}$)

Harmathy, T.Z. (1972a). “A New Look at Compartment Fires, Part I”, Fire Technology, Vol.8, No.3, pp.196-219.

Harmathy, T.Z. (1972b). “A New Look at Compartment Fires, Part II”, Fire Technology, Vol.8, No.4, pp.326-351.

Harmathy, T.Z. (1975). “The Role of Thermal Feedback in Compartment Fires”, Fire Technology, Vol. 11, No. 1, pp.48-54.

Harmathy, T.Z. (1993). “Fire Safety Design and Concrete”, Longman Scientific and Technical, 412pp.

Harmathy, T.Z. and Mehaffey, J.R. (1983). “Post-flashover Compartment Fires”, Fire and Materials, Vol.7, No.2, pp.49-61.

Heselden, A.J.M. (1973). “Results of an International Co-operative Programme on Fully-Developed Fires in Single Compartments”, Joint Fire Research Organisation, Paper 1, Symposium No.5, Fire-Resistance Requirements for Buildings - A New Approach, pp.1-13.

Janssens, M. (1992). “Room Fire Models”, Chapter 6, “Heat Release in Fires”, V. Babrauskas and S.J. Grayson, eds., Elsevier Applied Science, London, 644pp..

Peacock, R.D., Forney, G.P., Reneke, P.A., Portier, R.M., and Jones, W.W. (1993). “CFAST, the Consolidated Model of Fire Growth and Smoke Transport”, NIST Technical Note 1299, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Pettersson, O., Magnusson, S.E., and Thor, J. (1976). “Fire Engineering Design of Steel Structures”, Bulletin 52, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Sweden.

Poon, S.L. (1995). “A Design Fire for Use in Predicting the Performance of Exposed Structural Steel Members”, Fourth Pacific Structural Steel Conference, Singapore, Vol. 1 Steel Structures, eds. N.E. Shanmugam and Y.S. Choo, Pergamon, pp. 749-764.

Thomas, P.H. (1975). “Old and New Looks at Compartment Fires”, Fire Technology, Vol. 11, No. 1, pp.42-47.

Thomas, P.H. (1988). “Some Notes on Fires in Compartments”, Report LUTVDG/(TVBB-3033), Department of Fire Safety Engineering, Lund University, Sweden.

Thomas, P.H., and Heselden, A.J.M. (1972). “Fully-Developed Fires in Single Compartments. A Co-operative Research Programme of the Conseil International du Batiment”, Joint Fire Research Organisation, Fire Research Note No. 923.

Wickstrom, U. (1981/82). “Temperature Calculation of Insulated Steel Columns Exposed to Natural Fire”, Fire Safety Journal, Vol.4, pp.219-225.

Wickstrom, U. (1985). “Application of the Standard Fire Curve for Expressing Natural Fires for Design Purposes”, Fire Safety: Science and Engineering, ASTM STP 882, T.Z. Harmathy, ed., American Society for Testing and Materials, Philadelphia, pp.145-159.

APPENDIX C

FIRE LOADS

C1 INTRODUCTION

The fire load (quantity of combustible materials) is one of the factors that may influence the severity of a fire. A number of surveys of fire load for various occupancies have been conducted in various overseas countries. The results are summarised in the following sections. Proposed fire loads for the building classifications of the Building Code of Australia are tabulated based on these surveys.

Total fire loads consist of permanent (or fixed) fire loads and variable (or movable) fire loads. Permanent fire loads are those combustible materials which have a negligible variation during the service life of a structure and comprise building materials including the load-bearing structure, linings, finishes, and permanently installed devices. Variable fire loads are all combustible materials that may vary during the service life of a structure eg. furniture, storage goods, movable equipment.

Generally, in the following sections, the fire load is in terms of fire load density ie. fire load per unit floor area. Some data is in terms of the fire load per unit area of the surface bounding the fire compartment and is noted as such.

C2 AISI (1971) - U.S. DATA

AISI (1971) collects data on fire loads from the following references:

"Fire-Resistance Classifications of Building Constructions", Building Materials and Structures Report 92 (BMS 92), National Bureau of Standards, Washington, D.C., 1942.

Ingberg, S.H., Dunham, J.W., and Thompson, J.P. "Combustible Contents in Buildings", Building Materials and Structures Report 149 (BMS 149), National Bureau of Standards, Washington, D.C., 1957.

Bryson, J.O., and Gross, D. "Techniques for the Survey and Evaluation of Live Floor Loads and Fire Loads in Modern Office Buildings", Building Science Series 16 (BSS 16), National Bureau of Standards, Washington, D.C., 1967.

Although it is not stated, it seems that inventory techniques were used to obtain the survey data as "the weights of combustible items were obtained in sufficient number to enable the total weight within the areas surveyed to be determined". Allowance for combustible finishes (eg. wood trim, windows, shelves) was made by including one-half of their weights. Wood floors were included in the fire load, but not the weights of any framing members or structural parts of the buildings.

Fire loads for residential occupancies (dwellings and apartment buildings) from BMS 92 (see also Issen (1978)):

	Average fire load density							
	Movable property		Floors		Exposed woodwork other than floors**		Total	
	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*
Bedrooms (including closets)	5.0	450	2.8	250	2.6	240	10.4	940
Dining rooms	3.2	290	2.0	180	2.0	180	7.2	650
Hallways	1.0	90	3.0	270	6.5	590	10.5	950
Kitchens	1.2	110	2.5	230	3.1	280	6.8	620
Living rooms	3.9	350	2.4	220	1.8	160	8.1	740
Store rooms (apartment houses)	6.4	580	0.5	50	0.3	30	7.2	650
Closets								
Clothes	5.1	460	2.7	250	11.6	1050	19.4	1760
Linen	11.7	1060	3.0	270	21.4	1940	36.1	3280
Kitchen	4.0	360	3.0	270	23.2	2110	30.2	2740
Entire apartment or residence (average for all areas surveyed)	3.4	310	2.6	240	2.8	250	8.8	800

* conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

** includes doors, windows, baseboards, mouldings, trim, shelving, etc.

Total fire load density includes furnishings as well as floor finish, doors, windows, trim, frames, mouldings, shelving, etc.

Fire loads for educational occupancies (based on school buildings) from BMS 92:

	Average fire load density							
	Movable property		Floors		Exposed woodwork other than floors**		Total	
	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*
Typical classrooms	2.7	250	2.1	190	2.1	190	6.9	630
Laboratories								
Biology	5.0	450	2.2	200	1.2	110	8.4	760
Chemistry	5.1	460	2.1	190	1.2	110	8.4	760
Food and clothing	4.4	400	1.8	160	2.2	200	8.4	760
Physics	3.3	300	2.6	240	1.4	130	7.3	660
Mechanical drawing	6.0	540	2.6	240	2.0	180	10.6	960
Bookkeeping and typewriting	6.7	610	2.6	240	2.2	200	11.5	1040
Art rooms	6.5	590	1.8	160	1.5	140	9.8	890
Geography, music and lecture rooms	2.4	220	3.7	340	2.3	210	8.4	760
Library (stack room)	28.4	2580	2.1	190	5.4	490	35.9	3260
Lunch room	2.6	240	2.6	240	1.5	140	6.7	610
Woodworking shops	6.1	550	2.6	240	0.7	60	9.4	850
Storerooms								
Janitor's	35.9	3260	0.9	80	1.5	140	38.3	3480
Lumber	43.7	3970	1.3	120	0.7	60	45.7	4150
Paint	4.0	360	2.6	240	13.1	1190	19.7	1790
Paper	97.5	8850	0.0	0	0.7	60	98.2	8910
Textbooks	172.3	15640	0.7	60	0.6	50	173.6	15760
Approximate average for total useable area of six schools surveyed							7.2***	650***

* conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

** includes doors, windows, baseboards, mouldings, trim, etc.

*** Combustibles that are part of the structural framing are not included. Storerooms and library stacks are excluded as they are storage occupancies not educational occupancies; the combustible content for "office and files" was taken to be 25 percent of the total.

Fire loads for institutional occupancies (based on hospitals) from BMS 92:

	Average fire load density					
	Movable property		Exposed woodwork and floors**		Total	
	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*
Rooms (single)	0.5	50	3.2	290	3.7	340
Corridors	0	0	2.6	240	2.6	240
Waiting rooms	1.7	150	1.5	140	3.2	290
Janitor's closets and supplies	3.1	280	3.4	310	6.5	590
Doctor's offices	5.7	520	2.9	260	8.6	780
Nurses' offices and rooms	3.1	280	1.9	170	5.0	450
Nurses' infirmary	0.8	70	2.2	200	3.0	270
Diet kitchens and dining rooms	1.2	110	2.4	220	3.6	330
Laundries	4.4	400	0.6	50	5.0	450

Laundries and clothes storage	12.5	1130	0.6	50	13.1	1190
Dormitories	0.8	70	2.0	180	2.8	250
Pharmacy, dispensary and stores	5.8	530	1.9	170	7.7	700
Lockers, toilets and barber shops	0.2	20	1.2	110	1.4	130
Approximate average for entire useable floor area of three hospital buildings surveyed					5.7***	520***

*   conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

** combustible floor finish where present was ¼ inch thick linoleum (assumed equivalent to 1 lb/ft^2 wood); doors, windows, trim, mouldings, baseboards, etc. are included.

*** The approximate average was noted to be somewhat high.

Note: For the hospitals surveyed, in almost 90% of the floor area the combustible contents averaged less than 5 lb/ft^2 (450 MJ/m^2) and a density greater than 10 lb/ft^2 (910 MJ/m^2) existed in only 4% of the total floor area.
Jails and similar institutions contain virtually no combustible materials.

Fire loads for assembly occupancies from BMS 92:

	Average fire load density					
	Movable property		Exposed woodwork and floors**		Total	
	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*
Auditoriums	1.0	90	4.6	420	5.6	510
Gymnasiums	0.3	30	7.1	640	7.4	670
School lunchrooms	2.6	240	4.1	370	6.7	610

*   conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

Note: Exhibition halls may contain fire loads greater than for mercantile occupancies.

Fire loads for business occupancies from BSS 16 (based on one building of 221 rooms):

	Average fire load density					
	Movable property		Interior finish**		Total	
	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*	(lb / ft^2)	(MJ/m^2)*
Offices	2.4	220	1.4	130	3.8	340
Storerooms	2.7	250	1.5	140	4.2	380
Conference room	2.5	230	2.2	200	4.7	430
Lobbies	0.1	10	1.0	90	1.1	100
Libraries	7.3	660	1.0	90	8.3	750
File rooms	6.7	610	0.8	70	7.5	680

*   conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

** Includes floors, walls, ceilings, doors, windows, baseboards, trim, mouldings, etc.

Note: Average fire load after adjustment for combustibles stored in incombustible containers was 4 lb/ft^2 (360 MJ/m^2)

Based on a survey of a small number of buildings reported in BMS 149, mercantile occupancies such as stores, shops and salesrooms are expected to have average fire load densities of about 10 to 15 lb/ft^2 (910 to 1400 MJ/m^2, heat of combustion 18.6 MJ/kg). For two large mercantile buildings, 50 to 60% of the floor area had combustible contents not over 10 lb/ft^2 (910 MJ/m^2), from 30 to 35% had between 10 and 15 lb/ft^2 (910 to 1400 MJ/m^2), 10% had between 15 and 20 lb/ft^2 (1400 and 1800 MJ/m^2), and no more than 5% had more than 20 lb/ft^2 (1800 MJ/m^2). The approximate average fire load density based on this data was 12 lb/ft^2 (1100 MJ/m^2).

Both industrial and storage occupancies are subject to a wide variation in the quantity of combustibles they may contain. The following survey data for industrial occupancies was taken from BMS 149:

1. For two furniture factories, fire loads in the working areas ranged from 5 to 65 lb/ft^2 (450 to 5900 MJ/m^2); some storage areas of less than 5% of the floor area had greater loads; less than 10% of the floor area had loads greater than 30 lb/ft^2 (2700 MJ/m^2).
2. Fire loads for two mattress factories were only greater than 30 lb/ft^2 (2700 MJ/m^2) in a few areas; over half the total area had fire loads less than 10 lb/ft^2 (910 MJ/m^2).
3. In two clothing factories, 90% of the measured areas had fire loads less than 15 lb/ft^2 (1400 MJ/m^2); loads were greater than 30 lb/ft^2 (2700 MJ/m^2) in a few storage areas.
4. In a newspaper plant 85% of the area had fire loads less than 40 lb/ft^2 (3600 MJ/m^2), and in a general printing plant only storage areas (35% of total area) had loads exceeding 40 lb/ft^2.

BMS 149 reported the following fire loads for five storage occupancies:

Warehouse use	Stories	Average fire load density (lb / ft²)	(MJ/m²)*
Paper in rolls for printing plant	3	174	15800
General service	9	66	6000
Railroad terminal	8	18	1600
Department store	4	16	1500
Department store	6	11	1000

* conversion based on 1 lb/ft² = 4.88 kg/m² and heat of combustion = 18.6 MJ/kg

Occupancies that are classified as hazardous are buildings that store, process, or handle combustible, flammable or explosive solids, liquids or gases. Hazardous occupancies have dangers related to factors other than the fire load itself that may present a serious threat to life and property.

The general ranges of fire loads for various occupancies are:

Occupancy	Fire load density (lb / ft²)	(kg / m²)*	(MJ / m²)*
Residential	5 to 10	25 to 50	450 to 910
Educational	5 to 10	25 to 50	450 to 910
Institutional	5 to 10	25 to 50	450 to 910
Assembly	5 to 10	25 to 50	450 to 910
Business	5 to 10	25 to 50	450 to 910
Mercantile	10 to 15	50 to 75	910 to 1400
Industrial **	variable	variable	variable
Storage **	variable	variable	variable
Hazardous **	variable	variable	variable

* soft conversion based on 1 lb/ft² = 4.88 kg/m² and heat of combustion = 18.6 MJ/kg

** fire severity will depend on the specific occupancy

C3 CULVER (1976,1978) - U.S. OFFICE BUILDINGS

Fire load data was obtained using an inventory technique from a survey of 23 office buildings located in various regions throughout the United States. Fire load was not reduced to account for combustibles that do not burn completely because they are in steel enclosures. An equivalent weight of combustibles (lb/ft^2) was estimated for a wood with a heat of combustion of 8000Btu/lb (18.6 MJ/kg). The following tables present these values along with the conversion to MJ/m^2.

Government Buildings

Room use	Fire load density (lb / ft^2)				Fire load density (MJ / m^2)*			
	Total		Interior finish		Total		Interior finish	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
General	7.3	4.4	1.2	0.4	660	400	110	40
Clerical	5.8	5.2	1.2	0.5	530	470	110	50
Lobby	2.6	1.4	1.3	0.4	240	130	120	40
Conference	4.2	6.1	1.2	0.4	380	550	110	40
File	17.9	11.9	1.2	0.6	1620	1080	110	50
Storage	11.7	19.2	1.2	0.5	1060	1740	110	50
Library	30.2	7.8	1.0	0.1	2740	710	90	10
All rooms	7.3	7.3	1.2	0.4	660	660	110	40

* conversion based on 1 lb/ ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

Private Buildings

Room use	Fire load density (lb / ft^2)				Fire load density (MJ / m^2)*			
	Total		Interior finish		Total		Interior finish	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
General	7.7	4.3	1.9	0.4	700	390	170	40
Clerical	6.8	4.0	1.7	0.5	620	360	150	50
Lobby	5.0	4.2	1.7	0.6	450	380	150	50
Conference	5.9	4.6	1.8	0.4	540	420	160	40
File	16.2	12.9	1.8	0.6	1470	1170	160	50
Storage	13.2	11.7	1.7	0.9	1200	1060	150	80
Library	23.6	10.8	1.8	0.4	2140	980	160	40
All rooms	8.2	6.4	1.8	0.5	740	580	160	50

* conversion based on 1 lb/ ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

C4 ISSEN (1978) - SOUTH AFRICAN RESIDENTIAL

Issen (1978) reported a survey of contents (movable) fire load carried out by Williams and Dannenfeldt in South Africa as part of a project to develop criteria for the fire resistance required for fire barriers in residential occupancies. All furnishing items were weighed in six houses and two flats (apartments), and the fire load densities estimated.

Unit no.	Fire load density (kg/m²)									
	Bedrooms 1	Bedrooms 2	Bedrooms 3	Bedrooms 4	Lounge 1	Lounge 2	Dining room	Entrance hall passage	Study / sewing room	Kitchen
Houses										
A	21.4	14.1	-	-	11.2	-	-	9.2	-	8.7
B	20.4	12.1	19.0	21.4	8.7	-	10.2	*	17.5	10.7
C	21.4	18.0	20.4	28.2	9.7	18.5	21.4	*	-	5.3
D	21.4	29.6	32.6	-	11.7	-	11.7	*	23.8	18.9
E	12.6	9.7	14.6	-	6.8	-	14.1	*	-	5.8
F	29.6	22.8	24.3	-	6.3	-	39.8	15.6	-	13.6
Flats										
A	16.5	11.7	-	-	-	-	6.8 **	14.6	-	15.6
B	24.3	31.6	-	-	-	-	12.6 **	-	-	38.8

Unit no.	Fire load density (MJ/m²) ***									
	Bedrooms 1	Bedrooms 2	Bedrooms 3	Bedrooms 4	Lounge 1	Lounge 2	Dining room	Entrance hall passage	Study / sewing room	Kitchen
Houses										
A	400	260	-	-	210	-	-	170	-	160
B	380	230	350	400	160	-	190	*	330	200
C	400	330	380	520	180	340	400	*	-	100
D	400	550	610	-	220	-	220	*	440	350
E	230	180	270	-	130	-	260	*	-	110
F	550	420	450	-	120	-	740	290	-	250
Flats										
A	310	220	-	-	-	-	130 **	270	-	290
B	450	590	-	-	-	-	230 **	-	-	720

* negligible

** room actually described as “lounge / dining room”

*** conversion based on heat of combustion = 18.6 MJ/kg

C5 ISSEN (1980) - U.S. SINGLE-FAMILY RESIDENTIAL

Fire loads were surveyed using an inventory technique for 359 residences, consisting of 61 single family attached, 200 single family detached, and 98 mobile homes in the metropolitan Washington DC area. The average movable contents fire load density and average total fire load density are:

Type of residence	Average fire load density (lb / ft^2)		Average fire load density (MJ / m^2)*	
	Movable contents	Total	Movable contents	Total
Single family attached	6.7	12.1	610	1100
Single family detached	6.8	12.7	620	1150
Mobile home	5.6	17.7	510	1610

* conversion based on 1 lb/ ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

The higher total fire load for mobile homes is due to the more extensive use of plywood in the interior wall finish.

The fire loads by room type (where "other rooms" indicates rooms that had mixed functions or were being renovated or remodelled so that their main function was not apparent) are:

Single family attached

Room type	Fire load density (lb / ft^2)				Fire load density (MJ / m^2)*			
	Movable contents		Total		Movable contents		Total	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Hall	1.4	3.5	6.9	7.7	130	320	630	700
Bathroom	3.0	5.6	9.0	8.8	270	510	820	800
Kitchen	7.0	5.4	11.3	6.4	640	490	1030	580
Dining room	4.9	3.4	10.1	4.8	440	310	920	440
Living room	6.3	4.1	10.8	5.2	570	370	980	470
Family room	10.2	11.0	16.5	11.7	930	1000	1500	1060
Study	15.3	14.9	21.2	15.5	1390	1350	1920	1410
Bedroom	7.3	8.2	12.8	10.3	660	740	1160	930
Basement	5.1	7.2	9.8	7.4	460	650	890	670
Utility room	8.0	11.4	12.0	12.1	730	1030	1090	1100
Store room	16.8	30.3	23.3	30.3	1520	2750	2110	2750
Other rooms	15.6	19.7	25.7	15.5	1420	1790	2330	1410

* conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

Single family detached								
Room type	Fire load density (lb / ft²)				Fire load density (MJ / m²)*			
	Movable contents		Total		Movable contents		Total	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Hall	1.3	3.7	6.0	5.6	120	340	540	510
Bathroom	2.5	4.3	8.6	7.0	230	390	780	640
Kitchen	6.9	4.7	10.5	5.2	630	430	950	470
Dining room	4.9	4.3	9.9	5.5	440	390	900	500
Living room	6.1	5.2	11.0	6.4	550	470	1000	580
Family room	6.3	5.4	13.2	7.8	570	490	1200	710
Study	17.8	14.7	24.2	15.7	1620	1330	2200	1430
Bedroom	7.2	5.5	12.2	6.7	650	500	1110	610
Basement	12.5	59.4	17.0	60.3	1130	5390	1540	5470
Utility room	5.9	10.1	11.1	11.4	540	920	1010	1030
Store room	15.6	31.6	22.6	33.0	1420	2870	2050	3000
Other rooms	3.6	4.5	10.7	6.0	330	410	970	540

* conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

Mobile homes								
Room type	Fire load density (lb / ft²)				Fire load density (MJ / m²)*			
	Movable contents		Total		Movable contents		Total	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Hall	1.2	5.8	14.9	9.1	110	530	1350	830
Bathroom	4.5	3.5	20.6	7.3	410	320	1870	660
Kitchen	7.8	3.3	18.1	5.3	710	300	1640	480
Dining room	6.0	6.7	18.1	8.2	540	610	1640	740
Living room	5.1	2.8	15.6	6.6	460	250	1420	600
Family room	5.9	4.6	16.6	5.0	540	420	1510	450
Study	9.5	6.2	23.4	5.8	860	560	2120	530
Bedroom	5.7	3.1	18.3	5.1	520	280	1660	460
Utility room	4.3	5.2	20.1	6.0	390	470	1820	540
Store room	20.1	18.1	38.5	24.6	1820	1640	3490	2230

* conversion based on 1 lb/ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

C6 CAMPBELL (1986) - U.S. DATA

Campbell (1986) summarises some U.S. fire load data including that of Culver (1976, 1978). The following table presents some of the data as lb/ft^2 of wood equivalent along with the conversion to MJ/m^2.

Type of room	Contents fire load density (lb / ft^2)		Contents fire load density (MJ / m^2)*	
	Average	Standard deviation	Average	Standard deviation
Living room	3.9	1.13	350	103
Family room	2.7	0.65	250	59
Bedroom	4.3	1.15	390	104
Dining room	3.6	1.02	330	93
Kitchen	3.2	0.77	290	70
Hospital patient room	1.2	0.36	110	33
Nursing home patient room	2.6	0.62	240	56

* conversion based on 1 lb/ ft^2 = 4.88 kg/m^2 and heat of combustion = 18.6 MJ/kg

C7 CIB DESIGN GUIDE (1986)

C1 DATA SOURCES

The following tables of fire loads are taken from CIB W14 (1986) which summarised data from these references:

1) National Swedish Building Research Summaries R 34 : 1970 Nilsson, L., 1970, "Brandbelastning/Bostadslagenheter/Fire Loads in Flats", Statens Institut For Byggnadsforskning; Stockholm, Rapport R 34: 1970, Svensk Byggtjanst, Box 1403, S-11184 Stockholm.

2) Pettersson, O., Magnusson, S.E., and Thor, J., "Fire Engineering Design of Steel Structures", Publ. 50, Swedish Institute of Steel Construction, Stockholm 1976, (Swedish Edition 1974).

3) European Recommendations for the Fire Safety of Steel Structures; Ch. 2, Fire Exposure, "Fire Safety of Steel Structures", Technical Committee 3, European Convention for Constructional Steelwork, Avenue Louis 326, Bte 52, B-1050 Brussels, July 1981.

4) Bryl, S., "Brandbelastung in Hochbau", Schweizerische Bauzeitung, 24 April 1975; special reprint from: 93, Jahrgang, Heft 17.

5) Bryl, S., "Brandbelastung in Stahlbau", Teil III, Brandbelastung in Burogebauden, ECCS-III-74-2-D, , European Convention for Constructional Steelwork, Rotterdam 1974.

6) Bonetti, M., Kree, P., and Kruppa, J., "Estimation des Charges Mobilieres d'Incendie dans les Immeubles a Usage de Bureaux", Construction Metallique, No.3, Centre Technique Industriel de la Construction Metallique (C.T.I.C.M.), 20, Rue Jean Jaures, F-92807 Puteaux, September 1975.

7) Combessis, J.C., Fauconnier, R., and Cluzel, D., "Enquetes et Charges d'Incendie; Etablissements Recevant du Public, Charges Incendie Courbes, Temperature/Temps Correspondantes, Commande D.S.C. No. 005110", Institut Technique du Batiment et des Travaux Publics, 9 Rue la Perouse, F-75784 Paris Cedex 16, September 1983.

8) Beilage 2 der SIA-Dokumentation 81/1984, Brandrisikobewertung / Berechnungsvertahren SIA, Schweizerischer Ingenieur- und Architektenverein, Postfach, CH-8039 Zurich.

9) Campbell, J.A., "Confinement of Fire in Buildings", Fire Protection Handbook, 1981, National Fire Protection Association, Quincy, MA, Section 5.9.

10) Culver, C.G., "Survey Results for Fire Loads and Live Loads in Office Buildings", NBS Building Science Series 85, US Department of Commerce / National Bureau of Standards, May 1976.

11) Robertson, A.F., and Gross, D., "Fire Load, Fire Severity and Fire Endurance", Special Technical Publication 464, American Society for Testing and Materials, Philadelphia, PA,, 1970.

12) Gross, D., "Measurements of Fire Loads and Calculations of Fire Severity", Wood and Fiber, 9 (1), Special Fire Symposium Issue, Part I, spring 1977, Center for Fire Research, National Engineering Laboratory, National Bureau of Standards, Washington, DC.

13) Hass, R., "Statistical Investigations on Fire Load, System Geometry and Ventilation in Modern School Buildings", Res. Report No. BI7-810705-216 for the Bundesminister Fur Raumordnung, Bauwesen und Stadtebau, Technische Universitat Braunschweig, Institut fur Massivbau, Baustoffe und Brandschutz, 1981.

14) Schneider, U. and Max, U., "Brandlasterhebungen in Industrie Stahlhallen"; unpublished report, 1984.

In the following sections, q_f is the fire load per unit floor area, and q_t is the fire load per unit area of the surface bounding the fire compartment.

C2 DWELLINGS

Variable fire load densities in dwellings - fire load density q_f per unit floor area.

	Single value (MJ/m²)	Average (MJ/m²)	Standard deviation (MJ/m²)	Fractile (MJ/m²) 80%	90%	95%	Remarks
Swedish data [1,2,3] ✞							$q_f = q_t$ x 5.2
3 rooms		720	104	770			Characteristic value 80%
2 rooms		780	128	870			bedroom 630 living room 510
European data [4]							
6 rooms		500	180				$q_f = q_t$ x 5.2
5 rooms		540	125				5.2 = cubic measure
3 rooms		670	133	760	780	830	3.2 x 4.3 x 2.9
2 rooms		780	129	870	1020	950	
1 room		720	104	760	780	890	
Swiss risk evaluation [8]							
Flat		330					
USA data [9]							
Living room		350	104				
Family room		250	58				
Bedroom		390	104				
Dining room		330	92				
Kitchen		290	71				
All rooms		320	88				
USA data [11,12]							
Residence		750*					*total fire load including
Max. for linen closet		4440*					permanent fire load
Range of max. values for single occupied rooms		730-1270*					

✞ see list of references above

C3 HOSPITALS

Variable fire load densities in hospitals - fire load density q_f per unit floor area.

	Single value (MJ/m^2)	Average (MJ/m^2)	Standard deviation (MJ/m^2)	Fractile (MJ/m^2) 80%	90%	95%	Remarks
Swedish data [2,3] ✞							
Hospital bedroom				80			
European data [4]							
Hospitals		230		350		670	From The Netherlands
Swiss risk evaluation [8]							
Hospitals		330					
USA data [9]							
Hospital patient room		108	33				
USA data [11,12]							
Hospitals		250*					*total fire load including permanent fire load
Max. for							
service store		1720*					
laundry, clothes storage		2090*					
Range of max. values for single occupied room		270-1990*					

✞ see list of references above

C4 HOTELS

Variable fire load densities in hotels - fire load density q_f per unit floor area.

	Single value (MJ/m^2)	Average (MJ/m^2)	Standard deviation (MJ/m^2)	Fractile (MJ/m^2) 80%	90%	95%	Remarks
Swedish data [2,3] ✞							
Hotels		310	92	380			$q_f = q_t \times 4.7$
Bedroom				420			
European data [4]							
Bedrooms		310	104	400	470	510	
European data [7]							Bathroom included
Bedroom	182						permanent fire load = 25
Swiss risk evaluation [8]							
Hotels		330					

✞ see list of references above

C5 OFFICES

Variable fire load densities in offices - fire load density q_f per unit floor area.

	Single value (MJ/m^2)	Average (MJ/m^2)	Standard deviation (MJ/m^2)	Fractile (MJ/m^2) 80%	90%	95%	Remarks
Swedish data [2,3] †							Characteristic value 80%
Company							- all offices
management		272	126				investigated 675
Production							- technical office 720
management		355	168				
Officials		441	250				- admin. office 640
Office staff		417	210				
Special rooms		1172	798				
Technical rooms		278	109				
Rooms of							
communication		168	240				
All rooms		411	334				
European data [4]							
Company							
management		270	125				
Production							
management		360	170				
Officials		450	260				
Office staff		380	46				
Special rooms		1330	890				
Technical rooms		330	67				
Rooms of							
communication		170	220				
All rooms		420	370	570	740	950	
European data [5]							
Company							
management		270	125				
Production							
management		350	170				
Officials		440	250				
Office staff		420	210				
Special rooms		1170	790				
Technical rooms		280	108				
Rooms of							
communication		170	240				
All rooms		410	330	520	770	920	
European data [6]							
Company							
management		300	140				
Office staff		380	180				
Special rooms		1000	390				
Conference		220	117				
Various rooms		260	225				
Rooms of							
communication		80	83				
All rooms		330	400				
European data [7]							
Technical office	250						permanent fire load = 290
Swiss risk evaluation [8]							
Technical offices		580					
Admin. Offices		750					

† see list of references above

	Single value (MJ/m²)	Average (MJ/m²)	Standard deviation (MJ/m²)	Fractile (MJ/m²)			Remarks
				80%	90%	95%	
USA data - Government buildings [9,10] ✞							
General		555	365 a) **				
Clerical		415	425 **				
Lobby		115	92 **				
Conference		270	515 **				
File		1515 b)	1025 **				
Storage		950	1700 **				
Library		2650	695 **				
All rooms		555	625 **				
USA data - Private buildings [9,10]							
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 [11,12]							
Offices		1670*					*total fire load including permanent fire loads
excl. heavy files		960*					
Max. for heavy files		7800*					
Range of maximum values for single occupied room		635-3900*					

✞ see list of references above (for this table the references in CIB W14(1986) were apparently incorrect)

a) corrected from 285 using data from [10]

b) corrected from 1420 using data from [10]

** based on difference between values for total fire load and interior finish fire load from ref. 10

C6 SHOPPING CENTRES AND DEPARTMENT STORES

Variable fire load densities in shopping centres and department stores - fire load density q_f per unit floor area.

	Single value (MJ/m²)	Average (MJ/m²)	Standard deviation (MJ/m²)	Fractile (MJ/m²) 80%	90%	95%	Remarks
European data [4] ✞							
Shopping centre (floor area 3000 m²)			Local peak values				Explanation of very low values:
Articles of daily use		420					Sales area = 20 - 25% of
Foods		585					the total floor area.
Textiles		380	535				
Perfumery, toys, stationery store, household items		420	560				
Furniture, carpet		585	960				
European data [7]							
Furniture store	970						Permanent fire load = 200
Little supermarket	750						
Swiss risk evaluation [8]							
Food store		665					
Clothing store		585					
Perfumery		420					
Stationery store		665					
Furniture store		420					
Toy store		500					
Carpet store		835					
Department store		420					
USA data [11,12]							
Mercantile (department store)		935*					
Max. for paint dept.		4260*					*total fire load including
Warehouse							permanent fire loads
- General		2270*					
- Printing		15800*					
- Max. value		23200*					

✞ see list of references above

C7 INDUSTRIAL BUILDINGS

Variable fire load densities in industrial buildings - fire load density q_f per unit floor area.

	Single value (MJ/m²)	Average (MJ/m²)	Standard deviation (MJ/m²)	Fractile (MJ/m²) 80%	90%	95%	Remarks
German data [8,11,12,14] ✞							
Storage of combustible goods:							
< 150 kg/m^2		1780	1260	2560	3490	4490	Fractile values
> 150 kg/m^2		15360	10600	23190	33110	44330	calculated for a
Manufacturing and storage of combustible goods:							lognormal distribution
< 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	
Electrical devices (manufacturing, assembling, storage)		235	115	330	430	530	
Garaging, maintenance, exploitation of vehicles		190	105	270	340	420	
Manufacturing, processing, supply of ceramics and glassware		280	225	470	720	1010	
Swiss data	see separate table						

✞ see list of references above

C8 SCHOOLS

Variable fire load densities in schools - fire load density q_f per unit floor area.

	Single value (MJ/m²)	Average (MJ/m²)	Standard deviation (MJ/m²)	Fractile (MJ/m²) 80%	90%	95%	Remarks
Swedish data [2,3] ✝							$q_f = q_t \times 3.53$
Junior level		295	50	345			
Middle level		340	71	415			
Senior level		215	67	250			
All schools		285	83	340			
European data [4]							
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					
The Netherlands							
All schools		215		365		550	
Swiss risk evaluation [8]							
Schools		250					
USA data [11,12]							
School		1420*					*total fire load (variable and interior finish)
Max. for textbook storeroom		20670*					
Range of max. values for single occupied room		635-3540*					

✝ see list of references above

Fire loads in the individual groups of school rooms, from ref. 13 - fire load density q_f per unit floor area.

	Permanent fire load (MJ/m²)		Variable fire load (MJ/m²)		Total fire load (MJ/m²)	
	Mean	90% fractile	Mean	90% fractile	Mean	90% fractile
Classrooms	250	360	115	165	360	495
Rooms of teachers	435	900	375	720	815	1050
Special rooms	280	470	190	290	470	685
Material rooms	265	480	705	1330	965	1660
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
Others	345	575	190	465	535	1030

C8 SWEDISH DATA [1,2,3]✞

Fire load density q_t per unit area of the surface bounding the fire compartment.

Type of fire compartment	Average (MJ / m^2)	Standard deviation / (MJ / m^2)	Characteristic value (0.8 fractile) (MJ m^2)
Dwellings*			
two rooms and kitchen	150	24.7	168
three rooms and kitchen	139	20.1	149
Offices**			
technical offices	124	31.4	145
administrative offices	102	32.2	132
all offices investigated	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 investigated	80.4	23.4	96.3[a)]
Hospitals	116	36.0	147
Hotels**	67	19.3	81.6

* floor covering excluded

** only variable fire loads included

✞ see list of references above

a) corrected from 76.3

C9 AVERAGE FIRE LOAD DENSITIES - SWISS DATA

The following fire load densities (only variable fire load densities) are taken from *Beilage 1: Brandschutztechnische Merkmale verscheidener Nutzungen und Lagerguter* (ref. 8 above) and are defined as density per unit floor area (MJ/m^2).

Note that for the determination of the variable fire load of storage areas, the values given in the following table have to be multiplied by the height of storage in metres. Areas and aisles for transportation have been taken into consideration in an averaging manner.

The values are based on a large investigation carried out during the years 1967 to 1969 by a staff of 10 to 20 students under the guidance of the Swiss Fire Prevention Association for Industry and Trade with the financial support of the government civil defence organisation.

For each type of occupancy, storage and/or building, a minimum number of 10 to 15 samples were analysed: normally 20 or more samples are available. All values given in the following pages are average values. Unfortunately, it has been impossible to obtain the basic data sheets of this investigation. In order to estimate the corresponding standard deviations and the 80% - 90% and 95% fractile values, the data from this source were compared with data given in various sources. This comparison results in the following suggestions:

(a) For well-defined occupancies which are rather similar or with very limited differences in furniture and stored goods, eg dwellings, hotels, hospitals, offices and schools, the following estimates may suffice:

Coefficient of variation	=	30% - 50% of the given average value
90% fractile value	=	(1.35 - 1.65) x average value
80% fractile value	=	(1.25 - 1.5) x average value
Isolated peak values	=	2 x average value

(b) For occupancies that are rather dissimilar or with larger differences in furnishings and stored goods, eg shopping centres, department stores and industrial occupancies, the following estimates are tentatively suggested:

Coefficient of variation	=	50% - 80% of given average value
90% fractile value	=	(1.65 - 2.0) x average value
80% fractile value	=	(1.45 - 1.75) x average value
Isolated peak values	=	2.5 x average value

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Academy	300	
Accumulator forwarding	800	
Accumulator mfg.	400	800
Acetylene cylinder storage	700	
Acid plant	80	
Adhesive mfg.	1000	3400
Administration	800	
Adsorbent plant for combustible vapours	>1700	
Aircraft hangar	200	
Airplane factory	200	
Aluminium mfg.	40	
Aluminium processing	200	
Ammunition mfg.	special	
Animal food preparing, mfg.	2000	3300
Antique shop	700	
Apparatus forwarding	700	
Apparatus mfg.	400	
Apparatus repair	600	
Apparatus testing	200	
Arms mfg.	300	
Arms sales	300	
Artificial flower mfg.	300	200
Artificial leather mfg.	1000	1700
Artificial leather processing	300	
Artificial silk mfg.	300	1100
Artificial silk processing	210	
Artificial stone mfg.	40	
Asylum	400	
Authority office	800	
Awning mfg.	300	1000
Bag mfg. (jute, paper, plastic)	500	
Bakery	200	
Bakery, sales	300	
Ball bearing mfg.	200	
Bandage mfg.	400	
Bank, counters	300	
Bank offices	800	
Barrel mfg., wood	1000	800
Basement, dwellings	900	
Basketware mfg.	300	200
Bed sheeting production	500	1000
Bedding plant	600	
Bedding shop	500	
Beer mfg. (brewery)	80	
Beverage mfg., non-alcoholic	80	
Bicycle assembly	200	400
Biscuit factories	200	
Biscuit mfg.	200	
Bitumen preparation	800	3400
Blind mfg., venetian	800	300
Blueprinting firm	400	
Boarding school	300	

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Boat mfg.	600	
Boiler house	200	
Bookbinding	1000	
Bookstore	1000	
Box mfg.	1000	600
Brick plant, burning	40	
Brick plant. clay preparation	40	
Brick plant, drying kiln with wooden grates	1000	
Brick plant, drying room with metal grates	40	
Brick plant, drying room with wooden grates	400	
Brick plant, pressing	200	
Briquette factories	1600	
Broom mfg.	700	400
Brush mfg.	700	800
Butter mfg.	700	4000
Cabinet making (without woodyard)	600	
Cable mfg.	300	600
Café	400	
Camera mfg.	300	
Candle mfg.	1300	22400
Candy mfg.	400	1500
Candy packing	800	
Candy shop	400	
Cane products mfg.	400	200
Canteen	300	
Car accessory sales	300	
Car assembly plant	300	
Car body repairing	150	
Car paint shop	500	
Car repair shop	300	
Car seat cover shop	700	
Cardboard box mfg.	800	2500
Cardboard mfg.	300	4200
Cardboard products mfg.	800	2500
Carpenter shed	700	
Carpet dyeing	500	
Carpet mfg.	600	1700
Carpet store	800	
Cartwright's shop	500	
Cast iron foundry	400	800
Celluloid mfg.	800	3400
Cement mfg.	1000	
Cement plant	40	
Cement products mfg.	80	
Cheese factory	120	
Cheese mfg. (in boxes)	170	
Cheese store	100	
Chemical plants (rough average)	300	1000

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Chemist's shop	1000	
Children's home	400	
China mfg.	200	
Chipboard finishing	800	
Chipboard pressing	100	
Chocolate factory, intermediate storage	6000	
Chocolate factory, packing	500	
Chocolate factory, tumbling treatment	1000	
Chocolate factory, all other specialities	500	
Church	200	
Cider mfg. (without crate storage)	200	
Cigarette plant	300	
Cinema	300	
Clay, preparing	50	
Cloakroom, metal wardrobe	80	
Cloakroom, wooden wardrobe	400	
Cloth mfg.	400	
Clothing plant	500	
Clothing store	600	
Coal bunker	2500	
Coal cellar		10500
Cocoa processing	800	
Coffee-extract mfg.	300	
Coffee roasting	400	
Cold storage	2000	
Composing room	400	
Concrete products mfg.	100	
Condiment mfg.	50	
Congress hall	600	
Contractors		500
Cooking stove mfg.	600	
Coopering	600	
Cordage plant	300	600
Cordage store	500	
Cork products mfg.	500	800
Cosmetic mfg.	300	500
Cotton mills	1200	
Cotton wool mfg.	300	
Cover mfg.	500	
Cutlery mfg. (household)	200	
Cutting-up shop, leather, artificial leather	300	
Cutting-up shop, textiles	500	
Cutting-up shop, wood	700	
Dairy	200	
Data processing	400	
Decoration studio	1200	2000
Dental surgeon's laboratory	300	
Dentist's office	200	
Department store	400	

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Distilling plant, combustible materials	200	
Distilling plant, incombustible materials	50	
Doctor's office	200	
Door mfg., wood	800	1800
Dressing, textiles	200	
Dressing, paper	700	
Dressmaking shop	300	
Dry-cell battery	400	600
Dry cleaning	300	
Dyeing plant	500	
Edible fat forwarding	900	
Edible fat mfg.	1000	18900
Electric appliance mfg.	400	
Electric appliance repair	500	
Electric motor mfg.	300	
Electrical repair shop	600	
Electrical supply storage H<3 m	1200	
Electro industry	600	
Electronic device mfg.	400	
Electronic device repair	500	
Embroidery	300	
Etching plant glass/metal	200	
Exhibition hall, cars including decoration	200	
Exhibition hall, furniture including decoration	500	
Exhibition hall, machines including decoration	80	
Exhibition of paintings including decoration	200	
Explosive industry	4000	
Fertiliser mfg.	200	200
Filling plant/barrels		
liquid filled and/or barrels incombustible	<200	
liquid filled and/or barrels combustible:		
Risk Class I - IV	>3400	
Risk Class V (if higher, consider combustibility of barrels)	>1700	
Filling plant/small casks:		
liquid filled and casks incombustible	<200	
liquid filled and/or casks combustible:		
Risk Class I - IV	<500	
Risk Class V (if higher, consider combustibility of casks)	<500	

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Finishing plant, paper	500	
Finishing plant, textile	300	
Fireworks mfg.	special	2000
Flat	300	
Floor covering mfg.	500	6000
Floor covering store	1000	
Flooring plaster mfg.	600	
Flour products	800	
Flower sales	80	
Fluorescent tube mfg.	300	
Foamed plastics fabrication	3000	2500
Foamed plastics processing	600	800
Food forwarding	1000	
Food store	700	
Forge	80	
Forwarding, appliances partly made of plastic	700	
Forwarding, beverage	300	
Forwarding, cardboard goods	600	
Forwarding, food	1000	
Forwarding, furniture	600	
Forwarding, glassware	700	
Forwarding, plastic products	1000	
Forwarding, printed matters	1700	
Forwarding, textiles	600	
Forwarding, tinware	200	
Forwarding, varnish, polish	1300	
Forwarding, woodware (small)	600	
Foundry (metal)	40	
Fur, sewing	400	
Fur store	200	
Furniture exhibition	500	
Furniture mfg. (wood)	600	
Furniture polishing	500	
Furniture store	400	
Furrier	500	
Galvanic station	200	
Gambling place	150	
Glass blowing plant	200	
Glass factory	100	
Glass mfg.	100	
Glass painting	300	
Glass processing	200	
Glassware mfg.	200	
Glassware store	200	
Glazier’s workshop	700	
Gold plating (of metals)	800	3400
Goldsmith's workshop	200	
Grain mill, without storage	400	13000
Gravestone carving	50	
Graphic workshop	1000	
Greengrocer’s shop	200	
Hairdressing shop	300	

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Hardening plant	400	
Hardware mfg.	200	
Hardware store	300	
Hat mfg.	500	
Hat store	500	
Heating equipment room, wood or coal firing	300	
Heat sealing of plastics	800	
High-rise office building	800	
Homes	500	
Homes for aged	400	
Hosiery mfg.	300	1000
Hospital	300	
Hotel	300	
Household appliances, mfg.	300	200
Household appliances, sales	300	
Ice cream plant (including packaging)	100	
Incandescent lamp plant	40	
Injection moulded parts mfg. (metal)	80	
Injection moulded parts mfg. (plastic)	500	
Institution building	500	
Ironing	500	
Jewellery mfg.	200	
Jewellery shop	300	
Joinery	700	
Joiners (machine room)	500	
Joiners workbench	700	
Jute, weaving	400	1300
Laboratory, bacteriological	200	
Laboratory, chemical	500	
Laboratory, electric, electronic	200	
Laboratory, metallurgical	200	
Laboratory, physics	200	
Lacquer forwarding	1000	
Lacquer mfg.	500	2500
Large metal constructions	80	
Lathe shop	600	
Laundry	200	
Leather goods sales	700	
Leather product mfg.	500	
Leather, tanning, dressing, etc	400	
Library	2000	2000
Lingerie mfg.	400	
Liqueur mfg.	400	800
Liquor mfg.	500	800
Liquor store	700	

Type of occupancies	Fabrication (MJ/m²)	Storage (MJ/m²/m)	Type of occupancies	Fabrication (MJ/m²)	Storage (MJ/m²/m)
Loading ramp, including			Parking building	200	
goods (rough average)	800		Parquetry mfg.	2000	1200
Lumber room for			Perambulator mfg.	300	800
miscellaneous qoods	500		Perambulator shop	300	
			Perfume sale	400	
Machinery mfg.	200		Pharmaceutical mfg.	300	800
Match plant	300	800	Pharmaceuticals, packing	300	800
Mattress mfg.	500	500	Pharmacy (including		
Meat shop	50		storage)	800	
Mechanical workshop	200		Photographic laboratory	100	
Metal goods mfg.	200		Photographic store	300	
Metal grinding	80		Photographic studio	300	
Metal working (general)	200		Picture frame mfg.	300	
Milk, condensed, evaporated			Plaster product mfg.	80	
mfg.	200	9000	Plastic floor tile mfg.	800	
Milk, powdered, mfg.	200	10500	Plastic mfg.	2000	5900
Milling work, metal	200		Plastic processing	600	
Mirror mfg.	100		Plastic products fabrication	600	
Motion picture studio	300		Plumber's workshop	100	
Motorcycle assembly	300		Plywood mfg.	800	2900
Museum	300		Polish mfg.	1700	
Musical instrument sales	281		Post office	400	
			Potato, flaked, mfg.	200	
News stand	1300		Pottery plant	200	
Nitrocellulose mfg.	Special	1100	Power station	600	
Nuclear research	2100		Precision stone, cutting etc.	80	
Nursery school	300		Precision instrument mfg.		
			(containing plastic parts)	200	
Office, business	800		Precision instrument mfg.		
Office, engineering	600		(without plastic parts)	100	
Office furniture	700		Precision mechanics plant	200	
Office, machinery mfg.	300		Pressing, metal	100	
Office machine sales	300		Pressing, plastics, leather etc.	400	
Oilcloth mfg.	700	1300	Printing, composing room	300	
Oilcloth processing	700	2100	Printing ink mfg.	700	3000
Optical instrument mfg.	200	200	Printing, machine hall	400	
			Printing office	1000	
Packing, food	800				
Packing, incombustible goods	400		Radio and TV mfg.	400	
Packing material industry	1600	3000	Radio and TV sales	500	
Packing, printed matters	1700		Radio studio	300	
Packing, textiles	600		Railway car mfg.	200	
Packing, all other combustible			Railway station	800	
goods	600		Railway workshop	800	
Paint and varnish, mfg.	4200		Record player mfg.	300	200
Paint and varnish, mixing			Record repository,		
plant	2000		documents, see storage	4200	
Paint and varnish shop	1000		Refrigerator mfg.	1000	300
Painter's workshop	500		Relay mfg.	400	
Paint shop (cars, machines,			Repair shop, general	400	
etc.)	200		Restaurant	300	
Paint shop (furniture, etc.)	400		Retouching department	300	
Paper mfg.	200	10000	Rubber goods mfg.	600	5000
Paper processing	800	1100	Rubber goods store	800	

Type of occupancies	Fabrication (MJ/m²)	Storage (MJ/m²/m)	Type of occupancies	Fabrication (MJ/m²)	Storage (MJ/m²/m)
Rubber processing	600	5000	Tin can mfg.	100	
			Tinned goods mfg.	40	
Saddlery mfg.	300		Tinware mfg.	120	
Safe mfg.	80		Tyre mfg.	700	1800
Salad oil forwarding	900		Tobacco products mfg.	200	2100
Salad oil mfg.	1000	18900	Tobacco shop	500	
Sawmill (without wood yard)	400		Tool mfg.	200	
Scale mfg.	400		Toy mfg. (combustible)	100	
School	300		Toy mfg. (incombustible)	200	
Scrap recovery	800		Toy store	500	
Seed store	600		Tractor mfg.	300	
Sewing machine mfg.	300		Transformer mfg.	300	
Sewing machine store	300		Transformer winding	600	
Sheet mfg.	100		Travel agency	400	
Shoe factory, forwarding	600		Turnery (wood working)	500	
Shoe factory, mfg.	500		Turning section	200	
Shoe polish mfg.	800	2100	TV studio	300	
Shoe repair with manufacture	700		Twisting shop	250	
Shoe store	500				
Shutter mfg.	1000		Umbrella mfg.	300	400
Silk spinning (natural silk)	300		Umbrella store	300	
Silk weaving (natural silk)	300		Underground garage, private	>200	
Silverware	400		Underground garage, public	<200	
Ski mfg.	400	1700	Upholstering plant	500	
Slaughter house	40				
Soap mfg.	200	4200	Vacation home	500	
Soda mfg.	40		Varnishing, appliances	80	
Soldering	300		Varnishing, paper	80	
Solvent distillation	200		Vegetable, dehydrating	1000	400
Spinning mill, excluding			Vehicle mfg., assembly	400	
garnetting	300		Veneering	500	2900
Sporting goods store	800		Veneer mfg.	800	4200
Spray painting			Vinegar mfg.	80	100
metal goods	300		Vulcanising plant (without		
wood products	500		storage)	1000	
Stationery store	700				
Steel furniture mfg.	300		Waffle mfg.	300	1700
Stereotype plate mfg.	200		Warping department	250	
Stone masonry	40		Washing agent mfg.	300	200
Storeroom (workshop			Washing machine mfg.	300	40
storerooms etc)	1200		Watch assembling	300	40
Synthetic fibre mfg.	400		Watch mechanism mfg.	40	
Synthetic fibre processing	400		Watch repair shop	300	
Synthetic resin mfg.	3400	4200	Watch sales	300	
			Water closets	~0	
Tar-coated paper mfg.	1700		Wax products forwarding	2100	
Tar preparation	800		Wax products mfg.	1300	2100
Telephone apparatus mfg.	400	200	Weaving mill (without carpets)	300	
Telephone exchange	80		Welding shop (metal)	80	
Telephone exchange mfg.	100		Winding room	400	
Test room, electric appliances	200		Winding, textile fibres	600	
Test room, machinery	100		Window glass mfg.	700	
Test room, textiles	300		Window mfg. (wood)	800	
Theatre	300		Wine cellar	20	

Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)	Type of occupancies	Fabrication (MJ/m^2)	Storage (MJ/m^2/m)
Wine merchant's shop	200		Wood grinding	200	
Wire drawing	80		Wood pattern-making shop	600	
Wire factory	800		Wood preserving plant	3000	
Wood carving	700				
Wood drying plant	800		Youth hostel	300	

C10 KOSE ET AL. (1986) - JAPANESE DWELLINGS

Kose et al. (1986) surveyed by an inventory technique the movable fire load in 214 dwellings in apartment houses in the metropolitan Tokyo area. The occupants completed survey forms listing the combustible contents of the dwelling from which the fire load was estimated. Movable fire load included furniture and containers, stored goods in them such as documents, books, magazines and clothes, as well as carpets, curtains and draperies. The average movable fire load density was 33.9 kg/m^2 with a standard deviation of 11.7 kg/m^2 (average 630 MJ/m^2, standard deviation 220 MJ/m^2) based on heat of combustion of 18.6 MJ/kg.

C11 BUSH ET AL. (1991) - U.S. NON-RESIDENTIAL

Bush et al. (1991) estimated fire loads in U.S. urban areas based on previously published data. This was part of a study of the effects of fires generated by nuclear weapons (specifically in regard to "nuclear winter"). The estimated average total non-residential fire loads per unit floor area are:

Building type	Total fire load density		Building type	Total fire load density	
	(kg / m^2)	(MJ / m^2)*		(kg / m^2)	(MJ / m^2)*
INDUSTRIAL	50	930	WHOLESALE / WAREHOUSING	183	3400
Food processing plant	95	1770	Wholesale, warehouse (high)[a)]	250	4650
Textile, leather mill	95	1770	Wholesale, warehouse (low)[a)]	100	1860
Light assembly	60	1120	SERVICE	37	690
Heavy assembly	20	370	Office	60	1120
Paper, chemical, rubber, petroleum	75	1400	Medical hospital	10	190
Metal works, glass works	25	470	Medical clinic	20	370
Printing, publishing	155	2880	Lodging [b)]	40	740
Other industrial	50	930	Automobile service	20	370
Utility	25	470	Other service	50	930
Laboratory	30	560	Education	35	650
RETAIL	41	760	Assembly, entertainment (high)	20	370
Shopping centre	50	930	Assembly, entertainment (low)	10	190
Department store	40	740	OTHER	18	330
Food, drug store	35	650	Agricultural [c)]	25	470
Restaurant	25	470	Residential [d)]	45	840
Building materials, hardware	65	1210	Other (low) [e)]	15	280
Furniture, home furnishings	35	650	Vacant	5	90
Automobile dealer	20	370			
Other retail	50	930	U.S. Average	54	1000

* conversion based on heat of combustion = 18.6 MJ/kg

a) high indicates densely packed and almost entirely combustible eg. retail products; low indicates non-burnable contents eg. cold-storage buildings or low density eg. combined showroom-warehouse buildings

b) includes hotels, motels, boarding houses

c) includes barns and silos

d) living areas in non-residential buildings

e) includes parking garages and airplane hangars

C12 BUTCHER (1991) - BRITISH RECOMMENDATIONS

Butcher (1991) lists the following approximate fire load densities which are appropriate to the "Purpose Groups" (ie. occupancies) in the 1965 British Building Regulations (see also Butcher and Parnell (1983)). There is no indication whether these values correspond to average values or upper values that are unlikely to be exceeded.

Purpose Group	Fire Load Density (BTU / ft^2)	(lb/ ft^2)*	(kg / m^2)*	(MJ / m^2)
Domestic	40 000	5	25	465
Institutional	40 000	5	25	465
Other residential	40 000	5	25	465
Office	40 000 to 80 000	5 to 10	25 to 50	465 to 930
Shop	up to 400 000	up to 50	up to 250	up to 4650
Factory	up to 240 000	up to 30	up to 150	up to 2790
Assembly	40 000 to 80 000	5 to 10	25 to 50	465 to 930
Storage and general	up to 800 000	up to 100	up to 500	up to 9300

* wood equivalent

C13 CIB (1993)

The following recommended values for average fire load intensity and coefficient of variation are presented in CIB (1993) and are based on Swedish data:

Type of fire compartment	Average fire load (MJ / m^2)	Coefficient of variation
Dwellings		
Two rooms and a kitchen	550	0.15
Three rooms and a kitchen	450	0.15
Offices		
Technical offices	600	0.25
Administrative offices	500	0.30
Schools		
Junior level	350	0.15
Middle level	400	0.20
Senior level	250	0.25
Hospitals	450	0.30
Hotels	300	0.25

Presumably, the tabulated values are movable fire load only. The report notes that the fire load may be modelled by a lognormal distribution.

C14 CHOW AND CHEUNG (1995-96) - HONG KONG FACTORIES

Chow and Cheung (1995-96) surveyed 47 factories in Hong Kong (generally high-rise). The limits of total fire load density for the cumulative frequencies of 50%, 80% and 90% were 855 MJ/m^2, 1671 MJ/m^2 and 2424 MJ/m^2.

Factory number	Floor area	Fire load density (MJ/m^2)		
	(m^2)	Fixed	Movable	Total
1	100	950	2050	3000
2	100	950	493	1443
3	300	297	1339	1636
4	200	48	2925	2973
5	1000	48	870	917
6	100	114	519	633
7	100	950	218	1168
8	60	1583	200	1783
9	80	238	1135	1373
10	60	533	744	1277
11	40	2000	600	2600
12	400	50	1325	1375
13	90	211	408	619
14	800	37	1487	1524
15	200	190	464	654
16	500	100	250	350
17	400	100	110	210
18	100	950	3915	4865
19	600	172	23	195
20	2000	123	75	198
21	1000	150	145	295
22	40	250	140	390
23	50	320	417	737
24	200	400	418	818
25	300	317	1326	1643
26	100	570	390	960
27	100	950	795	1745
28	350	81	583	664
29	200	142	2093	2235
30	500	190	252	442
31	170	219	1434	1653
32	300	40	800	840
33	200	135	110	245
34	100	130	97	227
35	500	190	912	1102
36	100	760	760	1520
37	385	52	60	112
38	300	30	103	133
39	350	57	860	917
40	50	600	2757	3357
41	600	50	65	115
42	250	10	419	429
43	500	4	78	82
44	650	62	83	145
45	135	40	233	273
46	150	30	907	937
47	400	24	125	149

C15 NARAYANAN (1995) - N.Z. OFFICES

Fire load surveys were conducted in 5 life insurance offices in Wellington's central business district. The survey method consisted of weighing some items and using this weight for other similar items in the same room. The estimated values of fixed, movable and total fire load for each of the offices are given in the table along with the average values and standard deviations based on fitting a normal distribution to the data.

Office sample	Fixed fire load (MJ / m^2)	Movable fire load (MJ / m^2)	Total fire load (MJ / m^2)
A1	133	442	575
A2	103	323	426
A3	110	837	947
A4	112	678	790
A5	315	354	670
Average	164	476	681
Standard deviation	84	234	227

C16 BENNETTS ET AL. (1997) – AUSTRALIAN SHOPPING CENTRES

As part of Fire Code Reform Centre Project 6, fire loads for a large number of specialty shops, parts of a major department store and parts of a discount variety store in a major shopping centre in Melbourne were determined. The mass of each item of combustible material in the stores was estimated based on knowledge of the mass of similar items weighed in the laboratory, and this was converted to an equivalent mass of wood.

Shop Type	Number of shops	Fire load density (kg/m²)					
		Contents		Floor		Total	
		Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Accessories	6	35	20	6	4	41	19
Chemist / cosmetics	8	39	21	2	3	41	20
Clothing	42	36	19	5	5	41	19
Coffee lounge	5	40	15	2	3	43	16
Electrical / music	9	37	18	3	3	40	16
Entertainment	2	16	9	4	2	20	7
Eyewear	3	38	20	6	1	44	20
Food and beverage	16	39	33	1	3	40	34
Food shop	6	31	16	5	5	36	17
Footwear	10	56	30	5	2	61	31
Gifts	6	47	22	4	3	50	22
Hairdressing / beauty	7	45	40	1	2	46	39
Homewares/manchester	2	90	5	2	2	92	7
Jewellery	9	43	23	2	2	45	23
Medical	2	34	6	5	0	39	6
Miscellaneous	10	63	73	5	8	68	74
Photos	5	47	28	2	3	49	29
Sports	6	39	15	5	1	44	15
Stationery / bookshop	6	98	62	5	0	103	62
Travel	3	52	18	7	4	59	15
Toys / games / hobbies	5	47	32	3	2	50	32
Discount / variety	3	27	21	0	1	27	21
All specialty shops	171	44	32	4	4	48	33
Major stores	-	-	-	-	-	72	-

Shop Type	Number of shops	Fire load density (MJ/m²)					
		Contents		Floor		Total	
		Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Accessories	6	650	370	110	70	760	350
Chemist / cosmetics	8	730	390	40	60	760	370
Clothing	42	670	350	90	90	760	350
Coffee lounge	5	740	280	40	60	800	300
Electrical / music	9	690	330	60	60	740	300
Entertainment	2	300	170	70	40	370	130
Eyewear	3	710	370	110	20	820	370
Food and beverage	16	730	610	20	60	740	630
Food shop	6	580	300	90	90	670	320
Footwear	10	1040	560	90	40	1130	580
Gifts	6	870	410	70	60	930	410
Hairdressing / beauty	7	840	740	20	40	860	730
Homewares/manchester	2	1670	90	40	40	1710	130
Jewellery	9	800	430	40	40	840	430
Medical	2	630	110	90	0	730	110
Miscellaneous	10	1170	1360	90	150	1260	1380
Photos	5	870	520	40	60	910	540
Sports	6	730	280	90	20	820	280
Stationery / bookshop	6	1820	1150	90	0	1920	1150
Travel	3	970	330	130	70	1100	280
Toys / games / hobbies	5	870	600	60	40	930	600
Discount / variety	3	500	390	0	20	500	390
All specialty shops	171	820	600	70	70	890	610
Major stores	-	-	-	-	-	1340	-

* conversion based on heat of combustion = 18.6 MJ/kg

APPENDIX D

ENCLOSURE VENTILATION

D1 INTRODUCTION

The amount of ventilation to a compartment is one of the factors which influences the severity of a fire. Only limited data is available on the likely ventilation properties for different occupancies and that data is summarised in the following section. The results of a preliminary ventilation survey based on drawings for some typical buildings and measured values for shops in a shopping centre are presented in the next section. Finally, based on this information, the assumed ventilation is listed for each Building Code of Australia class considered in this project (classes 2 to 9 inclusive).

D2 EXISTING SURVEYS

Kawagoe and Sekine (1963) - Japanese Buildings

Kawagoe and Sekine (1963) tabulated the ventilation properties for 28 Japanese buildings but did not indicate the occupancy type - in fact, they classified buildings according to their fire load and opening factor rather than occupancy type.

Building no.	Floor area A_f (m^2)	Opening area A_v (m^2)	Opening height* h_v (m)	Total inside surface area, A_t (m^2)	Opening factor $A_v\sqrt{h_v}/A_t$ ($m^{\frac{1}{2}}$)
1	731	147.5	1.69	1839	0.104
2	280	67.5	1.51	810	0.102
3	240	30	0.893	830	0.034
6	250	60	2.59	564	0.17
6’	135	38	2.59	216	0.28
7	280	80	2.10	790	0.147
8	310	96	2.07	830	0.115
8’	167	50	2.07	410	0.175
9	952	284	2.19	2068	0.206
10	160	33	2.02	480	0.098
11	180	57	2.04	520	0.17
13	440	111	1.80	1300	0.114
14	630	193	1.85	1650	0.158
16	1570	259	1.74	3710	0.092
17	665	106	1.54	1710	0.07
18	825	440	2.25	2080	0.152
19	355	110	1.93	1050	0.152
19’	380	74	1.93	980	0.105
21	1450	370	2.19	3550	0.15
22	1050	370	2.19	2300	0.23
23	184	4.5	1.32	76	0.068
23’	275	6.6	1.32	100	0.076
24	750	270	2.59	1145	0.159
25	600	120	1.82	1650	0.098
26	1100	293	2.10	2560	0.165
27	320	35	1.99	850	0.051
27’	100	45	1.99	330	0.17
28	128	49	1.69	380	0.168

* Kawagoe and Sekine present $\sqrt{h_v}$ not h_v

The mean and standard deviation of the opening factor for this sample are 0.135 $m^{\frac{1}{2}}$ and 0.055 $m^{\frac{1}{2}}$, respectively.

Culver (1976) - U.S. Office Buildings

The following ventilation data was obtained as part of a survey of fire load data for 23 office buildings located in various regions throughout the United States.

Occupancy type	Room use	Opening factor $A_v\sqrt{h_v}/A_t$ $(ft^{\frac{1}{2}})$		Opening factor $A_v\sqrt{h_v}/A_t$ $(m^{\frac{1}{2}})$	
		Average	Standard deviation	Average	Standard deviation
Government	General	0.117	0.103	0.065	0.057
	Clerical	0.089	0.084	0.049	0.046
	Lobby	0.034	0.057	0.019	0.031
	Conference	0.033	0.067	0.018	0.037
	File	0.049	0.070	0.027	0.039
	Storage	0.008	0.032	0.004	0.018
	Library	0.064	0.090	0.035	0.050
Private	General	0.185	0.136	0.102	0.075
	Clerical	0.090	0.110	0.050	0.061
	Lobby	0.023	0.046	0.013	0.025
	Conference	0.087	0.138	0.048	0.076
	File	0.050	0.111	0.028	0.061
	Storage	0.007	0.032	0.004	0.018
	Library	0.035	0.066	0.019	0.036
Government and private	General and clerical	0.146	0.127	0.081	0.070

A_v = total opening area

h_v = height of opening

A_t = total area for internal surfaces of room (walls, floor, ceiling)

CIB Design Guide (1986) - German Schools

The following tables of room geometrical and ventilation properties for schools are from CIB W14 (1986) which in turn obtained the data from R. Hass, "Statistical Investigations on Fire Load, System Geometry and Ventilation in Modern School Buildings", Res. Report No. BI7-810705-216 for the Bundesminister fur Raumordnung, Bauwesen und Stadtebau, Technische Universitat Braunschweig, Institut fur Massivbau, Baustoffe und Brandschutz, 1981.

Geometrical properties of groups of rooms:

Groups of rooms	Floor base (m^2)		Total surrounding area (m^2)		Volume (m^3)		Height of room (m)	
	Mean value	90% fractile	Mean value	90% fractile	Mean value	90% fractile	Mean value	90% fractile
Classrooms	69.2	79.4	250.9	281.1	231.3	273.5	3.37	3.74
Rooms of teachers	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	47.4	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	900.0	3.59	4.00
Administration 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	225.0	3.56	3.75
Storerooms	69.9	172.5	260.4	597.5	246.0	645.0	3.44	3.62
Others	84.0	135.0	280.3	422.5	314.5	445.0	3.64	3.85

Face of openings of the groups of rooms:

Groups of rooms	External openings - vertical				External openings - horizontal				Internal openings - vertical			
	Mean value		90% fractile		Mean value		90% fractile		Mean value		90% fractile	
	A_v (m^2)	$\frac{A_v}{A_t}$	A_v (m^2)	$\frac{A_v}{A_t}$	A_v (m^2)	$\frac{A_v}{A_t}$	A_v (m^2)	$\frac{A_v}{A_t}$	A_v (m^2)	$\frac{A_v}{A_t}$	A_v (m^2)	$\frac{A_v}{A_t}$
Classrooms	15.3	0.06	21.4	0.08	0.23	0.001	0.30	0.001	3.8	0.02	5.9	0.02
Rooms of teachers	9.2	0.06	10.8	0.06	10.7	0.07	14.2	0.08	6.6	0.05	9.0	0.05
Special rooms	19.6	0.06	41.3	0.09	5.9	0.02	10.6	0.02	8.5	0.03	13.0	0.03
Material rooms	11.0	0.06	24.6	0.05	4.2	0.02	15.4	0.03	8.7	0.05	16.4	0.04
Lecture rooms	17.1	0.06	28.0	0.04	2.0	0.01	7.2	0.01	9.0	0.02	19.5	0.03
Administration rooms	12.6	0.07	21.8	0.07	-	-	-	-	6.2	0.04	9.0	0.03
Libraries	10.5	0.07	21.6	0.08	2.8	0.02	4.2	0.02	8.1	0.05	20.0	0.07
Storerooms	6.0	0.02	6.7	0.01	-	-	-	-	9.3	0.04	19.8	0.03
Others	22.2	0.08	26.0	0.06	-	-	-	-	8.3	0.03	16.8	0.04

Narayanan (1995) - N.Z. Offices

Fire load surveys were conducted in 5 life offices in Wellington's central business district. The following ventilation data was also obtained:

	Office Sample No.				
	A1	A2	A3	A4	A5
Floor area, A_f (m^2)	477	1116	1205	425	776
Vent area, A_v (m^2)	124	160	78.2	66.1	108
Total bounding surface area, A_t (m^2)	1163	2552	2743	1048	1891
Height of openings, h_v (m)	1.50	1.60	1.50	1.55	1.45
Opening factor, $A_v\sqrt{h_v}/A_t$ ($m^{\frac{1}{2}}$)	0.13	0.08	0.03	0.08	0.07

The opening factor mean and standard deviation for this small sample are $0.08\ m^{\frac{1}{2}}$ and $0.03\ m^{\frac{1}{2}}$, respectively.

D3 VENTILATION SURVEY

D3.1 Outline

In order to ascertain whether any trends can be observed for the distribution of ventilation properties for occupancies a preliminary survey was conducted based on

1. drawings for some typical flats, motels, a hotel and an aged-care building, and
2. a survey of dimensions and ventilation areas of shops in shopping centres.

The drawings had originally been collected as part of Fire Code Reform Project 4, and the shopping centre data was collected for the Fire Code Reform Project 6 Shopping Centre Review (Bennetts et al. (1997)).

The buildings according to their Building Code of Australia classes are:

Class 2

- 2 Storey Class 2 Building (Flats)
- 3-4 Storey Class 2 Building (Flats)
- 10 Storey Class 2 Building (Flats) < 25 m in effective height
- 30-40 Storey Class 2 Building (Flats) > 25 m in effective height

Class 3

- Motel, Lot 2 , corner Taylor and Hillyard Sts, Pialba
- Lochinvar Motel (Alterations and Additions), Lot 8, Windsor Road, Kellyville
- 2 Storey Class 3 Building (Aged Care)

Class 6

- Hotel (without accommodation), Hervey Bay
- Shops in a shopping centre, suburban Melbourne

This survey is very limited in that it considers only a small number of BCA classes, and within these classes generally only a small number of individual buildings.

D3.2 Results

From the drawings, the ventilation properties were calculated for selected compartments (but not for all compartments) within each building. Results are summarised for floor area A_f, opening area A_v, equivalent opening height h_v, opening factor $A_v\sqrt{h_v}\ /\ A_t$, and the opening area to floor area ratio $A_v\ /\ A_f$. Equivalent opening height h_v was calculated by two methods that gave very similar results (5% maximum difference). The simpler method involves calculating the weighted average opening height values by multiplying individual opening heights by their respective areas and dividing the sum by the total opening area.. Opening height values presented below were calculated by this method, and the opening factors are consistent with these opening heights. Only vertical openings, eg. door and windows, contribute to the ventilation in the buildings considered in this study.

The calculated opening (or ventilation) area, and therefore opening factor $A_v\sqrt{h_v}\ /\ A_t$, is considered to be the maximum possible value, and any value in the range from zero to this maximum value is possible in a fire situation. The typical range of opening factor for which it is expected that variations will make a significant difference to fire severity is 0.01 $m^{1/2}$ to 0.20 $m^{1/2}$ (see Kawagoe and Sekine (1963), Lie (1974), Pettersson et al. (1976)). Intermediate values of opening factor may result in maximum fire severity. There is not a one-to-one correspondence between opening factor and the opening area to floor area ratio A_v / A_f, and so it is not possible to give values of A_v / A_f that coincide with this range of opening factor.

The range of maximum values for the opening factor for Class 2 buildings (flats / home units) is 0.065 $m^{1/2}$ to 0.123 $m^{1/2}$ considering the unit as a whole, or 0.073 $m^{1/2}$ to 0.170 $m^{1/2}$ considering individual bedrooms. The range of A_v / A_f is 0.178 to 0.272 for the whole unit, and 0.290 to 0.613 for bedrooms.

Class 2	Floor Area A_f (m^2)	Opening Area A_v (m^2)	Opening Height h_v (m)	Opening Factor ($m^{1/2}$)	Area Ratio A_v / A_f
Flats (2 Storey)					
Unit 1 (Ground Floor)	82.75	14.74	1.47	0.065	0.178
Unit 1 (Ground Floor) - Bedroom 1 Only	14.00	4.07	1.62	0.075	0.290
Unit 1 (Ground Floor) - Bedroom 2 Only	10.59	4.07	1.62	0.092	0.384
Unit 5 (First Floor)	96.06	18.97	1.53	0.067	0.197
Unit 5 (First Floor) - Bedroom 1 Only	12.77	3.69	1.65	0.073	0.289
Unit 5 (First Floor) - Bedroom 2 Only	11.07	3.69	1.65	0.081	0.333
Flats (3 Storey)					
Unit 6 (First Floor)	84.41	22.76	1.92	0.117	0.270
Unit 6 (First Floor) - Bedroom 1 Only	16.53	9.07	2.03	0.170	0.549
Unit 6 (First Floor) - Bedroom 2 Only	11.99	7.35	2.10	0.167	0.613
Unit 7 (First Floor)	88.11	18.23	1.88	0.088	0.207
Unit 7 (First Floor) - Bedroom 1 Only	18.03	7.56	2.10	0.135	0.419
Unit 7 (First Floor) - Bedroom 2 Only	12.88	4.41	1.70	0.091	0.343
Flats (10 Storey)					
Unit 36, 44, 52 (Typical Floor)	88.16	16.38	2.10	0.085	0.186
Unit 35, 43, 51 (Typical Floor)	93.73	25.45	2.04	0.123	0.272
Flats (29 Storey)					
Unit 1	83.48	17.71	2.02	0.086	0.212
Unit 3	108.85	26.54	1.95	0.105	0.244

The range of maximum values for the opening factor for Class 3 buildings (in this case motels and aged care units) is 0.043 $m^{1/2}$ to 0.210 $m^{1/2}$ - the motel units are at the low end of this range and the aged care units at the upper end. The range of A_v / A_f is 0.129 to 0.426.

Class 3	Floor Area A_f (m^2)	Opening Area A_v (m^2)	Opening Height h_v (m)	Opening Factor ($m^{1/2}$)	Area Ratio A_v / A_f
Motel (Pialba)					
Unit 2 (units 3 to 13 similar)	29.40	4.78	1.49	0.050	0.163
Unit 14 (unit 1 similar)	40.07	6.40	1.39	0.053	0.160
Unit 16 (units 17 to 27 similar)	29.40	4.78	1.49	0.043	0.163
Unit 15 (unit 28 similar)	40.07	6.40	1.39	0.050	0.160
Manager's Unit	90.15	23.67	1.68	0.106	0.263
Unit 29	41.26	5.32	1.49	0.043	0.129
Average	45.06	8.56	1.49	0.057	0.173
Motel (Kellyville)					
Unit 1 (units 2 to 6 similar)	18.48	5.94	1.39	0.084	0.322
Aged Care (2 Storey)					
First Floor - North Wing	428.21	105.06	2.56	0.151	0.245
First Floor - Bedroom 1-70	16.21	6.91	2.05	0.134	0.426
First Floor - Dining/Lounge Room	81.31	33.15	2.46	0.210	0.408

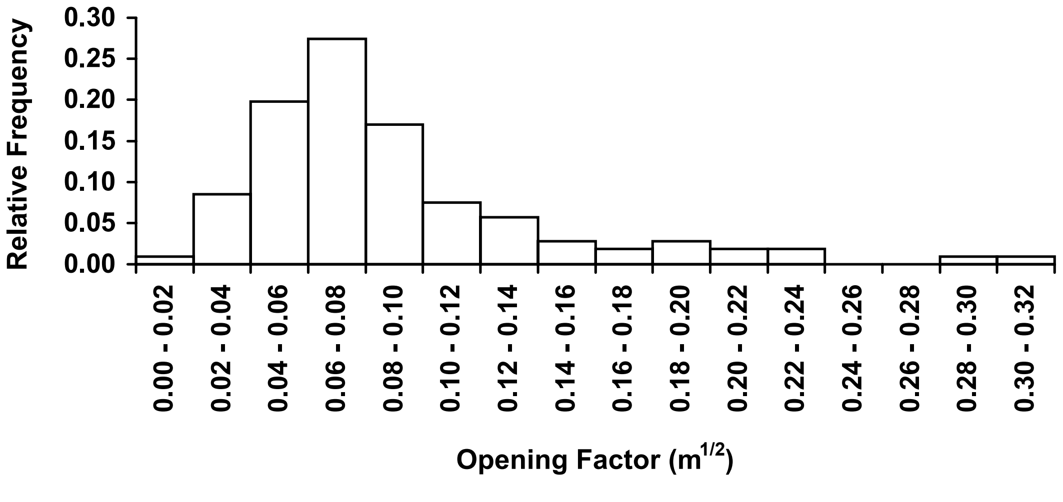
Of the Class 6 buildings, only the bar area of one hotel building was considered - the opening factor is 0.043 $m^{1/2}$, and A_v / A_f is 0.082.

Class 6 (hotel bar area)	Floor Area A_f (m^2)	Opening Area A_v (m^2)	Opening Height h_v (m)	Opening Factor ($m^{1/2}$)	Area Ratio A_v / A_f
Pub (Hervey Bay) Stage 1 (bars)	538.80	44.25	1.77	0.043	0.082

The remaining Class 6 data is for shops in a shopping centre. Shop dimensions and ventilation areas (doors and windows) were reported in the Fire Code Reform Project 6 Shopping Centre Review for a large number of specialty shops in a major shopping centre in Melbourne. Not all window areas could be determined. The opening factor $A_v \sqrt{h_v} \ / \ A_t$ was calculated for 106 of the 185 shops based on the ventilation areas and an assumed shop layout. The minimum and maximum values, along with the average and the standard deviation for the floor area, volume, opening area, opening height, total inside surface area, opening factor and the ratio of opening area to floor area are given in the following table.

Class 6 (shops in a shopping centre)	Minimum Value	Maximum Value	Average Value	Standard Deviation
Floor Area, A_f (m^2)	16	950	105	103
Volume, V (m^3)	49	2851	329	314
Opening Area, A_v (m^2)	3.0	59.7	17.4	9.9
Opening Height, h_v (m)	1.0	4.8	2.5	0.54
Total Inside Surface Area, A_t (m^2)	80.8	2367	359	259
Opening Factor, $A_v\sqrt{h_v} / A_t$ ($m^{1/2}$)	0.019	0.301	0.090	0.054
Area ratio, A_v / A_f	0.037	0.687	0.216	0.133

The distribution of the opening factor for the shops is plotted below



D4 VENTILATION FOR BCA CLASSES

The following table lists the Building Code of Australia classes considered by this project (ie. classes 2 to 9 inclusive), along with their assumed ventilation expressed as the opening factor $A_v \sqrt{h_v} / A_t$ for a compartment. Where considered appropriate, some current BCA classes have been divided into other non-BCA classes – these are clearly noted.

Class	Description	Opening factor $A_v \sqrt{h_v} / A_t$ ($m^{1/2}$)			Remarks
		Average	Standard deviation	C.O.V*	
2	A building containing two or more sole-occupancy units each being a separate dwelling.	0.10	0.03	0.3	Based on limited data from Preliminary Ventilation Survey.
3	*1 A residential building, other than a building of Class 1 or 2, which is a common place of long term or transient living for a number of unrelated persons.*				
3a**	(a) Accommodation for the aged, disabled or children; or	0.13	0.08	0.6	Based on limited data for aged-care building from the Preliminary Ventilation Survey. COV assumed.
3b**	(b) Others, including • a boarding-house, guest house, hostel, lodging-house or backpackers accommodation; or • a residential part of an hotel or motel; or • a residential part of a school; or • a residential part of a health-care building which accommodates members of staff.	0.06	0.03	0.5	Based on limited data for motels from the Preliminary Ventilation Survey.
4	A dwelling in a building that is Class 5, 6, 7, 8 or 9 if it is the only dwelling in the building.	0.10	0.03	0.3	No data available – values taken to be as for Class 2.
5	An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.	0.08	0.07	0.9	Based on Culver(1976) for U.S. office buildings.
6	*2 A shop or other building for the sale of goods by retail or the supply of services direct to the public, including-* (a) an eating room, cafe, restaurant, milk or soft-drink bar; or (b) a dining room, bar, shop or kiosk part of a hotel or motel; or (c) a hairdresser's or barber's shop, public laundry, or undertaker's establishment; or (d) market or sale room, showroom, or service station.	0.09	0.06	0.7	Based on data from Bennetts et al. (1997) for shops in shopping centres.

* C.O.V = coefficient of variation = standard deviation / average
** Not a current BCA class.

Class		Description	Opening factor $A_v\sqrt{h_v}/A_t$ ($m^{1/2}$) Average	Standard deviation	C.O.V**	Remarks
		3				
7		A building which is-				
	7a**	(a) a carpark				No data available.
		- open-deck	0.3	0.3	1	Arbitrary large value assumed.
		- enclosed	0.02	0.02	1	Arbitrary small value assumed.
	7b**	(b) for storage, or display of goods or produce for sale by wholesale.	0.09	0.06	0.7	No data available – values taken to be as for Class 6.
8		A laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.				
	8a**	(a) purpose-built	-	-	-	No recommended values – to be engineer designed.
	8b**	(b) general purpose	0.09	0.06	0.7	No data available – values taken to be as for Class 6.
9		A building of a public nature:				
	9a	(a) A health-care building; including those parts of the building set aside as a laboratory; or	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.
		(b) An assembly building, but excluding any other parts of the building that are of another Class, including				
	9b**	• a primary or secondary school, including a trade workshop, laboratory or the like; or	0.09	0.06	0.7	Average based on German school classrooms (CIB (1986)) with assumed opening height of 1.5m. COV assumed (as Class 6).
	9c**	• disco or nightclub; or	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.
	9d**	• exhibition hall; or	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.
	9e**	• theatre or public hall with stage; or	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.
	9f**	• theatre or public hall without stage; or	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.
	9g**	• other assembly buildings	0.09	0.06	0.7	No data available – values taken to be as for Class 9b.

* C.O.V = coefficient of variation = standard deviation / average
** Not a current BCA class.

Low, medium and high values for ventilation for each BCA class were derived from the previous table. The medium value was taken to be the average value, the low value is the average minus 1.65 times the standard deviation with a minimum opening factor of 0.02 $m^{1/2}$, and the high value is the average plus 1.65 times the standard deviation. The low and high values correspond to the 5 and 95 percentile values, respectively.

Class	Description	Opening factor $A_v\sqrt{h_v} / A_t$ ($m^{1/2}$)		
		Low	Medium	High
2	A building containing two or more sole-occupancy units each being a separate dwelling.	0.05	0.10	0.15
3	*4 A residential building, other than a building of Class 1 or 2, which is a common place of long term or transient living for a number of unrelated persons.*			
3a**	(a) Accommodation for the aged, disabled or children; or	0.02	0.13	0.26
3b**	(b) Others, including • a boarding-house, guest house, hostel, lodging-house or backpackers accommodation; or • a residential part of an hotel or motel; or • a residential part of a school; or • a residential part of a health-care building which accommodates members of staff.	0.02	0.06	0.11
4	A dwelling in a building that is Class 5, 6, 7, 8 or 9 if it is the only dwelling in the building.	0.05	0.10	0.15
5	An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.	0.02	0.08	0.20
6	*5 A shop or other building for the sale of goods by retail or the supply of services direct to the public, including-* (a) an eating room, cafe, restaurant, milk or soft-drink bar; or (b) a dining room, bar, shop or kiosk part of a hotel or motel; or (c) a hairdresser's or barber's shop, public laundry, or undertaker's establishment; or (e) market or sale room, showroom, or service station.	0.02	0.09	0.19
7	A building which is-			
7a**	(a) a carpark	0.02	0.1	0.3
7b**	(b) for storage, or display of goods or produce for sale by wholesale.	0.02	0.09	0.19
8	A laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.			
8a**	(a) purpose-built	0.02	0.09	0.19
8b**	(b) general purpose	0.02	0.09	0.19

** Not a current BCA class.

Class	Description	Opening factor $A_v\sqrt{h_v} / A_t$ (m$^{1/2}$)		
		Low	Medium	High
9	A building of a public nature:			
9a	(a) A health-care building; including those parts of the building set aside as a laboratory; or	0.02	0.09	0.19
	(b) An assembly building, but excluding any other parts of the building that are of another Class, including			
9b**	• a primary or secondary school, including a trade workshop, laboratory or the like; or	0.02	0.09	0.19
9c**	• disco or nightclub; or	0.02	0.09	0.19
9d**	• exhibition hall; or	0.02	0.09	0.19
9e**	• theatre or public hall with stage; or	0.02	0.09	0.19
9f**	• theatre or public hall without stage; or	0.02	0.09	0.19
9g**	• other assembly buildings	0.02	0.09	0.19

** Not a current BCA class.

D5 REFERENCES

Bennetts, I.D., Culton, M., Dickerson, M.L., Lewins, R., Poh, K.W., Poon, S.L., Ralph, R., Lee, A.C., and Beever, P.F. (1997). “Shopping Centre Review”, Project 6, BHP Research / Fire Code Reform Centre, BHPR/SM/R/G/058.

CIB W14 (1986). “Design Guide - Structural Fire Safety”, Fire Safety Journal, Vol. 10, No. 2, pp.75-137.

Culver, C.G. (1976). “Survey Results for Fire Loads and Live Loads in Office Buildings”, NBS Building Science Series 85, US Department of Commerce / National Bureau of Standards, May 1976.

Kawagoe, K. and Sekine, T. (1963). “Estimation of Fire Temperature-Time Curve in Rooms”, Occasional Report No. 11, Building Research Institute, Japan.

Lie, T.T. (1974). “Characteristic Temperature Curves for Various Fire Severities”, Fire Technology, vol. 10, no. 4, November, pp.315-326.

Narayanan, P. (1995). “Fire Severities for Structural Fire Engineering Design”, BRANZ Study Report 67, Building Research Association of New Zealand, New Zealand.

Pettersson, O., Magnusson, S.E., and Thor, J. (1976). “Fire Engineering Design of Steel Structures”, Bulletin 52, Division of Structural Mechanics and Concrete Construction, Lund Institute of Technology, Sweden.

APPENDIX E

CALCULATION OF EVACUATION USING GUIDELINES METHOD

E1 BACKGROUND

There is relatively little information in the literature, gathered into an accessible form, which may be used to estimate the overall time it takes people to leave a building, once a fire has started. As noted above, the evacuation time for people to get out once they start to move, has been widely studied, but reliable estimates for the response and coping times are still not available, and such data will always be difficult to gather, as there is a large psychological element, and a good deal of variability in human behaviour.

It should be noted in passing at this point however, that the popular concept of panic in response to a fire emergency is erroneous. People may behave anti-socially, though very often they do not, but in general they behave rationally according to the information that is to hand. That information may be inadequate or misleading, or people may have overlooked the existence of fire exits close at hand, but by and large there is little evidence of the irrational behaviour known as panic.

The Fire Engineering Guidelines has attempted to provide a calculation procedure for estimating the escape times from building fires. Though the Chapter in which the method is presented is very well referenced from international sources, it is not clear that the methodology may be directly derived from the sources quoted, and such derivation has not been published in the scientific literature. It has been observed that the use of the Guidelines method results in very long times for escape, such that even a modest fire in an office building for example would give rise to a large number of fatalities. This is not observed in practice, since deaths in office fires are relatively rare. Though the method may be treated as conservative, it must be used with caution.

The Guidelines method is useful in that it permits calculations for a range of occupancies to be calculated, and differences in the provision of types of alarm and levels of evacuation training to be taken into account. However, the extent to which the data upon which the method is based supports the figures deduced is unclear.
literature.

E2 SUMMARY OF METHOD FOR ESTIMATING ESCAPE TIME

E2.1 RELEVANT TIME CALCULATIONS

The Guidelines assumes that the time for people to make their way out of a building is made up as a sum of the cue time, the response time, the coping time and the time to move to a place of safety.

An estimate must be made first of all of the cue time. People within a building become aware of a fire, or an incident that may be a fire, in a number of different ways. They may smell smoke, see flames, hear breaking glass. These may be termed direct cues arising from the fire itself, likely to make people respond quickly and effectively to the fire emergency. People may also be subject to indirect cues such as hearing a fire alarm bell or being told by someone else that there is a fire. In the present approach, it is assumed that the cue time is zero, since the time prior to fire detection has no effect in the consideration of fire resistance. This is not necessarily a conservative assumption, but other conservative assumptions could be considered to cancel it out.

The response time is the time taken for people to realise that there is a fire and to do something as a result. The speed of response to the cues varies depending on a wide range of parameters to do with the location and activity of the people involved, their relationship to one another and the priorities they assign to the need to evacuate.

Having decided to respond, people may not necessarily escape, but spend their time in investigating and tackling the fire, warning and assisting others, locating or protecting valuables. This period of time is referred to in the Guidelines as the coping time.
When people finally decide to move there is a time associated with travel to the exits, movement along corridors, down stairs and out of doors. In order to calculate evacuation times, it is necessary to incorporate all of these factors into a total evacuation time. Of these three time periods, the response time, the coping time and the evacuation time, most is known about the latter, though in many building types, the time taken for the first two activities may exceed the evacuation time by a large factor. It is beyond the scope of this project to embark upon a comprehensive study of escape times, and use will be made of values available in the The Guidelines gives best, average and worst scenarios for the response and coping times, based on different types of fire cue and alarm system. Average times based on a fire alarm bellare used in the present analysis.

E2.2 WEIGHTING FACTORS

The system of scoring in order to weight the various parts of the evacuation time is deduced from a chart, Table 7.9 given in Chapter 7 of the Guidelines. The chart assesses 8 attributes for each occupancy, and is marked with stars to indicate the influence of a particular attribute on time to escape for a range of different occupancies. For example, in hospitals levels of alertness and mobility are likely to be low, and each is rated with one star for occupant response; in offices levels of alertness and mobility are likley to be high, and these attributes are rated with 5 stars. Within each occupancy the three most important attributes are unticked and the 5 lesser attributes are ticked. In arriving at a score for an occupancy the number of stars is multiplied by 0.4 for a ticked item, and by 2 for an unticked item. This score is then divided by 8, giving a maximum possible final score of 5 and a minimum of 1.

As pointed out by Marchant, each set of attributes should have the most important items ticked and that there should for consistency be five ticks out of the 8 attributes associated with each occupancy. However, in the published version of the table some of the lines have six ticks and some only four. As the allocation of ticks is subjective it is not easy to identify where the errors lie. However, Marchant has prepared proposed revisions of the table to correct the anomalies, and since his corrections appear to be reasonable, they will be adopted here.

E3 MULTI-STOREY OFFICES

E3.1 PRE-MOVEMENT TIME

The Guidelines method relies first on the identification of the cue that alerts people to the fire. In the case of a multi-storey building, it will be assumed here that the majority of people are alerted by a fire alarm bell, actuated by a smoke detector, a sprinkler system, or the operation by an individual of a break-glass alarm. The Guidelines gives an average time of response to a bell of 7 minutes, which must then be multiplied by a capability factor that relates to the occupancy. Capability factors are calculated from Table 7.9 in the Guidelines, corrected for obvious errors as noted above.

For an office, the response capability factor is 2.8 giving a response time of 20 minutes. Without informative warning systems, the Guidelines gives an average coping time of 6 minutes, and a coping capability factor for offices of 3.25, giving a total pre-movement time of 40 minutes.

E3.2 EVACUATION TIME

As noted above, a considerable amount of research has been carried out on evacuation times from tall buildings, principally by Pauls. He derived the following equation, claimed to be accurate to within a few per cent for uncontrolled evacuation of multi-storey buildings. It should be noted that controlled evacuation is to be preferred for a number of reasons, but provisions are not explicitly included in the BCA. The time for evacuation T in minutes is given by

$$T = 2 + 0.0117\ P \qquad \text{E3.1}$$

where P is the population per unit effective stair width in people per metre ($P < 800$). This last parameter requires a little more explanation. Pauls in his studies of human movement, has concluded that people as they move along corridors, through doorways and down stairs do not use the edges of the route and keep towards the centre. The effective doorway, corridor or stairway width achieved is 180mm narrower than that measured between balustrades. In a tall building, the parameter P is the total population of the building divided by the sum of the effective widths of all the stairways (in m). It is assumed that all occupants have access to all stairs.

The BCA determines the office population as 1 person per $10m^2$. The fact that this is known to be high introduces a degree of conservatism into the calculation. The BCA also demands that the total stair width be 10mm per person up to 200 people on a floor and 8.3 mm per person for each person over 200 on a floor. These widths are independent of building height. For buildings of 3 storeys or more there must be two stairs, and each must be at least 1m wide, notwithstanding any of the above calculations. By using these figures it is possible to estimate the total evacuation time from buildings of different heights and areas using equation D3.1. The results are summarised in Table D3.1. Populations for the ground floor have been ignored, as these people do not use the stairs.

It can be seen from Table D3.1 that because of the 1m width limit, the $1000m^2$ is over-provided with stairs and evacuation is very rapid. Above this area the time is fairly constant,

being in round numbers, 8 minutes for a 5-storey building, 15 minutes for a 10-storey building, 30 minutes for a 20-story building and 45 minutes for a 30-storey building.
The Guidelines required that these figures are multiplied by a further evacuation capability factor, which, since they are based on correlations of measurements, appears to be a bit severe. The Guidelines capability factor which needs to be applied for office buildings is 3.1, giving over 45 minutes evacuation time for a 10-storey building, and almost 2½ hours for a 30 storey building.

Area m^2	Number of Storeys						
	3	4	5	10	20	30	Note
1000	3.4	4.1	4.8	8.4	16	23	2 stairs - each 1m wide
2000	4.9	6.3	7.7	15	29	43	2 stairs - each 1m wide
3000	4.9	6.3	7.8	15	29	43	2 stairs - each 1.4m wide
4000	5.0	6.6	8.1	16	31	46	3 stairs - each 1.2m wide

Table E3.1 Time in minutes to evacuate office buildings of various heights and areas calculated from BCA provisions and equation E3.1.

E3.3 TOTAL EVACUATION TIME

To arrive at the total escape times, the figures in Table E3.1 must be multiplied by 3.1 and to these times must be added the 40 minutes pre-movement time, calculated above. This procedure gives the following table E3.2.

Area m^2	Number of Storeys						
	3	4	5	10	20	30	Note
1000	51	53	55	66	90	112	2 stairs - each 1m wide
2000	56	60	64	87	130	173	2 stairs - each 1m wide
3000	56	60	64	87	130	173	2 stairs - each 1.4m wide
4000	56	60	65	90	136	183	3 stairs - each 1.2m wide

Table E3.2 Total time in minutes for occupants to escape from office buildings of various heights and areas, calculated using Fire Engineering Guidelines method and Table D3.1

E4 MULTI-STOREY HOTELS AND HOSTELS

E4.1 PRE-MOVEMENT TIME

These buildings have been grouped together as representing a set of buildings with similar occupant types in that they may be asleep and possibly unfamiliar with the building. As above for offices, it is assumed that in the case of a multi-storey building, the majority of people are alerted by a fire alarm bell. The Guidelines gives an average time of response to a bell of 7 minutes, which must then be multiplied by a capability factor that relates to the occupancy.

For a hotel, the response capability factor is 3.15 giving a response time of 22 minutes. Without informative warning systems, the Guidelines gives an average coping time of 6 minutes, and a coping capability factor for hotels of 2.95, giving a total pre-movement time of 40 minutes. It should be noted that this time turns out to be the same as the pre-movement time for offices, in spite of the fact that people in offices are unlikely to be asleep and can communicate readily with one another.

E4.2 EVACUATION TIME

The BCA determines the hotel population as 1 person per 15m^2. The requirements for staircase widths are the same as those for the office buildings noted above. By using these figures it is possible to estimate the total evacuation time from buildings of different heights and areas using equation 10.1. The results are summarised in Table E4.1.

It can be seen that the evacuation times are less for the hotel, because the population is less and the minimum stairway widths apply for all but the largest floor plate. It should be noted that in practice, it may not be possible to locate 2 stairs on the larger floors such that the travel distance requirements of the BCA can be met. So it may be that one or more additional stairs which must be a least 1m wide would have to be added, which would reduce the evacuation times considerably.

Area m^2	Number of Storeys						
	3	4	5	10	20	30	Note
1000	3.0	3.4	3.9	6.3	11	16	2 stairs - each 1m wide
2000	3.9	4.9	5.8	11	20	30	2 stairs - each 1m wide
3000	4.9	6.3	7.7	15	29	43	2 stairs - each 1m wide
4000	4.8	6.2	7.6	15	29	42	2 stairs - each 1.3m wide

Table D4.1 Time in minutes to evacuate hotel buildings of various heights and areas calculated from BCA provisions and equation E3.1.

E4.3 TOTAL EVACUATION TIME

To arrive at the total escape times, the figures in Table E4.1 must be multiplied by 2.9 and to these times must be added the 40 minutes pre-movement time, calculated above. This procedure gives the following table E4.2.

Area m^2	Number of Storeys						
	3	4	5	10	20	30	Note
1000	49	50	51	58	72	86	2 stairs - each 1m wide
2000	51	54	57	71	98	126	2 stairs - each 1m wide
3000	54	58	62	83	124	166	2 stairs - each 1m wide
4000	54	58	62	82	123	163	2 stairs - each 1.3m wide

Table E4.2 Total time in minutes for occupants to escape from hotel buildings of various heights and areas, calculated using Fire Engineering Guidelines method and Table E4.1

E5 MULTI-STOREY APARTMENT BUILDINGS

E5.1 PRE-MOVEMENT TIME

Assuming that the occupants are alerted by a bell then the Guidelines response time is 7 minutes, with a response capability factor of 3.1, giving a response time of 28 minutes.
There is a further consideration here however. It may be assumed that in a high rise hotel, the actuation of a detector in any room would sound an alarm throughout the building. This is not the case in a block of apartments. Though a smoke alarm would be fitted in each apartment to comply with BCA requirements, this would not be wired to the main alarm system. There would have to be smoke in the corridor, or a break glass alarm would have to be actuated before the bell would start to ring. Such a sequence of events would be taken into account in a specific fire engineering design of an apartment building, but on a generic basis this is harder to account for.
Without an informative evacuation system, the coping time would be 6 minutes with a coping capability factor of 4.25, giving a coping time of 26 minutes.
The overall pre-movement time is therefore 54 minutes.

E6 EVACUATION TIME

The BCA does not give population figures for apartments, presumably on the basis that the 1m wide stairs are adequate for the relatively low population densities which are encountered in apartments. If we assume that a small apartment would be $100m^2$, with a population of perhaps 4 people then the population would be $25m^2$/person. This is considered to be very conservative. Using exactly the same method as before and with an evacuation capability factor of 3.3 gives the total escape times as shown in Table D5.1.

Area m^2	Number of Storeys						
	3	4	5	10	20	30	Note
1000	62	63	64	69	78	88	2 stairs - each 1m wide
2000	64	66	68	78	96	115	2 stairs - each 1m wide
3000	66	69	72	86	114	143	2 stairs - each 1m wide
4000	66	69	72	85	113	141	2 stairs - each 1m wide

Table D5.1 Total time in minutes for occupants to escape from apartment buildings of various heights and areas, calculated using Fire Engineering Guidelines method.

E7 SINGLE STOREY BUILDINGS WITH LARGE POPULATIONS

These buildings might include sports centres, stadiums, shopping centres, transport terminals, schools and exhibition halls where the time to evacuate is primarily determined by the time for which people queue at exits, plus the premovement time, as opposed to the high rise buildings described above, where a significant proportion of the time may be spent in the stairs. It is assumed here that:

- the BCA requires no more than a bell to alarm people even though owners may install PA systems which could be used in a fire
- the doorway width is 0.25m narrower than the exit width, as permitted by the BCA
- the effective doorway width is 0.3m narrower than the doorway measured width as given by Nelson and McLennan in the SFPE Handbook
- the rate of flow of people through doors is 1.3 persons/second/per m of effective width as given by Nelson and McLennan

Other large single storey buildings would be similar to the sports hall, as the BCA requirements for escape width are not specific to Class, apart from hospitals and open spectator stands. The main thing to notice is that the calculation method suggests that the time to clear a single storey building with a large population will be about 10 minutes once people start to move, regardless of the seating capacity, and use.

Following the same methodology as given in the Guidelines, response, coping and weighting factors have been calculated and applied to arrive at a total evacuation time. In the Guidelines the weighting factors are calculated differently for assembly buildings and for sports stadiums and stations. But in practice it can be seen from Table D6.2 that this distinction makes very little difference to the overall times calculated for people to escape. Once again it can be seen that 45-50 minutes covers all sizes and uses of single storey buildings with large populations.

Use of Building	Population	Number exits	Total exit width/m	Total doorway width/m	Total effective width/m	Evacuation time	Weighting factor	Evacuation time
Assembly Buildings	500	2	4.25	3.75	3.15	2.0	4.55	9.1
	1000	4	8.0	7.0	5.8	2.2	4.55	10
	2000	8	15.5	13.5	11.1	2.3	4.55	10.5
	3000	12	23	20	16.4	2.3	4.55	10.5
Sports Centres, Stations	500	2	4.25	3.75	3.15	2.0	3.95	7.9
	1000	4	8.0	7.0	5.8	2.2	3.95	8.7
	2000	8	15.5	13.5	11.1	2.3	3.95	9.1
	3000	12	23	20	16.4	2.3	3.95	9.1
Open Spectator Stands	2000	8	17	15	12.6	2.0	3.95	7.9
	5000	18	35	30.5	25.1	2.6	3.95	10.3
	20,000	60	125	110	92	2.8	3.95	11.1

Table D6.1 Total Escape Times in Minutes from Large Single Storey Buildings with High Populations

Use of Building	Population	Response time	Weighting factor	Coping time	Weighting factor	Evacuation time	Weighting factor	Total escape time
Assembly Buildings	500	7	2.4	6	3.55	2.0	4.55	47
	1000	7	2.4	6	3.55	2.2	4.55	48
	2000	7	2.4	6	3.55	2.3	4.55	49
	3000	7	2.4	6	3.55	2.3	4.55	49
Sports Centres, Stations	500	7	2.0	6	3.85	2.0	3.95	45
	1000	7	2.0	6	3.85	2.2	3.95	46
	2000	7	2.0	6	3.85	2.3	3.95	46
	3000	7	2.0	6	3.85	2.3	3.95	46
Open Spectator Stands	2000	7	2.0	6	3.85	2.0	3.95	45
	5000	7	2.0	6	3.85	2.6	3.95	47
	20,000	7	2.0	6	3.85	2.8	3.95	48

Table D6.2 Total Escape Times in Minutes from Large Single Storey Buildings with High Populations

E8 HOSPITALS, NURSING HOMES AND AGED CARE

These buildings are unlikely to be high rise, though they might be multi-storey. The occupants are likely to need assistance in evacuating, and may be slow in response and coping as well.

E9 SHOPS

Use of Building	Population	Response time	Weighting factor	Coping time	Weighting factor	Evacuation time	Weighting factor	Total escape time
Single Storey Shopping Centres	2000	7	3.05	6	3.6	2.3	4.65	54
	5000	7	3.05	6	3.6	2.3	4.65	
	20,000	7	3.05	6	3.6	2.3	4.65	
Multi Storey Shopping Centres	2000	7	3.05	6	3.6	2.3	4.65	54
	5000	7	3.05	6	3.6	2.3	4.65	
	20,000	7	3.05	6	3.6	2.3	4.65	

APPENDIX F

FIRE BRIGADE ACCESS TIMES

F1 INTRODUCTION

It is assumed here that the fire brigade require access to buildings with internal hydrants in the sense that fire resistance requirements will have to be calculated to make access to those hydrants possible during a fire. Naturally the fire resistance requirements do not alter the judgment which will be applied by fire officers at the scene to determine whether entry to a building is appropriate or not.

It is essential not only therefore to establish what this time is for real buildings, but also to identify the buildings in which there are hydrants to which the arguments could be applied.

F2 INTERNAL AND EXTERNAL HYDRANTS

The BCA demands that…..

E1.3 (a) A fire hydrant system must be provided to serve a building-

(i) having a total floor area greater than 500m² and

(ii) where a fire brigade service is available to attend a building fire.

(b) The fire hydrant system-

(i) must be installed in accordance with AS 2419.1; and

(ii) where internal hydrants are provided, they must serve only the storey on which they are located except that……..”

AS 2419.1 demands that…..

2.1 …Fire hydrants shall be provided within properties as required by the regulatory authority. Such hydrants may be required internally, externally, or on roofs…….

4.1 (Amdt 1 Oct 1996) gives details of provision and location of hydrants. Location is controlled by hose and hose stream coverage – 60 m hose + 10 m stream for external hydrants (but only 30m can be within the stairway), 30 m hose + 10 m stream for internal. Coverage revolves around floor coverage – there is no mention of external walls or roofs (except where occupants use the roof for evacuation).

4.3.1.3 says “Internal hydrants shall be provided to protect the whole building or those parts of the building not protected by external hydrants”. Just what is involved in protecting the whole building is left to the imagination.

Buildings where internal hydrants might be provided

1 Internal hydrants could be provided to meet the requirements in any building over 500m².

Internal hydrants must be provided in any building where the coverage requirements cannot be achieved with external hydrants. The 30m + 10m corresponds to the 40m exit travel distance in Class 5 – 9 buildings. It is not possible to specify which buildings (in terms of BCA groupings) must have internal hydrants as the coverage will depend on internal layout. However, any building where the distance from the ground to the upper floor is greater than 30m must have internal hydrants; and any building with a ground floor dimension greater than 70m must have internal hydrants.

Fire Control Time- Breakdown by Authority Type.

Fire Control Time

Data were obtained from the AIRS Data Base maintained at CSIRO for the year 1993/94.

Data were excluded from the statistics if AIRS Field A23 (*Type of Incident*) did not equal “11 Fire in a structure, involving a structure”.

Data were excluded from the statistics if AIRS Field A6 (*Alarm Date*) equalled ‘99/99/99’.

Data were excluded from the statistics if AIRS Field A25 (*Control or “Stop” Date*) equalled ‘99/99/99’.

Data were excluded from the statistics if AIRS Field A8 (*Alarm Time*) equalled 999999.

Data were excluded from the statistics if AIRS Field A26 (*Control or “Stop” Time*) equalled 999999.

Data were excluded from the statistics if AIRS Field A8 (*Alarm Time*) equalled 0.

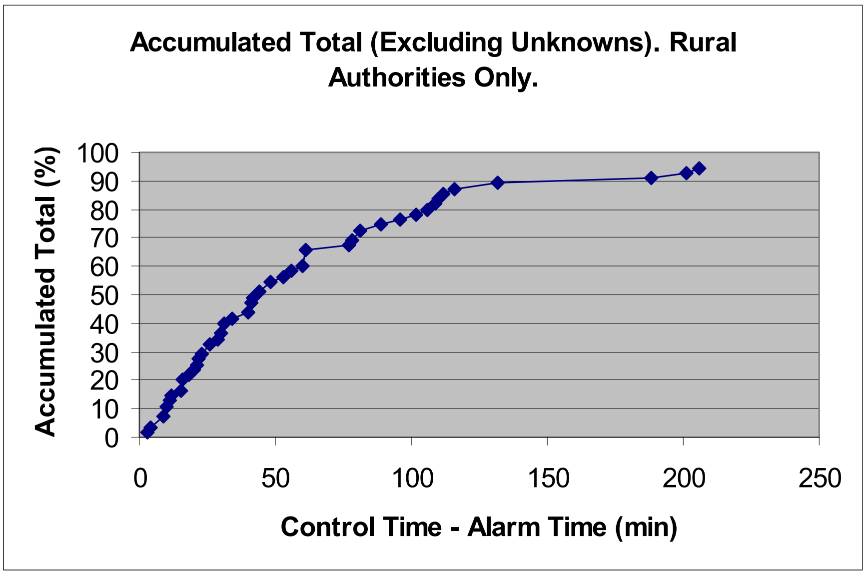
Data were excluded from the statistics if AIRS Field A26 (*Control or “Stop” Time*) equalled 0.

Data were excluded from the final plots if the extracted Code was unrecognised (possibly because an incorrect Code had been entered or the Code omitted).

The fire control times were estimated by using the differences in the *Control Time* and the *Alarm Time* (accounting for possible differences in the Control and Alarm dates).

The breakdown by Authorities was accomplished by using AIRS Field A2 (*Authority Type*). This field breaks the Authorities into the following groups:

- Predominantly urban.
- Mixed urban/rural.
- Predominantly rural.
- Predominantly forested.
- Aviation.


Accumulated Total (Excluding Unknowns). Rural Authorities Only.
Accumulated Total (%)
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
Control Time - Alarm Time (min)

APPENDIX G

MODEL FOR BARRIER FAILURE

BHPR/R/1997/006

Modelling Barrier Failure Times

by

S L Poon
I R Thomas
I D Bennetts

Refereed by: V R Beck

November 1997

Circulation: Unrestricted

DISCLOSURE NOTICE

(Please read before reading report)

PURPOSE:

This report describes methods for predicting the times of failure of barrier and structural elements of construction exposed to an enclosure fire in a building. The models have been coded into a computer program called BSpread which will be used as part of the development of Fire Code Reform Centre Project 4 Fire Safety System Model for residential buildings.

AUDIENCE:

The development work described in this report is part of an ongoing work for the Fire Code Reform Centre's Project 4 entitled "Fire Safety System Model - Residential Buildings".

ASSUMPTIONS/QUALIFICATIONS:

The methodology described in this report has been compared against selected published test results. BHP does not accept responsibility for any use of or reliance on the results of the method unless expressly agreed by in writing.

FURTHER INFORMATION:

EXTERNAL SOURCE MATERIALS:

BHP takes no responsibility for source materials used in this report that are not generated by BHP.

EXECUTIVE SUMMARY

This report describes the models that have been developed for predicting the failure times of barriers exposed to an enclosure fire in a building. Failure times due to failure from structural adequacy, integrity and insulation are considered. Models for the failure times of structural frame elements are also developed to be used in conjunction with barriers which depend upon the stability of the structural elements for support. Models have been developed for the following elements of construction:

- Steel Stud Walls
- Masonry Walls
- Concrete Walls and Shafts
- Concrete Beams and Slabs
- Concrete Columns
- Steel Structural Members
- Metal Shafts and Ducts

The work described in this report was undertaken as part of Fire Code Reform Centre Project 4 entitled "Fire Safety System Model - Residential Buildings". A computer program called BSpread has been written to be used as part of the development of the Fire Safety System Model for residential buildings.

The results of each of the models have been validated against selected published test results for thermal performance only. Structural performance is implied on the basis that the models for structural behaviour under elevated temperatures were adopted from established sources. Due to a paucity of tests on elements exposed to real fires, comparisons have only been possible with standard fire tests. However, it is believed that accuracy in the prediction of thermal response is not sensitive to the differences in the shape of the temperature time curves between real and standard fires.

Barriers which are not considered in this report are construction elements made of timber (e.g. timber stud wall, timber flooring) and barriers which have combustible linings.

The models can be extended to develop distribution functions of time-dependent failure probabilities of the barriers using a Monte Carlo simulation approach for the purpose of conducting a risk analysis. This is achieved by varying the input values for each barrier according to appropriate distribution functions over a large number of runs. These calculations are not done in this report.

The models have been developed to be relatively simple such that they will have a fast execution time and yet sufficiently accurate such that they can be incorporated into a risk assessment analysis. Overall, the models show reasonable and sometimes conservative predictions for its simplicity in structure.

CONTENTS

Page No.

Definitions

Barrier	A boundary element which may or may not be supported by a frame element
Barrier model	A model of a barrier for predicting its performance against exposure to fire. In the context of this report, barrier models include the consideration of frame elements which provide support to boundary elements and penetration elements such as ducts.
Boundary element	A construction element which forms the boundary or partition of an enclosure (e.g. wall, ceiling, and floor). Boundary elements may be structural or non-structural and function to separate spaces in buildings (hence sometimes called separation element).
Construction element	An element of building construction.
Design openings	Openings in boundary elements which are part of the building design. They include openings which can be in a closed or opened state such as a window or a door.
Enclosure	A space bounded by boundary elements.
Fire enclosure	An enclosure in which a fire develops.
Frame element	A structural line element of construction (e.g. beam, column). Note that all frame elements are structural elements.
Non-design openings	Openings in boundary elements which are not part of the building design.
Separation element	Boundary element.
Structural element	An element of construction which provides structural support to other elements of construction.

G1 INTRODUCTION

A fire developing in an enclosure has the potential to spread beyond the boundaries of the enclosure. The route by which a fire can spread is via any opening in the barriers which form the boundaries of the enclosure. Openings in barriers can either occur in a pre-existing state or in a developing state. In the former, the openings exist before the fire occurs and these can be classified as either design openings or non-design openings[1]. In the latter, the openings develop as a result of deterioration of the barriers which are being exposed to the effects of the fire. This report only considers the latter.

The type of barriers which are considered in this report are typical in many buildings. However, because they differ in function, construction material and behaviour in fires, separate consideration of each of them is necessary. In addition, because the behaviour of some barriers are dependent upon the structural system of the building for their support, the inter-dependency of the stability of these barriers requires a knowledge of how the structural system of the building behaves. It is beyond the scope of this report to consider the details of the structural system in its failure analysis of the barrier, particularly the structural redundancy and inter-dependency of the individual elements. However, simple relationships may be adopted to enable a simplified form of analysis. A consideration of this is presented in Appendix A.

The performance of the models which are developed herein adopts the following assumptions:

- The development of the fire is independent of the state of the barrier.

Obviously, the failure of a barrier will create a large opening to the fire enclosure. Because failure of barriers in fires only tends to occur during the fully developed stage of the fire, the fire conditions are therefore likely to be ventilation controlled to a large extent. This will therefore affect the growth and development of the fire and its resulting impact on other barriers.

- The performance of a given barrier is independent of other construction elements.

Although the elements of construction in a particular enclosure are interconnected in many ways, the behaviour of each barrier element is modelled assuming it is not affected by other connected elements.

- All of the models share exposure to the same fire.

Although the barriers are at different locations within an enclosure, it is assumed that they are all exposed to the same time-temperature curve. This is not unreasonable because at the fully-developed stage of the fire, nearly the entire space of the enclosure is at about the same temperature. However, this is not true for large enclosures where spatial variation of the fire is more significant.

The models have been developed to be relatively simple such that they will have a fast execution time and can be readily incorporated into a risk assessment analysis.

---

[1] See page viii for definitions

G2 GENERAL METHODOLOGY

G2.1 FAILURE MODES

For the purpose of a barrier functioning to prevent the spread of flames, failure is considered to have occurred when flames or hot gases pass through sufficiently to ignite combustibles located behind the barrier. Failure of barriers is deemed to have occurred upon collapse of the barrier or failure by loss of integrity of the barrier material modelled as a limiting temperature criterion. For failure by means of a limiting temperature rise on the unexposed surface of the barrier, consideration of an appropriate limiting temperature must be associated with the likelihood of igniting combustibles located on the unexposed side of the barrier. With the exception of failure by spalling in concrete elements, the times of occurrence of each failure mode generally adhere to the following rule

$$t_T \ngtr t_I \ngtr t_A$$

where t_T = the time of failure due to a limiting temperature rise on the unexposed surface

t_I = the time of occurrence of integrity failure of the barrier material

t_A = the time of occurrence of structural adequacy failure.

The failure to prevent spread of fire is only relevant for separation elements such as walls and floors. For structural elements which do not have a separating function (i.e. a frame element such as a beam or a column), their failure will need to be assessed in the context of how the means of flame spread are affected. This usually means assessing how failure of a particular structural element will affect the performance of barrier elements which depends upon its stability to remain in place. This is discussed in more detail in the Structural Response section (page 5).

2.1.1 Openings in Barriers

An important aspect of barrier failure is the existence of openings in a barrier. In addition to *design* openings such as an open door or an open window, the presence of *non-design openings* such as cracks or gaps in a barrier may also render the barrier ineffective, if it is of sufficient size. Non-design openings should be considered on a probabilistic basis with a value for the likelihood of its occurrence and should be amalgamated with probabilities of the likelihood of the occurrence of design openings.

Non-design openings are typically smaller than design openings. Hence, if the door or window is open, the presence of non-design openings is unlikely to be significant in terms of affecting the overall likelihood of spread. In residential buildings, however, the existence of any significant non-design openings in barriers of enclosures where the doors and windows tend to be shut is highly unlikely. This is due to the following reasons:

- Non-design openings in wall and ceiling barriers permit the passage of unwanted noise or airflow and therefore tend not to occur.
- Non-design openings in floors are also regarded as highly undesirable by the occupant and are therefore unlikely to occur.

G2.2 HEAT SOURCE - FIRE

The heat source to which the barriers are exposed to is a fire expressed as a temperature-time relationship. Hence any fire, including a standard fire, may be modelled as the heat source, provided the temperature-time curve is specified. Real or natural fires which develop in enclosures exhibit growth, fully developed and decay stages. For these fires, factors which affect the development of temperature in the enclosure include the fire load, openings in the enclosure and the thermal properties of the enclosing boundaries. Variation of these factors can only be considered *a priori* in the specification of the temperature-time curve.

In this report, only barriers made of *noncombustible* materials are considered.

G2.3 THERMAL RESPONSE

2.3.1 Modes of Heat Transfer

The fire is modelled as a hot gas medium to which the barrier is exposed to. The modes of heat transfer between the fire and the barrier surface are radiation and convection. The latter is only significant at lower temperatures during the growth stage. Inside the barrier, heat is conducted within the solid material. In barriers with air voids such as metal stud walls, the presence of the air in the voids is conservatively ignored.

2.3.1.1 Heat Transfer Between a Gas Medium and the Barrier Surface

The transfer of heat energy between a gas medium and a barrier surface exposed to the medium is given by

$$q_i = h(T_g - T_s) \qquad (1)$$

where

q_i = heat flux to barrier surface, W/m^2;
h = coefficient of heat transfer, W/m^2.K;
T_g = temperature of the gas medium, K;
T_s = temperature of the barrier surface, K.

The coefficient of heat transfer consists of the convective component and the radiative component, i.e.

$$h = h_c + h_r$$

where

h_c = convective heat transfer coefficient;
h_r = radiative heat transfer coefficient.

The convective heat transfer coefficient can be calculated from the empirical equation [1], [6]

$$h_c = 1.313\left|T_g - T_s\right|^{1/3}$$

where T_s is the surface temperature (K) and T_g is the gas temperature (K) to which the surface is exposed to. The radiative heat transfer coefficient is given by

$$h_r = \sigma\varepsilon\frac{T_g^4 - T_s^4}{T_g - T_s}$$

where σ = Stefan-Boltzmann constant
ε = emissivity

2.3.1.2 Heat Conduction Within Barrier

For a material with a relatively high conductivity (e.g. steel), the temperature within the material may be assumed to be constant throughout and the heat balance can be expressed as

$$q_i + q_o = \frac{m.c}{A}.\frac{dT_s}{dt} \qquad (2)$$

where

q_i = heat flux to barrier surface, W/m^2;
q_o = heat loss from the material (W/m^2);
m = mass, kg;
c = specific heat, J/kg/K;

A = area of exposed surface, m^2;
T_s = material temperature, K;
t = time, s.

For a material with a relatively low conductivity (e.g. concrete), a thermal gradient will exist across the cross-section. The transient changes in temperature within the material is solved using a one-dimensional finite difference approach. This involves discretizing the barrier cross-section into a number of layers parallel to its surface and solving the conservation equations over a time step period assuming that quasi steady state conditions prevail within that time across the layer. Hence equation 2 may be expressed as

$$q_i + q_o = \rho.c.\Delta x.\Delta T_s/\Delta t$$

where

q_i = eqn 1, between the exposed layer and the fire gases, and
= $k\Delta T/\Delta x$ between the other layers;
q_o = eqn 1, between the unexposed layer and the gases that it is in contact with, and
= $k\Delta T/\Delta x$ between the other layers;
k = thermal conductivity, W/m/K;
ΔT = change in temperature, K;
Δx = layer thickness, m;
ρ = material density, kg/m^3;
c = specific heat, J/kg/K;
Δt = time step, s.

Illustration on the use of the above equations to calculate the temperatures using a one-dimensional finite difference methodology is given in Appendix E.

In the case of steel stud walls, the plasterboard skins are considered as separate barriers. The temperature of the air space within the wall is taken as the average of the inside surface temperature of the plasterboard skins.

2.3.2 Effect of Fire on Material Properties of Barrier

In order to predict the behaviour of a barrier exposed to a given fire, the material properties which determine the behaviour of the barrier at elevated temperatures must be known. Details of this information are given in Appendix B.

2.3.3 Effect of Moisture In Barrier material

Some of the relatively porous material such as gypsum plasterboard and insulation material contain a significant amount of moisture. When the material is subjected to heat, the moisture is vapourized and is slowly driven off. The temperature of each layer in the material do not rise above 100 °C until all the moisture in the layer is vapourized. The energy per unit mass of material required to vapourize the moisture is calculated as

$$q_w = H_w \times m_w$$

where q_w = vapourization energy (J/kg)
H_w = heat of vapourization of water ($\approx 2.44 \times 10^6$ J/kg)
m_w = moisture content (kg/kg)

The effects of moisture on material properties at temperatures below 100°C have been ignored.

G2.4 STRUCTURAL RESPONSE

2.4.1 End Conditions

The degree of fixity at the ends of structural elements determine the form of structural behaviour and therefore the collapse mechanism which will lead to failure. For the purpose of this project, only simple span conditions have been conservatively considered. However, in the concrete beam and slab model, non-pin-ended conditions have been assumed to better reflect present design and construction practice.

2.4.2 Strength in Fire

The important considerations for structural adequacy in a member are its axial and bending capacities. The capacity of a structural member of a given configuration to withstand a given load is a function of its characteristic mechanical properties. As the property values change with temperature, the capacity of the member also changes. Failure is deemed to have occurred when either the axial or bending capacity, reduced due to the effects of the fire, is exceeded under the applied loads.

In addition, second-order effects may also determine the capacity limit of the member. Of particular significance is the amplification effects of axial loads on a vertical member such as a wall or a column known as P-Δ effects. These effects magnify the applied bending moment on the member due to lateral deformation caused by the axial loads and any offset which may exist between the location of the applied load and the centroid of the member cross-section. They become more pronounced in a fire because of the increased deformation under reduced material strength and possible thermal bowing. However, for residential buildings, it is considered adequate to assume that the vertical elements are sufficiently stocky such that P-Δ effects may be ignored.

2.4.3 Analysis

It is required that the level of analysis for structural behaviour in the determination of the time to failure be kept as simple as possible for the purpose of conducting a risk analysis. The level of sophistication which has been adopted in the analysis for determining the failure time of a barrier has been determined on the basis of its relative sensitivity in its behaviour to the effects of fire. Hence a limiting temperature criterion is sufficient for barriers (e.g. steel stud walls) whereas a structural adequacy analysis is required for others (e.g. concrete slabs). The analytical details for each model are given in the Failure Models section which starts in page 8. In addition, the following simplifications are adopted in being consistent with not considering P-Δ effects of vertically loaded members:

1. Concrete Walls and Shafts:
   Walls are considered to be effectively braced. Unbraced walls may be analysed as per concrete columns[2].

2. Concrete Columns:
   Columns are considered as stocky and bending capacity limitation due to P-Δ effect are ignored.

2.4.4 Structural Failure Path

Barriers are often supported by other structural elements. Failure of the supporting elements can lead to premature failure of the barrier. For example, failure of a column can lead to failure of part of a floor. The consideration of the performance of a floor as a barrier must therefore also consider the performance of the columns which support it. The association

---

[2] The walls may be conservatively approximated as blade columns with the smaller column dimension equal to twice the wall thickness.

between separation and structural elements depends upon the structural design system of the building. Considerations of possible associations are briefly described in Appendix A.

2.4.5 Redundancy

Failure of a structural element supporting a barrier may not necessarily lead to failure of the barrier. The loads supported by the structural element may be sufficiently redistributed to other structural elements without leading to collapse of a barrier which it directly supports. For example, failure of a secondary beam member tend not to cause failure of the portion of floor it supports. The redundancy of structural elements depends upon the structural design system of the building. Such effects are not specifically considered in the analysis. However, these effects may be accounted for by considering only critical elements in the system which would lead to failure of the barrier.

G2.5 INDEPENDENT BARRIER RANDOM VARIABLES

Independent barrier random variables refer to random variables of the barrier which influence the variation in the performance of the barrier in withstanding the effects of the fire. They are non fire dependent random variables. Although some of the thermo-physical properties are temperature dependent and are therefore a function of the fire temperature (e.g. specific heat, thermal conductivity), there is an independent variation in terms of how it is temperature dependent. For example, variations both between and within batches of the same type of insulation material will show some differences in their temperature dependencies even when subjected to the same fire.

Typical examples are variation in material properties, cross-sectional dimensions, material composition and application or placement during construction. The following table lists the independent (i.e. non fire dependent) random variables of barriers.

Material	Variability
Steel	variation in material properties, protection material properties, thickness, member dimensions[1].
Concrete	variation in material properties, composition, member dimensions[2], cover to steel reinforcement, spalling, application during construction.
Plasterboard	variation in material properties, composition, application during construction.
ALL	long-term degradation effects, particularly for friable materials.

[1] e.g. variation in actual prescribed steel sizes for a given design
[2] e.g. variation due to ponding effects during placement

G2.6 CALCULATING FAILURE PROBABILITIES

The barrier failure models presented herein will either predict a success or a failure at each time step during which the barrier is being exposed to the fire. However, the time of potential failure is dependent upon the initial configuration assumed for the barrier element. The initial configuration is determined on the basis that the barrier must be designed to withstand exposure under the standard temperature-time curve for a duration equal to the specified Fire Resistance Level (FRL). The failure time of the barrier exposed to real fire conditions is obtained for a barrier configuration that has a specified FRL.

The models can be extended to develop distribution functions of time-dependent failure probabilities of the barriers using a Monte Carlo simulation approach for the purpose of conducting a risk analysis. This is achieved by varying the input values for each barrier according to appropriate distribution functions over a large number of runs. These calculations are not done in this report

G3 FAILURE MODELS

G3.1 GENERAL

Specific input data is required by each model in order to predict its behaviour. The input data required generally comprises of:

- Temperature-time curve of the fire.
- Applied loads (where applicable).
- Thermal and mechanical properties of barrier materials as a function of temperature (default values are given in Appendix B).

In addition, the following input information is shared by the models:

TSpall	Limiting temperature for spalling (integrity failure) of concrete elements (~1500 K).
TInsFail	Limiting temperature for insulation failure of unexposed surface of wall elements (K)[3]. AS1530 Part 4 defines insulation failure as either an average temperature rise of 140K or a maximum temperature rise of 180K.
rhoConc	Density of concrete elements (kg/m^3).

The units adhere to an MKS (metre, Kelvin, second) format.

Specific input data are detailed in the description of each model. The notation for symbols used in the computer code have been used to describe the input data in order to facilitate the description of the computer notation.

The output of each of the barrier or element models are the times of failure for each of the respective failure modes.

The occurrence of spalling in concrete when exposed to high temperatures may be due to a number of factors, such as moisture content, permeability, local stresses, and the reduced strength at high temperatures. The limiting temperature of ~1500K (1200°C) [7] is an indicative approximation of the temperature level of the concrete when spalling can be expected to occur based on observations from experiments. It is not a precise value but it offers a guidance if no better information is available. Note that the concrete would have lost all its strength at this temperature (Appendix B).

Variation in the concrete density with respect to temperature may be allowed for by adjusting the temperature dependent specific heat capacity values such that

$$c'_T = \frac{c_T \rho_T}{rhoConc}$$

where c'_T = adjusted specific heat capacity values

c_T = temperature dependent specific heat

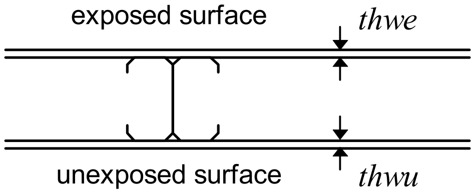
ρ_T = temperature dependent concrete density

See Appendix B for more details.

[3] See page 2 for further information.

G3.2 STEEL STUD WALLS

3.2.1 Typical cross-section



3.2.2 Input Data

- *thwe,thwu,swksm*
  thwe = thickness of exposed plasterboard skin (m)
  thwu = thickness of unexposed plasterboard skin (m)
  swksm = exposed surface area to mass ratio of the steel stud (m^2/kg)

- *pbMoist,pbDryDensity*
  pbMoist = moisture content of the plasterboard (=water mass/dry unit mass)
  pbDryDensity = plasterboard dry density (kg/m^3)

- *TFSS,TFPW*
  TFSS = limiting temperature for stability failure of steel studs (~1000 K)[4]
  TFPW = limiting temperature for integrity failure of plasterboard (~1000 K)[4]

3.2.3 Failure Model

Steel studs are initially shielded by the plasterboard layers until the limiting temperature in the plasterboard is reached. For simplicity, the limiting temperature is compared against the mid-internal temperature of the plasterboard. Failure of the plasterboard occurs by disintegration when the internal temperature exceeds its limiting temperature. Integrity failure of the barrier occurs when both skins disintegrate. Structural adequacy failure of the steel studs occur when the temperature of the steel stud exceeds its limiting temperature. The steel temperature is calculated based on Equation 2. It is expected that when the exposed skin fails, the steel stud will exceed its limiting temperature relatively quickly, as will integrity failure of the unexposed skin occur relatively quickly. Failure by insulation occurs when the unexposed skin exceeds the limiting temperature for insulation failure.

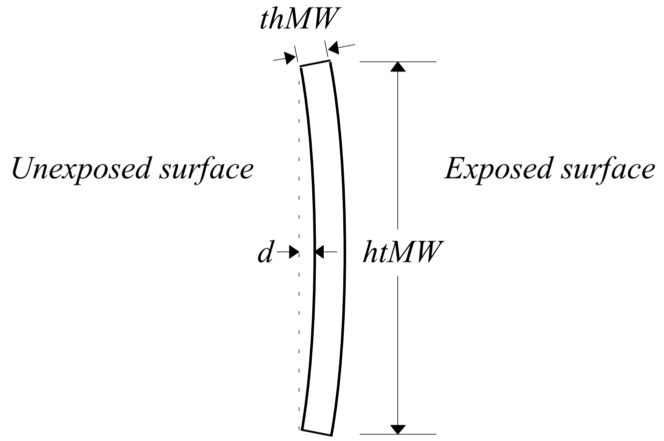
Loadbearing studs are not presently considered. However, they may be approximated using Eqn. 3 (page 16) and specifying an appropriate failure temperature.

---

[4] This is only an indicative value from experimental observations.

G3.3 MASONRY WALLS

3.3.1 Longitudinal cross-section



3.3.2 Input Data

- *thMW,htMW,rhoMasn*
  thMW = masonry wall thickness (m)
  htMW = effective height[5] of masonry wall (m)
  rhoMasn = density of masonry wall (kg/m³)

3.3.3 Failure Model

Failure occurs under the following conditions:

Structural adequacy: Lateral deflection from thermal bowing at mid height exceeds a critical deflection limit, or average wall temperature exceeds a limiting temperature.

Insulation: Unexposed surface temperature exceeds an insulation limiting temperature.

Integrity: Not modelled, but flagged when failure by structural adequacy occurs.

Conditions

The following conditions are assumed:

- Only single layer masonry walls are considered.
- The model is based on information obtained from standard fire tests [4], [5].
- The effect of load has been ignored because no significant trend on the collapse time was observed.
- The lateral deflection calculated at the midpoint of its effective height is approximated by considering the wall as having a uniform curvature, i.e.

$$d = \alpha \frac{H^2}{8w} \Delta T$$

where d = lateral deflection at midpoint of effective height (m)

[5] Unless the wall is specifically restrained against rotation, the effective height may be taken as the nominal height between the end supports. If the wall is free standing, i.e. the upper end not restrained, then the effective height may be taken as twice the nominal height.

α = coefficient of thermal expansion ($\approx 6 \times 10^{-6}$)

H = effective height of wall (*htMW*)

w = width or thickness of wall (*thMW*)

ΔT = temperature difference between the exposed and unexposed surfaces (K)

= $T_e - T_u$

where T_e = temperature of the exposed wall surface (°C)

T_u = temperature of the unexposed wall surface (°C)

However, observations from the tests indicate that the wall deflections deviate significantly in excess of the above predictions when the gas temperature is about 700°C and the corresponding exposed wall surface temperature is about 500°C. The increase in deflection, due to thermal degradation and changes in material properties under elevated temperatures, is crudely approximated by a applying a 'thermal degradation factor' to the calculated deflection, as follows:

$$d' = 1.6 \times d$$

From the standard fire test results [4], the differential temperature between the exposed and unexposed surfaces increases rapidly until about 30 to 60 minutes and then either stabilises or fails. Failure from lateral deflection is observed to occur when the deflection approaches the brick width. A slightly conservative limit for failure may be taken to be 0.9w m.

If the wall does not collapse but stabilises over an extended period of the order of 1-2 hours, then it will eventually fail by thermal degradation, depending upon its thickness. The time at which this occurs may be conservatively approximated by the time taken for the average temperature of the wall to reach 700 °C. The average wall temperature T_{av} is estimated by

$$T_{av} = (T_e + T_u)/2$$

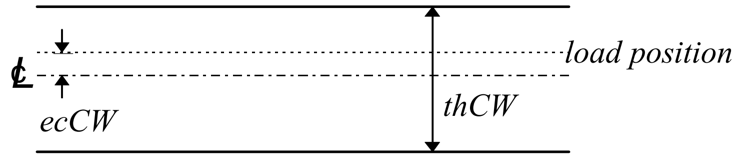
The failure limits for stability are summarised as follows:

$d' \geq 0.9w$ for lateral deflection

$T_{av} \geq 700°C$ for thermal degradation leading to collapse

G3.4 CONCRETE WALLS AND SHAFTS

3.4.1 Typical cross-section



3.4.2 Input Data

- *thCW,ecCW,cwFC*
  thCW = concrete wall thickness (m)
  ecCW = load eccentricity on concrete wall (m)
  cwFC = concrete strength at ambient temperatures (Pa)
- *bracedCW,cwLoad*
  bracedCW = braced wall (0=False, 1=True)
  cwLoad = combined line load (N/m)

3.4.3 Failure Model

Failure occurs under the following conditions:

Structural adequacy:	Applied load exceeds concrete strength as defined below.
Insulation:	Unexposed surface temperature exceeds insulation limiting temperature.
Integrity:	Concrete temperature exceeds spalling temperature.

3.4.3.1 Conditions

No in-plane horizontal forces exist.
Shear forces are not critical.

3.4.3.2 Braced Wall

Refer AS3600 Clause 11.3 [2] for requirements of a braced wall.

The maximum strength per unit length of a braced wall in compression shall be taken as N_{uw} where

$$N_{uw} = (t_w - 1.2e)\, 0.6f'_{cT}$$

where

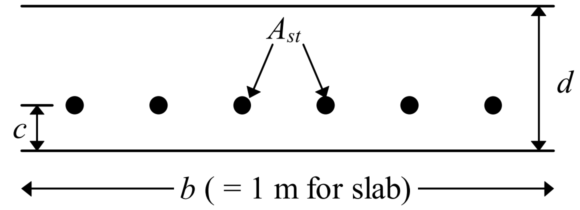
t_w = wall thickness (refers to *thCW* in figure above)
e = the eccentricity of the load measured at right angles to the plane of the wall (refers to *ecCW* in figure above)
f'_{cT} = the characteristic strength of the concrete at elevated temperatures averaged over the cross-section (default values in Appendix B).

3.4.3.3 Unbraced Wall

Not considered.

G3.5 CONCRETE BEAMS AND SLABS

3.5.1 Typical cross-section



3.5.2 Input Data

- *cbB,cbD,cbCp,cbCn,cbAp,cbAn,cbFyr,cbFc*
  cbB = width of element (b, m)
  cbD = depth of element (d, m)
  cbCp = cover depth of the centroid of the positive steel reinforcement (c^+, m)
  cbCn = cover depth of the centroid of the negative steel reinforcement (c^-, m)
  cbAp = area of positive reinforcement (A^+_{st}, m^2/m)
  cbAn = area of negative reinforcement (A^-_{st}, m^2/m)
  cbFyr = yield strength of reinforcement at ambient temperatures (Pa)
  cbFc = concrete strength at ambient temperatures (Pa)

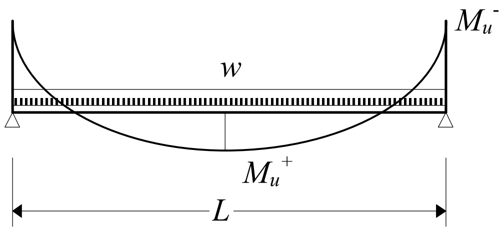
- *cbLoad,cbSpan*
  cbLoad = uniform load (N/m)
  cbSpan = element span (m)

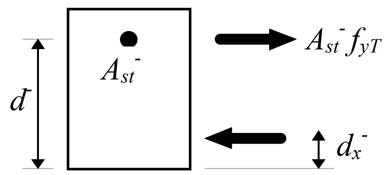
3.5.3 Failure Model

The element is assumed to be exposed to the fire from the bottom surface. Failure occurs under the following conditions:

Structural adequacy:	Applied load exceeds concrete strength as defined below.
Insulation:	Unexposed surface temperature (top side) exceeds insulation limiting temperature.
Integrity:	Concrete temperature exceeds spalling temperature.

A typical internal span is assumed as shown below:





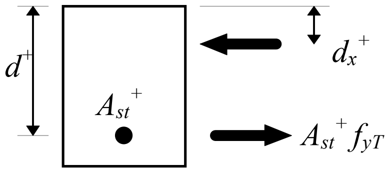
The negative bending moment capacities at the ends are calculated as follows:

$$M_u^- = A_{st}^- f_{yT}\left(d^- - d_x^-\right)$$

where

A^-_{st} = area of negative reinforcement (*cbAn*)
f_{yT} = yield strength of negative reinforcement at temperature T (default values in Appendix B)
d^- = effective depth of section in negative bending
d_x^- = distance from slab soffit to resultant compressive force in negative bending

The positive bending moment capacity at midspan is calculated as follows:



$$M_u^+ = A_{st}^+ f_{yT}\left(d^+ - d_x^+\right)$$

where

A^+_s = area of positive reinforcement (*cbAp*)
f_{yT} = yield strength of positive reinforcement at temperature T
(default values in Appendix B)
d^+ = effective depth of section in positive bending
d_x^+ = distance from slab soffit to resultant compressive force in positive bending

Structural adequacy failure is considered to have occurred when the sum of the negative and positive moment capacities reaches $wL^2/8$, i.e.

$$M_u^+ + M_u^- \geq wL^2/8$$

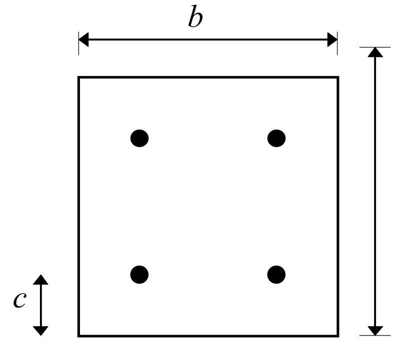
where

w = uniform combined load on the member (*cbLoad*)
L = element span (*cbSpan*)

.

G3.6 CONCRETE COLUMNS

3.6.1 Typical cross-section



3.6.2 Input Data

- *ccBi,ccDi,ccCp,ccAp,ccFyr,ccFc*
  ccBi = width of cross-section (*b*, m) *ccDi* = depth of cross-section (*d*, m)
  ccCp = cover depth to centroid of reinforcement (*c*, m)
  ccAp = area of steel reinforcement at exposed face (A_{st}, m²)
  ccFyr = yield strength of reinforcement at ambient temperatures (Pa)
  ccFc = concrete strength at ambient temperatures (Pa)
- *ccgG,ccgQ,ccG,ccQ,ccPhi*
  ccgG = partial load factor for dead load in fire *ccgQ* = partial load factor for live load in fire
  ccG = applied axial dead load (N) *ccQ* = applied axial live load (N)
  ccPhi = ratio of the actual to nominal steel reinforcement strength

3.6.3 Failure Model

The column is assumed to be equally exposed on all sides. Structural failure is considered to have occurred when either the axial strength of the concrete is exceeded or the temperature of the reinforcement exceeds the critical temperature determined in accordance with the procedure for the steel structural members (i.e. Equations 3 and 4 in page 16). The axial strength is determined based on the average strength capacity of the column, ie

$$N_{uc} = \int_0^{D/2} f'_{cT} p_y \, dy$$

where

f'_{cT} = the strength of the concrete at temperature T, determined at a distance y from the surface (default values in Appendix B).

p_y = perimeter of the region located at a distance y from the surface.

y = distance from the surface

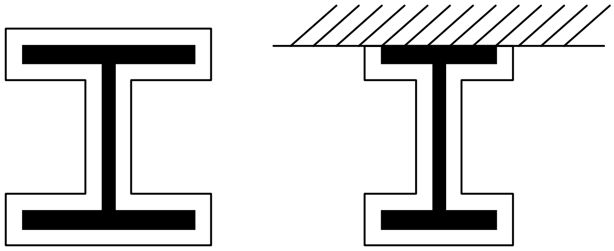
D = the lesser of the column side dimensions.

The column reinforcement refers to the main steel reinforcement and its supporting lateral reinforcement. For slender columns, the reinforcing steel offers resistance to the applied loads in tension (flexure) as well as in compression. As the columns become more stocky, the resistance in flexure reduces. However, at all times, the reinforcing steel provides lateral restraint to confine the concrete in order that its designed compressive stress can be achieved. Because this is a strength requirement, it is therefore not unreasonable to associate its critical temperature using the load ratio approach defined by equations 3 and 4.

Insulation failure is not modelled. However for consistency with the barrier models in the output data, insulation failure is flagged when structural failure occurs.

G3.7 STEEL STRUCTURAL MEMBERS

3.7.1 Typical cross-sections



3.7.2 Input Data

For steel beams:

- *sbksm,sbgG,sbgQ,sbG,sbQ,sbPhi*
  sbksm = 3-sided exposed surface area to mass ratio (m^2/kg)
  sbgG = partial load factor for dead load in fire
  sbgQ = partial load factor for live load in fire
  sbG = characteristic dead line load (N/m)
  sbQ = characteristic live line load (N/m)
  sbPhi = ratio of the mean to nominal steel beam strength
- *sbith,sbirhod,sbiw,sbicp,sbikp*
  sbith = insulation thickness (m)
  sbirhod = dry density of insulation (kg/m^3)
  sbiw = moisture content ratio of insulation (=water mass/dry unit mass, kg/kg)
  sbicp = specific heat of insulation material (J/kg/K)
  sbikp = thermal conductivity of insulation material (W/m/K)

For steel columns:

- *scksm,scgG,scgQ,scG,scQ,scPhi*
  scksm = 4-sided exposed surface area to mass ratio (m^2/kg)
  scgG = partial load factor for dead load in fire
  scgQ = partial load factor for live load in fire
  scG = axial dead load (N)
  scQ = axial live load (N)
  scPhi = ratio of the mean to nominal steel strength
- *scith,scirhod,sciw,scicp,scikp*
  scith = insulation thickness (m)
  scirhod = dry density of insulation (kg/m^3)
  sciw = moisture content ratio of insulation (=water mass/dry unit mass, kg/kg)
  scicp = specific heat of insulation material (J/kg/K)
  scikp = thermal conductivity of insulation material (W/m/K)

3.7.3 Failure Model

Structural failure is considered to have occurred when the average steel temperature exceeds the critical temperature T_c calculated as follows (Clause 12.5 [3]):

$$T_c = 905 - 690\,R \qquad (3)$$

where

R = load ratio,

$$= \frac{\gamma_G G + \gamma_Q Q}{(1.25G + 1.5Q)\phi} \qquad (4)$$

where

γ_G = partial load factor for dead load in fire conditions (*sbgG, scgG*)

γ_Q = partial load factor for live load in fire conditions (*sbgQ, scgQ*)

G = characteristic dead load (*sbG, scG*)

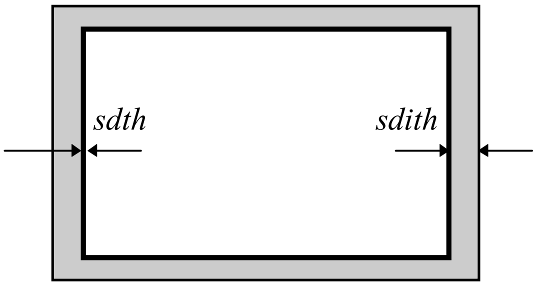
Q = characteristic live load (*sbQ, scQ*)

ϕ = ratio of the actual to nominal strength (*sbPhi, scPhi*)

For consistency in the output with the other models, insulation and integrity failures are considered to occur when structural adequacy failure occurs.

G3.8 METAL SHAFTS AND DUCTS

3.8.1 Typical cross-section



3.8.2 Input Data

- *sdith,sdirho,sdiw,sdicp,sdikp*
  sdith = insulation thickness (m)
  sdirho = insulation density (kg/m^3)
  sdiw = moisture content ratio of insulation (=water mass/dry unit mass, kg/kg)
  sdicp = specific heat of insulation material (J/kg/K)
  sdikp = thermal conductivity of insulation material (W/m/K)

- *TsdCr,sdth,sdrho*
  TsdCr = failure temperature of steel sheeting (~1000 K)
  sdth = thickness of steel sheeting (m)
  sdrho = density of steel sheeting (kg/m^3)

3.8.3 Failure Model

Failure for all the modes are considered to have occurred when the steel sheeting temperature exceeds its limiting temperature, *TsdCr*. As thin walled elements, the limiting temperature is comparable with that for steel studs, *TFSS*. However, unlike steel studs, the steel sheeting does not bear loads and is likely to continue to act as a membrane at high temperatures. From observations in standard fire tests, performance of ducts tend to surpass the structure which supports it.. The model also conservatively ignores the cooling effect of the presence of the air void within the duct.

G4 VALIDATION OF MODELS

The results of each of the models have been validated against selected published test results for thermal performance only. This has generally been the approach adopted in the determination of structural code provisions for fire resistance. With the exception of masonry wall tests, elevated temperature tests on loaded structural elements are not normally carried past their thermal failure point (based on temperature limit criteria) to the point of collapse. Usually, failure from structural stability is imminent near the thermal failure point due to the significant loss of strength in the material at this stage. Hence, tests are usually stopped at this point to avoid a catastrophic collapse. In addition, the structural behaviour of loadbearing elements is implied on the basis that the models for structural behaviour under elevated temperatures were adopted from established methods or principles.

Due to a paucity of tests on elements exposed to real fires, comparisons have only been possible with standard fire tests. However, it is believed that prediction of thermal performance is not sensitive to the temperature time curve differences between real and standard fires.

Details of the validation are provided in Appendix C. The model predictions are generally reasonable in comparison to more sophisticated methods that may have been adopted.

The steel stud wall model predictions are quite good except that it is unable to allow for the inflow of hot gases penetrating the deteriorating plasterboard skin towards the thermal failure limit. During this period, the measured temperatures are up to about 100°C higher than predicted. However, the prediction of failure times (or times when the tests were stopped) are quite close.

The masonry wall model is based entirely on available test observations.

The thermal predictions for steel are generally quite good. It is believed that this is due to the uniformity of the material providing more consistent thermal properties. Also, its high conductivity and non dependence on moisture enables relatively simplified modelling assumptions.

The model predictions for concrete members, however, are generally more conservative in comparison. It is not known exactly why this is so. Considering that the heat transfer model has been validated against a one dimensional analytical solution (Appendix E), it is suspected that the errors could arise from the input values and thermal related phenomena (e.g. moisture migration) in the concrete material. Due to the variability in material and its composition, the thermal properties of concrete are inherently more variable and show stronger dependence on temperature and moisture content.

Overall, the models show reasonable and sometimes conservative predictions for its simplicity in structure.

G5 CONCLUSION

This report describes the models that have been developed for predicting the failure times of barriers exposed to an enclosure fire in a building. Failure times due to failure from structural adequacy, integrity and insulation are considered. Models for the failure times of structural frame elements are also developed to be used in conjunction with barriers which depend upon the stability of the structural elements for support. Models have been developed for the following elements of construction:

- Steel Stud Walls
- Masonry Walls
- Concrete Walls and Shafts
- Concrete Beams and Slabs
- Concrete Columns
- Steel Structural Members
- Metal Shafts and Ducts

The work described in this report was undertaken as part of Fire Code Reform Centre Project 4 entitled "Fire Safety System Model - Residential Buildings". A computer program called BSpread has been written to be used as part of the development of the Fire Safety System Model for residential buildings.

The results of each of the models have been validated against selected published test results for thermal performance only. Structural performance is implied on the basis that the models for structural behaviour under elevated temperatures were adopted from established sources. Due to a paucity of tests on elements exposed to real fires, comparisons have only been possible with standard fire tests. However, it is believed that accuracy in the prediction of thermal response is not sensitive to the differences in the shape of the temperature time curves between real and standard fires.

Barriers which are not considered in this report are construction elements made of timber (e.g. timber stud wall, timber flooring) and barriers which have combustible linings.

The models can be extended to develop distribution functions of time-dependent failure probabilities of the barriers using a Monte Carlo simulation approach for the purpose of conducting a risk analysis. This is achieved by varying the input values for each barrier according to appropriate distribution functions over a large number of runs. These calculations are not done in this report.

The models have been developed to be relatively simple such that they will have a fast execution time and yet sufficiently accurate such that they can be incorporated into a risk assessment analysis. Overall, the models show reasonable and sometimes conservative predictions for its simplicity in structure.

G6 REFERENCES

[1] McAdams, W.H., "Heat Transmission", 3rd Edition, McGraw-Hill, New York (Chap. 13), 1954.

[2] Australian Standard AS 3600-1994, "Concrete Structures", Standards Association of Australia.

[3] Australian Standard AS 4100-1990, "Steel Structures", Standards Association of Australia.

[4] Byrne, S.M., "Experimental Study of the Effect of Applied Load and Slenderness Ratio on the Fire-Resistance Rating of Loadbearing Brick Walls", Experimental Building Station, Department of Construction, MP No. 482, May 1978.

[5] Lawrence, S.J. and Gnanakrishnan, N., "The Fire Resistance of Masonry Walls", Technical Record 531, National Building Technology Centre, April 1988.

[6] Harmathy, T.Z., "Fire Safety Design & Concrete", Longman, Scientific and Technical, 1993.

[7] Bennetts, I.D., "Behaviour of concrete elements in fire - Part 2", Report no. MRL/PS23/82/005, Melbourne Research Laboratories, Clayton, Victoria, Australia, 1982.

[8] Bennetts, I.D., Proe, D.J. and Thomas, I.R., "Guidelines for Assessment of Fire Resistance of Structural Steel Members", Australian Institute of Steel Construction, September 1987.

G7 SIGNATURE PAGE

Report written by:

S L Poon

Senior Research Engineer

I R Thomas

Senior Research Associate

I D Bennetts

Senior Research Associate

Approved by:

G K Stark

Acting Manager Research - Market Programs

G8 APPENDIX A. STRUCTURAL DEPENDENCY

This appendix provides an indicative means of considering the overall failure of a barrier due to effects of structural failure path and redundancy described earlier in page 5.

TABLE 1. STRUCTURAL DEPENDENCY OF BARRIERS

Walls:	Floors:
LB (3F) NLB (3F) + Support Member (Ignore)	LB (3F) LB (3F) + Column (1F) LB (3F) + Main Beam (1F) LB (3F) + Wall Support (1F)

where

LB = Load Bearing
NLB = Non-Load Bearing
3F = three failure modes, i.e. insulation, integrity and structure
1F = single failure mode, i.e. structure

For a barrier consisting of two elements, the probability of failure of the barrier can be calculated using the following equation

$$P_F = 1 - (1 - P_A) \times (1 - P_B)$$

where

P_F = failure probability of the barrier
P_A = failure probability of the LB/NLB barrier
P_B = failure probability of the supporting element

Note that not all of the failure probabilities of the elements are relevant in any given enclosure. For example, in a small enclosure, free-standing columns are uncommon and the main beams, if any, tend to be aligned along the wall boundaries.

G9 APPENDIX B. MATERIAL PROPERTIES

Temperature dependent thermal conductivity and specific heat properties are required for concrete, steel and plasterboard materials. The data for these may be specified using the format described in Appendix D.

This appendix details the default material property data used by BSpread. The data for thermal conductivity and specific heat properties given below will be used if they are not specified.

G9.1 CONCRETE

9.1.1 Stress-strain relationships

The strength and deformation properties of uniaxially stressed concrete at elevated temperatures is taken from Ref. [3]. The reduced concrete strength at elevated temperature T °C is obtained by applying the corresponding reduction factor $k_{c,T}$ to the strength at 20°C. Hence

$$f'_{cT} = f'_c \times k_{c,T}$$

The strength reduction factor $k_{c,T}$ and the peak strain $\varepsilon_{cu,T}$ at elevated temperatures are shown in Table 2.

TABLE 2. STRENGTH AND DEFORMATION REDUCTION PROPERTIES OF NORMAL WEIGHT CONCRETE AT ELEVATED TEMPERATURES

Concrete Temperature T °C	$k_{c,T}$	$\varepsilon_{cu,T} \times 10^3$
20	1.00	2.5
100	0.95	3.5
200	0.90	4.5
300	0.85	6.0
400	0.75	7.5
500	0.60	9.5
600	0.45	12.5
700	0.30	14.0
800	0.15	14.5
900	0.08	15.0
1000	0.04	15.0
1100	0.01	15.0
1200	0.00	15.0

The concrete stress-strain relationship at elevated temperatures is obtained as follows:

$$\sigma_{c,T} = f_{c,T}\left[3\varepsilon_r/2 + \varepsilon_r^3\right]$$

where $\varepsilon_r = \varepsilon_{c,T}/\varepsilon_{cu,T}$

and $\varepsilon_{c,T}$ = strain at elevated temperature T °C.

9.1.2 Specific Heat

The specific heat of concrete at elevated temperatures c_s (J/kg·K) is obtained from Ref. [4] as follows:

$$c_c = \begin{cases} (0.005T + 1.7)/\rho_c \times 10^6 & 0 \le T \le 200^\circ C \\ 2.7/\rho_c \times 10^6 & 200 < T \le 400^\circ C \\ (0.013T - 2.5)/\rho_c \times 10^6 & 400 < T \le 500^\circ C \\ (-0.013T + 10.5)/\rho_c \times 10^6 & 500 < T \le 600^\circ C \\ 2.7/\rho_c \times 10^6 & T > 600^\circ C \end{cases}$$

where ρ_c = density of concrete (kg/m³)
~ 2400 kg/m³ for normal weight concrete

9.1.3 Thermal conductivity

The thermal conductivity of siliceous aggregate concrete at elevated temperatures k_c (W/m·K) is obtained from Ref. [4] as follows:

$$k_c \begin{cases} -0.000625T + 1.5 & 0 \le T \le 800^\circ C \\ 1.0 & T > 800^\circ C \end{cases}$$

G9.2 STEEL

9.2.1 Elastic Modulus:

The elastic modulus[6] is based on Ref. [1] which gives the following relationships for determining the elastic modulus of steel at elevated temperatures.

$$\frac{E(T)}{E(20^\circ C)} = \begin{cases} 1.0 + \dfrac{T}{2000 \ln(T/1100)} & T \le 600^\circ C \\ \dfrac{690(1 - T/1000)}{T - 53.5} & 600^\circ C < T \le 1000^\circ C \end{cases}$$

9.2.2 Strength:

The strength is based on Ref. [2] which gives the following relationships for determining the yield stress of steel at elevated temperatures.

$$\frac{F_y(T)}{F_y(20^\circ C)} = \begin{cases} 1.0 & T \le 250^\circ C \\ \dfrac{720 - T}{470} & T > 250^\circ C \end{cases}$$

9.2.3 Specific Heat

The specific heat of steel at elevated temperatures c_s (J/kg·K) is obtained from Ref. [4] as follows:

[6] The steel elastic modulus is used in the calculation of the steel reinforcing strain to determine the location of the neutral axis in the cross-section.

$$c_s \begin{cases} (0.004T + 3.3)/\rho_s \times 10^6 & 0 \le T \le 650^\circ C \\ (0.068T - 38.3)/\rho_s \times 10^6 & 650 < T \le 725^\circ C \\ (-0.086T + 73.35)/\rho_s \times 10^6 & 725 < T \le 800^\circ C \\ 4.55/\rho_s \times 10^6 & T > 800^\circ C \end{cases}$$

where ρ_s = density of steel (kg/m³)
= 7850 kg/m³

9.2.4 Thermal conductivity

The thermal conductivity of steel at elevated temperatures k_s (W/m·K) is obtained from Ref. [4] as follows:

$$k_s \begin{cases} -0.022T + 48 & 0 \le T \le 900^\circ C \\ 28.2 & T > 900^\circ C \end{cases}$$

G9.3 PLASTERBOARD

9.3.1 Specific Heat

The specific heat of gypsum plasterboard at elevated temperatures c_g (J/kg·K) is obtained from Ref. [5] as follows:

$$c_g = \begin{cases} 6.146T + 1.377 & 20 \le T < 78^\circ C \\ 150T - 9858 & 78 \le T < 85^\circ C \\ 262T - 1.9501 & 85 \le T < 97^\circ C \\ 476T - 40311 & 97 \le T < 124^\circ C \\ 154507 - 1097T & 124 \le T < 139^\circ C \\ 16601 - 105T & 139 \le T < 148^\circ C \\ 1189 - 1.27T & 148 \le T < 373^\circ C \\ 714 & 373 \le T < 430^\circ C \\ 1151 - 1.014T & 430 \le T < 571^\circ C \\ 1.877T - 501 & 571 \le T < 609^\circ C \\ 44.2T - 26300 & 609 \le T < 662^\circ C \\ 3000 & 662 \le T < 670^\circ C \\ 103570 - 150T & 670 \le T < 685^\circ C \\ 571 & T \ge 685^\circ C \end{cases}$$

9.3.2 Thermal conductivity

The thermal conductivity of gypsum plasterboard at elevated temperatures k_g (W/m·K) is obtained from Ref. [5] as follows:

$$k_g = \begin{cases} 0.25 & 20 \le T < 100^\circ C \\ 0.12 & 100 \le T < 400^\circ C \\ 0.00035T - 0.01 & 400 \le T < 800^\circ C \\ 0.0013T - 0.77 & T \ge 800^\circ C \end{cases}$$

G9.4 REFERENCES

[1] Bennetts, I.D., Proe, D.J. and Thomas, I.R., "Guidelines for Assessment of Fire Resistance of Structural Steel Members", Australian Institute of Steel Construction, September 1987.

[2] Australian Standard AS 3600-1994, "Concrete Structures", Standards Association of Australia.

[3] Eurocode 4 - Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design, ENV 1994-1-2.

[4] Lie, T.T. (ed.), "Structural Fire Protection: Manual of Practice", ASCE Manuals and Reports on Engineering Practice No. 78, 1992.

[5] Sultan, M.A., "A Model for Predicting Heat Transfer Through Noninsulated Unloaded Steel-Stud Gypsum Board Wall Assemblies Exposed to Fire", Fire Technology, Third Quarter, 1996.

G10 APPENDIX C. VALIDATION OF MODELS

The results of each of the models have been validated against selected published test results for thermal performance only. Structural performance is implied on the basis that the models for structural behaviour under elevated temperatures were adopted from proficient sources. Due to a paucity of tests on elements exposed to real fires, comparisons have only been possible with standard fire tests. However, it is believed that prediction of thermal performance is not sensitive to the temperature time curve differences between real and standard fires.

VALIDATION OF STEEL STUD WALL BARRIER FAILURE MODEL

The model predictions have been compared against two published test results:

1. Mohamed A. Sultan, "A Model for Predicting Heat Transfer Through Noninsulated Unloaded Steel-Stud Gypsum Board Wall Assemblies Exposed to Fire", Fire Technology Third Quarter, 1996.
2. Collier, P.C.R.,"Design of LoadBearing Light Timber Framed Walls for Fire Resistance: Part 2". Study Report No. 43, Building Research Association of New Zealand, 1992.

The test results by Collier are for a 10mm plasterboard whilst Sultan used 16mm fire rated plasterboard. For both test, the model used the plasterboard properties reported in Sultan's paper[7]. The results are shown in Figure 1 and Figure 2. In the figures, the points are experimental results and the lines are the model predictions. In both cases, the model predicted the plasterboard temperatures reasonably well

The model assumes that failure (complete loss of the plasterboard skin) occurs when the mid-temperature of the exposed plasterboard skin reached 700 °C. This is based on observations made by Sultan (in reference 2 above) that the exposed plasterboard skin was losing its integrity when the surface temperature on the inside (unexposed) surface reached 600 °C. This may be seen in Figure 1, where the temperature of the cavity surface of the exposed plasterboard skin shows a slight increase as it approaches 600 °C. It was reported that the plasterboard was beginning to disintegrate at this temperature and hence more of the hot gases were penetrating the wall cavity. The failure time prediction compared reasonably well.

Figure 2 shows the results of two (A and B) full scale fire tests of loadbearing light timber framed walls reported by Collier. The tests were stopped when the walls were judged no longer able to support the applied load. The model predicted a failure time beyond the measured completion times of the tests by about 4 minutes. The prediction is reasonable because the temperature of the inner surface of the unexposed skin (point 3) has not approached the temperature of the inner surface of the exposed skin (point 1) as has been observed in Figure 1.

The prediction of the effect of moisture in the plasterboard is not unreasonable although there appear to be a 'stepped' effect as the moisture is being vapourised. This is because the temperatures shown are the temperatures of the plasterboard slices. As moisture is vapourised, latent heat is lost. However, moisture is not assumed to dissipate through the plasterboard slices, although in practice this would occur.

---

[7] Collier did not report the thermophysical properties of the test wall.

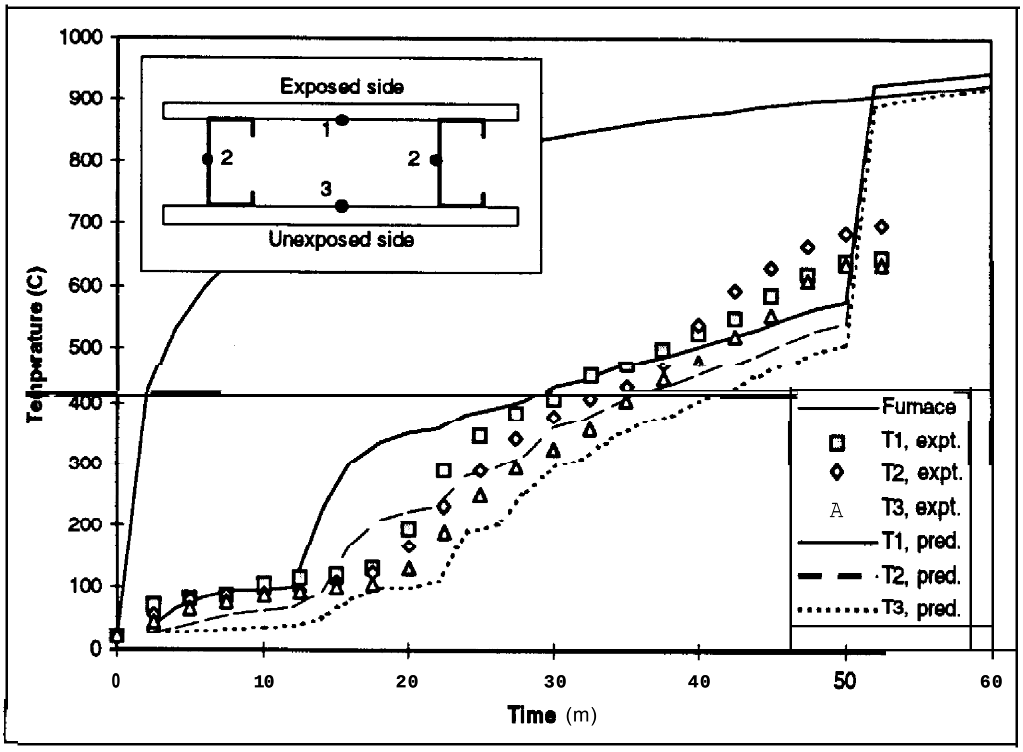


FIGURE 1. NRCC (SULTAN 1996), 16MM PLASTERBOARD

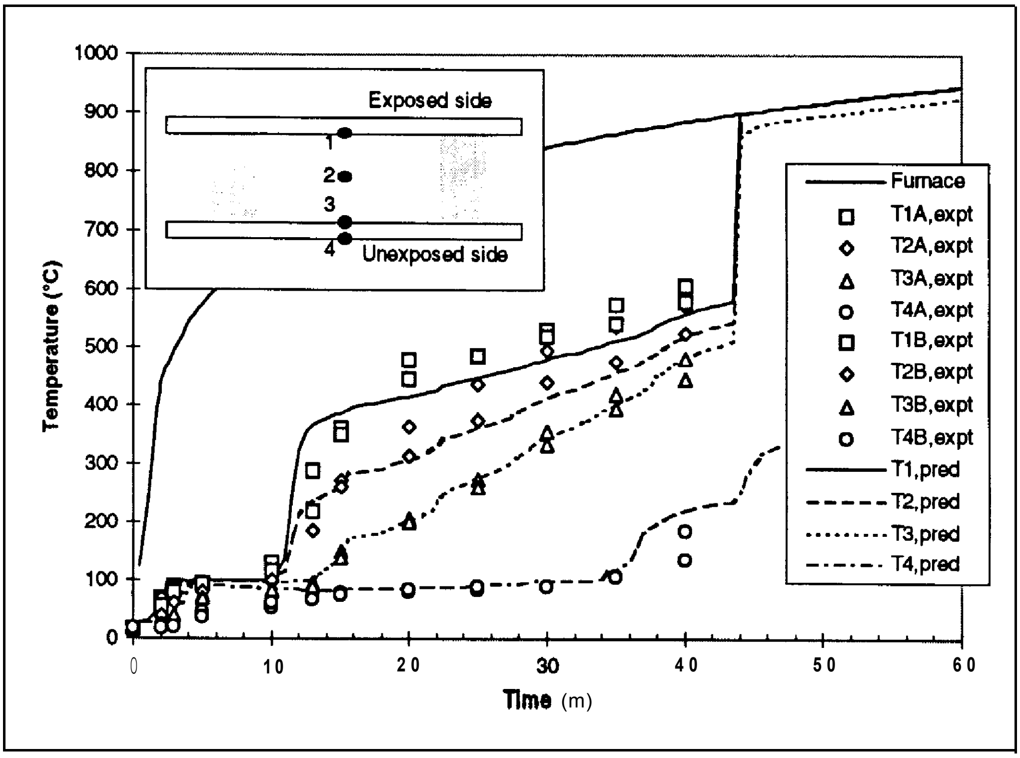


FIGURE 2. BRANZ (COLLIER, 1992), 9.5MM PLASTERBOARD

VALIDATION OF MASONRY WALL MODEL

The model predictions are compared against the test results reported in references [4] and [5]. Details of the test specimens are summarized in Table 3.

TABLE 3. MASONRY WALL TEST TEST

Test	Nominal wall height (m)	Wall thickness (m)	Time to collapse (min)	Deflection prior to failure (mm)
LB25A	3.0	0.09	27	78
LB25B	3.0	0.09	31	81
LB25C	3.0	0.09	34	88
LB25D	3.0	0.09	29	81
LB25E	3.0	0.09	35	97
LB25F	3.0	0.09	39	106
LB26A	2.4	0.09	191	64
LB26B	2.4	0.09	164	73
LB26C	2.4	0.09	136	73
LB26D	2.4	0.09	104	75
LB26E	2.4	0.09	131	80
LB26F	2.4	0.09	171	93
LB28	2.1	0.09	220	66
LB29	2.7	0.09	65	79

The specimens above were taken from reference [4]. They have all been subjected to a standard fire test and are laterally restraint at the top and bottom ends of the wall. Tests LB25 and LB26 are loaded tests with applied loads of 125, 100, 75, 50, 25, and 17.4 percent of their permissible loads for specimens A to F respectively. The predicted times for failure in accordance with the limits defined in page 11 are listed in Table 4.

TABLE 4. SUMMARY OF PREDICTED RESULTS

Test	Time to reach critical deflection limit (min)	Time to reach critical average temperature (min)	Time to reach insulation failure (min)
LB25A-F	28	106	48
LB 26A-F	n.r.	106	48
LB28	n.r.	106	48
LB29	n.r.	106	48

Note: n.r. means critical deflection limit was not reached.

The failure times from the loaded tests show a great deal of scatter within each loaded test group, The LB25 tests failed due to excessive deflection between 27 and 39 minutes and the LB26 tests failed much later due to thermal degradation at times ranging from 2 to 3 hours.

The model predicted a deflection failure time of 28 minutes for the LB25 tests. For the other tests, the model crudely predicted failure due to thermal degradation to occur at 106 minutes. Insulation failure at the unexposed side was predicted to occur at 48 minutes.

VALIDATION OF CONCRETE BARRIERS

Concrete barrier elements in fire are strongly dependent upon its thermal performance during exposure to fire. In particular, the capacity of the element depends upon the reduced strength of the concrete at elevated temperatures and the thermal protection provided to the embedded steel reinforcement.

The thermal predictions of the model have been compared against two published test results:

1. United Kingdom Institute of Structural Engineers (WISE), "Design and Detailing of Concrete Structures for Fire Resistance"
2. Lie, T. T. and Lin, T.D., "Fire Performance of Reinforced Concrete Columns", Fire Safety: Science and Engineering, ASTM STP 882, T-Z. Harmathy, Ed., American Society for Testing and Materials, Philadelphia, 1985, pp. 176-205.

These tests exposed the elements in a furnace subjected to a standard fire time-temperature relationship. The comparisons are made against temperature measurements taken within the element at various distances from the exposed surface of the element

The results from Ref. 1 above are for a 120 mm concrete slab and the results from Ref. 2 are for a 500 x 500 mm concrete column, using default concrete material properties given in Appendix B. Comparisons shown in Figure 3 and Figure 4 indicate that the model predictions are generally conservative except at cover depths of 80 mm or more. The results with 5% moisture content appear to provide closer predictions at smaller cover depths.

The predictions are also relatively sensitive to the amount of moisture due to the relatively gentle slope of the temperature time curve, i.e. a relatively large change in exposure time is required to affect a correspondingly small change in temperature.

The reasons for the variation in temperature predictions are not clearly understood. Considering that the heat transfer model has been validated against a one dimensional analytical solution (Appendix E), it is suspected that the errors would arise from the input values and thermal related phenomena (e.g. moisture migration) in the concrete material. Due to the variability in material and its composition, the thermal properties of concrete are therefore inherently more variable and shows stronger dependence on temperature and moisture content.

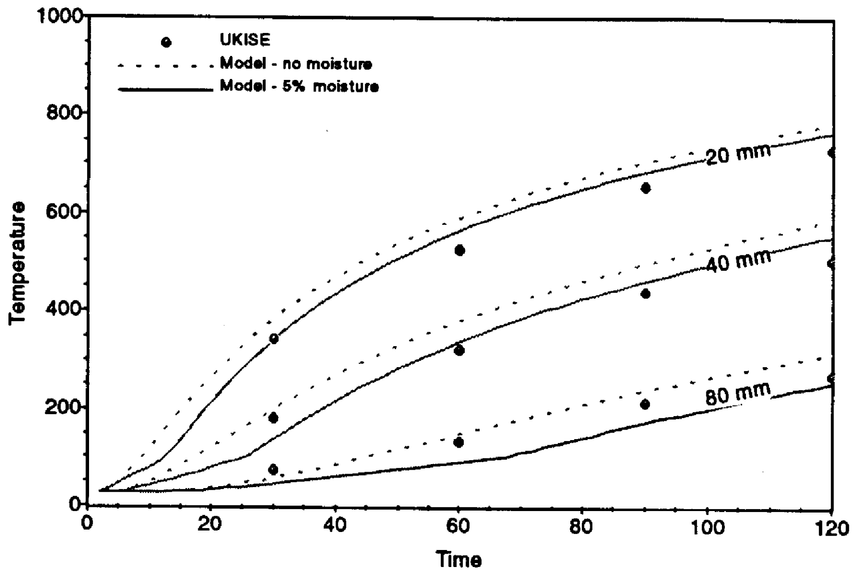


FIGURE 3. COMPARISON WITH UKISE RESULTS

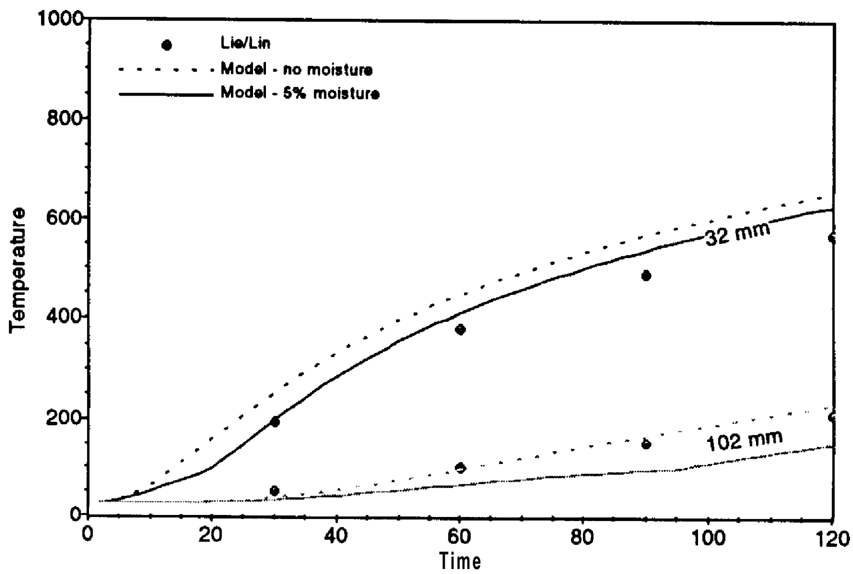


FIGURE 4. COMPARISON WITH LIE AND LIN'S RESULTS

VALIDATION OF STEEL BEAM AND STEEL COLUMN MODELS

The model predictions have been compared against the test results reported in:

1. Proe, D.J., "Ultimate Strength of Simply-Supported Composite Beams in Fire", BHP Melb. Res. Lab. Rep. No. MRL/PS69/89/007, December 1989.
2. Bennetts, I.D., Proe, D.J. and Thomas, I.R., "Simulation of the fire testing of structural elements by calculation - thermal response", Steel Construction, Vol. 19 No. 3, Nov. 1985, AISC.

Details of the test specimens are summarized in Table 5.

TABLE 5. TEST SPECIMEN DETAILS

Test	Section	Element	Exposure	Insulation thickness mm	k_{sm} m^2/t	Report
BFT-211	200UB25	Steel Beam	3 sides	31	30.8	1
BFT-213	200UB25	Steel Beam	3 sides	66	30.8	1
BFT-40	150UC30	Steel Column	4 sides	50	20.7	2
BFT-41	310UC283	Steel Column	4 sides	19	4.9	2

The beams support a concrete slab and are protected on three sides with sprayed insulation material The columns are protected on all sides with boarded material. The specimens have all been subjected to the standard fire test. Results of the model are compared against experimental results in Figure 5 for steel beams and Figure 6 for steel columns. Solid lines in the figures represent model predictions whilst markers represent test points. The model is first run assuming no moisture in the insulation material (Model runs) and a second run with 10% moisture (ModelW runs). From both figures, it can be seen that the model gives reasonably good predictions. It is also apparent in Figure 6 that the insulation material for test BFT-41 had little or no moisture.

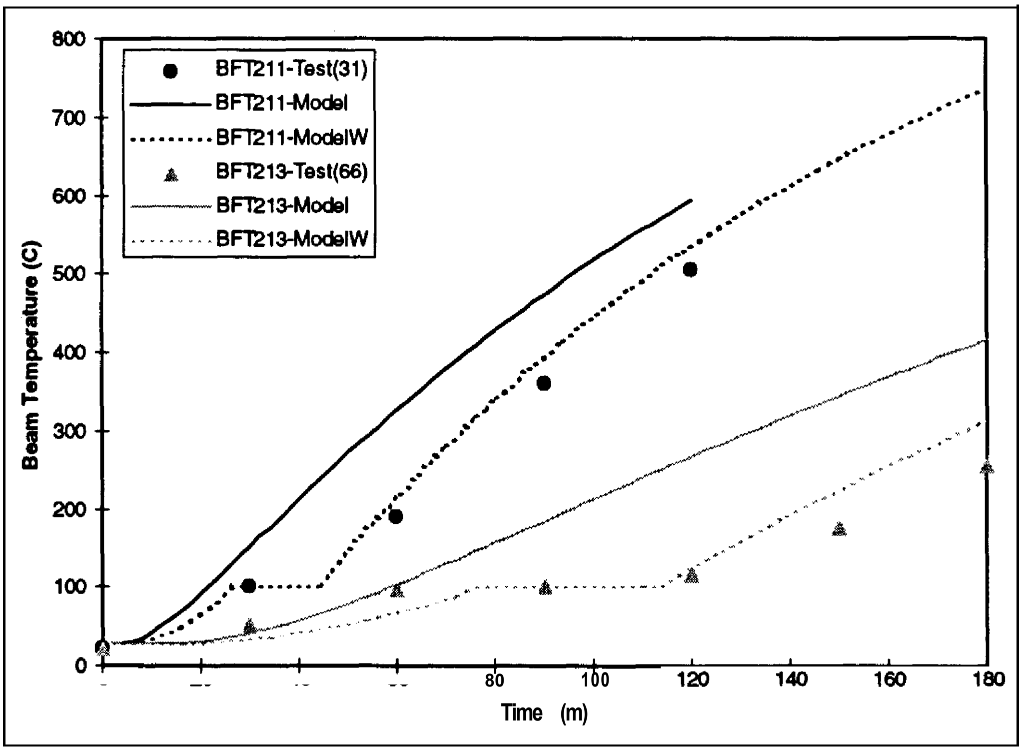


FIGURE 5. STEEL BEAM TEMPERATURES

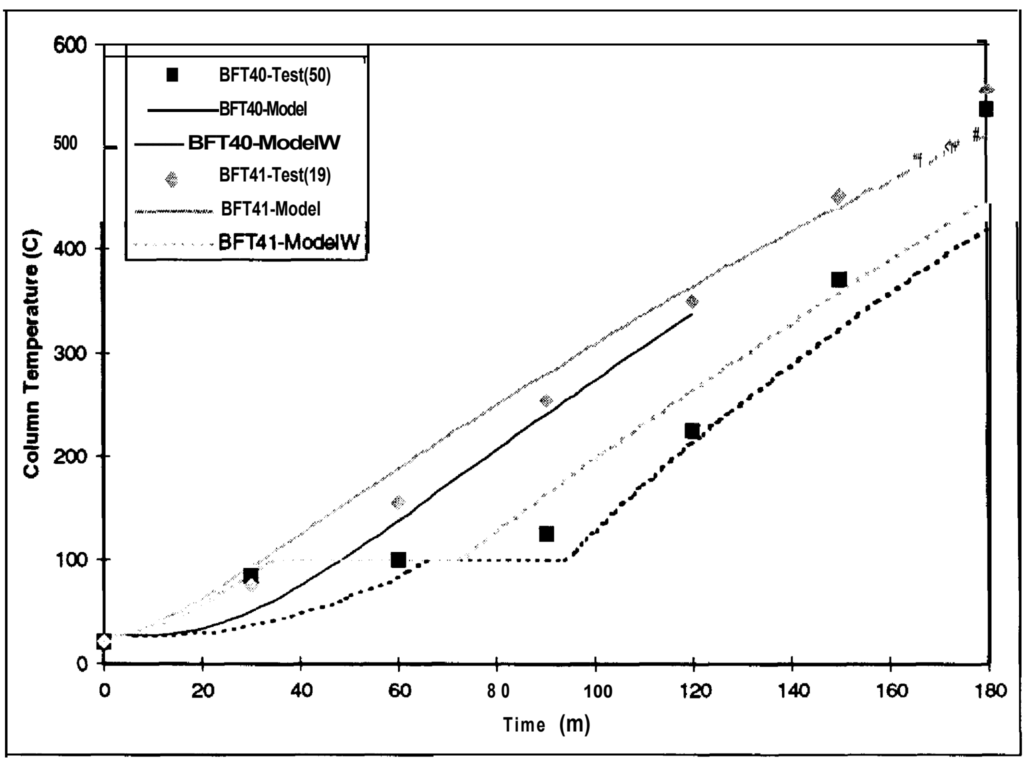


FIGURE 6. STEEL COLUMN TEMPERATURES.

VALIDATION OF STEEL DUCT MODEL

Figure 7 shows the temperature distribution within the insulation layer of the steel duct. Tg is the gas temperature and T1 to T10 are the predicted temperatures of each slice of the insulation with T1 being the exposed surface temperature and T10 being the unexposed surface temperature which is also taken as the steel sheeting temperature.

The properties of the insulation material are taken from test BFT-213 (see above) which has a 66mm sprayed on insulation material. Because the exposed surface area to mass ratio of the sheeting (= 0.127 m^2/kg) is much larger than the steel beam (= 0.0308 m^2/kg for 200UB25), the sheeting temperature can therefore be expected to be higher than the steel beam temperature for the same exposed fire conditions. This is observed when comparing T10 in Figure 7 with BFT213-Test(66) in Figure 5. However, no known unrestricted publications on results for insulated steel ducts were available for making a better comparison. If a failure temperature of the steel sheeting is taken as 1000K (-727 ^{o}C), then the duct in this case would be approaching its failure temperature after 180 mins.

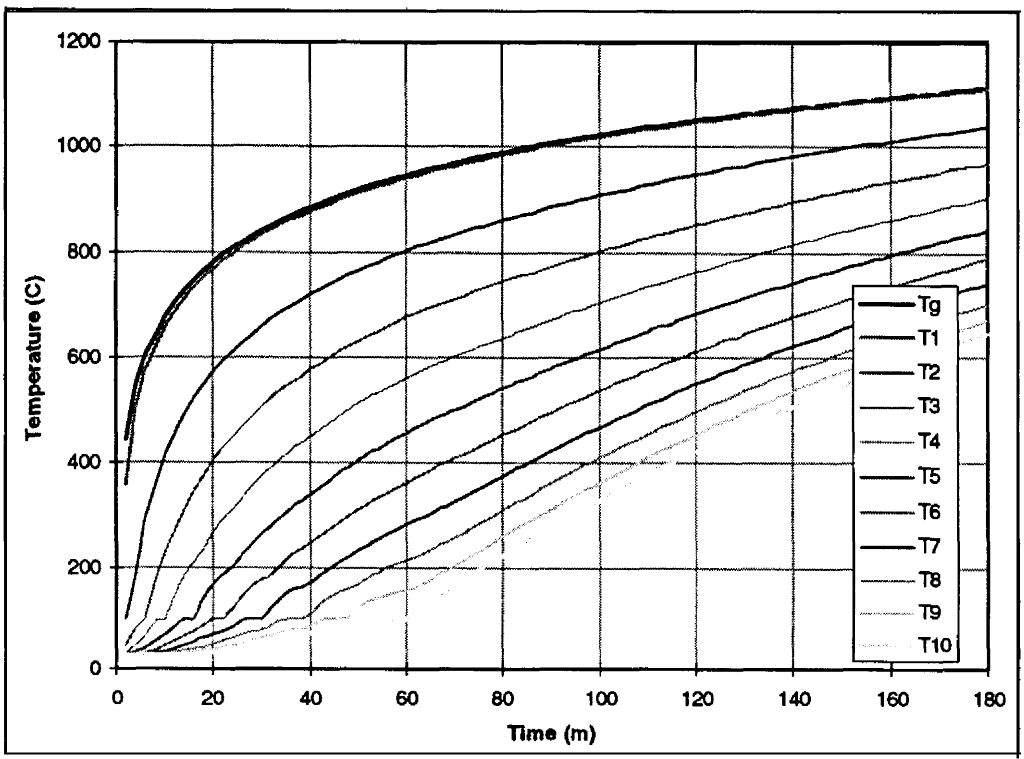


FIGURE 7. STEEL DUCT INSULATION TEMPERATURES

G11 APPENDIX D. BSPREAD - BARRIER SPREAD PROGRAM

APPENDIX D. BSPREAD - BARRIER SPREAD PROGRAM

DESCRIPTION

BSpread is a computer program for determining the times at which barrier type elements of construction in buildings may fail, as they are exposed to a fire prescribed as a series of time-temperature points. Failure of a barrier enables fire to spread beyond the location of the barrier. BSpread is written in Lahey's Fortran 90 and requires a 32-bit DOS-based environment to run, such as a DOS shell in Windows 95. It has not been tested in any other environment.

GENERAL USAGE

The spread of fire out of an enclosure may occur either via openings which pre-exist (*design* or *non-design* openings) in the boundaries of the enclosure (e.g. open door/window, large penetrations in walls/floor) or via the breakdown of barriers such that large openings result enabling the fire to spread through the barrier. Obviously, spread via pre-existing openings would occur very much earlier than spread via barriers which failed. The use of BSpread is therefore limited to assessing the routes of fire spread to spaces which have been protected by the barriers and in which spread had not occurred via openings. BSpread does not account for the presence of pre-existing openings which may enable fire to spread prior to the failure of barriers.

BSpread also assesses the performance of structural (non-barrier type) elements of construction which certain barrier elements may depend upon in order for it to remain in place. If the extent of the structural role of these elements and its association with the dependent barrier elements are known, then the performance of the structurally dependent barriers can be assessed.

RUNNING BSPREAD

Prior to running BSpread, an input data file and two associated data files must be prepared beforehand. These are detailed in the sections which follow.

Upon running BSpread (refer operating system manual for instructions), the user will be prompted to enter the data filename. The data filename without the file extension is required. The program assumes a '.dat' file extension for the input data file and creates an output file with a '.out' file extension.

INPUT DATA DOCUMENTATION

The input data file contains the information to be used by the program and can be created using any suitable text editor. The program consistently assumes units of meter, Kelvin, seconds, kilogram, and Newton. The format of the input data is as follows:

GENERAL

Line 1: *RunTitle*

where *RunTitle*	is the title of the run (≤ 80 characters, enclosed in quotes)

Line 2: *tInc,tEnd*

where	*tInc*	is the time increment for the transient barrier failure modelling (s)
	tEnd	is the time at which the modelling of the effects of fire on the barriers end (s)

FIRE DATA

Line 3: *FireFile*

where	*FireFile*	is the name of the data file containing the time-temperature values of the fire enclosure. e.g. c:\dos\fire\Fire\test.da1

Line 4: *icTm,icTp,xfTm,xfTp*

where	*icTm*	is the column no for Time (1 or 2)
	icTp	is the column no for Gas Temperature (2 or 3)
	xfTm	is a multiplier to convert Time to seconds (1.0 if Time is already in seconds, 60.0 to convert Time from minutes to seconds, 3600.0 to convert Time from hours to seconds)
	xfTp	is the offset to convert °C to K (0.0 if Gas Temperature is already in K or 273.15 if Gas Temperature is in °C)

COMMON PROPERTIES

Line 5: *PropFile*

where	*PropFile*	is the name of the data file containing thermal material properties for concrete, steel and plasterboard (see Data format for *PropFile*).

Line 6: *TSpall,TInsFail,rhoConc,wConc*

where	*TSpall*	is the temperature at which the concrete spalls. If spalling is not modelled, enter a very large number (K).
	TInsFail	is the critical temperature on the unexposed side of a boundary element surface which upon exceeding constitutes an insulation failure of the element (K).
	rhoConc	is the concrete density (kg/m^3)
	wConc	is the concrete moisture content (kg/kg)

STEEL STUD WALLS

Line 7: *thwe,thwu,swksm*

where	*thwe*	is the thickness of the plasterboard skin exposed to the fire (m)
	thwu	is the thickness of the plasterboard skin on the unexposed side (m)
	swksm	is the exposed surface area per unit mass of the steel studs (m^2/kg)

Line 8: *pbMoist,pbDryDensity*

where	*pbMoist*	is the ratio of moisture content in the plasterboard (=water mass/dry unit mass, kg/kg)
	pbDryDensity	is the dry density of the plasterboard (kg/m^3)

Line 9: *TFSS,TFPW*

where *TFSS* is the temperature corresponding to structural adequacy failure of the steel studs (K)

TFPW is the temperature corresponding to integrity failure of the plasterboard skin (K)

MASONRY WALL

Line 10: *thMW,htMW,rhoMasn*

where *thMW* is the thickness of the masonry wall (m)

htMW is the effective height of the masonry wall (m)

rhoMasn is the density of masonry wall (kg/m³)

CONCRETE WALL

Line 11: *thCW,ecCW,cwFc*

where *thCW* is the thickness of the concrete wall (m)

ecCW is the eccentricity of the vertically applied load off the centroid of the concrete wall (m)

cwFc is the characteristic value of the 28 day compressive strength of the concrete wall (Pa)

Line 12: *ib,cwLoad*

where *ib* is an indicator flag for a braced concrete wall (0=False, 1=True)

cwLoad is the linear line load on the wall (N/m)

CONCRETE BEAM/SLAB

Line 13: *cbB,cbD,cbCp,cbCn,cbAp,cbAn,cbFyr,cbFc*

where *cbB* is the width of the concrete beam (m)

cbD is the depth of the concrete beam (m)

cbCp is the cover depth of the centroid of the positive steel reinforcement measured from the beam soffit (m)

cbCn is the cover depth of the centroid of the negative steel reinforcement measured from the top of the beam surface (m)

cbAp is the cross-sectional area of the positive steel reinforcement (m^2/m)

cbAn is the cross-sectional area of the negative steel reinforcement (m^2/m)

cbFyr is the yield strength of the reinforcing steel (Pa)

cbFc is the characteristic value of the 28 day compressive strength of the concrete beam (Pa)

Line 14: *cbLoad,cbSpan*

where *cbLoad* is the uniformly distributed load on the concrete beam (N/m)

cbSpan is the span of the concrete beam (m)

CONCRETE COLUMN

Line 15: *ccBi,ccDi,ccCp,ccAp,ccFyr,ccFc*

where *ccBi* is the width of the concrete column (m)

ccDi	is the depth of the concrete column (m)
ccCp	is the cover depth of the centroid of the steel reinforcement measured from the concrete surface (m)
ccAp	is the cross-sectional area of the steel reinforcement (m^2)
ccFyr	is the yield strength of the reinforcing steel (Pa)
ccFc	is the characteristic value of the 28 day compressive strength of the concrete column (Pa)

Line 16: *ccgG,ccgQ,ccG,ccQ,ccPhi*

where *ccgG*	is the partial load factor for dead load in fire
ccgQ	is the partial load factor for live load in fire
ccG	is the applied design dead axial load (N)
ccQ	is the applied design live axial load (N)
ccPhi	is the ratio of the actual to nominal steel reinforcement strength

STEEL BEAMS

Line 17: *sbksm,sbgG,sbgQ,sbG,sbQ,sbPhi*

where *sbksm*	is the exposed surface area to mass ratio - 3 sided (m^2/kg)
sbgG	is the partial load factor for dead load in fire
sbgQ	is the partial load factor for live load in fire
sbG	is the applied design dead line load (N/m)
sbQ	is the applied design live line load (N/m)
sbPhi	is the ratio of the actual to nominal steel beam strength

Line 18: *sbith,sbirhod,sbiw,sbicp,sbikp*

where *sbith*	is the thickness of insulation (m)
sbirhod	is the dry density of the insulation material (kg/m^3)
sbiw	is the moisture content ratio in the insulation material (=water mass/dry unit mass, kg/kg)
sbicp	is the specific heat of the insulation material (J/kg/K)
sbikp	is the thermal conductivity of the insulation material (W/m/K)

STEEL COLUMNS

Line 19: *scksm,scgG,scgQ,scG,scQ,scPhi*

where *scksm*	is the exposed surface area to mass ratio - 4 sided (m^2/kg)
scgG	is the partial load factor for dead load in fire
scgQ	is the partial load factor for live load in fire
scG	is the applied design dead load (N)
scQ	is the applied design live load (N)
scPhi	is the ratio of the actual to nominal steel column strength

Line 20: *scith,scirhod,sciw,scicp,scikp*

where *scith*	is the thickness of insulation (m)
scirhod	is the dry density of the insulation material (kg/m^3)

sciw	is the moisture content ratio in the insulation material (=water mass/dry unit mass, kg/kg)
scicp	is the specific heat of the insulation material (J/kg/K)
scikp	is the thermal conductivity of the insulation material (W/m/K)

METAL SHAFTS AND DUCTS

Line 21: *sdith,sdirho,sdicp,sdikp,sdiw*

where	*sdith*	is the thickness of insulation (m)
	sdirho	is the dry density of the insulation material (kg/m^3)
	sdiw	is the moisture content ratio in the insulation material (=water mass/dry unit mass, kg/kg)
	sdicp	is the specific heat of the insulation material (J/kg/K)
	sdikp	is the thermal conductivity of the insulation material (W/m/K)

Line 22: *TsdCr,sdth,sdrho*

where	*TsdCr*	is the critical temperature corresponding to structural adequacy failure of the steel sheeting (K)
	sdth	is the thickness of the steel sheeting (m)
	sdrho	is the density of the steel sheeting (kg/m^3)

SAMPLE DATA FILE

A sample listing of a datafile in accordance with the layout described above is as follows:

```
"Sample run"
120 3600
StdFire.lis
1 2 1.0 273.15
LieProp.lis
1473.0 500.0 2400.0 0.05
0.010 0.010 0.554
0.20 600.0
1000.0 1000.0
0.090 3.0 2400
0.20 0.01 32.0e6
1 0.83e6
1.2 0.35 0.055 0.055 0.0028 0.0032 400.0e6 25.0e6
55.0e3 8.0
0.6 0.6 0.055 0.0033 400.0e6 32.0e6
1.1 0.4 2.8e6 1.2e6 1.0
0.0181 1.1 0.4 26.4e3 9.6e3 1.0
0.017 360.0 0.10 861.0 0.105
0.0103 1.1 0.4 2640e3 960e3 1.0
0.012 360.0 0.10 861.0 0.105
0.066 360.0 0.10 861.0 0.105
1000.0 0.001 7850.0
```

DATA FORMAT FOR FIREFILE

FireFile contains the time-temperature values and is usually the output file of a fire model. The format of the data must be such that both the time and temperature columns must be in the first three data columns of the file. There must not be any text preceding the data.

The following is a listing of a standard fire time-temperature data file.

```
0     20
3     70
8     129
15    185
25    240
40    297
60    349
90    404
120   445
180   502
250   550
360   603
500   651
720   705
960   748
1440  809
1920  851
2600  897
3800  953
5700  1014
7500  1055
10500 1106
14000 1149
18000 1186
22000 1216
```

DATA FORMAT FOR PROPFILE

PropFile contains the thermal conductivity and specific heat values as a function of temperature for concrete, steel and plasterboard materials respectively. The input data layout for each material is generally structured as follows:

Line 1: n_k,n_c

where	n_k	is the number of thermal conductivity points
	n_c	is the number of specific heat points

Lines 2 to $1+n_k$: T_i,k_i

where	T_i	is the temperature of point i (K)
	k_i	is the thermal conductivity of the material at temperature T_i (W/m/K)

Lines $2+n_k$ to $1+n_k+n_c$: T_i,c_i

where	T_i	is the temperature of point i (K)
	c_i	is the specific heat of the material at temperature T_i (J/kg/K)

Line $2+n_k+n_c$: *cteMW,doWmax,TcrMW,thdgf*

where	*cteMW*	is the thermal expansion coefficient for bricks
	doWmax	is the maximum ratio of lateral deflection to wall width
	TcrMW	is the critical temperature for failure due to thermal degradation (K)
	thdgf	is the thermal degradation factor for deflection

e.g.

```
3 2
293.0 1.78
388.0 1.28
1273.0 0.66
273.0 1042.0
1273.0 1042.0
```

```
3 6
273.0 60.0
1073.0 27.0
1273.0 27.0
273.0 546.0
448.0 546.0
790.0 646.0
1053.0 737.0
1210.0 1019.0
1375.0 1019.0
5 4
273.0 0.24
348.0 0.24
493.0 0.12
573.0 0.13
1273.0 0.25
273.0 1700.0
375.0 1700.0
400.0 600.0
1273.0 600.0
6e-6 0.9 973.0 1.6
```

OUTPUT

The output is in two parts. The first part is reprinted information of the input data which was read by the program. The second part is the results section.

RESULTS SECTION

The results section is a summary of the three failure mechanisms of the barrier performance over the time exposed to the fire. The codes used in the results section are as follows:

t	=	time (s)
T	=	temperature (°C)
SSW	=	Steel Stud Wall
CCW	=	Concrete Wall
CCB	=	Concrete Beam/Slab
CCC	=	Concrete Column
STB	=	Structural Steel Beam
STC	=	Structural Steel Column
MTS	=	Metal Steel Shaft
AIT	=	Failures by Structural Adequacy, Integrity and Insulation (Temperature) respectively.
F	=	Occurrence of failure corresponding to the mode represented by its location beneath the 'AIT' column.

SAMPLE RUN

Using the sample data file shown in page 5, the corresponding output from the program is shown below:

```
BSpread: Barrier Spread Program
Written by Leong Poon, BHP Research, August 1997

INPUT information

DATA file: Sample
Run Title: Sample run
```

```
Modelling times
Time increment (s):   120.
End simulation (s):  3600.

Fire data
Fire data file: StdFire.lis
Col no for Time:      1
Col no for Temp:      2
Multiplier to convert time to secs:    1.0
Offset to convert C to K:  273.15

Common properties
Thermal properties data file: LieProp.lis
Concrete spalling temperature (K): 1473.0
Temperature for Insulation Failure Criterion (K):  500.0
Concrete density (kg/m3): 2400.0
Concrete moisture (kg/kg):  0.0500

Steel Stud Wall
Thickness of exposed plasterboard skin (m):  0.0160
Thickness of unexposed plasterboard skin (m):  0.0160
Exposed surface area to unit mass of steel stud (m2/kg):  0.3000
Plasterboard moisture content:  0.2000
Plasterboard dry density (kg/m3):  850.0
Temperature for Structural Adequacy Failure of Steel Studs (K): 1000.0
Temperature for Integrity Failure of plasterboard (K): 1000.0

Masonry Wall
Thickness (m):  0.0900
Height (m):    3.0
Density (kg/m3): 2400.0

Concrete Wall
Thickness (m):  0.0800
Vertical load eccentricity (m):  0.0100
Concrete strength (Pa): 0.320E+08
Braced wall flag (F=False,T=True):  T
Line load (N/m): 0.573E+06

Concrete Beam/Slab
Width (m):  1.0000
Depth (m):  0.0800
Positive Reo Cover depth from bot surface (m):  0.0200
Negative Reo Cover depth from top surface (m):  0.0200
Area of Positive steel reo (m2):  0.000757
Area of Negative steel reo (m2):  0.000757
Yield strength of reo (Pa): 0.450E+09
Concrete strength (Pa): 0.250E+08
Uniformly distributed load (N/m): 0.633E+04
Span (m):  5.0000

Concrete Column
Width (m):  0.6000
Depth (m):  0.6000
Reo Cover depth from exposed surface (m):  0.0300
Area of steel reo (m2):  0.003300
Yield strength of reo (Pa): 0.400E+09
Concrete strength (Pa): 0.320E+08
Partial dead load factor:   1.100
Partial live load factor:   0.400
Design dead load (N): 0.225E+07
Design live load (N): 0.160E+07
Ratio of actual to nominal strength:   1.000

Steel Beam
3-sided exposed area to mass ratio (m2/kg):  0.0181
Partial dead load factor:   1.100
Partial live load factor:   0.400
Design dead load (N): 0.240E+05
Design live load (N): 0.240E+05
Ratio of actual to nominal strength:   1.000
```

Insulation thickness (m): 0.0120
Insulation dry density (kg/m3): 305.0
Insulation moisture content ratio: 0.1000
Insulation specific heat: 900.0
Insulation thermal conductivity: 0.1250

Steel Column
4-sided exposed area to mass ratio (m2/kg): 0.0103
Partial dead load factor: 1.100
Partial live load factor: 0.400
Design dead load (N): 0.288E+06
Design live load (N): 0.144E+06
Ratio of actual to nominal strength: 1.000
Insulation thickness (m): 0.0130
Insulation dry density (kg/m3): 305.0
Insulation moisture content ratio: 0.1000
Insulation specific heat: 900.0
Insulation thermal conductivity: 0.1250

Metal Shaft/Duct
Insulation thickness (m): 0.0440
Insulation dry density (kg/m3): 305.0
Insulation moisture content ratio: 0.1000
Insulation specific heat: 900.0
Insulation thermal conductivity: 0.1250
Temperature for Structural Adequacy Failure of Steel Studs (K): 1000.0
Thickness of steel sheeting (m): 0.0010
Density of steel sheeting (kg/m3): 7850.0

RESULTS

t (s)	T (C)	SSW AIT	MSW AIT	CCW AIT	CCB AIT	CCC AIT	STB AIT	STC AIT	MTS AIT
120.	445.	.	.	.	.	.	.	.	.
240.	543.	.	.	.	.	.	.	.	.
360.	603.	.	.	.	.	.	.	.	.
480.	644.	.	.	.	.	.	.	.	.
600.	676.	.	.	.	.	.	.	.	.
720.	705.	.	.	.	.	.	.	.	.
840.	726.	.	.	.	.	.	.	.	.
960.	748.	.	.	.	.	.	.	.	.
1080.	763.	.	.	.	.	.	.	.	.
1200.	778.	.	.	.	.	.	.	.	.
1320.	794.	.	.	.	.	.	.	.	.
1440.	809.	.	.	.	.	.	.	.	.
1560.	820.	.	.	.	.	.	.	.	.
1680.	830.	.	.	.	.	.	.	.	.
1800.	840.	.	.	.	.	.	.	.	.
1920.	851.	.	.	.	.	.	.	.	.
2040.	859.	.	.	.	.	.	.	.	.
2160.	867.	.	.	.	.	.	.	.	.
2280.	875.	.	.	.	.	.	.	.	.
2400.	883.	.	.	.	.	.	.	.	.
2520.	892.	.	.	.	.	.	.	.	.
2640.	899.	.	.FFF.	.	.	.	.	.	.
2760.	904.	.	.FFF.	.	.	.	.	.	.
2880.	910.	.	.FFF.	.	.	.	.	.	.
3000.	916.	.	.FFF.	.	.	.	.	.	.
3120.	921.	.	.FFF.	.	.	.	.	.	.
3240.	927.	.	.FFF.	.	.	.	.	.	.
3360.	932.	.	.FFF.	.	.	.	.	.	.
3480.	938.	.FFF	.FFF.	.	.	.	.	.	.
3600.	944.	.FFF	.FFF.	.	.	.	.	.	.

G12 APPENDIX E. ONE DIMENSIONAL HEAT TRANSFER

This appendix describes a one dimensional heat transfer methodology for calculating the temperature of a barrier material exposed to a hot gas medium.

12.1.1.1 Heat Transfer Between the Gas Medium and the Barrier Surface

The transfer of heat energy between the gas medium and the barrier surface exposed to the gas is given by

$$q_i = h(T_g - T_s) \qquad \text{(E1)}$$

where

q_i = heat flux to barrier surface, W/m^2;
h = coefficient of heat transfer, $W/m^2.K$;
T_g = temperature of the gas medium, K;
T_s = temperature of the barrier surface, K.

The coefficient of heat transfer consists of the convective component and the radiative component, i.e.

$$h = h_c + h_r$$

where

h_c = convective heat transfer coefficient;
h_r = radiative heat transfer coefficient.

The convective heat transfer coefficient may be calculated from the empirical equation [14],

$$h_c = 1.313\left|T_s - T_a\right|^{1/3}$$

where T_s is the surface temperature (K) and T_a is the ambient temperature (K). The radiative heat transfer coefficient is given by

$$h_r = \sigma\varepsilon\frac{T_s^4 - T_a^4}{T_s - T_a}$$

12.1.1.2 Heat Conduction Within the Barrier

For barriers with a relatively low conductivity, a thermal gradient will exist across the cross-section. The transient changes in temperature within the barrier is solved using a one-dimensional finite difference approach. This involves discretizing the barrier cross-section into a number of layers parallel to its surface and solving the conservation equations over a time step period assuming that quasi steady state conditions prevail within that time across the layer. The temperature within the barrier may be assumed to be constant throughout and the heat balance can be expressed as

$$q_i + q_o = \rho.c.\Delta x.\Delta T_s/\Delta t \qquad \text{(E2)}$$

where

q_i = eqn (E1), between the exposed layer and the fire gases, and
= $k\Delta T/\Delta x$ between the other layers;
q_o = eqn (E1), between the unexposed layer and the gases that it is in contact with, and
= $k\Delta T/\Delta x$ between the other layers;
k = thermal conductivity, W/m/K;
ΔT = change in temperature, K;
Δx = layer thickness, m;
ρ = barrier density, kg/m^3;

c = specific heat, J/kg/K;
Δt = time step, s.

Figure 1 shows a sectional view of a barrier plate subdivided into a number of layers.

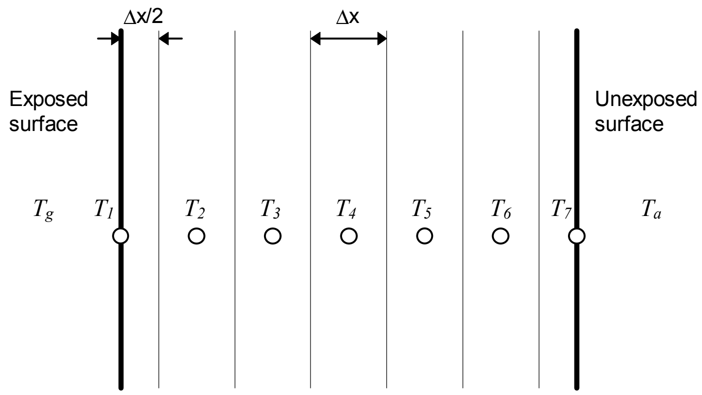


FIGURE 1. SUBDIVISION OF A BARRIER PANEL

Applying equation (E2) at the exposed layer, node 1,

$$h(T_g - T_1) + k.\Delta T/\Delta x = \rho.c.\Delta x.\Delta T_s/2\Delta t$$

or

$$h(T_g - T_1) + k(T_2 - T_1)/\Delta x = \rho.c.\Delta x.(T'_1 - T_1)/2\Delta t$$

The new temperature T'_1 can then be calculated.

Similarly, at the unexposed layer, node 7,

$$k.\Delta T/\Delta x + h(T_a - T_8) = \rho.c.\Delta x.\Delta T_s/2\Delta t$$

or

$$k.(T_7 - T_8)/\Delta x + h(T_a - T_8) = \rho.c.\Delta x.(T'_8 - T_8)/2\Delta t$$

The new temperature T'_8 can then be calculated.

At the intermediate layers, say node 4,

$$k.(T_3 - T_4)/\Delta x + k.(T_5 - T_4)/\Delta x = \rho.c.\Delta x.(T'_4 - T_4)/2\Delta t$$

The new temperature T'_4 can then be calculated.

12.1.1.3 Validation

To illustrate the accuracy of the method, the results of the finite difference analysis are compared against an analytical solution [1] for the following input data

Thermal conductivity, k	0.952	W/m·K
Volume specific heat, ρc	1.594×10^6	J/m^3·K
Thickness of wall, D	0.2032	m
Coefficient of heat transfer at the unexposed surface	16.02	W/m²·K
Initial temperature of wall temperature of ambient air	297	K
'Idealized' fire temperature and temperature of exposed surface	1261	K

The results are shown in Figure E1 at quarter sections along the wall cross-section.

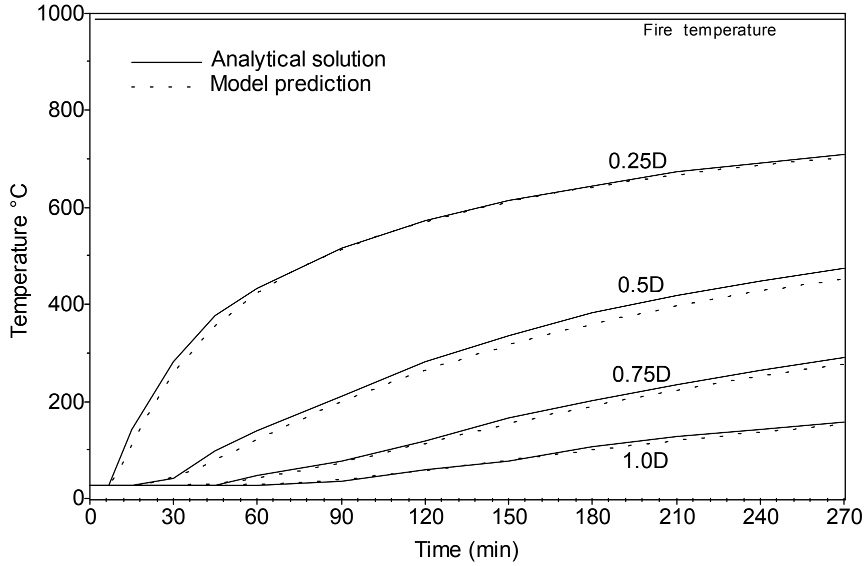


FIGURE E1. COMPARISON OF ANALYTICAL AND NUMERICAL SOLUTIONS

12.1.1.4 Reference

[1] Harmathy, T.Z., "Fire Safety Design & Concrete", Longman, Scientific and Technical, 1993.

BSPREAD RESULTS

The figures in Table G1 are the estimated failure time in seconds for the temperatures and durations shown using BSpread.

The temperature profile for the design fires are the specified (maximum) temperature (Tmax) at the start of the fire with the temperature falling linearly to 500 °C at the time corresponding to the duration. These temperature profiles are shown in Figure G1.

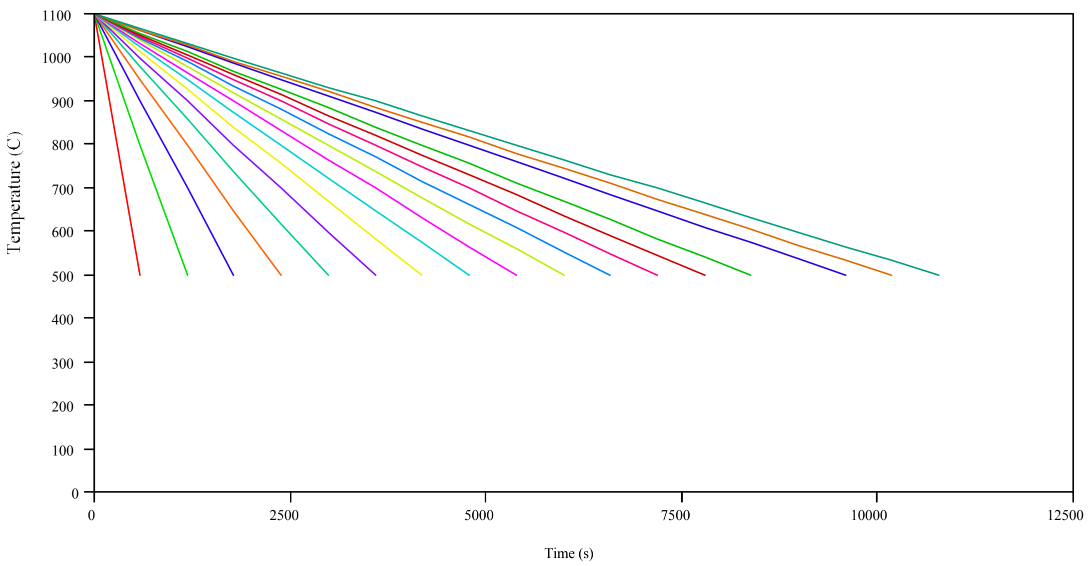


Figure G1 Temperature-Time Relation ships for the Design Fires Used in Table G1

In Table G1 the duration, in seconds, is given in the column marked t500.

An entry of "Nil" in Table G1 means no failure is predicted.

The remaining columns represent each of the structural and barrier elements considered as follows:

SSW	Steel stud wall
MW	Masonry wall
CW	Concrete wall
CB	Concrete beam
CC	Concrete column
SB	Steel beam
SC	Steel column
MSD	Insulated steel duct

Examination of Table G1 shows that for each FRL most of the elements fail within a similar time period (generally within ±5 minutes). This is to be expected and comes about because elements designed to just survive a specific period in the standard fire test are likely to have similar sensitivity to other time-temperature histories.

Table G1 BSpread Results

FRL = 30 minutes

Tmax **1250**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
1200	360	120	840	660	600	Nil	Nil	Nil
1800	**300**	**120**	**600**	**540**	**540**	**1080**	**1080**	**600**
2400	300	120	540	480	480	960	960	600
3000	300	120	540	480	480	960	960	600
3600	300	120	480	480	480	900	900	540
4200	300	120	300	300	360	900	900	540
4800	300	120	300	300	300	900	900	540
5400	300	120	300	300	300	900	900	540
6000	300	120	300	300	300	900	900	540
6600	300	120	240	240	240	900	900	540
7200	300	120	240	240	240	900	900	540
7800	300	120	240	240	240	900	900	540
8400	300	120	240	240	240	900	900	540
9000	300	120	240	240	240	900	900	540
9600	300	120	240	240	240	900	900	540
10200	300	120	240	240	240	900	900	540
10800	300	120	240	240	240	900	900	540

Tmax **1200**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
1200	360	120	1080	Nil	840	Nil	Nil	Nil
1800	**360**	**120**	**660**	**600**	**600**	**1140**	**1140**	**660**
2400	360	120	600	540	540	1020	1020	660
3000	360	120	600	540	540	1020	1020	600
3600	300	120	540	540	540	960	960	600
4200	300	120	540	540	480	960	960	600
4800	300	120	540	540	480	960	960	600
5400	300	120	540	480	480	960	960	600
6000	300	120	540	480	480	960	960	600
6600	300	120	540	480	480	960	960	600
7200	300	120	540	480	480	900	900	600
7800	300	120	540	480	480	900	900	600
8400	300	120	540	480	480	900	900	540
9000	300	120	540	480	480	900	900	540
9600	300	120	540	480	480	900	900	540
10200	300	120	480	480	480	900	900	540
10800	300	120	480	480	480	900	900	540

FRL = 30 minutes

Tmax	**1150**								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	360	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	**360**	**120**	**780**	**660**	**660**	**1200**	**1200**	**780**
	2400	360	120	660	600	600	1080	1080	720
	3000	360	120	660	600	600	1080	1080	660
	3600	360	120	600	600	540	1020	1020	660
	4200	360	120	600	600	540	1020	1020	660
	4800	360	120	600	540	540	1020	1020	660
	5400	360	120	600	540	540	1020	1020	600
	6000	360	120	600	540	540	960	960	600
	6600	360	120	600	540	540	960	960	600
	7200	360	120	600	540	540	960	960	600
	7800	360	120	600	540	540	960	960	600
	8400	360	120	600	540	540	960	960	600
	9000	360	120	540	540	540	960	960	600
	9600	360	120	540	540	540	960	960	600
	10200	360	120	540	540	540	960	960	600
	10800	360	120	540	540	540	960	960	600

Tmax	**1100**								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	1800	**420**	**180**	**900**	**780**	**780**	**1320**	**1320**	**900**
	2400	360	180	780	720	660	1200	1200	780
	3000	360	120	720	660	660	1140	1140	720
	3600	360	120	720	660	660	1080	1080	720
	4200	360	120	660	660	600	1080	1080	720
	4800	360	120	660	600	600	1080	1080	660
	5400	360	120	660	600	600	1020	1020	660
	6000	360	120	660	600	600	1020	1020	660
	6600	360	120	660	600	600	1020	1020	660
	7200	360	120	660	600	600	1020	1020	660
	7800	360	120	660	600	600	1020	1020	660
	8400	360	120	660	600	600	1020	1020	660
	9000	360	120	660	600	600	1020	1020	660
	9600	360	120	660	600	600	1020	1020	660
	10200	360	120	660	600	600	1020	1020	660
	10800	360	120	600	600	600	1020	1020	660

FRL = 30 minutes

Tmax **1050**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
1800	**Nil**	**180**	**1080**	**1200**	**Nil**	**1440**	**1440**	**Nil**
2400	420	180	900	840	840	1260	1260	900
3000	420	180	840	780	780	1200	1200	840
3600	420	180	780	720	720	1140	1140	780
4200	420	180	780	720	720	1140	1140	780
4800	420	180	780	720	720	1140	1140	780
5400	420	180	780	720	660	1140	1140	720
6000	360	180	720	720	660	1080	1080	720
6600	360	180	720	660	660	1080	1080	720
7200	360	180	720	660	660	1080	1080	720
7800	360	180	720	660	660	1080	1080	720
8400	360	180	720	660	660	1080	1080	720
9000	360	180	720	660	660	1080	1080	720
9600	360	180	720	660	660	1080	1080	720
10200	360	180	720	660	660	1080	1080	720
10800	360	180	720	660	660	1080	1080	720

Tmax **1000**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	**Nil**	**300**	**1380**	**Nil**	**Nil**	**1620**	**1620**	**Nil**
2400	1560	240	1080	1080	1080	1380	1380	1080
3000	1440	240	1020	900	900	1260	1260	960
3600	1380	240	960	900	840	1260	1260	900
4200	480	240	900	840	840	1200	1200	840
4800	480	240	900	840	780	1200	1200	840
5400	420	240	840	780	780	1200	1200	840
6000	420	240	840	780	780	1200	1200	840
6600	420	240	840	780	780	1200	1200	840
7200	420	240	840	780	780	1140	1140	840
7800	420	240	840	780	780	1140	1140	780
8400	420	240	840	780	780	1140	1140	780
9000	420	240	840	780	780	1140	1140	780
9600	420	240	840	780	780	1140	1140	780
10200	420	240	840	780	780	1140	1140	780
10800	420	240	840	780	720	1140	1140	780

FRL = 30 minutes

Tmax **950**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	**Nil**	**Nil**	**1560**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
2400	Nil	480	1260	Nil	Nil	1500	1500	Nil
3000	1560	420	1140	1200	1200	1380	1380	1200
3600	1500	360	1080	1080	1080	1320	1320	1080
4200	1440	360	1080	1020	1020	1320	1320	1020
4800	1380	360	1020	960	960	1320	1320	960
5400	1380	300	1020	960	960	1260	1260	960
6000	1380	300	1020	960	960	1260	1260	960
6600	1380	300	960	960	960	1260	1260	960
7200	1320	300	960	900	900	1260	1260	900
7800	1320	300	960	900	900	1260	1260	900
8400	1320	300	960	900	900	1260	1260	900
9000	1320	300	960	900	900	1260	1260	900
9600	1320	300	960	900	900	1200	1200	900
10200	1320	300	960	900	900	1200	1200	900
10800	1320	300	960	900	900	1200	1200	900

Tmax **900**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	1740	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	1560	Nil	Nil	1620	1620	Nil
3000	1740	Nil	1380	Nil	Nil	1500	1500	Nil
3600	1620	Nil	1260	1440	1500	1440	1440	Nil
4200	1560	Nil	1260	1320	1320	1440	1440	1260
4800	1560	600	1200	1260	1260	1380	1380	1200
5400	1500	540	1200	1200	1200	1380	1380	1140
6000	1500	540	1140	1140	1140	1380	1380	1140
6600	1500	540	1140	1140	1140	1380	1380	1080
7200	1500	480	1140	1140	1140	1320	1320	1080
7800	1440	480	1140	1080	1140	1320	1320	1080
8400	1440	480	1140	1080	1080	1320	1320	1080
9000	1440	480	1080	1080	1080	1320	1320	1080
9600	1440	480	1080	1080	1080	1320	1320	1080
10200	1440	480	1080	1080	1080	1320	1320	1020
10800	1440	480	1080	1080	1080	1320	1320	1020

FRL = 30 minutes

Tmax **850**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	1740	Nil	Nil	1860	1860	Nil
3000	Nil	Nil	1680	Nil	Nil	1680	1680	Nil
3600	1800	Nil	1560	Nil	Nil	1620	1620	Nil
4200	1800	Nil	1440	1860	2100	1560	1560	Nil
4800	1740	Nil	1440	1680	1740	1500	1500	Nil
5400	1680	4800	1380	1560	1620	1500	1500	1680
6000	1680	4740	1380	1500	1560	1500	1500	1500
6600	1620	4680	1320	1440	1500	1500	1500	1440
7200	1620	4620	1320	1440	1440	1440	1440	1380
7800	1620	4620	1320	1380	1440	1440	1440	1380
8400	1620	4560	1320	1380	1380	1440	1440	1320
9000	1620	4560	1320	1380	1380	1440	1440	1320
9600	1560	4500	1260	1380	1380	1440	1440	1320
10200	1560	4500	1260	1320	1380	1440	1440	1320
10800	1560	4500	1260	1320	1320	1440	1440	1260

Tmax **800**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	1980	Nil	Nil	2100	2100	Nil
3000	Nil	Nil	1860	Nil	Nil	1860	1860	Nil
3600	Nil	Nil	1800	Nil	Nil	1740	1740	Nil
4200	2040	Nil	1800	Nil	Nil	1740	1740	Nil
4800	1920	Nil	1740	Nil	Nil	1680	1680	Nil
5400	1920	5220	1680	2760	Nil	1680	1680	Nil
6000	1860	5160	1620	2100	2340	1620	1620	Nil
6600	1860	5100	1620	1980	2160	1620	1620	Nil
7200	1800	5040	1560	1920	2040	1620	1620	Nil
7800	1800	5040	1560	1860	1980	1620	1620	Nil
8400	1800	4980	1560	1860	1920	1560	1560	Nil
9000	1800	4920	1560	1800	1860	1560	1560	Nil
9600	1800	4920	1500	1740	1860	1560	1560	2160
10200	1740	4920	1500	1740	1800	1560	1560	1980
10800	1740	4860	1500	1740	1800	1560	1560	1920

FRL = 30 minutes

Tmax	750								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	2280	Nil	Nil	2400	2400	Nil
	3000	Nil	Nil	2160	Nil	Nil	2100	2100	Nil
	3600	Nil	Nil	2041	Nil	Nil	1980	1980	Nil
	4200	Nil	Nil	1980	Nil	Nil	1920	1920	Nil
	4800	Nil	Nil	1980	Nil	Nil	1860	1860	Nil
	5400	2220	Nil	1920	Nil	Nil	1860	1860	Nil
	6000	2100	5160	1920	Nil	Nil	1800	1800	Nil
	6600	2040	5640	1920	3300	Nil	1800	1800	Nil
	7200	1980	5580	1920	2940	4080	1800	1800	Nil
	7800	1980	5520	1920	2760	3180	1800	1800	Nil
	8400	1980	5520	1860	2640	2940	1740	1740	Nil
	9000	1980	5460	1860	2580	2820	1740	1740	Nil
	9600	1980	5400	1860	2520	2700	1740	1740	Nil
	10200	1980	5400	1860	2460	2640	1710	1740	Nil
	10800	1980	5340	1800	2400	2580	1740	1740	Nil

Tmax	700								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	2460	Nil	Nil	2400	2400	Nil
	3600	Nil	Nil	2340	Nil	Nil	2220	2220	Nil
	4200	Nil	Nil	2280	Nil	Nil	2160	2160	Nil
	4800	Nil	Nil	2280	Nil	Nil	2100	2100	Nil
	5400	Nil	Nil	2220	Nil	Nil	2100	2100	Nil
	6000	Nil	Nil	2220	Nil	Nil	2040	2040	Nil
	6600	Nil	6420	2160	Nil	Nil	2040	2040	Nil
	7200	Nil	6300	2160	Nil	Nil	1980	1980	Nil
	7800	Nil	6240	2160	Nil	Nil	1980	1980	Nil
	8400	Nil	6180	2160	Nil	Nil	1980	1980	Nil
	9000	2520	6120	2160	4380	Nil	1980	1980	Nil
	9600	2340	6060	2100	4020	Nil	1980	1980	Nil
	10200	2280	6000	2100	3840	5400	1980	1980	Nil
	10800	2280	6000	2100	3720	4620	1980	1980	Nil

FRL = 30 minutes

Tmax	650								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	120	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	120	Nil	2940	Nil	Nil	2760	2760	Nil
	3600	120	Nil	2820	Nil	Nil	2580	2580	Nil
	4200	120	Nil	2700	Nil	Nil	2460	2460	Nil
	4800	120	Nil	2640	Nil	Nil	2400	2400	Nil
	5400	120	Nil	2580	Nil	Nil	2400	2400	Nil
	6000	120	Nil	2580	Nil	Nil	2340	2340	Nil
	6600	120	Nil	2520	Nil	Nil	2340	2340	Nil
	7200	120	Nil	2520	Nil	Nil	2280	2280	Nil
	7800	120	7200	2520	Nil	Nil	2280	2280	Nil
	8400	120	7080	2520	Nil	Nil	2280	2280	Nil
	9000	120	7020	2460	Nil	Nil	2280	2280	Nil
	9600	120	6960	2460	Nil	Nil	2220	2220	Nil
	10200	120	6840	2460	Nil	Nil	2220	2220	Nil
	10800	120	6840	2460	Nil	Nil	2220	2220	Nil

Tmax	600								
	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	3360	Nil	Nil	3000	3000	Nil
	4200	Nil	Nil	3240	Nil	Nil	2880	2880	Nil
	4800	Nil	Nil	3180	Nil	Nil	2820	2820	Nil
	5400	Nil	Nil	3120	Nil	Nil	2760	2760	Nil
	6000	Nil	Nil	3060	Nil	Nil	2760	2760	Nil
	6600	Nil	Nil	3060	Nil	Nil	2700	2700	Nil
	7200	Nil	Nil	3000	Nil	Nil	2700	2700	Nil
	7800	Nil	Nil	3000	Nil	Nil	2640	2640	Nil
	8400	Nil	8340	3000	Nil	Nil	2640	2640	Nil
	9000	Nil	8220	2940	Nil	Nil	2640	2640	Nil
	9600	Nil	8100	2940	Nil	Nil	2640	2640	Nil
	10200	Nil	8040	2940	Nil	Nil	2640	2640	Nil
	10800	Nil	7980	2940	Nil	Nil	2580	2580	Nil

FRL = 30 minutes

Tmax 550

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	3480	3480	Nil
4200	Nil	Nil	3840	Nil	Nil	3420	3420	Nil
4800	Nil	Nil	3780	Nil	Nil	3360	3360	Nil
5400	Nil	Nil	3780	Nil	Nil	3300	3300	Nil
6000	Nil	Nil	3720	Nil	Nil	3240	3240	Nil
6600	Nil	Nil	3720	Nil	Nil	3240	3240	Nil
7200	Nil	Nil	3660	Nil	Nil	3240	3240	Nil
7800	Nil	Nil	3660	Nil	Nil	3180	3180	Nil
8400	Nil	Nil	3660	Nil	Nil	3180	3180	Nil
9000	Nil	Nil	3600	Nil	Nil	3180	3180	Nil
9600	Nil	9600	3600	Nil	Nil	3180	3180	Nil
10200	Nil	9540	3600	Nil	Nil	3180	3180	Nil
10800	Nil	9480	3600	Nil	Nil	3120	3120	Nil

Tmax 500

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	3960	3960	Nil
4800	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
5400	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
6000	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
6600	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
7200	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
7800	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
8400	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
9000	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
9600	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
10200	Nil	Nil	4560	Nil	Nil	3960	3960	Nil
10800	Nil	Nil	4560	Nil	Nil	3960	3960	Nil

Tmax STD F T

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 45 minutes

Tmax	**1250**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	480	120	1740	Nil	Nil	Nil	Nil	Nil
	2400	480	120	1620	1140	1200	2160	Nil	Nil
	3000	480	120	1560	960	1080	1860	1860	1380
	3600	420	120	1560	960	1020	1740	1740	1260
	4200	420	120	1500	900	960	1680	1680	1200
	4800	420	120	1500	900	960	1680	1620	1200
	5400	420	120	1500	900	960	1620	1560	1200
	6000	420	120	1500	840	960	1620	1560	1140
	6600	420	120	1500	840	960	1620	1560	1140
	7200	420	120	1500	840	900	1620	1500	1140
	7800	420	120	1500	840	900	1560	1500	1140
	8400	420	120	1500	840	900	1560	1500	1140
	9000	420	120	1500	840	900	1560	1500	1140
	9600	420	120	1500	840	900	1560	1500	1140
	10200	420	120	1500	840	900	1560	1500	1140
	10800	420	120	1440	840	900	1560	1500	1080

Tmax	**1200**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	540	120	1800	Nil	Nil	Nil	Nil	Nil
	2400	480	120	1680	1440	1440	2400	Nil	Nil
	3000	480	120	1620	1140	1200	1980	2040	1560
	3600	480	120	1620	1080	1140	1860	1860	1380
	4200	480	120	1560	1020	1080	1800	1800	1320
	4800	480	120	1560	960	1080	1740	1740	1320
	5400	480	120	1560	960	1020	1740	1680	1260
	6000	480	120	1560	960	1020	1680	1680	1260
	6600	480	120	1560	960	1020	1680	1620	1260
	7200	480	120	1560	900	1020	1680	1620	1200
	7800	480	120	1560	900	1020	1680	1620	1200
	8400	480	120	1500	900	1020	1620	1560	1200
	9000	480	120	1500	900	1020	1620	1560	1200
	9600	480	120	1500	900	960	1620	1560	1200
	10200	480	120	1500	900	960	1620	1560	1200
	10800	480	120	1500	900	960	1620	1560	1200

FRL = 45 minutes

Tmax	**1150**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	540	120	1740	Nil	Nil	Nil	Nil	Nil
	3000	540	120	1680	1380	1380	2100	2280	1860
	3600	480	120	1680	1200	1260	1980	2040	1560
	4200	480	120	1620	1140	1200	1920	1920	1440
	4800	480	120	1620	1080	1200	1860	1860	1440
	5400	480	120	1620	1080	1140	1800	1800	1380
	6000	480	120	1620	1080	1140	1800	1740	1380
	6600	480	120	1620	1020	1140	1800	1740	1320
	7200	480	120	1620	1020	1080	1740	1740	1320
	7800	480	120	1620	1020	1080	1740	1680	1320
	8400	480	120	1560	1020	1080	1740	1680	1320
	9000	480	120	1560	1020	1080	1740	1680	1260
	9600	480	120	1560	1020	1080	1740	1680	1260
	10200	480	120	1560	1020	1080	1740	1680	1260
	10800	480	120	1560	1020	1080	1680	1680	1260

Tmax	**1100**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	180	1860	Nil	Nil	Nil	Nil	Nil
	3000	600	180	1800	Nil	1740	2280	2520	Nil
	3600	540	180	1740	1440	1500	2100	2160	1860
	4200	540	180	1740	1320	1380	2040	2040	1620
	4800	540	180	1680	1260	1320	1980	1980	1560
	5400	540	180	1680	1200	1260	1920	1920	1500
	6000	540	180	1680	1200	1260	1920	1860	1500
	6600	540	180	1680	1200	1260	1860	1860	1440
	7200	540	180	1680	1140	1200	1860	1860	1440
	7800	540	180	1680	1140	1200	1860	1800	1440
	8400	540	180	1680	1140	1200	1860	1800	1440
	9000	540	180	1680	1140	1200	1800	1800	1380
	9600	540	180	1680	1140	1200	1800	1800	1380
	10200	540	180	1620	1140	1200	1800	1740	1380
	10800	540	180	1620	1140	1200	1800	1740	1380

FRL = 45 minutes

Tmax	1050								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	240	1980	Nil	Nil	Nil	Nil	Nil
	3000	Nil	240	1860	Nil	Nil	2520	2940	Nil
	3600	Nil	240	1860	2160	1860	2280	2400	Nil
	4200	660	240	1800	1620	1620	2160	2220	1980
	4800	600	240	1800	1500	1560	2100	2160	1800
	5400	600	180	1800	1440	1500	2040	2100	1740
	6000	600	180	1740	1381	1440	2040	2040	1680
	6600	600	180	1740	1380	1440	1980	1980	1620
	7200	600	180	1740	1320	1380	1980	1980	1620
	7800	600	180	1740	1320	1380	1980	1920	1560
	8400	600	180	1740	1320	1380	1920	1920	1560
	9000	600	180	1740	1320	1320	1920	1920	1560
	9600	600	180	1740	1260	1320	1920	1920	1560
	10200	600	180	1740	1260	1320	1920	1920	1500
	10800	600	180	1740	1260	1320	1920	1860	1500

Tmax	1000								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	420	2160	Nil	Nil	Nil	Nil	Nil
	3000	Nil	360	2040	Nil	Nil	2820	Nil	Nil
	3600	Nil	300	1980	Nil	Nil	2460	2700	Nil
	4200	Nil	300	1920	Nil	2100	1340	2460	Nil
	4800	2340	300	1920	1920	1860	2220	2340	2220
	5400	2280	300	1860	1740	1740	2220	2220	2040
	6000	2220	300	1860	1680	1680	2160	2220	1920
	6600	2160	300	1860	1620	1620	2100	2160	1860
	7200	2100	300	1860	1560	1620	2100	2100	1800
	7800	2100	300	1860	1560	1560	2100	2100	1800
	8400	2040	300	1860	1560	1560	2040	2100	1740
	9000	780	300	1800	1500	1560	2040	2040	1740
	9600	720	300	1800	1500	1560	2040	2040	1740
	10200	720	300	1800	1500	1500	2040	2040	1680
	10800	720	300	1800	1500	1500	2040	2040	1680

FRL = 45 minutes

Tmax	950							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	2340	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	2160	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	2100	Nil	Nil	2700	3060	Nil
	4200	Nil	600	2040	Nil	Nil	2520	2700	Nil
	4800	Nil	540	2040	Nil	2640	2400	2580	Nil
	5400	2580	480	1980	2520	2220	2340	2460	Nil
	6000	2460	480	1980	2220	2100	2340	2400	2400
	6600	2340	480	1980	2040	1980	2280	2340	2220
	7200	2340	420	1980	1980	1920	2280	2340	2160
	7800	2280	420	1980	1920	1920	2220	2280	2100
	8400	2280	420	1920	1860	1860	2220	2280	2040
	9000	2220	420	1920	1860	1800	2220	2220	1980
	9600	2220	420	1920	1800	1800	2160	2220	1980
	10200	2220	420	1920	1800	1800	2160	2220	1980
	10800	2220	420	1920	1740	1740	2160	2220	1920

Tmax	900								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	2400	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	2280	Nil	Nil	3000	Nil	Nil
	4200	Nil	Nil	2220	Nil	Nil	2760	3060	Nil
	4800	Nil	Nil	2220	Nil	Nil	2640	2820	Nil
	5400	Nil	4800	2160	Nil	Nil	2580	2700	Nil
	6000	Nil	4800	2160	Nil	2940	2520	2640	Nil
	6600	2700	4740	2100	3120	2640	2460	2580	Nil
	7200	2640	4680	2100	2700	2460	2460	2520	Nil
	7800	2580	4680	2100	2580	2400	2400	2520	2760
	8400	2520	4620	2100	2460	2340	2400	2460	2580
	9000	2460	4620	2100	2340	2280	2400	2460	2460
	9600	2460	4620	2100	2280	2220	2340	2460	2400
	10200	2460	4560	2100	2280	2160	2340	2400	2400
	10800	2400	4560	2040	2220	2160	2340	2400	2340

FRL = 45 minutes

Tmax	**850**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	2640	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	2520	Nil	Nil	3360	Nil	Nil
	4200	Nil	Nil	2460	Nil	Nil	3060	3540	Nil
	4800	Nil	Nil	2400	Nil	Nil	2880	3180	Nil
	5400	Nil	5220	2340	Nil	Nil	2820	3060	Nil
	6000	Nil	5160	2340	Nil	Nil	2760	2940	Nil
	6600	Nil	5100	2340	Nil	Nil	2700	2880	Nil
	7200	Nil	5040	2280	Nil	3840	2640	2820	Nil
	7800	3150	5040	2280	Nil	3360	2640	2760	Nil
	8400	2940	4980	2280	3840	3120	2580	2760	Nil
	9000	2880	4980	2280	3420	3000	2580	2700	Nil
	9600	2820	4920	2280	3240	2880	2580	2700	Nil
	10200	2760	4920	2220	3120	2820	2520	2640	Nil
	10800	2760	4920	2220	3000	2760	2520	2640	3360

Tmax	**800**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	2820	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	2700	Nil	Nil	3420	4200	Nil
	4800	Nil	Nil	2640	Nil	Nil	3240	3660	Nil
	5400	Nil	Nil	2580	Nil	Nil	3120	3420	Nil
	6000	Nil	5640	2580	Nil	Nil	3000	3300	Nil
	6600	Nil	5580	2520	Nil	Nil	2940	3240	Nil
	7200	Nil	5520	2520	Nil	Nil	2880	3120	Nil
	7800	Nil	5460	2520	Nil	Nil	2880	3120	Nil
	8400	Nil	5460	2520	Nil	Nil	2820	3060	Nil
	9000	Nil	5400	2460	Nil	Nil	2820	3000	Nil
	9600	Nil	5340	2460	Nil	4380	2820	3000	Nil
	10200	Nil	5340	2460	Nil	4080	2760	2940	Nil
	10800	Nil	5280	2460	5340	3900	2760	2940	Nil

FRL = 45 minutes

Tmax	750							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	3240	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	3060	Nil	Nil	3900	Nil	Nil
	4800	Nil	Nil	3000	Nil	Nil	3600	4320	Nil
	5400	Nil	Nil	2940	Nil	Nil	3480	3960	Nil
	6000	Nil	Nil	2880	Nil	Nil	3360	3780	Nil
	6600	Nil	6240	2880	Nil	Nil	3300	3660	Nil
	7200	Nil	6120	2820	Nil	Nil	3240	3600	Nil
	7800	Nil	6060	2820	Nil	Nil	3180	3480	Nil
	8400	Nil	6000	2760	Nil	Nil	3180	3480	Nil
	9000	Nil	5940	2760	Nil	Nil	3120	3420	Nil
	9600	Nil	5940	2760	Nil	Nil	3120	3360	Nil
	10200	Nil	5880	2760	Nil	Nil	3060	3360	Nil
	10800	Nil	5820	2760	Nil	Nil	3060	3300	Nil

Tmax	700								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	3600	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	3420	Nil	Nil	4140	Nil	Nil
	5400	Nil	Nil	3360	Nil	Nil	3900	4680	Nil
	6000	Nil	Nil	3300	Nil	Nil	3780	4380	Nil
	6600	Nil	Nil	3240	Nil	Nil	3720	4260	Nil
	7200	Nil	6960	3240	Nil	Nil	3660	4140	Nil
	7800	Nil	6840	3180	Nil	Nil	3600	4020	Nil
	8400	Nil	6780	3180	Nil	Nil	3540	3960	Nil
	9000	Nil	6720	3120	Nil	Nil	3480	3900	Nil
	9600	Nil	6660	3120	Nil	Nil	3480	3840	Nil
	10200	Nil	6600	3120	Nil	Nil	3480	3840	Nil
	10800	Nil	6540	3120	Nil	Nil	3420	3780	Nil

FRL = 45 minutes

Tmax	**650**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	4080	Nil	Nil	4740	Nil	Nil
	5400	Nil	Nil	3960	Nil	Nil	4500	Nil	Nil
	6000	Nil	Nil	3840	Nil	Nil	4320	5220	Nil
	6600	Nil	Nil	3780	Nil	Nil	4200	4980	Nil
	7200	Nil	Nil	3720	Nil	Nil	4140	4860	Nil
	7800	Nil	Nil	3720	Nil	Nil	4080	4740	Nil
	8400	Nil	7800	3660	Nil	Nil	4020	4620	Nil
	9000	Nil	7680	3660	Nil	Nil	4020	4560	Nil
	9600	Nil	7620	3600	Nil	Nil	3960	4500	Nil
	10200	Nil	7560	3600	Nil	Nil	3960	4440	Nil
	10800	Nil	7500	3600	Nil	Nil	3900	4440	Nil

Tmax	**600**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	4680	Nil	Nil	5220	Nil	Nil
	6000	Nil	Nil	4560	Nil	Nil	5040	Nil	Nil
	6600	Nil	Nil	4500	Nil	Nil	4920	5940	Nil
	7200	Nil	Nil	4440	Nil	Nil	4800	5760	Nil
	7800	Nil	Nil	4380	Nil	Nil	4740	5640	Nil
	8400	Nil	Nil	4380	Nil	Nil	4680	5520	Nil
	9000	Nil	Nil	4320	Nil	Nil	4620	5460	Nil
	9600	Nil	8940	4320	Nil	Nil	4620	5340	Nil
	10200	Nil	8880	4260	Nil	Nil	4560	5340	Nil
	10800	Nil	8760	4260	Nil	Nil	4560	5280	Nil

FRL = 45 minutes

Tmax	**550**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	5520	Nil	Nil	5820	Nil	Nil
	6600	Nil	Nil	5460	Nil	Nil	5700	Nil	Nil
	7200	Nil	Nil	5400	Nil	Nil	5640	6780	Nil
	7800	Nil	Nil	5340	Nil	Nil	5580	6660	Nil
	8400	Nil	Nil	5340	Nil	Nil	5520	6600	Nil
	9000	Nil	Nil	5280	Nil	Nil	5460	6540	Nil
	9600	Nil	Nil	5280	Nil	Nil	5460	6480	Nil
	10200	Nil	Nil	5220	Nil	Nil	5400	6420	Nil
	10800	Nil	10440	5220	Nil	Nil	5400	6360	Nil

Tmax	**500**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	6480	Nil	Nil	6540	Nil	Nil
	7200	Nil	Nil	6480	Nil	Nil	6540	Nil	Nil
	7800	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
	8400	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
	9000	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
	9600	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
	10200	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
	10800	Nil	Nil	6480	Nil	Nil	6540	7800	Nil
Tmax	STD								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
		Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

FRL = 60 minutes

Tmax	**1250**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3000	840	120	2700	Nil	Nil	Nil	Nil	Nil
	3600	780	120	2580	2040	2220	3180	3480	Nil
	4200	780	120	2520	1860	1920	2820	2880	2460
	4800	780	120	2460	1740	1800	2640	2640	2220
	5400	720	120	2460	1680	1740	2520	2580	2100
	6000	720	120	2400	1620	1740	2460	2460	2040
	6600	720	120	2400	1620	1680	2400	2400	2040
	7200	720	120	2400	1560	1680	2400	2400	1980
	7800	720	120	2400	1560	1620	2340	2340	1980
	8400	720	120	2400	1560	1620	2340	2340	1920
	9000	720	120	2400	1560	1620	2280	2280	1920
	9600	720	120	2340	1500	1620	2280	2280	1920
	10200	720	120	2340	1500	1620	2280	2280	1860
	10800	720	120	2340	1500	1560	2280	2280	1860

Tmax	**1200**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	120	2820	Nil	Nil	Nil	Nil	Nil
	3600	900	120	2700	Nil	Nil	Nil	Nil	Nil
	4200	840	120	2640	2100	2220	3000	3120	Nil
	4800	840	120	2580	1920	2040	2820	2880	2520
	5400	840	120	2520	1860	1980	2700	2700	2340
	6000	780	120	2520	1800	1920	2580	2640	2220
	6600	780	120	2520	1740	1860	2580	2580	2160
	7200	780	120	2460	1740	1800	2520	2520	2160
	7800	780	120	2460	1680	1800	2460	2460	2100
	8400	780	120	2460	1680	1800	2460	2460	2100
	9000	780	120	2460	1680	1740	2400	2460	2040
	9600	780	120	2460	1680	1740	2400	2400	2040
	10200	780	120	2460	1620	1740	2400	2400	2040
	10800	780	120	2460	1620	1740	2400	2400	1980

FRL = 60 minutes

Tmax	1150								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	120	2940	Nil	Nil	Nil	Nil	Nil
	3600	Nil	120	2820	Nil	Nil	Nil	Nil	Nil
	4200	1020	120	2760	2580	Nil	3300	3480	Nil
	4800	960	120	2700	2220	2400	3000	3120	3060
	5400	900	120	2640	2100	2220	2880	2940	2640
	6000	900	120	2640	2040	2100	2760	2820	2520
	6600	900	120	2580	1980	2040	2700	2760	2400
	7200	840	120	2580	1920	2040	2640	2700	2340
	7800	840	120	2580	1860	1980	2640	2640	2280
	8400	840	120	2580	1860	1980	2580	2640	2280
	9000	840	120	2580	1860	1920	2580	2580	2220
	9600	840	120	2520	1800	1920	2580	2580	2220
	10200	840	120	2520	1800	1920	2520	2520	2160
	10800	840	120	2520	1800	1860	2520	2520	2160

Tmax	1100								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	180	3000	Nil	Nil	Nil	Nil	Nil
	4200	Nil	180	2880	Nil	Nil	3660	3960	Nil
	4800	Nil	180	2820	2760	3120	3300	3420	Nil
	5400	Nil	180	2760	2460	2640	3120	3180	3300
	6000	1080	180	2760	2280	2460	3000	3060	2880
	6600	1020	180	2700	2220	2340	2880	2940	2700
	7200	960	180	2700	2160	2280	2820	2880	2580
	7800	960	180	2700	2100	2220	2820	2820	2520
	8400	960	180	2700	2100	2160	2760	2820	2460
	9000	960	180	2640	2040	2160	2760	2760	2460
	9600	960	180	2640	2040	2100	2700	2760	2400
	10200	900	180	2640	1980	2100	2700	2700	2400
	10800	900	180	2640	1980	2100	2700	2700	2340

FRL = 60 minutes

Tmax	**1050**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	300	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	240	3180	Nil	Nil	Nil	Nil	Nil
	4200	Nil	240	3060	Nil	Nil	4200	Nil	Nil
	4800	Nil	240	2940	Nil	Nil	3600	3780	Nil
	5400	Nil	240	2940	3060	Nil	3360	3480	Nil
	6000	Nil	240	2880	2760	2940	3240	3300	Nil
	6600	Nil	240	2880	2580	2760	3120	3180	3240
	7200	Nil	180	2820	2460	2640	3060	3120	3000
	7800	Nil	180	2820	2400	2580	3000	3060	2880
	8400	Nil	180	2820	2340	2520	2940	3000	2820
	9000	Nil	180	2820	2340	2460	2940	3000	2760
	9600	Nil	180	2760	2280	2400	2880	2940	2700
	10200	1200	180	2760	2280	2400	2880	2940	2640
	10800	1200	180	2760	2280	2340	2880	2880	2640

Tmax	**1000**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	360	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	360	3420	Nil	Nil	Nil	Nil	Nil
	4200	Nil	300	3240	Nil	Nil	Nil	Nil	Nil
	4800	Nil	300	3180	Nil	Nil	3960	4320	Nil
	5400	Nil	300	3120	Nil	Nil	3660	3840	Nil
	6000	Nil	300	3060	3960	Nil	3480	3600	Nil
	6600	Nil	300	3000	3180	36900	3360	3480	Nil
	7200	Nil	300	3000	3000	3240	3300	3360	Nil
	7800	Nil	300	3000	2880	3060	3240	3300	3540
	8400	Nil	300	2940	2760	2940	3180	3240	3300
	9000	Nil	300	2940	2700	2880	3120	3180	3180
	9600	Nil	300	2940	2640	2820	3120	3180	3120
	10200	Nil	300	2940	2580	2760	3060	3120	3060
	10800	Nil	300	2940	2580	2700	3060	3120	3000

FRL = 60 minutes

Tmax	**950**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	3540	Nil	Nil	Nil	Nil	Nil
	4800	Nil	600	3420	Nil	Nil	4560	Nil	Nil
	5400	Nil	540	3300	Nil	Nil	4080	4320	Nil
	6000	Nil	540	3240	Nil	Nil	3840	4020	Nil
	6600	Nil	480	3240	Nil	Nil	3660	3440	Nil
	7200	Nil	480	3180	4140	Nil	3600	3720	Nil
	7800	Nil	480	3180	3660	4080	3480	3600	Nil
	8400	Nil	480	3120	3420	3720	3420	3540	Nil
	9000	Nil	480	3120	3300	3540	3420	3480	4320
	9600	Nil	420	3120	3180	3420	3360	3420	3900
	10200	Nil	420	3120	3120	3300	3360	3420	3720
	10800	Nil	420	3060	3060	3240	3300	3360	3600

Tmax	**900**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	3840	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	3720	Nil	Nil	Nil	Nil	Nil
	5400	Nil	4860	3600	Nil	Nil	4560	4980	Nil
	6000	Nil	4800	3540	Nil	Nil	4260	4500	Nil
	6600	Nil	4800	3480	Nil	Nil	4080	4260	Nil
	7200	Nil	4740	3420	Nil	Nil	3900	4080	Nil
	7800	Nil	4740	3420	Nil	Nil	3840	3960	Nil
	8400	Nil	4680	3360	5100	Nil	3780	3900	Nil
	9000	Nil	4680	3360	4440	5400	3720	3840	Nil
	9600	Nil	4620	3360	4140	4620	3660	3780	Nil
	10200	Nil	4620	3300	3960	4320	3600	3720	Nil
	10800	Nil	4620	3300	3780	4140	3600	3660	Nil

FRL = 60 minutes

Tmax	**850**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	4080	Nil	Nil	Nil	Nil	Nil
	5400	Nil	5280	3960	Nil	Nil	5280	Nil	Nil
	6000	Nil	5220	3840	Nil	Nil	4740	5160	Nil
	6600	Nil	5160	3780	Nil	Nil	4500	4800	Nil
	7200	Nil	5100	3720	Nil	Nil	4320	4560	Nil
	7800	Nil	5100	3720	Nil	Nil	4260	4440	Nil
	8400	Nil	5040	3660	Nil	Nil	4140	4320	Nil
	9000	Nil	5040	3660	Nil	Nil	4080	4260	Nil
	9600	Nil	4980	3600	Nil	Nil	4020	4140	Nil
	10200	Nil	4980	3600	6060	Nil	3960	4140	Nil
	10800	Nil	4920	3600	5340	Nil	3960	4080	Nil

Tmax	**800**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	4620	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	4440	Nil	Nil	Nil	Nil	Nil
	6000	Nil	5700	4320	Nil	Nil	5460	Nil	Nil
	6600	Nil	5640	4200	Nil	Nil	5100	5460	Nil
	7200	Nil	5580	4140	Nil	Nil	4860	5160	Nil
	7800	Nil	5520	4080	Nil	Nil	4740	4980	Nil
	8400	Nil	5520	4020	Nil	Nil	4620	4860	Nil
	9000	Nil	5460	4020	Nil	Nil	4500	4740	Nil
	9600	Nil	5400	3960	Nil	Nil	4440	4680	Nil
	10200	Nil	5400	3960	Nil	Nil	4380	4560	Nil
	10800	Nil	5400	3960	Nil	Nil	4380	4560	Nil

FRL = 60 minutes

Tmax	**750**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	5100	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	4860	Nil	Nil	Nil	Nil	Nil
	6600	Nil	6300	4740	Nil	Nil	5880	5460	Nil
	7200	Nil	6180	4680	Nil	Nil	5520	5160	Nil
	7800	Nil	6120	4560	Nil	Nil	5340	4980	Nil
	8400	Nil	6060	4500	Nil	Nil	5220	4860	Nil
	9000	Nil	6000	4500	Nil	Nil	5100	4740	Nil
	9600	Nil	6000	4440	Nil	Nil	4980	4680	Nil
	10200	Nil	5940	4380	Nil	Nil	4920	4560	Nil
	10800	Nil	5940	4380	Nil	Nil	4860	4560	Nil

Tmax	**700**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	5700	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	5460	Nil	Nil	Nil	Nil	Nil
	7200	Nil	7020	5340	Nil	Nil	6420	7080	Nil
	7800	Nil	6960	5220	Nil	Nil	6120	6660	Nil
	8400	Nil	6840	5160	Nil	Nil	5940	6360	Nil
	9000	Nil	6780	5100	Nil	Nil	5820	6180	Nil
	9600	Nil	6720	5040	Nil	Nil	5700	6060	Nil
	10200	Nil	6660	4980	Nil	Nil	5580	5940	Nil
	10800	Nil	6600	4980	Nil	Nil	5520	5820	Nil

FRL = 60 minutes

Tmax	**650**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	6540	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	6300	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	6180	Nil	Nil	7080	Nil	Nil
	8400	Nil	7920	6060	Nil	Nil	6840	7500	Nil
	9000	Nil	7800	5940	Nil	Nil	6660	7260	Nil
	9600	Nil	7740	5880	Nil	Nil	6540	7080	Nil
	10200	Nil	7620	5820	Nil	Nil	6420	6900	Nil
	10800	Nil	7560	5760	Nil	Nil	6360	6780	Nil

Tmax	**600**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	7440	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	7260	Nil	Nil	7980	Nil	Nil
	9000	Nil	Nil	7140	Nil	Nil	7860	8520	Nil
	9600	Nil	9060	7020	Nil	Nil	7620	8280	Nil
	10200	Nil	9000	6960	Nil	Nil	7500	8160	Nil
	10800	Nil	8880	6900	Nil	Nil	7440	7980	Nil

FRL = 60 minutes

Tmax	**550**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	8700	Nil	Nil	9000	Nil	Nil
	9600	Nil	Nil	8580	Nil	Nil	8880	Nil	Nil
	10200	Nil	Nil	8520	Nil	Nil	8820	9540	Nil
	10800	Nil	10560	8460	Nil	Nil	8700	9420	Nil

Tmax	**500**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	10140	Nil	Nil
	10800	Nil	Nil	10260	Nil	Nil	10140	Nil	Nil
	STD								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
		Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

FRL = 90 minutes

Tmax	1250								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	120	4200	Nil	Nil	Nil	Nil	Nil
	4800	Nil	120	4080	Nil	Nil	Nil	Nil	Nil
	5400	Nil	120	3960	Nil	Nil	Nil	Nil	Nil
	6000	Nil	120	3900	4020	4140	5160	5100	Nil
	6600	Nil	120	3840	3660	3660	4740	4680	4380
	7200	Nil	120	3780	3480	3420	4500	4440	3960
	7800	2160	120	3780	3360	3300	4380	4260	3780
	8400	1980	120	3720	3240	3180	4260	4140	3660
	9000	1920	120	3720	3180	3120	4200	4080	3600
	9600	1920	120	3720	3120	3060	4140	4020	3480
	10200	1860	120	3660	3060	3060	4080	3960	3480
	10800	1860	120	3660	3060	3000	4020	3900	3420

Tmax	1200								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	120	4260	Nil	Nil	Nil	Nil	Nil
	5400	Nil	120	4140	Nil	Nil	Nil	Nil	Nil
	6000	Nil	120	4020	Nil	Nil	5700	5820	Nil
	6600	Nil	120	3960	4260	4500	5100	5100	Nil
	7200	Nil	120	3960	3900	3960	4860	4800	4740
	7800	Nil	120	3900	3720	3720	4680	4560	4260
	8400	Nil	120	3900	3600	3540	4560	4440	4080
	9000	Nil	120	3840	3480	3480	4440	4320	3900
	9600	Nil	120	3840	3420	3420	4380	4260	3840
	10200	2280	120	3840	3360	3360	4320	4200	3720
	10800	2160	120	3780	3300	3300	4260	4140	3660

FRL = 90 minutes

Tmax	1150							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	180	4500	Nil	Nil	Nil	Nil	Nil
	5400	Nil	180	4320	Nil	Nil	Nil	Nil	Nil
	6000	Nil	180	4260	Nil	Nil	Nil	Nil	Nil
	6600	Nil	180	4140	Nil	Nil	5640	5640	Nil
	7200	Nil	180	4140	4620	Nil	5220	5160	Nil
	7800	Nil	180	4080	4260	4380	4980	4920	Nil
	8400	Nil	180	4020	4020	4080	4860	4740	4680
	9000	Nil	180	4020	3900	3900	4740	4620	4440
	9600	Nil	180	3960	3780	3780	4620	4560	4260
	10200	Nil	180	3960	3720	3720	4560	4440	4140
	10800	Nil	180	3960	3660	3660	4500	4380	4080

Tmax	1100								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	300	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	180	4800	Nil	Nil	Nil	Nil	Nil
	5400	Nil	180	4560	Nil	Nil	Nil	Nil	Nil
	6000	Nil	180	4440	Nil	Nil	Nil	Nil	Nil
	6600	Nil	180	4380	Nil	Nil	6300	6480	Nil
	7200	Nil	180	4320	Nil	Nil	5700	5700	Nil
	7800	Nil	180	4260	5220	Nil	5400	5400	Nil
	8400	Nil	180	4200	4740	5100	5220	5160	Nil
	9000	Nil	180	4200	4500	4620	5100	4980	5400
	9600	Nil	180	4140	4320	4440	4980	4860	4920
	10200	Nil	180	4140	4200	4260	4860	4800	4680
	10800	Nil	180	4140	4080	4140	4800	4740	4560

FRL = 90 minutes

Tmax	**1050**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	420	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	360	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	300	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	300	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	300	4860	Nil	Nil	Nil	Nil	Nil
	6000	Nil	300	4740	Nil	Nil	Nil	Nil	Nil
	6600	Nil	300	4620	Nil	Nil	Nil	Nil	Nil
	7200	Nil	300	4560	Nil	Nil	6360	6420	Nil
	7800	Nil	300	4500	Nil	Nil	5880	5940	Nil
	8400	Nil	300	4440	Nil	Nil	5640	5640	Nil
	9000	Nil	300	4380	5460	Nil	5460	5460	Nil
	9600	Nil	300	4380	5100	5520	5340	5280	Nil
	10200	Nil	300	4380	4860	5100	5220	5160	6060
	10800	Nil	300	4320	4680	4860	5160	5100	5460

Tmax	**1000**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	4800	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	4740	5280	Nil	Nil	Nil	Nil	Nil
	6000	Nil	540	5040	Nil	Nil	Nil	Nil	Nil
	6600	Nil	540	4920	Nil	Nil	Nil	Nil	Nil
	7200	Nil	480	4860	Nil	Nil	Nil	Nil	Nil
	7800	Nil	480	4740	Nil	Nil	6540	6600	Nil
	8400	Nil	480	4680	Nil	Nil	6180	6180	Nil
	9000	Nil	480	4680	Nil	Nil	5940	5940	Nil
	9600	Nil	480	4620	6900	Nil	5820	5760	Nil
	10200	Nil	420	4620	6000	Nil	5640	5640	Nil
	10800	Nil	420	4560	5640	6540	5580	5520	Nil

FRL = 90 minutes

Tmax	950								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	5040	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	4980	5520	Nil	Nil	Nil	Nil	Nil
	6600	Nil	4980	5340	Nil	Nil	Nil	Nil	Nil
	7200	Nil	4920	5220	Nil	Nil	Nil	Nil	Nil
	7800	Nil	4860	5100	Nil	Nil	7440	7680	Nil
	8400	Nil	4860	5040	Nil	Nil	6840	6960	Nil
	9000	Nil	4860	4980	Nil	Nil	6540	6600	Nil
	9600	Nil	4800	4920	Nil	Nil	6360	6360	Nil
	10200	Nil	4800	4920	Nil	Nil	6180	6180	Nil
	10800	Nil	4800	4860	Nil	Nil	6060	6000	Nil

Tmax	900								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	5400	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	5340	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	5280	5880	Nil	Nil	Nil	Nil	Nil
	7200	Nil	5280	5700	Nil	Nil	Nil	Nil	Nil
	7800	Nil	5220	5580	Nil	Nil	Nil	Nil	Nil
	8400	Nil	5160	5460	Nil	Nil	7800	8040	Nil
	9000	Nil	5160	5400	Nil	Nil	7320	7440	Nil
	9600	Nil	5160	5340	Nil	Nil	7020	7080	Nil
	10200	Nil	5100	5280	Nil	Nil	6780	6840	Nil
	10800	Nil	5100	5220	Nil	Nil	6660	6660	Nil

FRL = 90 minutes

Tmax	**850**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	5820	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	5760	6600	Nil	Nil	Nil	Nil	Nil
	7200	Nil	5700	6300	Nil	Nil	Nil	Nil	Nil
	7800	Nil	5640	6120	Nil	Nil	Nil	Nil	Nil
	8400	Nil	5580	6000	Nil	Nil	Nil	Nil	Nil
	9000	Nil	5580	5880	Nil	Nil	8280	8580	Nil
	9600	Nil	5520	5820	Nil	Nil	7860	8040	Nil
	10200	Nil	5520	5760	Nil	Nil	7560	7680	Nil
	10800	Nil	5460	5700	Nil	Nil	7320	7440	Nil

Tmax	**800**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	6300	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6240	7200	Nil	Nil	Nil	Nil	Nil
	7800	Nil	6180	6900	Nil	Nil	Nil	Nil	Nil
	8400	Nil	6120	6720	Nil	Nil	Nil	Nil	Nil
	9000	Nil	6060	6600	Nil	Nil	Nil	Nil	Nil
	9600	Nil	6000	6480	Nil	Nil	9000	9360	Nil
	10200	Nil	6000	6360	Nil	Nil	8520	8760	Nil
	10800	Nil	5940	6300	Nil	Nil	8220	8400	Nil

FRL = 90 minutes

Tmax	**750**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6900	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	6840	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	6780	7740	Nil	Nil	Nil	Nil	Nil
	9000	Nil	6720	7500	Nil	Nil	Nil	Nil	Nil
	9600	Nil	6660	7320	Nil	Nil	Nil	Nil	Nil
	10200	Nil	6600	7200	Nil	Nil	9840	Nil	Nil
	10800	Nil	6540	7140	Nil	Nil	9420	9720	Nil

Tmax	**700**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	7740	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	7620	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	7560	8940	Nil	Nil	Nil	Nil	Nil
	9600	Nil	7500	8640	Nil	Nil	Nil	Nil	Nil
	10200	Nil	7440	8400	Nil	Nil	Nil	Nil	Nil
	10800	Nil	7380	8220	Nil	Nil	Nil	Nil	Nil

FRL = 90 minutes

Tmax	650								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	8760	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	8640	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	8580	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	8460	9960	Nil	Nil	Nil	Nil	Nil

Tmax	600								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	10140	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	10020	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 90 minutes

Tmax	**550**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**500**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Tmax	STD								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
		Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

FRL = 120 minutes

Tmax	1250							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	5820	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	5820	5940	Nil	Nil	Nil	Nil	Nil
	7200	Nil	5760	5820	Nil	Nil	Nil	Nil	Nil
	7800	Nil	5760	5700	Nil	Nil	Nil	Nil	Nil
	8400	Nil	5760	5580	Nil	Nil	7440	7980	Nil
	9000	Nil	5700	5520	Nil	6120	6960	7200	Nil
	9600	Nil	5700	5520	Nil	5580	6660	6840	Nil
	10200	Nil	5700	5460	Nil	5280	6480	6600	6720
	10800	Nil	5700	5400	Nil	5100	6300	6420	6300

Tmax	1200								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	6000	6240	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6000	6060	Nil	Nil	Nil	Nil	Nil
	7800	Nil	5940	5940	Nil	Nil	Nil	Nil	Nil
	8400	Nil	5940	5880	Nil	Nil	8280	Nil	Nil
	9000	Nil	5880	5760	Nil	Nil	7560	7980	Nil
	9600	Nil	5880	5700	Nil	Nil	7200	7440	Nil
	10200	Nil	5880	5700	Nil	6240	6900	7080	Nil
	10800	Nil	5880	5640	Nil	5820	6720	6840	7860

FRL = 120 minutes

Tmax	1150								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	6240	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6180	6420	Nil	Nil	Nil	Nil	Nil
	7800	Nil	6180	6240	Nil	Nil	Nil	Nil	Nil
	8400	Nil	6120	6120	Nil	Nil	Nil	Nil	Nil
	9000	Nil	6120	6060	Nil	Nil	8340	Nil	Nil
	9600	Nil	6120	6000	Nil	Nil	7800	8220	Nil
	10200	Nil	6060	5940	Nil	Nil	7440	7740	Nil
	10800	Nil	6060	5880	Nil	7500	7260	7440	Nil

Tmax	1100								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6480	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	6420	6660	Nil	Nil	Nil	Nil	Nil
	8400	Nil	6420	6480	Nil	Nil	Nil	Nil	Nil
	9000	Nil	6360	6360	Nil	Nil	Nil	Nil	Nil
	9600	Nil	6360	6300	Nil	Nil	8580	9360	Nil
	10200	Nil	6300	6240	Nil	Nil	8100	8520	Nil
	10800	Nil	6300	6180	Nil	Nil	7800	8100	Nil

FRL = 120 minutes

Tmax	**1050**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	6780	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	6720	7140	Nil	Nil	Nil	Nil	Nil
	8400	Nil	6720	6900	Nil	Nil	Nil	Nil	Nil
	9000	Nil	6660	6780	Nil	Nil	Nil	Nil	Nil
	9600	Nil	6660	6660	Nil	Nil	Nil	Nil	Nil
	10200	Nil	6600	6600	Nil	Nil	9000	9720	Nil
	10800	Nil	6600	6540	Nil	Nil	8520	9000	Nil

Tmax	**1000**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	7140	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	7080	7740	Nil	Nil	Nil	Nil	Nil
	8400	Nil	7020	7440	Nil	Nil	Nil	Nil	Nil
	9000	Nil	7020	7260	Nil	Nil	Nil	Nil	Nil
	9600	Nil	6960	7140	Nil	Nil	Nil	Nil	Nil
	10200	Nil	6960	7020	Nil	Nil	10200	Nil	Nil
	10800	Nil	6900	6960	Nil	Nil	9480	10260	Nil

FRL = 120 minutes

Tmax	950								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	7500	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	7440	8220	Nil	Nil	Nil	Nil	Nil
	9000	Nil	7440	7920	Nil	Nil	Nil	Nil	Nil
	9600	Nil	7380	7740	Nil	Nil	Nil	Nil	Nil
	10200	Nil	7380	7560	Nil	Nil	Nil	Nil	Nil
	10800	Nil	7320	7440	Nil	Nil	10800	Nil	Nil

Tmax	900								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	7980	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	7980	8880	Nil	Nil	Nil	Nil	Nil
	9600	Nil	7920	8580	Nil	Nil	Nil	Nil	Nil
	10200	Nil	7860	8340	Nil	Nil	Nil	Nil	Nil
	10800	Nil	7800	8160	Nil	Nil	Nil	Nil	Nil

FRL = 120 minutes

Tmax	850								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	8640	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	8580	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	8520	9420	Nil	Nil	Nil	Nil	Nil
	10800	Nil	8460	9120	Nil	Nil	Nil	Nil	Nil

Tmax	800								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	9420	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	9360	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	9300	10620	Nil	Nil	Nil	Nil	Nil

FRL = 120 minutes

Tmax	**750**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	10380	Nil	Nil	Nil	Nil	Nil	Nil
Tmax	**700**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 120 minutes

Tmax	**650**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**600**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 120 minutes

Tmax	**550**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**500**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Tmax	STD								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
		Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

FRL = 180 minutes

Tmax	1250								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	9060	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	9000	10020	Nil	Nil	Nil	Nil	Nil
	10800	Nil	9000	9780	Nil	Nil	Nil	Nil	Nil

Tmax	1200								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	9360	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	9360	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	9300	10380	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	1150								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	9720	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	9660	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	1100								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	10140	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	10080	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	**1050**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	10620	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**1000**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	950								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	900								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	**850**							
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**800**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	750								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	700								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	**650**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**600**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

FRL = 180 minutes

Tmax	**550**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil

Tmax	**500**								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Tmax	STD F T								
	t500	SSW	MW	CW	CB	CC	SB	SC	MSD
		Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail

APPENDIX H

CALCULATION OF FIRE SEVERITIES

APPENDIX H

CALCULATION OF FIRE SEVERITIES

Introduction

Fires in buildings occur in a virtually infinite variety of enclosure sizes and shapes. In estimating the *severity* of fires that may occur in an enclosure it is important that the effect of enclosure size, shape and ventilation be understood. In addition the type of fuel may also influence the fire severity.

The severity of a fire in an enclosure for the present purpose is defined as a combination of temperatures reached by the fire gases and the duration of those temperatures. In general, the gas temperature varies continuously through a fire, with major variations occurring at the beginning and end of the fire and sometimes at various intermediate times.

The severity of possible fires in an enclosure in a building must be estimated in order to properly develop an engineering design of the fire safety system for the building. The *severity* of a fire in an enclosure is dependent on a number of factors including the size, shape and ventilation of the enclosure and the fire load in the enclosure. In investigating the severity of fires to be considered in estimating the fire resistance requirements for barrier and structural elements for buildings it became apparent that the estimates obtained using available fire models and correlation formulae were unreliable for the broad range of enclosure sizes, shapes and ventilation arrangements that are possible. The range of enclosure sizes that it is desired to cover ranges from 4 m wide by 8 m deep by 2.4 m high to 100 m by 50 m by 6 m high and 60 m by 60 m by 3 m high.

A variety of studies conducted on various factors that might influence fire severity have been conducted and reported separately[1].

Reference 1 reports an experimental program designed to investigate the influence on the burning rate of opening width and enclosure shape by comparing the burning rate and behaviour of fires in long enclosures and wide enclosures with similar opening. Fire tests were conducted in enclosures 1500 mm by 600 mm by 300 mm high with ventilation openings of several widths. It was found that the behaviour and fuel mass loss rates of fires in long and wide enclosures differ markedly if the width of the ventilation opening is less than the full width of the enclosure. When the ventilation opening width is equal to that of the enclosure the flows within the enclosure are essentially two-dimensional but when the opening width is less than that of the enclosure the flows within the enclosure are three-dimensional. The mass loss rates for the same opening size in wide enclosures were found to be substantially greater than those for long enclosures for both full width and partial width openings by a factor of from 1.8 to 2.7. In addition the fire severity (particularly the duration of high temperatures) varied with position in the enclosure, more so for deep enclosures than for wide enclosures.

Another factor of importance is the effect of the position of the openings in each end of enclosures with two vents. Attachment 1 reports on an investigation of this aspect again using small enclosures. This investigation included a comparison of the cross ventilation (two vent) cases with single vent cases in identical shape and size enclosures.

Attachment 2 presents the results of an investigation of the severity of fires in small enclosures with uniform fuel load throughout and a single vent. The investigation covered a wide range of enclosure shapes and opening sizes. It was found that a good correlation could be obtained using all of the variables specifying the geometry of the enclosure and vent. Better and somewhat simpler correlations can be obtained if the data is divided into segments, in part reflecting the differences in behaviour identified in Reference 1. The categories identified with $D/W \geq 2$, and $D/W < 2$ and $w/W = 1$ and $w/W < 1$.

This investigation was complemented by an investigation of the influence of fuel position in long enclosures with a single vent reported in Attachment 3. In this investigation a single tray of fuel was used in each enclosure, but the position of the tray was varied systematically through the tests. It was found that there was significant variation in fire severity for an identical quantity of fuel burnt in different positions in otherwise identical enclosures. There was little variation in the maximum temperatures recorded for each enclosure size, the major variations in fire severity resulted from variations in the duration of burning and high temperatures.

A major international investigation of fire severity in enclosures with uniform fire loads was conducted under the auspices of CIB about thirty years ago[2]. The relevant data from this investigation has been reviewed and reanalysed in Attachment 4. In this investigation the vent height was always identical to the enclosure height. Several crib designs were used with both the stick thickness and spacing being varied. A good correlation for the mass loss rate was obtained using only the vent width and height, the enclosure width and the stick spacing. A correlation using the above variables except for the enclosure width was substantially less satisfactory, indicating that the vent dimensions alone are not sufficient to give an accurate prediction of mass loss rate or duration of burning.

The experimental programs that have formed the basis of these studies have all been at less than full scale. In this report available full scale data is summarised and examined and compared with the above mentioned smaller scale data.

The rate of burning (as measured by heat release rate or mass loss rate) in enclosure fires is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$ [3], which means that it is directly proportional to the vent width w and height h raised to the power 1.5, that is $h^{1.5}$. Thus, for the same size ventilation openings the same rate of burning is expected.

The following terminology and nomenclature is used for the clear internal dimensions of the enclosure (Figure 1):

- width (*W*) - horizontal dimension parallel to the plane of the ventilation opening
- depth (*D*) - horizontal dimension perpendicular to the plane of the ventilation opening
- height (*H*) - vertical dimension from the bottom surface to the top surface

The following terminology and nomenclature is used for the dimensions of the ventilation opening:

- opening width (*w*) - the clear horizontal dimension
- opening height (*h*) - the clear vertical dimension
- sill height (*s*) - the vertical dimension from the enclosure floor to the bottom of the opening

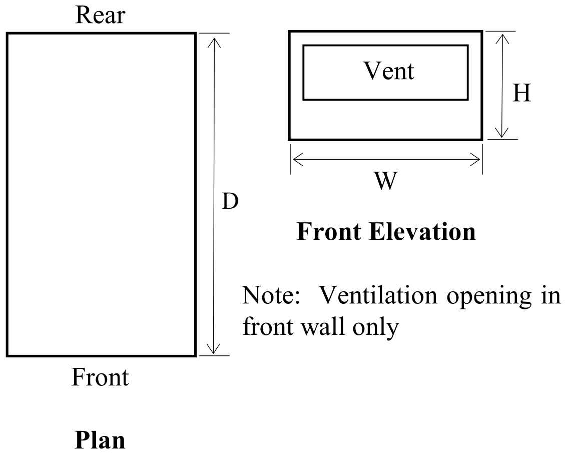


Figure 1 Enclosure Details

The range of enclosure sizes required to be covered for Project 3 are shown in Table 1. The smallest are 4 m by 8 m and these are moderately close in size to the enclosures used in the VUT tests. The next larger enclosures are 5 m by 20 m and 6 m by 20 m and these are close to the enclosures used in the BSC tests. The remaining enclosures are all considerably larger and there are no tests available with similar sized enclosures, so a high degree of extrapolation will be necessary in these cases.

Table 1 Enclosure and Vent Sizes for Project 3

W (m)	*D* (m)	*H* (m)
4	8	2.4
4	8	3
5	20	2.4
5	20	3
5	20	4
6	20	3
8	4	2.4
8	4	3
20	5	2.4
20	5	3
20	5	4
20	6	3
30	50	5
50	30	5
50	100	2.4
50	100	5
50	100	6
60	60	3
100	50	2.4
100	50	5
100	50	6

w (m)	*h* (m)
4	0.39 - 0.78
5	0.83 - 1.65
6	1.14
8	0.59 - 2.4
20	0.9 - 2.4
30	1.13 - 1.70
50	2.04 - 5.0
60	1.52 - 3.0
100	2.4 - 6.0

Experimental Programs

The experimental programs conducted at less than full scale have been described elsewhere[1]. and Attachments 1, 2, 3 and 4.

The **full scale** experimental programs that have been used in this study are summarised in Table A1 in Appendix A. They have been confined to tests in enclosures with a single opening where details of the fuel, ventilation, construction and resulting enclosure temperatures are available. The enclosure sizes are summarised in Table 2 and range from *2.4 m wide by 3.7 m deep by 2.4 m high* to *5.6 m wide by 22.9 m deep by 2.8 m high* and *8.6 m wide by 5.9 m deep by 3.9 m high*. The vent sizes vary widely and are also summarised in Table 2. The fuel used varied considerably as did the bounding wall materials (Table A1).

It is obvious in Table 2 that the enclosure and vent sizes used in most of these tests are smaller than even the smallest enclosures of interest for Project 3 (Table 1).

Table 2 Summary of Enclosure and Vent Sizes in Full Scale Tests

D	*W*	*H*	Tests
3.36	3.6	3.13	10
3.65	3.65	3.13	23
3.66	2.44	2.44	1
3.71	7.7	2.9	5
5.4	3.6	2.4	6
5.595	5.595	2.75	1
5.9	8.6	3.9	10
7.57	9.98	4.055	1
22.78	5.465	2.68	1
22.855	5.595	2.75	7

w	*h*	*s*	Tests
0.76	2.03	0	1
0.9	1.06	2	1
1.18	2.18	0.9	8
1.37	2.75	0	1
1.78	2.36	1.54	2
1.95	2.18	0.9	1
2.139	1.73	1.02	1
2.4	1.5	0.9	3
2.65	1.36	1.47	23
3.16	1.67	0.2	3
3.55	2.36	1.54	7
5.065	2.68	0	1
5.195	0.375	2.375	1
5.195	1.47	1.28	2
5.595	2.75	0	3
6.1	0.915	1.985	3
6.1	1.83	1.07	2
6.67	2.08	1.575	1
7.1	2.36	1.54	1

The experiments and experimental programs represented by these full scale data were conducted independently and generally for specific purposes. Thus the distribution of the enclosure and vent sizes and shapes is by chance, rather than by design. This means that there are severe limitations on the coverage compared with that which would be desirable for a complete investigation of the influence of various variables.

In examining the data from these tests it has become obvious that there are phenomena and characteristics in larger enclosures that do not have approximately equal width, depth and height that are not normally recognised in tests of smaller (essentially cube shaped) rooms. These phenomena include uneven burning and widely varying temperatures in the room after flashover would normally have been expected to occur[1].

In the small scale experimental programs it has been found that the behaviour of fires in enclosures is strongly influenced by the width of the vent compared with the width of the enclosure. When the width of the vent was equal to the width of the enclosure the flows through the enclosure resulting from the fire were found to be two-dimensional. In contrast, when the vent width was substantially less than the enclosure width the flows within the enclosure were three-dimensional and the burning rate was found to be greater than in the other case for the same vent size. In the enclosures with two-dimensional flows the hot gases leaving the enclosure were seen to generally occupy the top third of the vent. However, in the enclosures with three-dimensional flows they were seen to occupy the top two-thirds of the vent. Only three of the tests included in this sample had the vent width equal to the enclosure width ($w/W = 1$) and these were in deep enclosures in which the effects of the three dimensional flows are expected to be seen only while the burning is near the vent. The remainder ranged from $w/W = 0.21$ to 0.93 but there were few tests at the lower ratios.

Because the tests were conducted for a variety of purposes the data recorded varies and is limited. In none of the experiments at full scale was the heat release or the mass loss measured. This means that the mass loss has had to be estimated from the duration of the tests and the fire load. Thus there is likely to be considerable error in some of the estimates of mass loss rate. The average mass loss rate has been estimated by dividing the total fire load by the time over which the temperature in the enclosure was greater than 500°C. This is an arbitrary criterion but is believed to reasonably accurately represent the period of significant burning. The actual period from ignition to extinguishment may well have been anything from somewhat longer than this period to much greater than this period, judging from some of the temperature-time records available and by comparison with similar tests we have conducted.

Ideally, the data from the full scale tests would be used to examine the influence of enclosure and vent size and shape on the burning rate in enclosures. But this is not possible because large proportions of the tests are concentrated at certain enclosure sizes and shapes, making it impossible to meaningfully compare results for various enclosure or vent shapes or determine the influence of enclosure size or shape with any degree of certainty. Similarly with vents, because large proportions of the tests are concentrated at certain vent sizes and shapes (and because these are often associated with certain enclosure sizes and shapes) it is not possible to meaningfully determine the influence of vent size or shape with any degree of certainty. In addition there is a relatively small quantity of data available.

In the small scale tests using wood cribs the measured maximum mass loss rate varied between 1.2 and 2.5 times the average mass loss rate (95% of fuel mass to 5% of fuel mass) with the mean of the ratio of maximum to average mass loss rate being 1.7. It is assumed that a similar ratio is relevant for the full scale tests and the estimated average mass loss has been multiplied by 1.7 to estimate the maximum mass loss rate. It is also assumed in what follows that the R_{8030} mass loss rate recorded for the CIB tests approximates the maximum mass loss rate. It is expected that this assumption is reasonable based on the mass loss records of the small scale wood crib tests.

In the following rather than using the mass loss rate (kg/s) the nominal heat output (MW) is used. This is obtained directly from the mass loss rate by multiplying by the heat of combustion which is taken as 17 MJ/kg for wood and 27 MJ/kg for the liquid fuel used in the small scale tests.

Discussion of the Full Scale Experiments

A series of experiments were conducted for BSC at FRS on in enclosures about 22.9 m deep by 5.6 m wide by 2.8 m high, with one test on a smaller enclosure about 5.6 m square and 2.8 m high (Table A1). The fuel was wood cribs and the enclosures were highly insulated with 50 mm of ceramic fibre blanket insulation. Five of the tests had $w/W < 1$ and three had $w/W = 1$. As the enclosure width and height were constant through the tests and the depth was the same in all but one tests it is not possible to investigate the effect these might have on the mass loss rate or maximum temperature.

In Figure 2 temperature-time curves are shown for three cross-sections in an enclosure *5.6 m wide by 22.9 m deep by 2.8 m high* with wood cribs uniformly distributed over the floor area and a single full height ventilation opening in one 5.6 m wall. The cross-sections at which the temperatures were recorded were 3.3, 11.3 and 19.3 m in from the ventilation opening. During this and similar tests it was observed that, although the fire was started simultaneously in the three cribs in the row at the rear of the enclosure (that is, the row furthest from the ventilation opening), the fire quickly travelled forward. Once burning was established in the front row of cribs burning of the rear cribs ceased. The front cribs then burned, then the second row of cribs and so on as the fire travelled back through the rows of cribs in the enclosure with the fuel nearest the opening being consumed.

These observations are clearly reflected in the temperature-time curves for the three thermocoupled cross-sections in the enclosure (Figure 2). After ignition, the temperature at all three cross-sections began to rise, most rapidly at the rear and slowest at the front. The temperatures of the rear and then middle cross-sections peaked briefly and then declined substantially. The temperature at front (the cross-section nearest the ventilation opening) stayed high for a much longer period, and as it began to fall the temperature at the middle cross-section began to rise again. It peaked again but for a longer period than previously. As the temperatures in this region began to fall those at the rear cross-section again rose to a peak. Thus the shape of the temperature-time curves for the three cross-sections are quite different and the three cross-sections "see" different fire severities (temperature-time curves).

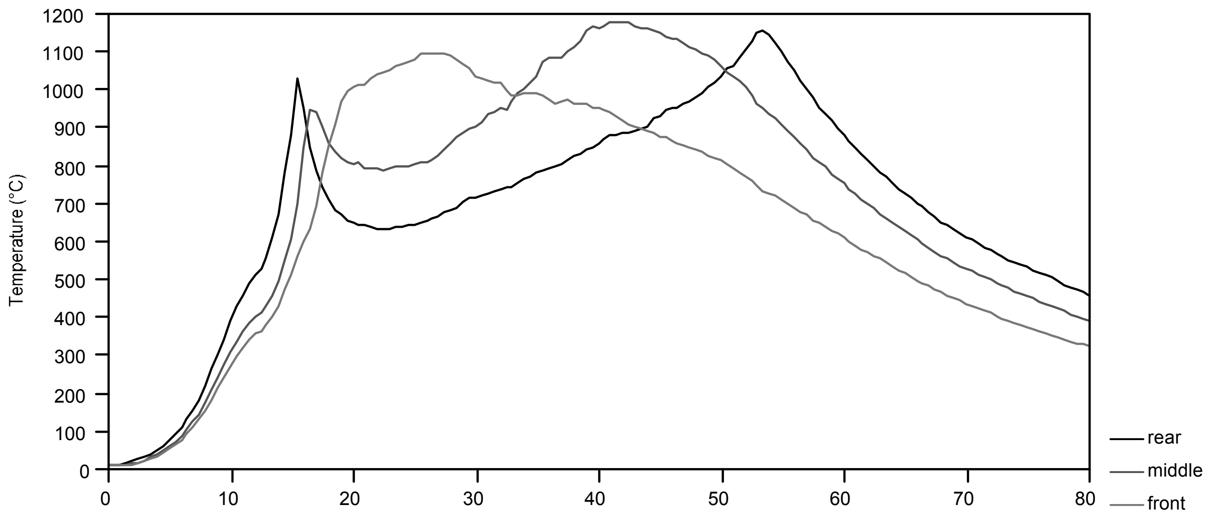


Figure 2 Temperature-Time Relationships for Three Cross-sections in an Enclosure 5.6 m Wide, 22.9 m Deep and 2.8 m High (Ignition at Rear)

This is illustrated even more clearly in the temperature-time curves for an identical enclosure but with all cribs ignited simultaneously (Figure 3). After a brief period of burning throughout the enclosure the cribs in the rear of the enclosure ceased burning whilst the cribs nearest the ventilation opening burned vigorously. As these front cribs burnt out the fire progressed back through the enclosure.

The temperature at the front cross-section rose rapidly (Figure 3), whilst those at the other cross-sections did so progressively more slowly with distance from the ventilation opening. As the cribs in the front of the enclosure burned out and the temperature there began to fall the temperature further back in the enclosure continued to rise. Once the temperature at the middle cross-section peaked and began to fall it was exceeded by the temperature at the rear of the enclosure.

Again the shape of the temperature-time curves for the three cross-sections are quite different - the three cross-sections "see" quite different fire severities (temperature-time curves).

These observations imply that in this size or shape enclosure “flashover” does not appear to result in sufficiently dynamic mixing of the gases in the enclosure to result in uniform conditions or temperatures throughout the enclosure.

For the five BSC tests with $w/W < 1$ and using ceramic fibre insulation a least squares regression on the nominal heat output using only the vent width and height results in the following expression (R in MW):

$$R = 2.70 \times w^{0.710} \times h^{1.094} \qquad (1)$$

and the correlation of this estimate of the heat output with the nominal average heat output is shown in Figure 4. It is obvious that this expression provides a very good estimate of the nominal heat output for the tests that it is based on.

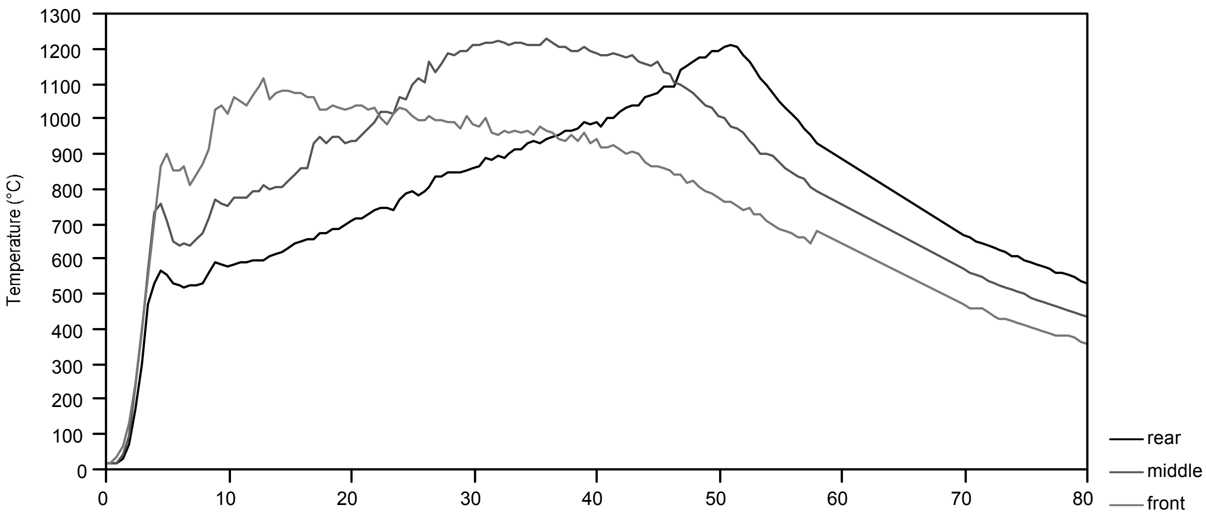


Figure 3 Temperature-Time Relationships for Three Cross-sections in an Enclosure 5.6 m Wide, 22.9 m Deep and 2.8 m High (Simultaneous Ignition)

Equation 1 will be used as a basis of comparison of this group of tests with several others.

The correlation of Equation 1 with the remainder of the BSC tests is rather less impressive (Figure 5). In Figure 5 the additional tests can be identified by comparison with Figure 4. The group of three tests are those with $w/W = 1$, and the single test below them is one where $w/W < 1$ but for this particular test the ceramic fibre insulation (used in all of the other tests) was covered with plasterboard.

If Equation 1 is used to estimate the mass loss rate for the tests with $w/W = 1$ the estimated heat output is 27.7 MW but the nominal average heat output varies between 17.3 MW and 19.0 MW. This discrepancy between the nominal (for $w/W = 1$) and calculated (for $w/W < 1$) heat output, with the nominal average heat output being significantly less than the calculated, is in line with the findings from the small enclosure tests[1], although is perhaps greater than expected for low *W/D* enclosures. An even larger discrepancy that is less easily rationalised is apparent between the predicted heat output and the nominal average heat output for the same enclosure with plaster board installed over the ceramic fibre lining and the opening very similar to that used in one of the above tests (predicted = 25.0 MW, measured = 11.7 MW).

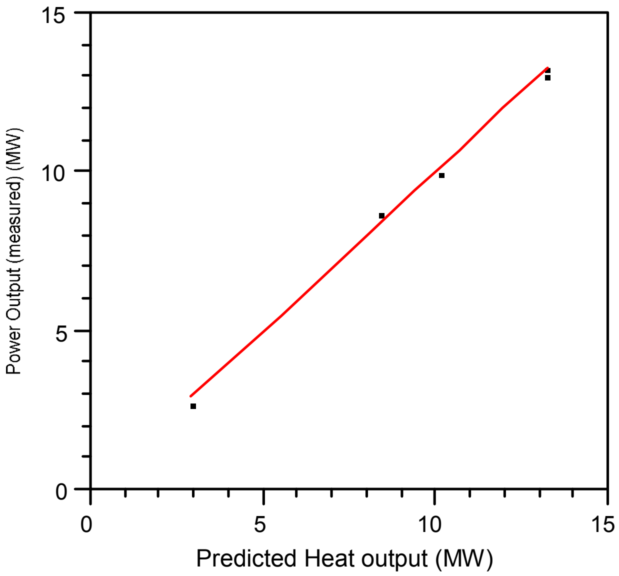


Figure 4 BSC Tests with w/W < 1 and Ceramic Fibre Insulation

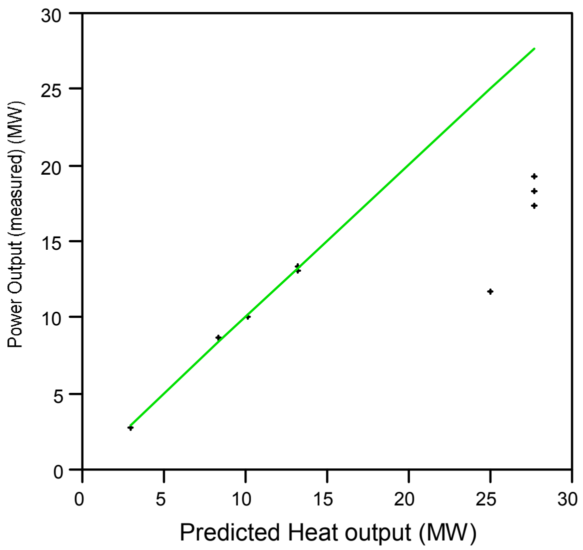


Figure 5 All BSC Tests

An earlier program of tests conducted by BSC and FRS took place in an enclosure 8.6 m wide by 5.9 m deep by 3.9 m high. In these tests the vent height was constant at 2.36 m but three vent widths 1.78 m, 3.55 m and 7.1 m were used. There were two tests at the first width, six at the second and one at the third. For comparison, using Equation 1, the estimated heat outputs for the three vent heights were 10.4, 17.0 and 27.9 MW with the nominal average heat output being 11.9 and 13.6; 18.9, 19.2, 20.4, 24.5, 24.5 and 30.6; and 36.7 MW respectively (Figure 6). Thus the heat outputs range from about 10 to 80% above those expected based on Equation 1. It is also interesting to note that the linings of the enclosures varied through some of these tests, with the linings with lower insulating properties correlating with tests with higher heat outputs, rather than the opposite which might be expected based on the BSC plaster lining test mentioned above (Table A1).

As several of these tests were duplicates it is of interest to note the variability of the recorded temperatures. The maximum temperatures in the six tests at 3.55 m vent width ranged from 630 °C to 1080 °C and the temperatures of the two tests at 1.78 m vent width were 750 and 870 °C. Two of the tests at 3.55 m vent width had highly insulated walls and the temperature range for this group was 630 to 1080 °C, while two had less wall insulated walls and the temperatures of these tests were 730 and 850 °C.

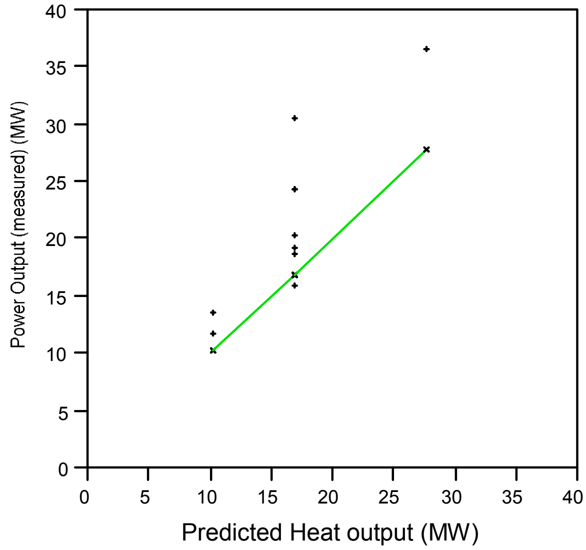


Figure 6 Comparison of BSC 83 with Equation 1 Prediction

A third set of tests conducted at the predecessor of FRS were conducted in an enclosure about 3.7 m deep by 7.7 m wide by 2.9 m high with the vent width constant at 6.1 m. Two vent heights were used: 1.07 m (three tests) and 1.99 m (two tests). Again using Equation 1 for comparison the estimated heat outputs for the two vent heights were 8.8 and 18.9 MW. The nominal average heat outputs were 9.9, 11.7 and 12.2; and 17.1 and 20.1 MW (Figure 7). The first group are slightly higher than expected but the second group are around the values expected.

The temperature ranges for these tests were 710 to 1180 °C and 795 to 1070 °C respectively. All of these tests had highly insulated walls.

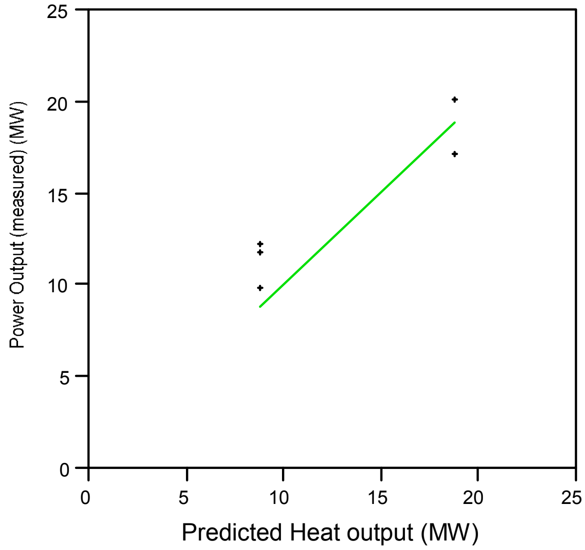


Figure 7 JFRO Tests Compared with Equation 1

A large number of tests have been conducted at CTICM in three series, but here they will be treated together. Many of the tests have the same enclosure and vent dimensions, so they provide an estimate of the variability in the results for one laboratory (it might be expected that greater variability would occur between laboratories). The enclosures were about 3.4 or 3.7 m deep, 3.6 or 3.7 m wide and 3.1 m high. A large proportion of the tests were done in the enclosure 3.7 m square in plan and 3.1 m high and with vent width of 2.65 m and height of 1.47 m (23 tests). Other vent dimensions used were 2.18 m wide by 0.9 m and 1.18 m high (eight tests), and 1.06 m wide by 2 m high. Using Equation 1 the estimated heat output f63Ca vent 0.9 m wide by 1.06 m high is 2.7 MW , which may be compared with the nominal average value of 5.3 MW. Fo3Ca vent 1.18 m wide by 2.18 m high Equation 1 predictsCa heat output is 7.1 MW and range of nominal average values was 12.4 to 17.5 MW. Fo3Ca vent 1.95 m wide by 2.18 m high Equation 1 predicts a heat output of 10.2 MW and the nominal average value was 25.0 MW. Fo3Ca vent 2.65 m wide by 1.36 m high estimated heat output is 7.7 MW and range of nominal average values was 7.3 to 9.4 MW. Thus, except f63Cthe last group the nominal average values are generally about twice the estimated values (Figure 8).

For the 23 tests in the 3.65 m square by 3.13 m high enclosure with a 2.65 m wide by 1.36 m high vent the temperature range was 1001 to 1221 °C. Fo3Cthe 8 tests in the enclosure 3.6 m by 3.36 m by 3.13 m high and a vent 1.18 m wide by 2.18 m high the temperature range was 660 to 990 °C. All of these tests had highly insulated walls.

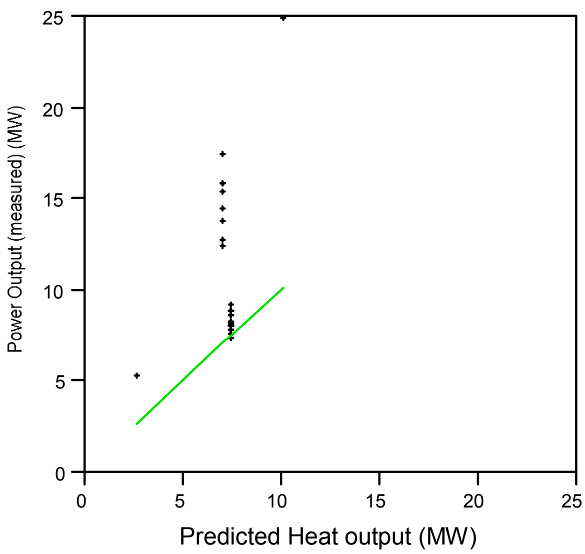


Figure 8 CTICM Tests Compared with Equation 1

Tests conducted at VUT in an enclosure 5.4 m deep by 3.6 m wide by 2.4 m high with two opening sizes 3.16 m wide by 1.67 m high and 2.4 m wide and 1.5 m high resulted in nominal average heat outputs of 18.0, 19.4 and 24.7 MW for the first and 19.4, 20.9 and 20.9 MW for the second compared with Equation 1 estimates of 7.8 and 10.7 MW. Thus the measured values are from about two to three times the estimated values.

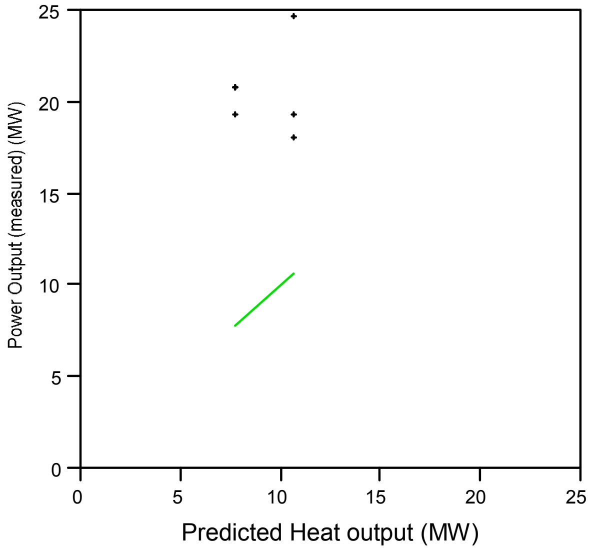


Figure 9 VUT

If all of the data for *w/W < 1* is pooled and a similar analysis conducted the following results:

$$R = 9.50 \times W^{-0.033} \times D^{-0.313} \times H^{-0.342} \times w^{0.525} \times h^{1.388} \quad (r^2 = 0.57) \qquad (2)$$

or, in terms of the vent dimensions only:

$$R = 5.41 \times w^{0.366} \times h^{1.014} \quad (r^2 = 0.50) \qquad (3)$$

In both cases the estimate of any individual result is subject to confidence limits of about ±10 MW (Figures 10 and 11). In these figures the middle line is the mean and the lines either side are the 95% confidence limit lines.

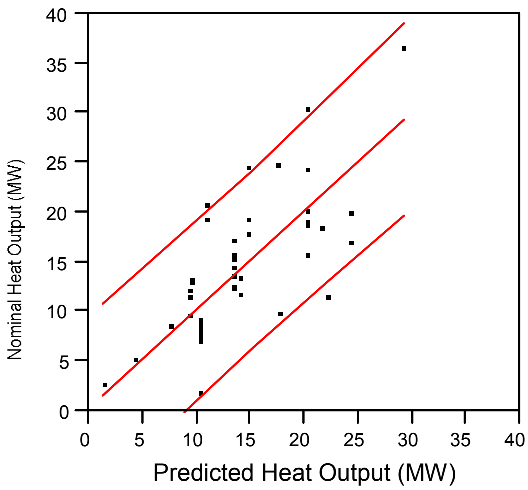


Figure 10 Comparison with Equation 2

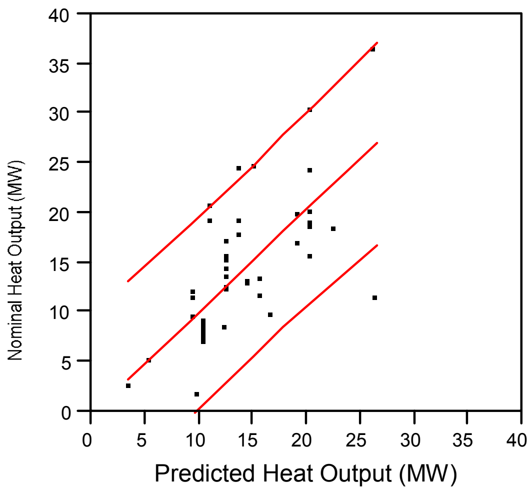


Figure 11 Comparison with Equation 3

As there are only three tests in the full scale tests with *w/W = 1* it is not possible to conduct a similar analysis for the *w/W = 1* case.

Examining the three tests for the *w/W = 1* case closely the only differences between the tests were the fire load density (which appears to have had little or no effect on the heat output or enclosure temperatures) and whether the fire was lit only in the rear cribs (two tests) or in all cribs simultaneously (which also appears to have had little or no effect).

Combination of Small, CIB and Full Scale Test Data

Estimating Burning Rate and Fire Duration

The data from the three data sets are different and to combine them assumptions have to be made. The mass loss was measured in the small scale and CIB test but not in the full scale tests. In the small scale tests the entire mass records are available and from them the maximum mass loss rate and the average mass loss rate have been obtained. In the CIB tests only the average mass loss rate between 80% of the initial fuel mass and 30% of the initial mass is available. Based on examination of the small scale test mass loss records it is assumed that this mass loss rate would be very close to the maximum rate of mass loss, and it is on this basis that the combination of these sets of data has been made. In the full scale test program only the initial mass of fuel is available. It has been assumed that all of the fuel is burned and (as indicated earlier) that the period of significant burning is approximately equal to the time for which the enclosure temperature is above 500 °C. This time has then been used to calculate the average mass loss rate and the maximum mass loss rate calculated from it by multiplying by 1.7 as explained earlier. These assumptions have enabled the three data sets to be combined.

In examining the combined data from the small enclosure tests, the CIB testing program and the collection of full scale test data it becomes obvious that great care has to be taken in conducting regression analyses of the data and in drawing conclusions on the physics governing fires in enclosures based on those analyses. The need for caution is illustrated through an examination of the data in Tables 3, 4, and 5.

Table 3 Correlation of Variables

Variable	W	D	H	wv	hv
W	1.0000	0.6080	0.8541	0.8209	0.8055
D	0.6080	1.0000	0.5797	0.6276	0.5904
H	0.8541	0.5797	1.0000	0.6872	0.8804
wv	0.8209	0.6276	0.6872	1.0000	0.6169
hv	0.8055	0.5904	0.8804	0.6169	1.0000

Table 3 presents the correlations of the dimensions of the enclosures and vents. A number close to 1 represents a high correlation whereas a number close to zero means there is no correlation between the variables. It can be seen that most of the variables are highly correlated with at least one other variable, with the possible exception of the enclosure depth *D*. This means that in regression analysis it is not possible to tell which, if any, of these variables is likely to be related to changes in the dependent variable and often one variable emerges in the regression representing the major effect of the correlated variables and the other variables effectively provide a minor adjustment of the overall trend. Very slight changes to the data can result in what are apparently major changes to the regression formula if the variable representing the major effect changes. However, comparison of the results of these apparently very different formulae will show that they actually produce very similar results in the range of the data. Nevertheless, very wide divergences can occur if the formula is extrapolated beyond the range of the data on which it is based. The effect of the correlation of the variables in this case can be seen in Tables 4 and 5 which are discussed below.

In Reference 1 it has been shown that there are major differences in the behaviour of fires with full width ventilation openings and those with partial width openings. These differences result in substantially different severities (particularly fire durations) in otherwise identical enclosures with ventilation openings of identical size[1]. Thus in the following the data is examined in two groups:

w/W = 1 (in Tables 4 and 5) and *w/W < 1* (in Tables 6 and 7). Tables 4 and 5 are based on all of the experimental data mentioned above with a full width opening ($w/W = 1$) and Tables 6 and 7 are based on all of the experimental data with a partial width opening ($w/W < 1$).

In these tables two sets of correlation/regression data are given. Tables 4 and 6 relate to the correlation of the variables themselves. Tables 5 and 7 relate to regression formulae of the form:

$$R = C \times W^{nW} \times D^{nD} \times H^{nH} \times w^{nw} \times h^{nh} \qquad \text{(A)}$$

In Tables 5 and 7 one or more of the variables have been used in with Equation A and the correlation between the resulting values and the mass loss rate is given on the same line of the tables.

Table 4 Results of Regression Analyses for Enclosures with a Full Width Opening ($w/W = 1$)

Variable	W	D	H	hv
W	1.0000	0.6298	0.8333	0.8143
D	0.6298	1.0000	0.7127	0.6979
H	0.8333	0.7127	1.0000	0.9924
hv	0.8143	0.6979	0.9924	1.0000

Table 5 Results of Regression Analyses for Enclosures with a Full Width Opening ($w/W = 1$)

C	nW = nw	nD	nH	nh	Correlation Coefficient
0.27	2.15	0.00	0.00	0.00	0.75
0.65	0.00	1.07	0.00	0.00	0.91
1.17	0.00	0.00	2.72	0.00	0.94
1.17	0.00		0.00	2.73	0.94
0.53	0.85	0.66	0.00	0.00	0.97
0.44	1.17	0.00	1.70	0.00	0.97
0.44	1.17	0.00	0.00	1.69	0.97
1.20	0.00	0.41	1.44	0.00	0.96
1.21	0.00	0.43	0.00	1.39	0.96
1.16	0.00	0.00	2.94	-0.21	0.94
0.66	0.79	0.34	0.90	0.00	0.98
0.67	0.72	0.35	0.00	0.87	0.98
0.67	0.78	0.35	-0.28	1.15	0.98
0.44	1.17	0.00	1.71	-0.02	0.97
0.67	0.78	0.35	0.00	0.87	0.98

Inspection of Table 4 shows that the variables (the dimensions of the enclosure and vent) are highly correlated, remembering in addition that as *w = W*, *w* and *W* are perfectly correlated.

As shown in Table 5 when each individual or combination of variables is used in Equation A the correlation of the result with the heat output is quite high when each variable is used singly, with little difference between them. The best correlation using Equation A automatically involves all of the independent variables but almost as good a correlation can be obtained with the enclosure height omitted, this being the case because the enclosure height and opening height are very highly correlated. Also of interest is fact that the values obtained for the correlation involving both the opening width and height are rather different to those obtained by Kawagoe[7] and that the correlation coefficient for this case is no better than that obtained using the enclosure width, depth and height in any combination of pairs.

Table 6 Results of Regression Analyses for Enclosures with a Partial Width Opening ($w/W < 1$)

Variable	W	D	H	wv	hv
W	1.0000	0.5604	0.8128	0.8435	0.7526
D	0.5604	1.0000	0.5107	0.6269	0.4556
H	0.8128	0.5107	1.0000	0.7568	0.8438
wv	0.8435	0.6269	0.7568	1.0000	0.5544
hv	0.7526	0.4556	0.8438	0.5544	1.0000

Table 7 Results of Regression Analyses for Enclosures with a Partial Width Opening ($w/W < 1$)

C	nW	nD	nH	nw	nh	Correlation Coefficient
1.41	1.22	0.00	0.00	0.00	0.00	0.60
3.47	0.00	0.57	0.00	0.00	0.00	0.36
1.63	0.00	0.00	1.81	0.00	0.00	0.71
4.54	0.00	0.00	0.00	0.82	0.00	0.59
3.43	0.00	0.00	0.00	0.00	1.97	0.64
1.41	1.12	0.12	0.00	0.00	0.00	0.61
1.47	0.44	0.00	1.27	0.00	0.00	0.74
2.10	0.78	0.00	0.00	0.37	0.00	0.64
2.08	0.64	0.00	0.00	0.00	1.16	0.70
1.45	0.00	0.18	1.67	0.00	0.00	0.72
4.36	0.00	0.05	0.00	0.78	0.00	0.59
3.15	0.00	0.19	0.00	0.00	1.67	0.66
1.83	0.00	0.00	1.43	0.32	0.00	0.74
1.89	0.00	0.00	1.26	0.00	0.85	0.77
3.39	0.00	0.00	0.00	0.543	1.31	0.80
1.43	0.40	0.06	1.26	0.00	0.00	0.74
2.05	0.76	0.04	0.00	0.35	0.00	0.64
2.05	0.59	0.08	0.00	0.00	1.11	0.71
1.62	0.30	0.00	1.21	0.20	0.00	0.75
1.77	0.23	0.00	1.07	0.68	0.70	0.78
3.67	-0.09	0.00	0.00	0.58	1.37	0.80
3.86	0.00	-.024	0.00	0.64	1.55	0.81
2.27	0.00	0.00	0.70	0.41	0.96	0.83
3.57	-0.452	-0.229	0.729	0.683	1.53	0.85

A similar inspection of Tables 6 and 7 reveals that in all cases the correlations are not as good as for the previous case (Tables 4 and 5). However, a similar pattern emerges in regard to the precision of the correlations. In terms of the individual dimensions of the enclosure and the heat output the best correlation is with the width of the enclosure, and the worst with the enclosure depth. In the correlations using combinations of the enclosure and vent dimensions the combination using only the vent width and height is quite a good correlation but the correlation using all of the enclosure and vent dimensions is distinctly better. Combinations using the enclosure width and height are almost as good as those with the vent width and height which again give values rather different from the values obtained by Kawagoe[7].

The question is what does all of this mean? It appears that in general all that can be said from these correlations is that as enclosures get bigger so do the vents, and so does the burning rate. There is little to indicate that any particular combination of dimensions has greater virtue or physical significance than another, except perhaps that correlations using all of the variables give the best correlations (but not necessarily greatly better than simpler combinations). It may, perhaps, be inferred from the tables that the rate of burning (mass loss rate or heat release rate) is not simply dependent on the vent dimensions, but rather, on the size and shape of the vent and its relationship to the enclosure size and shape.

Thus, comparing Tables 5 and 7 it appears worthwhile separating the cases covered by each table as the results in the two tables are distinctly different and it has been established previously that there are differences in the mechanisms in enclosures of these types. However, there is a problem with the available full scale data in this regard, as there is little data at full scale for *w/W = 1* and even for the *w/W < 1* case the data is skewed in that reasonably long enclosures are represented but wide enclosures are not. Nevertheless, the data is all that is available so recommendations must, for now, be based on it.

Thus it is recommended that the following expressions be used:

w/W = 1	$R = 0.435 \times w^{1.17} \times h^{1.69}$	($r^2 = 0.97$)	(4)
w/W < 1	$R = 3.39 \times w^{0.543} \times h^{1.31}$	($r^2 = 0.80$)	(5)

These may be compared with Kawagoe's formula:

$$R = 1.56 \times w^{1.0} \times h^{1.5} \qquad (r^2 = 0.66) \qquad (6)$$

(The range of enclosure and vent sizes used by Kawagoe to develop the relationship is not available to the author. Based on Figure 10.1 of Reference 7 there were about 27 tests. Based on the range of ventilation factors it appears that the characteristic dimensions of the vents used by Kawagoe ranged from about 0.3 m to about 5 m, a similar range as available to this study.)

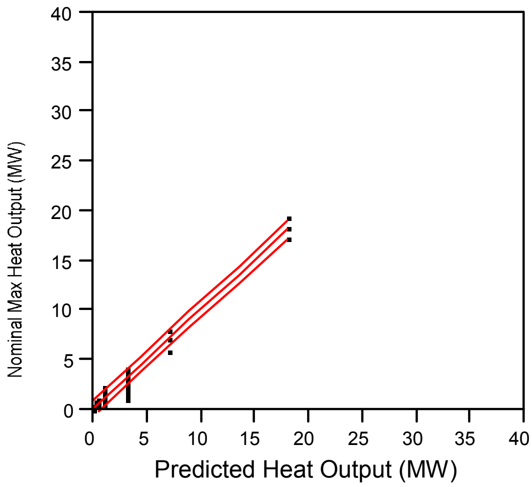


Figure 12 w/W = 1, Correlation of Equation 4 with Test Data

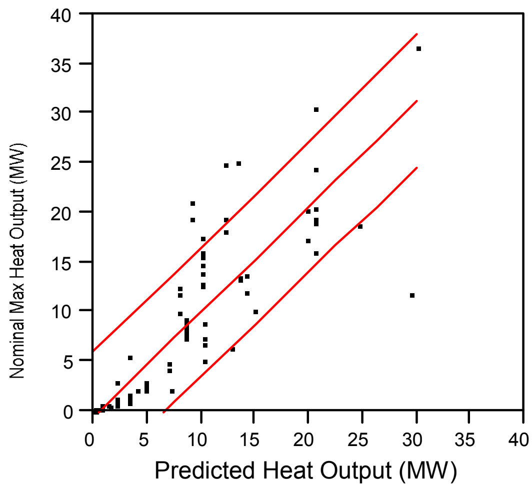


Figure 13 w/W < 1, Correlation of Equation 5 with Test Data

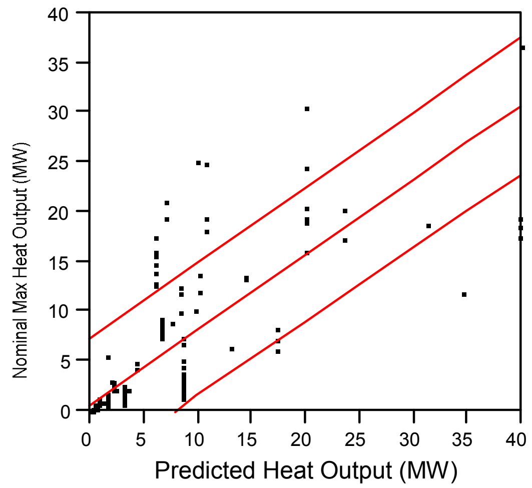


Figure 14 All w/W, Correlation of Equation 6 with Test Data

Figure 12 shows the very good correlation between the predicted and nominal maximum heat outputs for the $w/W = 1$ case, but it should be understood that this is over a limited range of vent sizes and there are only three tests at the highest size. Figure 13 shows considerably more scatter for the case $w/W < 1$, but nevertheless considerably less scatter than for Kawagoe's expression (Figure 14).

The correlation of Equations 4 and 5 with Kawagoe's formula is shown in Figures 15 and 16 for the range of vent sizes included in the database. Similar correlations, but for the range of vent sizes required for Project 3 are shown in Figures 17 and 18.

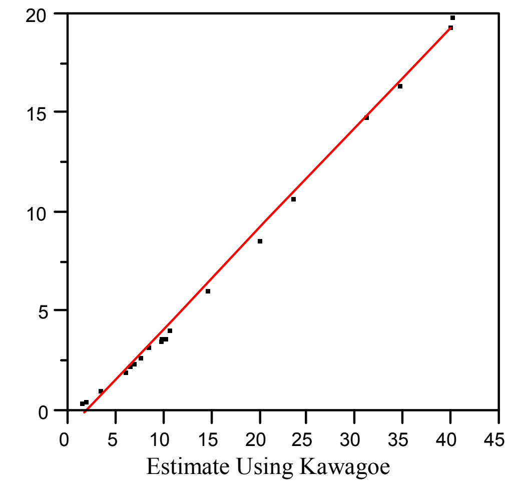


Figure 15 Correlation of Equation 4 with Equation 6 for *w/W = 1*

Figure 15 shows that Equation 4 correlated very well with Kawagoe's formula over the range of data (r^2 = 0.997) but the magnitude is approximately half of Kawagoe's estimate (= 0.51 x K - 0.97)

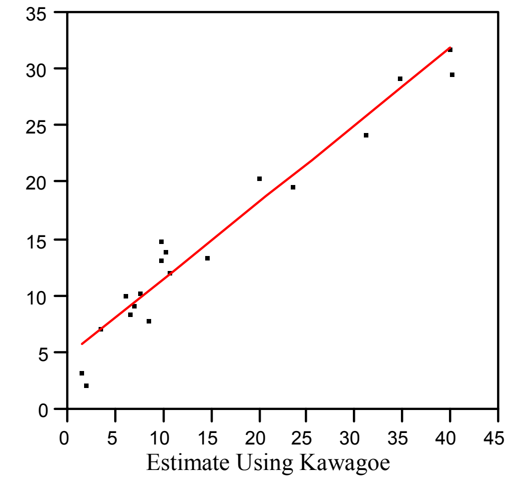


Figure 16 Correlation of Equation 5 with Equation 6 for *w/W* < *1*

Figure 16 shows that Equation 5 also correlated quite well with Kawagoe's formula over the range of data (r^2 = 0.95). The magnitude is closer to Kawagoe's estimate (= 0.68 x K + 4.8) but this is by virtue of an offset and an only a slightly closer slope.

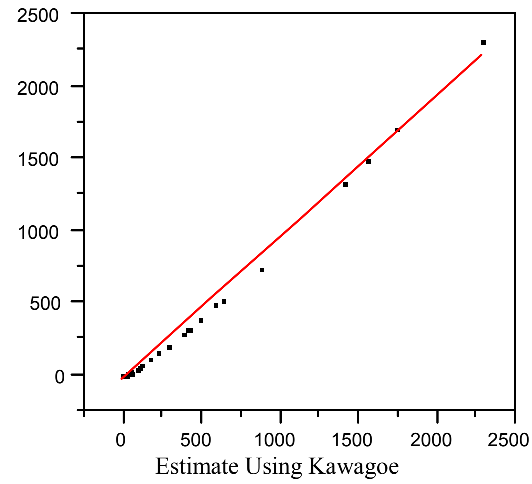


Figure 17 Correlation of Equation 4 with Equation 6

Figure 17 shows that Equation 4 correlates well with Kawagoe's formula over the range of data (r^2 = 0.995). The magnitude is very close to Kawagoe's estimate (= 0.98 x K - 32). However, this is at odds with the relationship over the range of the data, where the estimate using Equation 4 is about half Kawagoe's estimate.

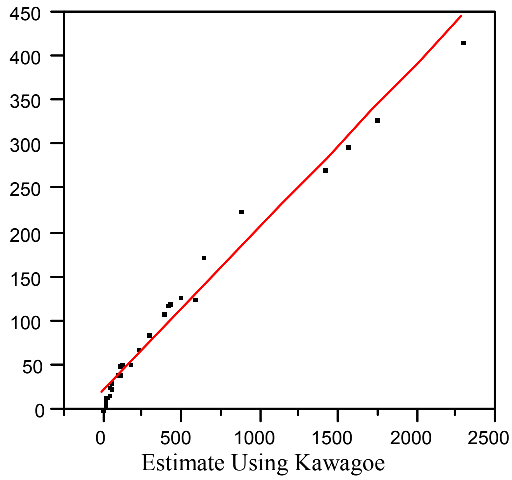


Figure 18 Correlation of Equation 5 with Equation 6

Figure 18 shows that Equation 6 also appears to correlate well with Kawagoe's formula over the range of data (r^2 = 0.95). But the magnitude is greatly different from Kawagoe's estimate (= 0.19 x K + 19). The offset has little effect with the relationship being dominated by the slope of 0.19. Again this is at odds with the relationship between these two estimates over the range of the data, where the Equation 6 estimate and Kawagoe's estimate are about the same.

This illustrates a problem.

None of the formulae have any theoretical basis - all, including Kawagoe's formula, are empirical expressions that correlate reasonably well with the experimental data. However, outside the range of the data they diverge and are not capable of providing a reliable estimate. This is illustrated in Figure 19 in which several of the correlations from Table 4 are plotted against Kawagoe's formula for the range of enclosure and opening sizes required for Project 3. Inspection of Figure 19 reveals that the predictions based on the formulae diverge widely. The user is left with the question of which (if any) to use, when none have any greater validity than any other.

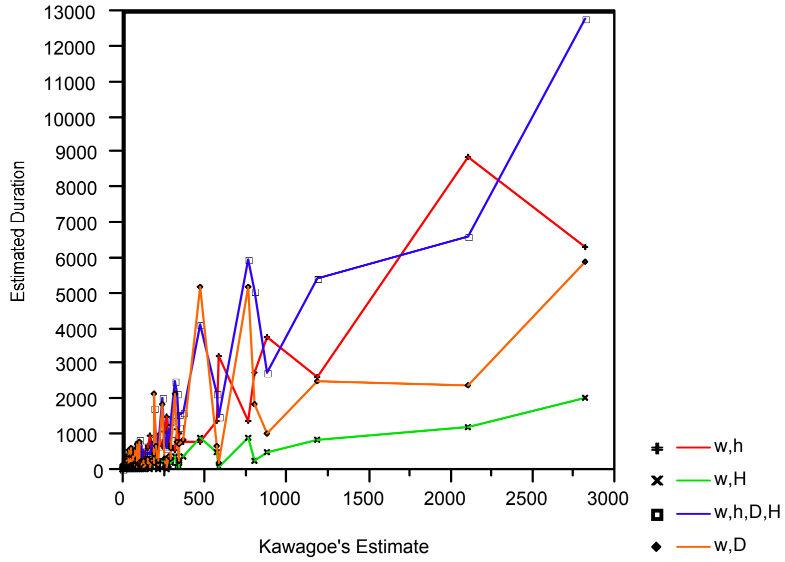


Figure 20 Comparison of Various Fire Duration Estimates (minutes) with Kawagoe's Estimate for the Range of Enclosure and Opening Dimensions for Project 3

Estimating Maximum Temperature

The variation of the maximum recorded temperature is plotted against enclosure and vent dimensions in Figure 21. The basis for the temperature varies slightly between the various test programs, but the figures used are assumed to represent a general maximum temperature reached in the tests. The variation in temperature in the CIB tests (which were all for the same room lining materials) was very high and no basis for close estimation of temperature was obtained for that data. For the small scale tests, little systematic variation in temperature was found over most of the range of tests. In that case (and this is reflected to some extent also in the CIB and full scale data) the major systematic variation in temperature was a reduction in temperature as the duration of burning became very long.

Shown in Figure 21 (and subsequent figures) are lines of best fit (generally parabolic, because a parabolic fit generally gave a significantly higher correlation coefficient than a straight line) and 95 percentiles on the temperatures. In Figure 21 it is obvious that there is some systematic variation in the maximum temperature with the dimensions of the enclosure and vent but that this variation is in the midst of great variability. It appears at least possible that there is a scale effect with higher temperatures being associated with larger enclosures. This may also be responsible for the apparent increase in temperature with increase in heat release rate (Figure 22), but as with the increase in temperature with increase in enclosure and vent dimensions, there seems to be some limit beyond which the effect is reversed.

It is commonly claimed that the temperature varies with the ratio of the total surface area of the enclosure (A_t) to the ventilation factor ($A\sqrt{h}$). A least squares regression has been conducted to check on this effect resulting in equation 7. In this equation the terms A_t, w and h have been combined to produce the best correlation.

$$T_m = 869 \times A_t^{0.0061} \times w^{0.044} \times h^{0.050} \qquad (r^2 = 0.26)$$

(7)

The resulting correlation is shown in Figure 23, where it is obvious that there is still a very large degree of scatter in the results. A similar regression combining in the same way the dimensions of the enclosure and the vent results in a slightly better correlation as shown in Figure 24. The resulting relationship is shown in equation 8.

$$T_m = 869 \times W^{0.0061} \times D^{0.00} \times H^{000} \times w^{0.044} \times h^{0.050} \qquad (r^2 = 0.28) \qquad (8)$$

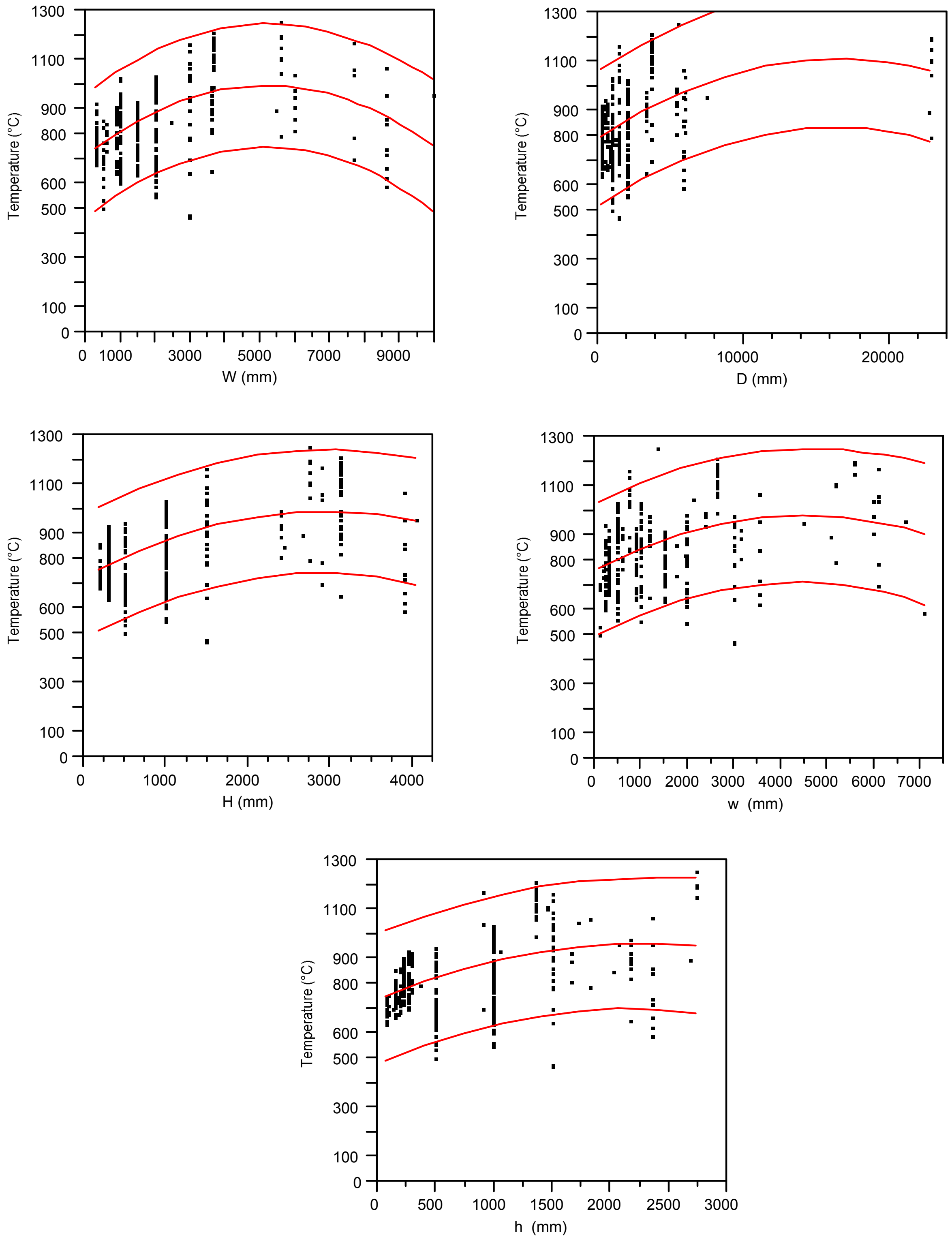


Figure 21 Variation of Maximum Temperature with Enclosure and Vent Dimensions

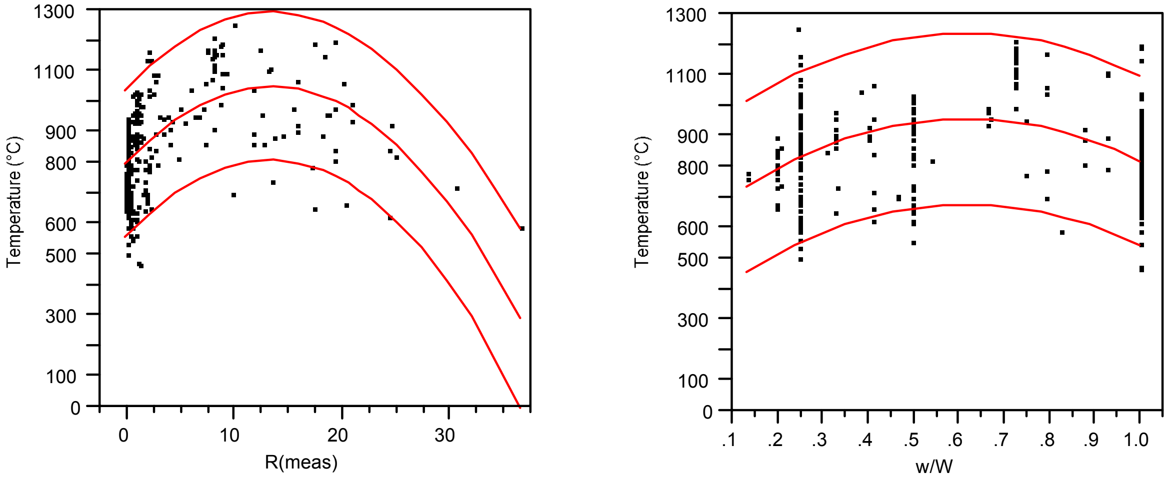


Figure 22 Variation of Maximum Temperature with Rate of Burning and w/W

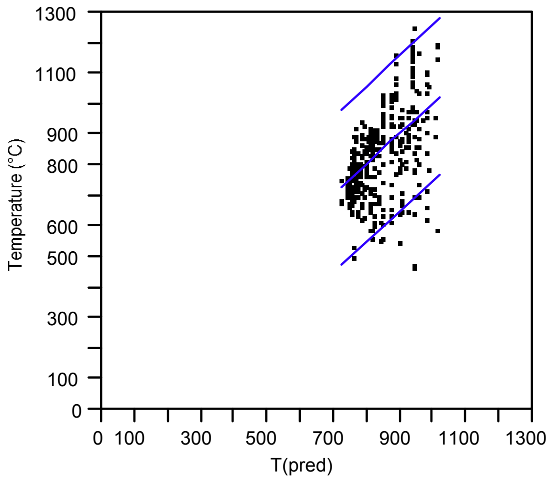


Figure 23 Correlation of Maximum Temperature with Equation 7

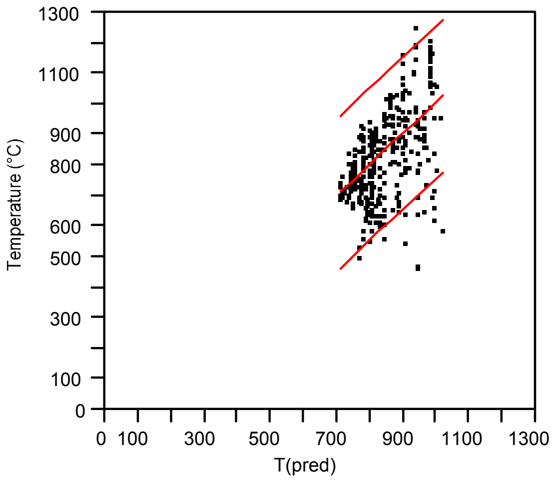


Figure 24 Correlation of Maximum Temperature with Equation 8

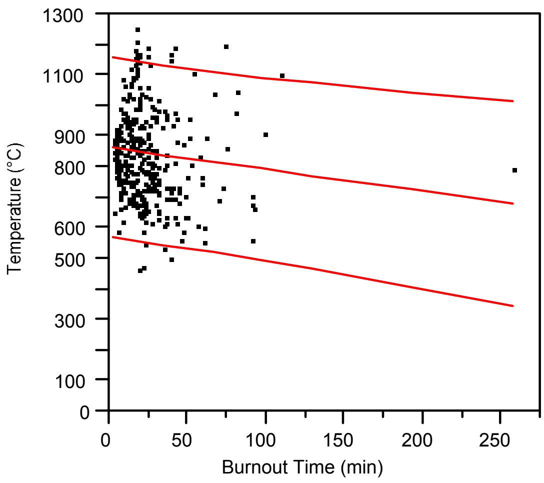


Figure 25 Correlation of Maximum Temperature with Burnout Time

In Figure 25 the correlation of the maximum temperature and the burnout time is shown. There appears to be some slight relationship for longer burnout times but there is clearly not a strong relationship at lower burnout times.

A reasonably close approximation to the upper limit of these temperatures can be obtained using Equation 9

$$T_m = 1000H^{0.12} \qquad (9)$$

However, it is not recommended that this equation be used to estimate the maximum temperature because any accuracy that may be assumed by users would be a mistake. It is recommended that a temperature of 1100°C be used, except perhaps when very low burning rates (associated with very low ventilation) are apparent.

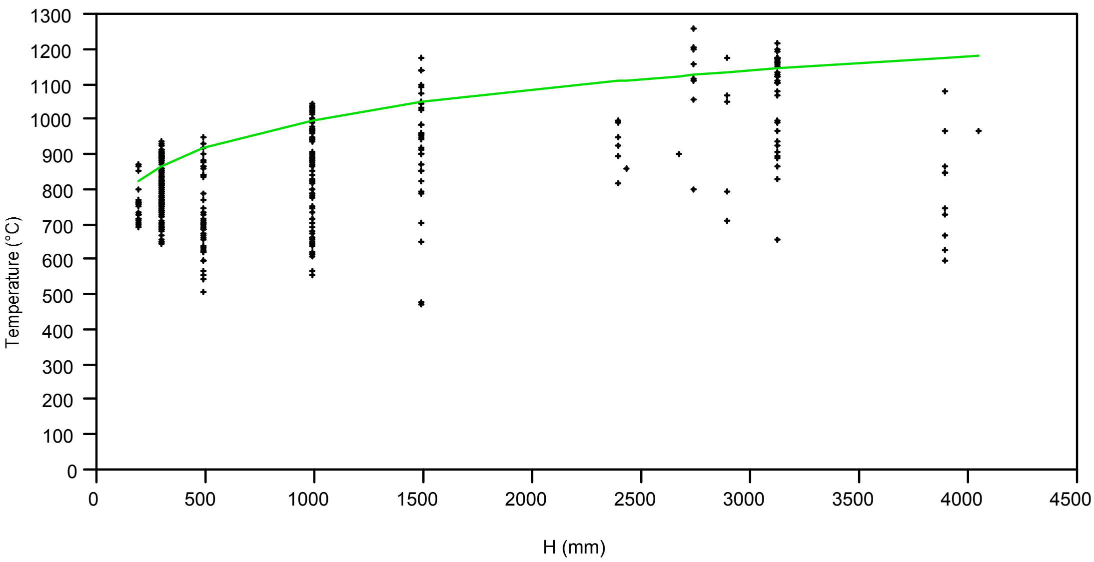


Figure 25 Recommended Maximum Temperature Curve (points are measured temperatures)

Predictions for Project 3 Enclosures

The enclosures, fuel loads and ventilation conditions of interest in Project 3 are shown in Table A2. As mentioned above these (particularly in relation to size) are considerably different from the enclosures covered by the experimental data.

It is not considered advisable to extrapolate significantly from the conditions represented by the experimental data. Consequently some consideration is required of how to treat the enclosures that require significant extrapolation.

Apart from the enclosure and vent dimensions, the other major departure from the experimental data is the fire load, which in many of the enclosures is considerably greater than used in the tests. Examination of the test results has revealed that for the quite limited range of fire loads covered, the changes in the fire load have little or no effect on the rate of burning. Thus, the duration of burning is essentially proportional to the fire load. It will be assumed that this remains true throughout the range of fire loads required for Project 3 although it is by no means certain that this is indeed the case for the very high fire loads specified for some occupancies.

With the recommendation that a single enclosure temperature be adopted the duration of high temperatures (assumed closely related to the duration of burning) becomes de facto a surrogate for fire severity. (It also appears from Figure 22 that there is no significant difference between the $w/W = 1$ and $w/W < 1$ cases in regard to temperatures.) As discussed above, small scale testing and the regression formulae developed above indicate that for a given vent size a full width vent ($w/W = 1$) results in longer fire durations than partial width vents. In terms of the objectives of Project 3, related to determination of FRL's for deemed to satisfy requirements it is conservative (that is, longer fire durations and thus higher FRL's will result) if it is assumed all vents are full width vents. Thus Equation 4 will be used in preference to Equation 5 for determination of fire duration.

Considering now the enclosure and vent size issues. The enclosure sizes 4 m by 8 m, 8 m by 4 m and 5 and 6 m by 20 m are within the range covered by the data and therefore can be addressed using Equations 4, 5 and 9. The remaining enclosure sizes 20 m by 5 and 6 m, 30 m by 50 m, 50 m by 100 m, 60 m by 60 m and 100 m by 50 m (see Table 1) are outside this range and therefore are not covered.

Fire duration and temperature results based on Equations 4 and 9 for the range of enclosures considered to be covered by the data are given in Table A3.

The fire duration is obtained from the following formula:

$$t_{500} = \frac{Q \times D}{\left(\frac{R}{1.7}\right) \times 60} \text{ (minutes)} \qquad (10)$$

This relates the total fire load per unit width of enclosure (and vent) divided by the maximum burning rate estimated using Equation 4 to the fire duration (taken as the time for which temperatures are above 500 °C). The 1.7 term adjusts the estimated maximum burning rate back to an average rate.

Before considering how to cover those enclosures requiring extrapolation it is worthwhile considering the results obtained from Equation 4 for the largest enclosures covered by the data. Therefore an enclosure 5 m wide by 20 m deep with a full width vent will be considered. The vent heights required for the large enclosures (Table A2) range include 0.91, 1.13, 1.21, 1.52, 1.70, 2.04, 2.40, 2.89, 3.00, 4.08, 4.34, 4.63, 5.00 and 6.00 m. The only vent height in the data for an enclosure of this approximate size is 2.75 m high. However in the smaller enclosures there are a variety of vent heights less than this, so it is presumed that smaller vents are reasonably covered by relationships based on the data. As pointed out in References ?, ? and ? the flows observed in enclosures with full width vents are essentially two-dimensional and thus it is expected that the gas flows and thus burning rate are essentially proportional to the width of the enclosure and vent. A regression has been carried out on the data similar to Equation 4 but with the index for the vent width w constrained to 1.0. The resulting relationship is Equation 11.

$$w/W = 1 \qquad R = 0.53 \times w \times h^{1.8} \qquad (r^2 = 0.97) \qquad (11)$$

This relationship (with $w = 1.0$ m) produces the results shown in Table 6 for unit width vents and the range of vent heights required. Note that vent heights greater than 3 m are a significant extrapolation from the data.

Table 6 Burning Rate and Fire Duration for a Range of Vent Heights

h (m)	R (MW/m)	$t_{<500}$ (minutes) for D = 20 m and Q = 1000 MJ/m^2
0.91	0.45	1267
1.13	0.66	858
1.21	0.75	759
1.52	1.13	503
1.70	1.38	411
2.04	1.91	296
2.40	2.56	221
2.89	3.58	158
3.00	3.83	148
4.08	6.66	85
4.34	7.44	76
4.63	8.36	68
5.00	9.60	59
6.00	13.33	42

The resulting fire durations for an enclosure 20 m deep with the fire load densities relevant for these enclosures are shown in Table 7.

Inspection of Table 7 reveals that for all but the lowest fire loads and greatest vent heights the fire durations are very high. Thus, it is expected that for enclosures of greater depth (but having the same vent height) the fire durations will be even greater.

Interpolation within Table 7 reveals that the actual duration for the enclosure that is just over 20 m deep with a 2.75 m high vent is close to the predicted duration. However, the durations for a similar depth enclosure at much smaller vent heights are much greater than those actually obtained.

Table 7 Fire Durations

	Fire Duration (minutes) for 20 m deep enclosure and specified fire load density (MJ/m^2)													
	Fire Load Density (MJ/m^2													
h (m)	**121**	**170**	**201**	**309**	**410**	**590**	**600**	**1000**	**1401**	**1600**	**1600**	**1904**	**5508**	**13005**
0.91	153	215	254	392	519	747	760	1266	1775	2027	2027	2412	6979	16477
1.13	104	146	172	265	352	506	515	858	1202	1373	1373	1634	4726	11159
1.21	92	129	152	235	311	448	455	758	1063	1214	1214	1444	4179	9866
1.52	61	86	101	156	206	297	302	503	705	805	805	958	2772	6544
1.7	50	70	83	127	169	243	247	411	576	658	658	783	2266	5350
2.04	36	50	59	92	121	175	178	296	415	474	474	564	1632	3853
2.4	27	38	44	68	91	130	133	221	310	354	354	421	1218	2876
2.89	19	27	32	49	65	93	95	158	222	253	253	301	872	2058
3	18	25	30	46	61	87	89	148	207	237	237	282	815	1925
4.08	10	14	17	26	35	50	51	85	119	136	136	162	469	1107
4.34	9	13	15	24	31	45	46	76	107	122	122	145	419	990
4.63	8	12	14	21	28	40	41	68	95	108	108	129	373	881
5	7	10	12	18	24	35	35	59	83	94	94	112	325	767
6	5	7	9	13	17	25	26	42	60	68	68	81	234	553

The figures in Table 7 indicate that for many deeper enclosures with moderate to very high fire load densities the possible fire durations are very great. Possibly in these cases extrapolation is unnecessary, as the fire durations are such that it is obvious that fires of such durations in buildings are simply unacceptable and also that the fire resistance level that would be required to withstand fires of such durations would be well over even the greatest fire resistances specified for buildings. In such cases it might be argued that systems preventing such fires occurring are more appropriate than attempting to physically confine or resist them by specifying a fire resistance level.

Conclusions

Estimates of the duration and maximum temperatures that might be experienced in fires in small enclosures have been made and are presented in Table A2.

Prediction of the duration and maximum temperatures that might be experienced in fires in large enclosures (but with sizes that are quite realistic for many buildings) is subject to great uncertainty as the test data that is available is only for smaller enclosures. Extrapolation based on such data as is available would require assumption of the form of the relationships between the variables. This is not possible at this stage.

Acknowledgments

The author is grateful to Rob Ralph, Michael Culton and Paul Tisch for carrying out the experimental program and to Ian Bennetts for support and valuable discussions.

References

1. Thomas, I.R. and Bennetts, I.D., *Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures, Submitted for IAFSS Symposium 1999.*
2. Thomas, P.H. and Heselden, A.J.M., *Fully Developed Fires in Single Compartments. A Cooperative Research Programme of the CIB,* CIB Report No 20, Fire Research Note 923.
3. Drysdale, D., *An Introduction to Fire Dynamics*, Wiley (1985).

Table A1

Test	Origin	D (m)	W (m)	H (m)	Maximum Heat Output (MW)	Fuel Type	FL	w (m)	h (m)	s (m)	BM Type	K (MW)	T °C
T7	VUT 1	5.4	3.6	2.4	19.4	NF	29	3.16	1.67	0.2	H	10.6	820
T8	VUT 2	5.4	3.6	2.4	20.9	NF	29	2.4	1.5	0.9	H	6.88	1000
T9	VUT 3	5.4	3.6	2.4	20.9	NF	29	2.4	1.5	0.9	H	6.88	950
T10	VUT 4	5.4	3.6	2.4	18.1	NF	29	3.16	1.67	0.2	H	10.6	900
T12	VUT 6	5.4	3.6	2.4	19.4	NF	29	2.4	1.5	0.9	H	6.88	990
T13	VUT 7	5.4	3.6	2.4	24.7	NF	29	3.16	1.67	0.2	H	10.6	930
T14c	BSC LSC1	22.9	5.6	2.75	19.4	WC	40	5.595	2.75	0	VH	39.8	1210
T15c	BSC LSC2	22.9	5.6	2.75	18.4	WC	20	5.595	2.75	0	VH	39.80	1160
T16c	BSC LSC3	22.9	5.6	2.75	13.4	WC	20	5.195	1.47	1.28	VH	14.4	1120
T17c	BSC LSC4	22.9	5.6	2.75	13.2	WC	40	5.195	1.47	1.28	VH	14.4	1110
T18c	BSC LSC5	22.9	5.6	2.75	8.80	WC	20	2.139	1.73	1.02	VH	7.60	1060
T19c	BSC LSC6	22.9	5.6	2.75	2.8	WC	20	5.195	0.375	2.375	VH	1.88	800
T20	BSC LSC7	5.6	5.6	2.75	10.1	WC	20	1.37	2.75	0	VH	9.75	1260
T21c	BSC LSC8	22.8	5.5	2.68	11.8	WC	20.6	5.065	2.68	0	H	34.7	905
T22c	BSC LSC9	22.9	5.6	2.75	17.4	WC	20	5.595	2.75	0	VH	39.8	1200
T24	BSC83-2	5.9	8.6	3.9	20.4	WC	10	3.55	2.36	1.54	H	20.1	670
T26	BSC83-4	5.9	8.6	3.9	36.7	WC	15	7.1	2.36	1.54	H	40.2	600
T27	BSC83-5	5.9	8.6	3.9	19.3	WC	15	3.55	2.36	1.54	H	20.1	850
T28	BSC83-6	5.9	8.6	3.9	11.8	WC	15	1.78	2.36	1.54	H	10.1	870
T30	BSC83-8	5.9	8.6	3.9	18.8	WC	20	3.55	2.36	1.54	H	20.1	970
T36	BSC83-14	5.9	8.6	3.9	30.5	WC	15	3.55	2.36	1.54	L	20.1	730
T37	BSC83-15	5.9	8.6	3.9	13.6	WC	15	1.78	2.36	1.54	L	10.1	750
T39	BSC83-17	5.9	8.6	3.9	24.4	WC	20	3.55	2.36	1.54	L	20.1	850
T41	BSC83-19	5.9	8.6	3.9	24.4	WC	15	3.55	2.36	1.54	H	20.1	630
T42	BSC83-20	5.9	8.6	3.9	15.9	MC	15	3.55	2.36	1.54	H	20.1	1080
T47	JFRO15-4	3.71	7.7	2.9	9.83	WC	15	6.1	0.915	1.985	H	8.33	710
T48	JFRO15-5	3.71	7.7	2.9	17.2	WC	30	6.1	1.83	1.07	H	23.6	795
T49	JFRO15-6	3.71	7.7	2.9	11.8	WC	30	6.1	0.915	1.985	H	8.33	1050
T50	JFRO15-7	3.71	7.7	2.9	20.1	WC	60	6.1	1.83	1.07	H	23.6	1070
T51	JFRO15-8	3.71	7.7	2.9	12.3	WC	60	6.1	0.915	1.985	H	8.33	1180
T52	CTICM 123	3.36	3.6	3.13	5.30	FP	30	0.9	1.06	2	H	1.53	940
T53	CTICM 130	3.36	3.6	3.13	17.48	FP	15	1.18	2.18	0.9	H	5.93	660
T54	CTICM 131	3.36	3.6	3.13	14.6	FP	20	1.18	2.18	0.9	H	5.93	900
T55	CTICM 132	3.36	3.6	3.13	12.8	FP	22	1.18	2.18	0.9	H	5.93	870
T56	CTICM 133	3.36	3.6	3.13	15.9	FP	30	1.18	2.18	0.9	H	5.93	930
T57	CTICM 134	3.36	3.6	3.13	15.9	FP	30	1.18	2.18	0.9	H	5.93	910
T58	CTICM 135	3.36	3.6	3.13	12.5	FP	30	1.18	2.18	0.9	H	5.93	970
T59	CTICM 136	3.36	3.6	3.13	15.4	FP	45	1.18	2.18	0.9	H	5.93	990
T60	CTICM 137	3.36	3.6	3.13	13.8	FP	45	1.18	2.18	0.9	H	5.93	890
T61	CTICM 143	3.36	3.6	3.13	25.0	FP	30	1.95	2.18	0.9	H	9.79	830
T70	CTICM/CDCE - 2	3.65	3.65	3.13	8.94	WC	39	2.65	1.36	1.47	H	6.56	1107
T71	CTICM/CDCE - 3	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1110
T72	CTICM/CDCE - 4	3.65	3.65	3.13	8.94	WC	39	2.65	1.36	1.47	H	6.56	1105
T73	CTICM/CDCE - 5	3.65	3.65	3.13	8.94	WC	58.5	2.65	1.36	1.47	H	6.56	1200
T74	CTICM/CDCE - 6	3.65	3.65	3.13	7.58	WC	39	2.65	1.36	1.47	H	6.56	1180
T75	CTICM/CDCE - 7	3.65	3.65	3.13	7.83	WC	29.3	2.65	1.36	1.47	H	6.56	1082
T76	CTICM/CDCE - 8	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1124
T77	CTICM/CDCE - 9	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1124
T78	CTICM/CDCE - 10	3.65	3.65	3.13	8.63	WC	39	2.65	1.36	1.47	H	6.56	1001
T79	CTICM/CDCE - 11	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1176
T80	CTICM/CDCE - 12	3.65	3.65	3.13	8.34	WC	39	2.65	1.36	1.47	H	6.56	1164
T81	CTICM/CDCE - 13	3.65	3.65	3.13	7.36	WC	39	2.65	1.36	1.47	H	6.56	1072

T82	CTICM/CDCE - 14	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1221
T83	CTICM/CDCE - 15	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1159
T84	CTICM/CDCE - 16	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1134
T85	CTICM/CDCE - 17	3.65	3.65	3.13	7.82	WC	39	2.65	1.36	1.47	H	6.56	1155
T86	CTICM/CDCE - 18	3.65	3.65	3.13	8.17	WC	29.3	2.65	1.36	1.47	H	6.56	1133
T87	CTICM/CDCE - 19	3.65	3.65	3.13	8.63	WC	39	2.65	1.36	1.47	H	6.56	1196
T88	CTICM/CDCE - 20	3.65	3.65	3.13	7.58	WC	39	2.65	1.36	1.47	H	6.56	1171
T89	CTICM80-1	3.65	3.65	3.13	8.94	WC	39	2.65	1.36	1.47	H	6.56	1166
T91	CTICM80-3	3.65	3.65	3.13	9.27	WC	39	2.65	1.36	1.47	H	6.56	1108
T92	CTICM80-4	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1177
T93	CTICM80-5	3.65	3.65	3.13	8.07	WC	39	2.65	1.36	1.47	H	6.56	1176

VUT 1-7: Alam and Beever: Flashover Tests
BSC LSC 1-9: BSC Natural Fires in Large Scale Compartments
BSC 82-2 to BSC 83-20: Document missing
JFRO 15-4 to 15-8: Document missing
CTICM: Arnault, Ehm and Kruppa, Doc No 2.10.20-3
CTICM: CDCE-2 to 20: Document missing
CTICM 80-1 to 5: Report No 1.019-2, September 1980

Table A2

Class	W (m)	D (m)	H (m)	w (m)	h (m)	OF	FL	FL (kg/m^2)	Equ 4 w/W=1	Equ 5 w/W<1	Equ 6 K
2 & 4	5	20	2.4	5	1.65	0.04	590	34.7	234	107	59
2 & 4	5	20	2.4	5	1.65	0.04	1000	58.8	397	182	101
2 & 4	5	20	2.4	5	1.65	0.04	1600	94.1	636	291	161
2 & 4	20	5	2.4	20	1.03	0.1	590	34.7	99	94	30
2 & 4	20	5	2.4	20	1.03	0.1	1000	58.8	167	159	51
2 & 4	20	5	2.4	20	1.03	0.1	1600	94.1	268	254	81
2 & 4	20	5	2.4	20	1.96	0.19	590	34.7	33	41	11
2 & 4	20	5	2.4	20	1.96	0.19	1000	58.8	56	69	19
2 & 4	20	5	2.4	20	1.96	0.19	1600	94.1	90	110	31
3a	4	8	2.4	4	0.78	0.04	300	17.6	177	52	37
3a	4	8	2.4	4	0.78	0.04	500	29.4	295	86	61
3a	4	8	2.4	4	0.78	0.04	780	45.9	460	135	96
3a	8	4	2.4	8	1.28	0.13	300	17.6	34	19	9
3a	8	4	2.4	8	1.28	0.13	500	29.4	56	32	15
3a	8	4	2.4	8	1.28	0.13	780	45.9	88	49	23
3a	8	4	2.4	8	2.4	0.28	300	17.6	12	8	4
3a	8	4	2.4	8	2.4	0.28	500	29.4	19	14	6
3a	8	4	2.4	8	2.4	0.28	780	45.9	30	22	9
3b	4	8	2.4	4	0.39	0.02	300	17.6	574	128	104
3b	4	8	2.4	4	0.39	0.02	500	29.4	957	213	174
3b	4	8	2.4	4	0.39	0.02	780	45.9	1493	332	271
3b	8	4	2.4	8	0.59	0.06	300	17.6	125	52	28
3b	8	4	2.4	8	0.59	0.06	500	29.4	209	86	47
3b	8	4	2.4	8	0.59	0.06	780	45.9	326	135	74
3b	8	4	2.4	8	1.18	0.12	300	17.6	39	21	10
3b	8	4	2.4	8	1.18	0.12	500	29.4	64	35	16
3b	8	4	2.4	8	1.18	0.12	780	45.9	100	55	26
3b	30	50	5	30	1.13	0.02	300	17.6	396	508	133
3b	30	50	5	30	1.13	0.02	500	29.4	659	847	222
3b	30	50	5	30	1.13	0.02	780	45.9	1029	1321	345
3b	50	30	5	50	2.04	0.06	300	17.6	79	180	33
3b	50	30	5	50	2.04	0.06	500	29.4	132	299	55
3b	50	30	5	50	2.04	0.06	780	45.9	205	467	86
3b	50	30	5	50	4.08	0.12	300	17.6	24	73	12
3b	50	30	5	50	4.08	0.12	500	29.4	40	122	19
3b	50	30	5	50	4.08	0.12	780	45.9	63	190	31
5	4	8	3	4	0.39	0.02	280	16.5	536	119	97
5	4	8	3	4	0.39	0.02	800	47.1	1531	340	278
5	4	8	3	4	0.39	0.02	1700	100.0	3253	723	591
5	8	4	3	8	0.79	0.08	280	16.5	72	33	17
5	8	4	3	8	0.79	0.08	800	47.1	205	95	49
5	8	4	3	8	0.79	0.08	1700	100.0	436	202	105
5	8	4	3	8	2.06	0.21	280	16.5	14	9	4
5	8	4	3	8	2.06	0.21	800	47.1	40	27	12
5	8	4	3	8	2.06	0.21	1700	100.0	84	58	25
5	60	60	3	60	1.52	0.02	280	16.5	233	532	95
5	60	60	3	60	1.52	0.02	800	47.1	666	1521	272
5	60	60	3	60	1.52	0.02	1700	100.0	1415	3232	579
5	60	60	3	60	3	0.08	280	16.5	74	221	35
5	60	60	3	60	3	0.08	800	47.1	211	631	99
5	60	60	3	60	3	0.08	1700	100.0	447	1340	210
5	60	60	3	60	3	0.21	280	16.5	74	221	35
5	60	60	3	60	3	0.21	800	47.1	211	631	99
5	60	60	3	60	3	0.21	1700	100.0	447	1340	210

6	5	20	3	5	1.21	0.03	410	24.1	276	112	66
6	5	20	3	5	1.21	0.03	1000	58.8	673	272	160
6	5	20	3	5	1.21	0.03	1900	111.8	1278	517	304
6	20	5	3	20	0.91	0.09	410	24.1	85	77	25
6	20	5	3	20	0.91	0.09	1000	58.8	208	187	62
6	20	5	3	20	0.91	0.09	1900	111.8	395	355	117
6	20	5	3	20	2.02	0.2	410	24.1	22	27	8
6	20	5	3	20	2.02	0.2	1000	58.8	53	66	19
6	20	5	3	20	2.02	0.2	1900	111.8	102	126	35
6	50	100	5	50	3.09	0.03	410	24.1	178	477	81
6	50	100	5	50	3.09	0.03	1000	58.8	434	1165	197
6	50	100	5	50	3.09	0.03	1900	111.8	824	2213	375
6	100	50	5	100	4.63	0.09	410	24.1	39	194	22
6	100	50	5	100	4.63	0.09	1000	58.8	95	473	54
6	100	50	5	100	4.63	0.09	1900	111.8	180	898	102
6	100	50	5	100	5	0.2	410	24.1	34	175	19
6	100	50	5	100	5	0.2	1000	58.8	83	428	48
6	100	50	5	100	5	0.2	1900	111.8	158	813	91
7a	5	20	2.4	5	0.83	0.02	120	7.1	155	54	34
7a	5	20	2.4	5	0.83	0.02	200	11.8	258	90	57
7a	5	20	2.4	5	0.83	0.02	310	18.2	400	139	88
7a	20	5	2.4	20	1.03	0.1	120	7.1	20	19	6
7a	20	5	2.4	20	1.03	0.1	200	11.8	33	32	10
7a	20	5	2.4	20	1.03	0.1	310	18.2	52	49	16
7a	20	5	2.4	20	2.4	0.3	120	7.1	5	6	2
7a	20	5	2.4	20	2.4	0.3	200	11.8	8	11	3
7a	20	5	2.4	20	2.4	0.3	310	18.2	12	16	5
7a	50	100	2.4	50	2.4	0.02	120	7.1	80	194	35
7a	50	100	2.4	50	2.4	0.02	200	11.8	133	323	58
7a	50	100	2.4	50	2.4	0.02	310	18.2	206	501	89
7a	100	50	2.4	100	2.4	0.1	120	7.1	35	133	17
7a	100	50	2.4	100	2.4	0.1	200	11.8	58	222	29
7a	100	50	2.4	100	2.4	0.1	310	18.2	90	344	45
7a	100	50	2.4	100	2.4	0.3	120	7.1	35	133	17
7a	100	50	2.4	100	2.4	0.3	200	11.8	58	222	29
7a	100	50	2.4	100	2.4	0.3	310	18.2	90	344	45
7b	5	20	4	5	1.2	0.03	1600	94.1	1095	441	260
7b	5	20	4	5	1.2	0.03	5500	323.5	3766	1516	894
7b	5	20	4	5	1.2	0.03	13000	764.7	8901	3584	2113
7b	20	5	4	20	0.9	0.09	1600	94.1	338	303	100
7b	20	5	4	20	0.9	0.09	5500	323.5	1163	1043	344
7b	20	5	4	20	0.9	0.09	13000	764.7	2750	2464	814
7b	20	5	4	20	2	0.2	1600	94.1	87	107	30
7b	20	5	4	20	2	0.2	5500	323.5	299	369	104
7b	20	5	4	20	2	0.2	13000	764.7	708	873	245
7b	50	100	6	50	2.89	0.03	1600	94.1	775	2029	348
7b	50	100	6	50	2.89	0.03	5500	323.5	2666	6974	1196
7b	50	100	6	50	2.89	0.03	13000	764.7	6300	16483	2826
7b	100	50	6	100	4.34	0.09	1600	94.1	169	824	95
7b	100	50	6	100	4.34	0.09	5500	323.5	582	2831	325
7b	100	50	6	100	4.34	0.09	13000	764.7	1376	6692	769
7b	100	50	6	100	6	0.2	1600	94.1	98	540	58
7b	100	50	6	100	6	0.2	5500	323.5	335	1856	200
7b	100	50	6	100	6	0.2	13000	764.7	792	4387	472
8	5	20	4	5	1.2	0.03	170	10.0	116	47	28
8	5	20	4	5	1.2	0.03	600	35.3	411	165	98
8	5	20	4	5	1.2	0.03	1400	82.4	959	386	228
8	20	5	4	20	0.9	0.09	170	10.0	36	32	11

8	20	5	4	20	0.9	0.09	600	35.3	127	114	38
8	20	5	4	20	0.9	0.09	1400	82.4	296	265	88
8	20	5	4	20	2	0.2	170	10.0	9	11	3
8	20	5	4	20	2	0.2	600	35.3	33	40	11
8	20	5	4	20	2	0.2	1400	82.4	76	94	26
					6	0.2	170	10.0	10	57	
		50	6	100	6	0.2	600	35.3	37	202	
		50	6	100	6	0.2	1400	82.4	85	472	
9a	6	20	3	6	1.14	0.03	200	11.8	143	64	35
9a	6	20	3	6	1.14	0.03	350	20.6	251	112	61
9a	6	20	3	6	1.14	0.03	550	32.4	394	176	96
9a	20	6	3	20	1.03	0.09	200	11.8	40	38	12
9a	20	6	3	20	1.03	0.09	350	20.6	71	67	22
9a	20	6	3	20	1.03	0.09	550	32.4	111	105	34
9a	20	6	3	20	2.29	0.2	200	11.8	10	14	4
9a	20	6	3	20	2.29	0.2	350	20.6	18	24	6
9a	20	6	3	20	2.29	0.2	550	32.4	29	37	10
9b	5	20	3	5	1.21	0.03	440	25.9	296	120	71
9b	5	20	3	5	1.21	0.03	750	44.1	505	204	120
9b	5	20	3	5	1.21	0.03	1200	70.6	807	326	192
9b	20	5	3	20	0.91	0.09	440	25.9	91	82	27
9b	20	5	3	20	0.91	0.09	750	44.1	156	140	46
9b	20	5	3	20	0.91	0.09	1200	70.6	249	224	74
9b	20	5	3	20	2.02	0.2	440	25.9	24	29	8
9b	20	5	3	20	2.02	0.2	750	44.1	40	50	14
9b	20	5	3	20	2.02	0.2	1200	70.6	64	79	22

Attachment 1

Fire Severity in Enclosures with Cross Ventilation

by

I R Thomas
BHP Research Melbourne Laboratories

Introduction

Fires in buildings occur in a virtually infinite variety of enclosure sizes and shapes. In estimating the *severity* of fires that may occur in an enclosure it is important that the effect of enclosure size, shape and ventilation be understood. A comparison of long and wide enclosures with single vents has been reported previously[1]. Another factor of importance is the effect of the position of openings on each side (or end) of an enclosure with one or two vents. This paper reports on small enclosure tests that address this aspect. Comparison of these with identical shape and size enclosures with single ventilation openings of similar size is also included.

The rate of burning (as measured by heat release rate or mass loss rate) in enclosure fires is usually assumed to be proportional to the opening size[2], directly proportional to the width and to the height raised to the power 1.5. Thus, for the same size ventilation openings the same rate of burning is expected. The experimental program reported below enables comparison of several fires in enclosures with similar total openings but with the openings positioned differently in the walls. An extensive experimental program covering fires in enclosures with single ventilation openings is reported elsewhere[3].

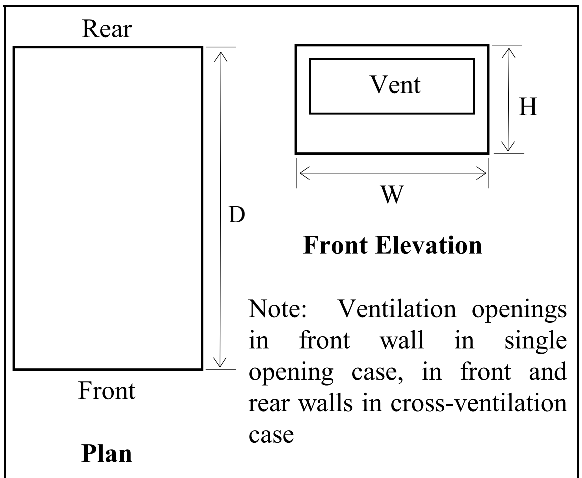


Figure 1 Enclosure Details

The following terminology and nomenclature is used for the clear internal dimensions of the enclosure (Figure 1):

- width (W) - horizontal dimension parallel to the plane(s) of the ventilation opening(s)
- depth (D) - horizontal dimension perpendicular to the plane(s) of the ventilation opening(s)
- height (H) - vertical dimension from the bottom surface to the top surface

The following terminology and nomenclature is used for the dimensions of the ventilation opening(s):

- opening width (w) - the clear horizontal dimension
- opening height (h) - the clear vertical dimension
- sill height (s) - the vertical dimension from the enclosure floor to the bottom of the opening

Experimental Program

The enclosures used in the cross-ventilation tests were all 300 mm wide, 1500 mm deep and 200 or 300 mm high (interior dimensions), with the roof, floor and walls of 3 mm steel sheet. In addition, a number of tests were conducted with one side wall of the steel enclosures replaced by glass. This enabled viewing of the development of the fires and of the gas flows that developed. The effect of the glass wall on the fires was minor compared with the effects of the changes in ventilation.

In each test 2.5 litres of liquid fuel (96% ethanol and 4% methanol) in five trays each 250 mm square and 25 mm high (each containing 500 ml of fuel) was burned.

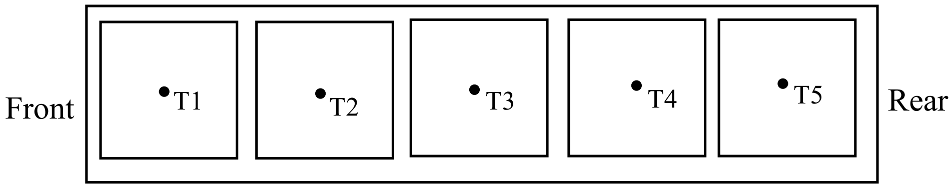


Figure 2 Tray and Thermocouple Positions and Numbers

Temperatures were recorded using five Type K mineral insulated thermocouples each 20 mm from the roof and placed centrally over a tray of fuel (Figure 2). Temperature readings were taken every 15 seconds. The fuel mass loss was recorded by weighing the entire enclosure. The mass loss was recorded manually at 15 second intervals using a digital scale able to resolve to 0.01 kg. The vent and enclosure shapes and sizes tested are shown in Table 1.

Burning of Trays in the Open

Single trays of 500 ml of the liquid fuel were burned in the open to establish the duration of burning in the free-burn situation.

Figure 3 Burning of Single Tray in Open

When burned in the open the fuel burned on all sides of the tray with the flames covering the entire tray. The flames were generally symmetrical and central above the tray (Figure 3).

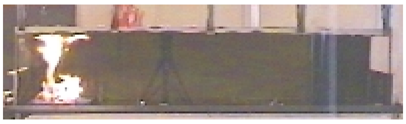
In the open, single trays containing 500 ml of this fuel burned in an average of 418 seconds. When five trays spaced as in the 300 mm by 1500 mm enclosures were burned in the open, the burnout time averaged of 539 seconds, about 26% longer than for a single tray.

Cross-Ventilation Tests

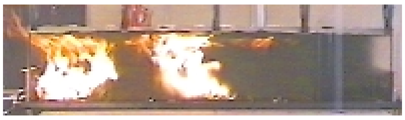
The behaviour of the fires and flows through the enclosures depended on the position of the openings. The tray furthest from the lowest vent was ignited first when the ambient temperature made this possible. If the ambient temperature was sufficiently high, flames flashed briefly throughout the enclosure before stable burning commenced in the tray adjacent to the vent in the single vent tests, and in the cross-ventilation cases, adjacent to the lowest vent or adjacent to both vents in tests with vents at the same sill height in both the front and rear walls.

In the single vent case[3], when it was possible, the fire was usually lit in the tray furthest from the ventilation opening. In such cases the fire rapidly migrated to the tray closest to the vent without burning much of the fuel and burned along the edge of the tray closest to the vent until the tray was empty. The fire then burned on the front edge of the next tray and so on until all of the fuel in the enclosure was exhausted. The fire burned in one tray at a time despite the presence of other trays of fuel further from the vent.

In the cross-ventilation cases where the vents were of the same size and at the same height the flows were symmetrical for most of the time with flow both into and out of each opening (Figures 4 and 5). In cases when it was possible to start the fire in one tray (as in the tests shown in Figures 4 and 5) the fuel in the adjacent tray ignited soon after the first was ignited. Then the fuel in the next (third) tray ignited, but as soon as this became established burning ceased in the second tray. This pattern continued until only the two end trays adjacent to the vents were burning. Once the fuel in these trays was exhausted burning commenced in the second trays in from each end. Finally the middle tray ignited and burned. The flows in the enclosure were, for most of the time, symmetrical with both vents having inwards flows at the bottom and outwards flows at the top. Effectively, each half of the enclosure appeared to behave as though the enclosure was half the actual length and had an opening at one end only. Occasionally the flow would largely be in at one end and out of the other, but this was not a stable situation and soon reverted to the symmetrical flows described.

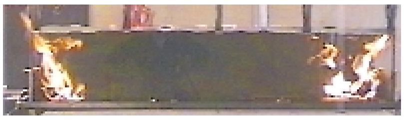


(a) Fire ignited in one end tray



(b) Fire splits and second fire moves towards other vent

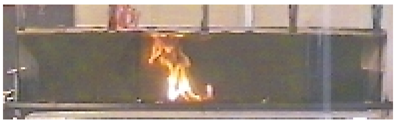
(c) Second fire nears second vent, fire in first tray still burning



(d) Fire in both end trays with fuel in both nearly exhausted

(e) Fire moving between trays

(f) Fire in adjacent trays

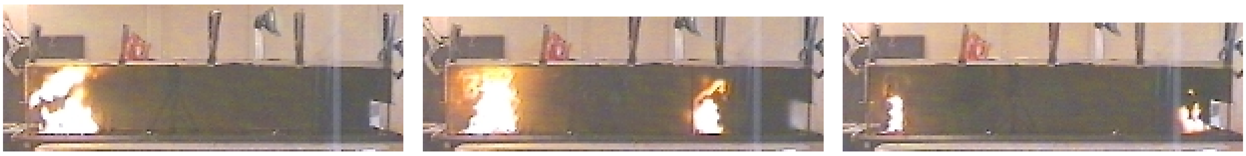


(g) Fire in middle tray, fuel almost exhausted

Figure 4 Images from Video Record of Fire in Enclosure 300 mm Wide, 1500 mm Deep and 300 mm High with Full Width Ventilation Opening at Top of Each End Wall

The behaviour in the enclosures with the opening at the top at one end and at the bottom at the other end was quite different. As mentioned previously, if the ambient temperature was high enough that the fuel throughout the enclosure "flashed" when the ignition flame was introduced into the enclosure, stable burning was established in the tray closest to the low ventilation opening and the other trays of fuel did not burn. When the fuel in that tray was exhausted the fire transferred to the next tray and so on until finally the tray nearest the high ventilation opening burned. From this description it is obvious that the flow that quickly became established was almost entirely **in** at the end with the lower opening and **out** at the other end. However, occasionally small flames were emitted from the lower opening. The flame extension at the other end for most of the time was very large and occasionally a very large ball of flame erupted from this end. The trays did not burn simultaneously - burning occurred preferentially in the tray with fuel closest to the low end. Thus the fuel in the tray at the low end burned first, the second tray from this end next, and so on until the tray closest to the end with the high opening burned.

When the ambient temperature was low enough that there was no "flash" at ignition the tray nearest the high vent was ignited. The burned in this tray for a short time, but well before the fuel in the tray was exhausted, burning transferred to the second tray and the first tray went out (Figure 6). This tray again burned for a short time and the fire then transferred to the middle tray, whereupon the fire in the second tray went out. This process continued until the tray nearest the low vent was burning. Once the fire had transferred away from the high vent there was a large flare out of the high vent. It appears that fuel was being evaporated from the trays between the tray that was burning and the high vent, but there was insufficient oxygen in the gas flow to burn it and it burned on contact with the air outside the high vent. It is noteworthy that the transfer of the fire from the high vent end to the low vent end was against the prevailing airflow and was somewhat slower than the transfer that occurred after ignition in the enclosures with single vents and those with both vents at the same height.



(a) Fire ignited in one end tray

(b) Fire splits and second fire moves towards other vent

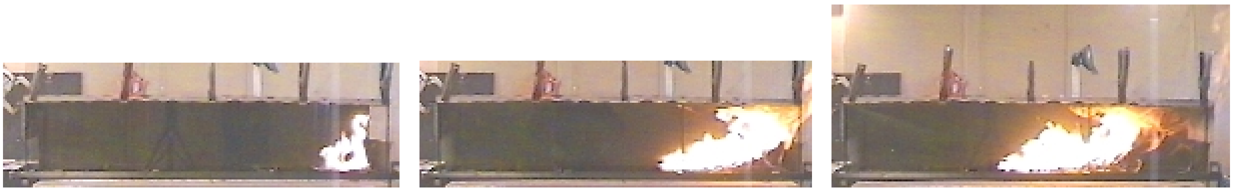
(c) Second fire nears second vent, fire in first tray still burning

(d) Fuel in end trays used and fire moves to second trays from ends

(e) Fire moves towards centre

(f) Fire finishes in middle of enclosure

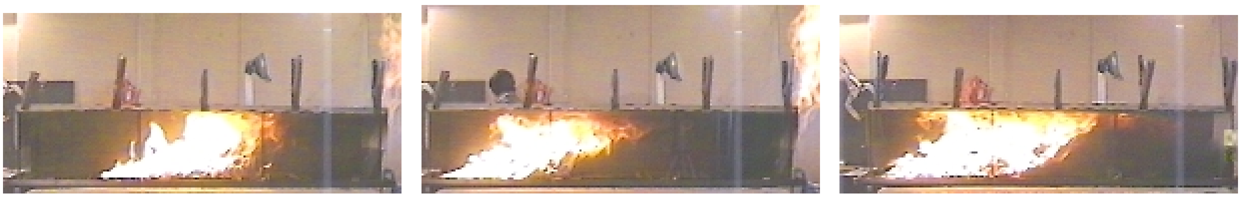
Figure 5 Images from Video Record of Fire in Enclosure 300 mm Wide, 1500 mm Deep and 300 mm High with Full Width Ventilation Opening at Bottom of Each End Wall



(a) Fire started in tray nearest high vent

(b) Fire moves towards lower vent with much fuel still in first tray

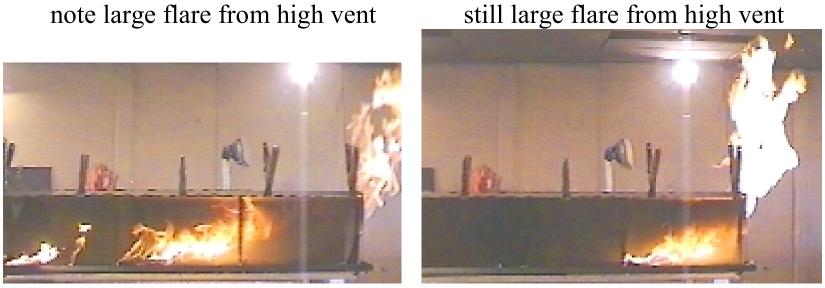
(c) Fire in middle tray, note large flare out of vent



(c) Fire in second tray from low vent, note large flare from high vent

(d) Fire in tray close to low vent, still large flare from high vent

(e) Fire in second tray from low vent



(f) Fire moving to middle tray, large flare still from high vent

(g) Fire returns to high vent end as fuel closer to low vent exhausted

Figure 6 Images from Video Record of Fire in Enclosure 300 mm Wide, 1500 mm Deep and 300 mm High with Full Width Ventilation Opening at Bottom of Each End Wall at Bottom of One End Wall and Top of Other End Wall

Once the fuel in the tray closest to the low vent was exhausted the fire transferred to the second tray from the low vent end and so on. In some tests the fuel in one or more of the subsequent trays was exhausted prior to this transfer and the fire skipped to the next tray with fuel.

Examples of temperature histories for several of the tests are given in Figures 7 to 10. The temperatures mirror the observed behaviour. In Figures 7 and 8 which are for enclosures with equal height openings at both ends, once the brief peak temperatures associated with the initial spread or transition of the fire have passed, the temperature in a region (that is, near a thermocouple) remains comparatively low until the fire moves close to that region. Thus, the tops of the enclosures at the ends are at high temperatures for much longer than the middle of the enclosures.

Table 1 Data for Enclosures with Openings at Both Ends

Width (mm)	**Depth (mm)**	**Height (mm)**	**Vent Width (mm)** (Front)	**Vent Height (mm)** (Front)	**Sill Height (mm)** (Front)	**Vent Width (mm)** (Rear)	**Vent Height (mm)** (Rear)	**Sill Height (mm)** (Rear)	**Burnout Time (s)**	**Maximum Temperature (°C)**
300	1500	200	300	200	0	300	200	0	1260	878
300	1500	200	300	200	0	300	200	0	1241	869
300	1500	200	300	100	100	300	100	100	2007	904
300	1500	200	300	100	100	300	100	100	2610	840
300	1500	200	300	100	100	300	100	100	2310	800
300	1500	200	300	100	0	300	100	0	3055	697
300	1500	200	300	100	0	300	100	0	3055	676
300	1500	200	300	100	0	300	100	100	932	837
300	1500	200	300	100	0	300	100	100	892	817
300	1500	300	300	275	25	300	275	25	657	907
300	1500	300	300	275	25	300	275	25	655	892
300	1500	300	300	150	150	300	150	150	1369	851
300	1500	300	300	125	25	300	125	25	1667	851
300	1500	300	300	125	25	300	150	150	820	894
300	1500	300	300	125	25	300	150	150	823	870
300	1500	300	300	125	25	300	150	150	812	878

Figures 9 and 10 are both for enclosures with the vent at the front low and at the rear high, but the test in Figure 9 was ignited near the high vent (at the rear) and that in Figure 10 was ignited near the low vent (near the front).

Figures 11 and 12 show the variation in fuel mass with time during tests with the 200 and 300 mm high enclosures respectively. In both figures the variation of mass with time is reasonably linear (that is, the mass loss rate is reasonably constant) throughout most tests. There is no obvious explanation of the variations between some of the nominally identical tests. Generally though, the repeatability of similar tests is very good. In Figure 11 the mass loss is most rapid with 100 mm openings at the bottom on one end and at the top on the other end. The next most rapid is for enclosures with 200 mm openings both ends and the least rapid is for enclosures with 100 mm openings at the bottom both ends. Unlike the cases mentioned previously, there is significant variation between tests with 100 mm openings at the top both ends, with the slowest falling just under the lines for 100 mm openings at the bottom both ends. There is a significant bi-linearity of the other two tests. The results for the 300 mm high enclosures (Figure 12) are a little different, with the lines for enclosures with 275 mm openings at both ends and those for enclosures with a

125 mm opening at the bottom on one end and a 150 mm opening at the top at the other end being very similar. However, the mass loss was substantially slower for the enclosures with 150 mm openings at the top and for those with 125 mm openings at the bottom, with the former being the faster of these by a small margin.

The overall burnout time results for enclosures with openings at both ends are presented in Figure 13 along with the burnout times for similar enclosures with a single ventilation opening[3].

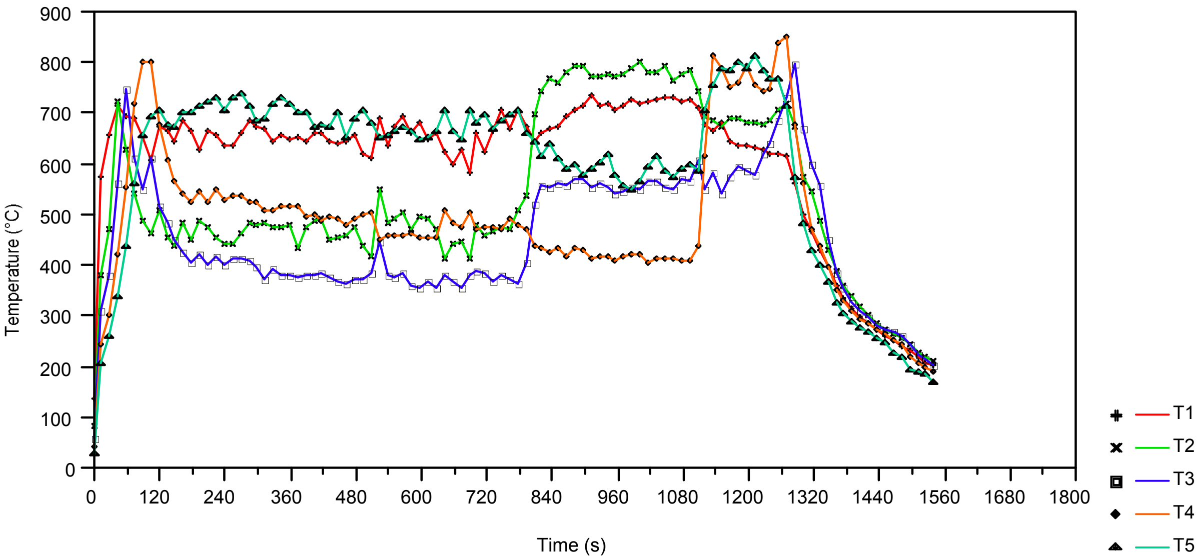


Figure 7 Temperature History of Enclosure 300 mm Wide, 1500 mm Long and 300 mm High with Vents 300 mm Wide by 150 mm High at Top of Each End

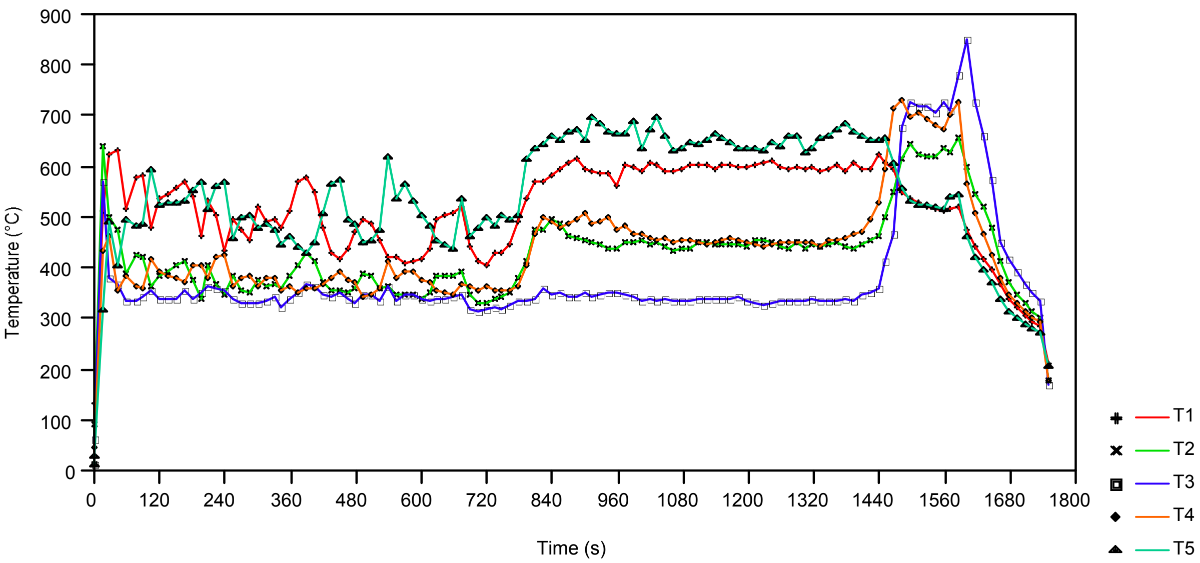


Figure 8 Temperature History of Enclosure 300 mm Wide, 1500 mm Long and 300 mm High with Vents 300 mm Wide by 125 mm High at Bottom of Each End

The burnout time for the *1500 mm long by 200 mm high* enclosures with both ends completely open averaged 1250 seconds which is longer than the burnout time for the *600 mm long by 200 mm high* enclosure with a single 200 mm high opening but shorter than the average for the similar *900 mm long by 200 mm high* enclosures. It is less than a third of the average burnout time for the *1500 mm long by 200 mm high* enclosure with a single 200 mm high opening.

Several of the *1500 mm long by 200 mm high enclosures* have the same total opening area. The shortest burnout time among these (average 912 seconds) is for the enclosure with 100 mm high openings at the bottom at one end and the top at the other end. The others with openings at both ends have average burnout times 2.5 and 3.3 times this for both openings at the top and bottom respectively. In comparison, the *1500 mm long by 200 mm high enclosure* with a single 200 mm high opening has an average burnout time 4.5 times longer.

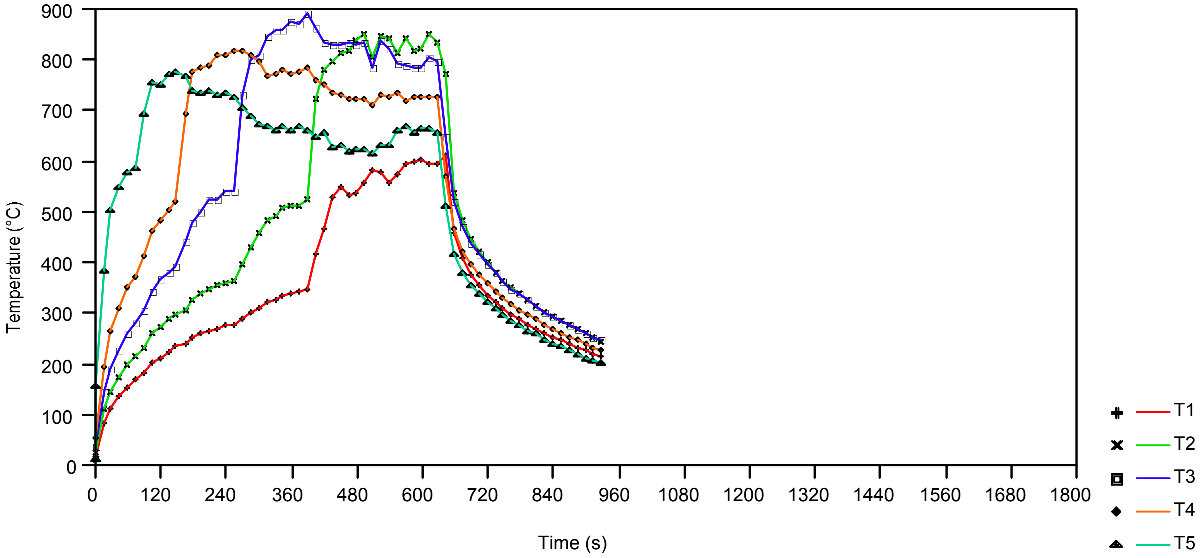


Figure 9 Temperature History of Enclosure 300 mm Wide, 1500 mm Long and 300 mm High with Vents 300 mm Wide by 150 mm High at Top one End, 125 High at Bottom other End (Ignition high end)

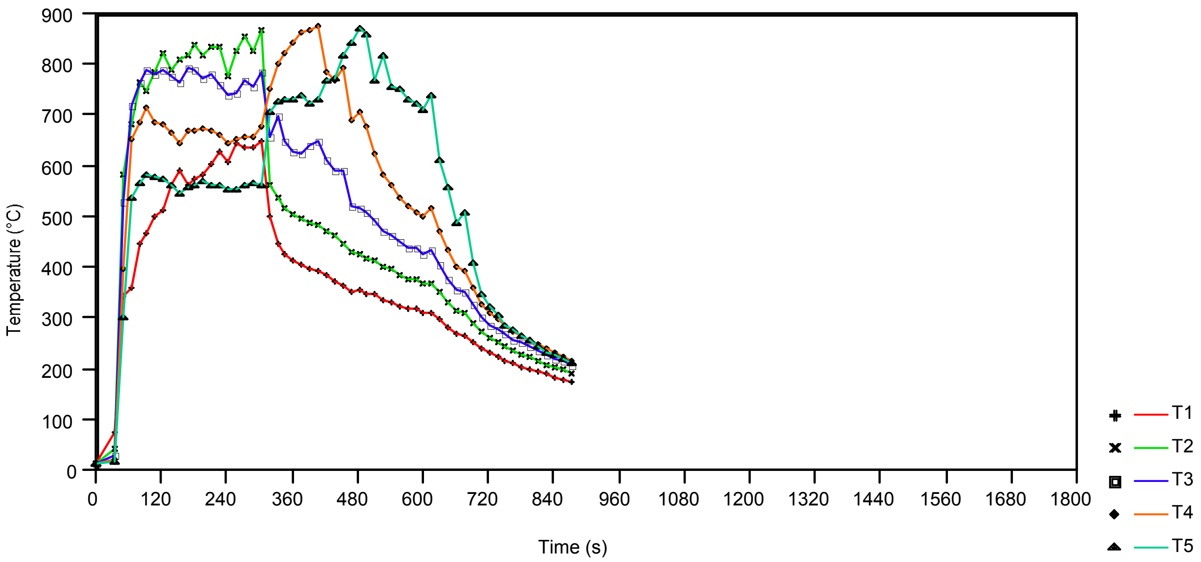


Figure 10 Temperature History of Enclosure 300 mm Wide, 1500 mm Long and 300 mm High with Vents 300 mm Wide by 150 mm High at Top one End, 125 High at Bottom other End (Ignition low end)

The differences are a little less for the 300 mm high enclosures.

The burnout time for the *1500 mm long by 300 mm high* enclosures with 275 mm high openings at both ends averaged 656 seconds which is longer than the burnout time for the *600 mm long by 300 mm high* enclosure with a single 275 mm high opening (564 seconds) but shorter than the average for the similar *900 mm long by 300 mm high* enclosures (863 seconds). It is slightly greater than a third of the average burnout time for the *1500 mm long by 300 mm high* enclosure with a single 275 mm high opening (1789 seconds).

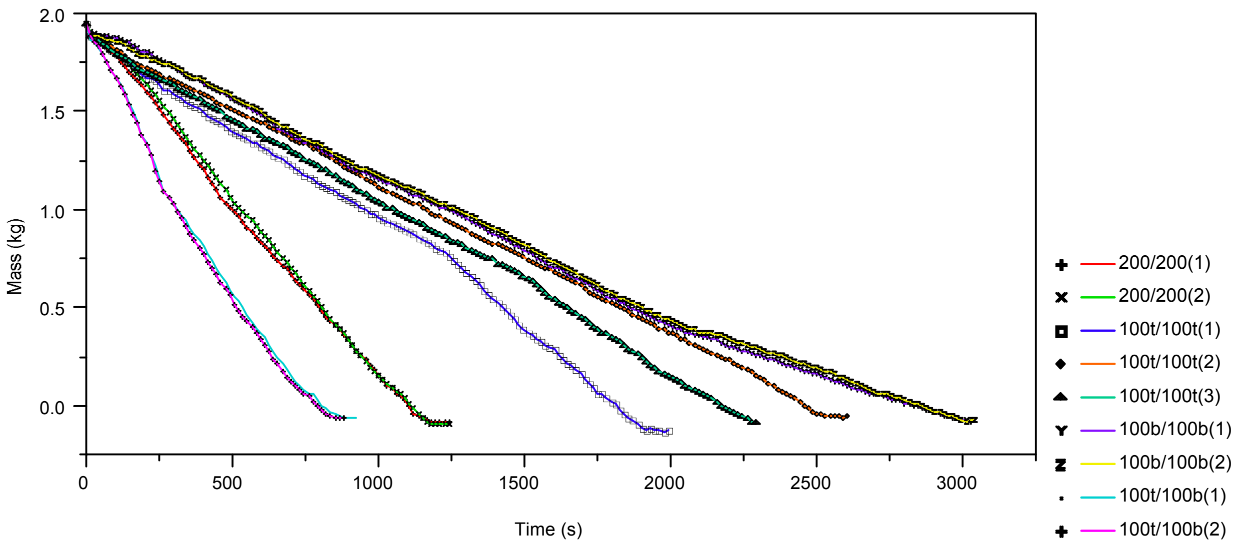


Figure 11 Variation in Fuel Mass During Tests in Enclosure 300 mm Wide, 1500 mm Long and 200 mm High

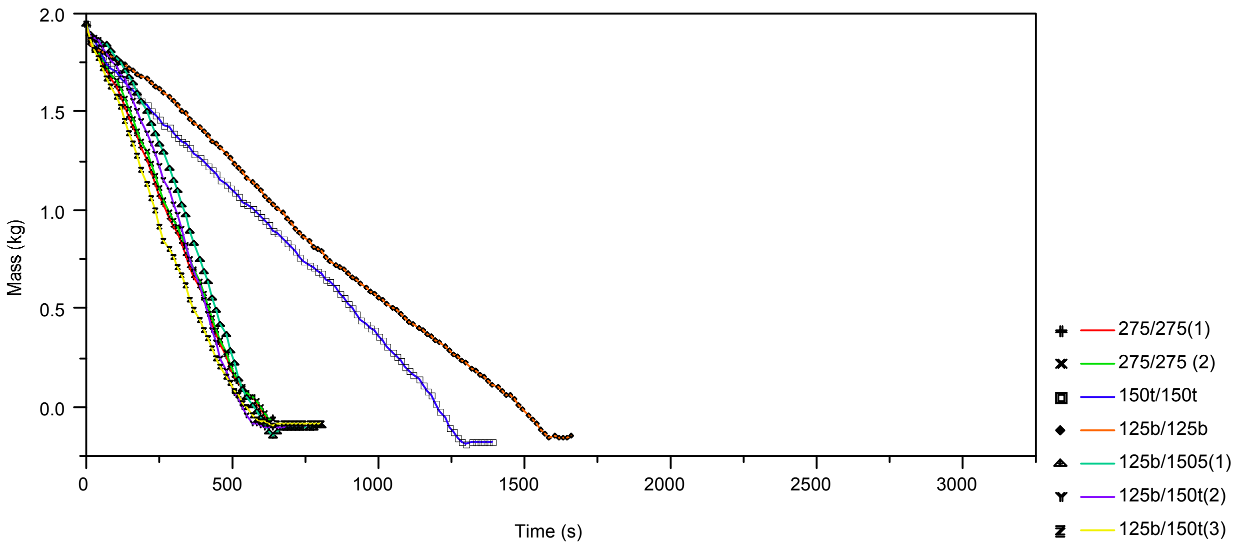


Figure 12 Variation in Fuel Mass During Tests in Enclosure 300 mm Wide, 1500 mm Long and 300 mm High

As for the *1500 mm long by 200 mm high enclosures*, several of the *1500 mm long by 300 mm high enclosures* have very similar total opening areas. The shortest burnout time among these (average 817 seconds) is for the enclosure with a 125 mm high opening at the bottom at one end and a 150 mm opening at the top at the other end. In comparison, the burnout time for the *1500 mm long by 300 mm high enclosure* with 150 mm high openings at the top of both ends was 1.7 times as long and the burnout time for the same size enclosure with 125 mm high openings at the bottom of both ends was twice as long. In comparison, the *1500 mm long by 300 mm high enclosure* with a single 275 mm high opening has an average burnout time 2.2 times as long.

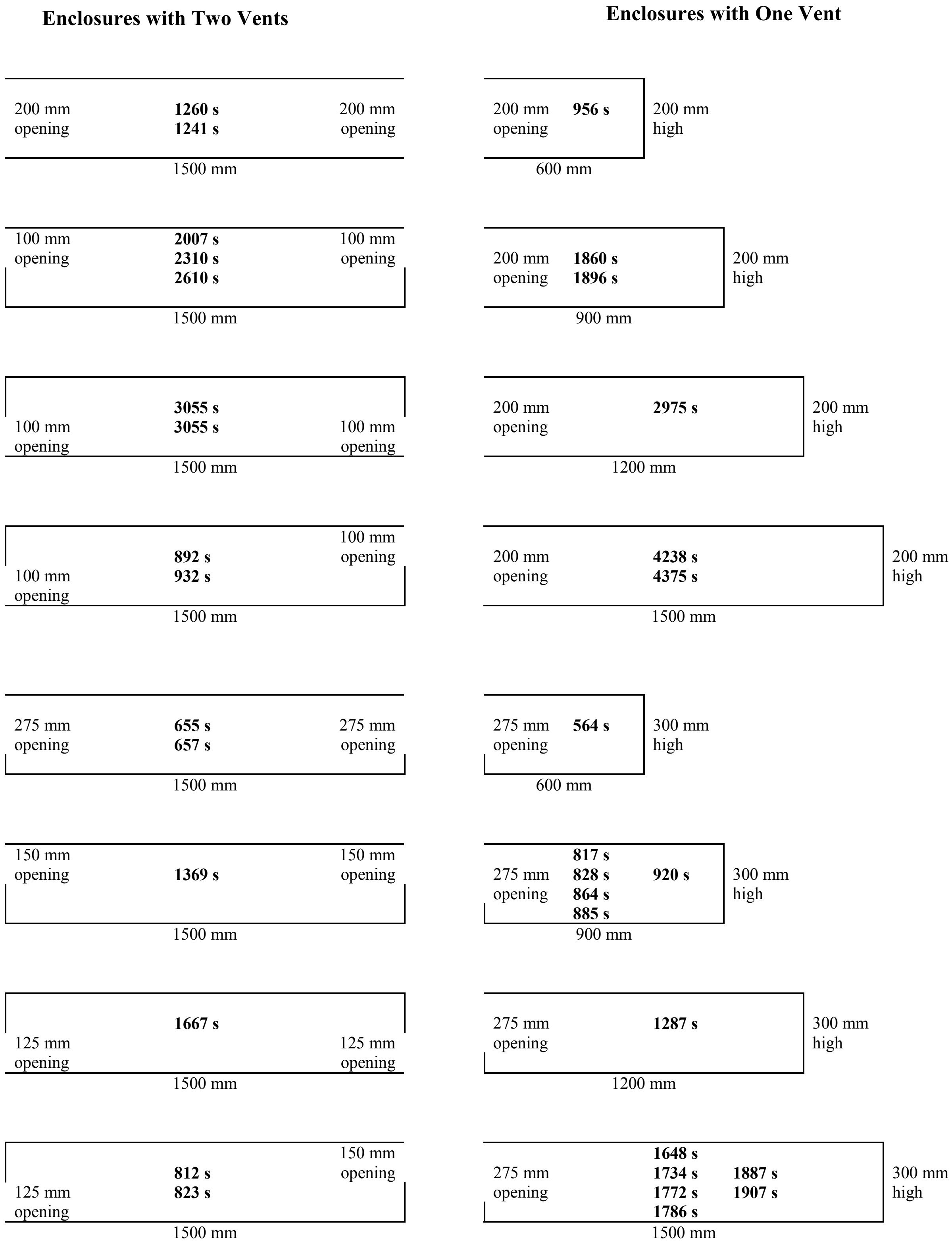


Figure 13 Burnout Times for Enclosures with Openings Both Ends and Similar Enclosures with Single Openings for Comparison

Conclusions

Thus it is clear that great differences in burnout time (and thus average burning rate) occur in enclosures even though they have similar total opening areas. Relatively small differences in the maximum temperatures in the enclosures occurred (Table 1).

Based on these results it is obvious that the position and relative positions of the ventilation openings are very important in determining the severity of fires in enclosures. Openings at different levels on opposite sides of an enclosure lead to the shortest burnout times and thus the least severe fires. Significant differences occur between this case and the burnout times for enclosures with both openings at the top and those with both openings at the bottom.

Acknowledgments

The author is grateful to Rob Ralph, Michael Culton and Paul Tisch for carrying out the experimental program.

References

1. Thomas, I.R. and Bennetts, I.D., *Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures, Submitted for IAFSS Symposium 1999.*
2. Drysdale, D., *An Introduction to Fire Dynamics*, Wiley (1985).

Attachment 2

Fire Severity in Single Vent Enclosures with Uniform Fire Load

by

I R Thomas
BHP Research Melbourne Laboratories

Introduction

The severity of possible fires in a building must be estimated in order to properly develop an engineering design of the fire safety system for the building. The *severity* of a fire in an enclosure is dependent on a number of factors including the size, shape and ventilation of the enclosure. In investigating the severity of fires to be considered in estimating the fire resistance requirements for barrier and structural elements for buildings it became apparent that the estimates obtained using available fire models and correlation formulae were unreliable for the broad range of enclosure sizes, shapes and ventilation arrangements that are possible.

A comparison of fire severity in long and wide enclosures with single vents has been reported previously[1]. Another factor of importance that has previously been reported is the effect of the position of the openings in each end of enclosures with two vents[2]. Reference 2 included a comparison of the cross ventilation (two vent) cases with single vent cases in identical shape and size enclosures.

The rate of burning (as measured by heat release rate or mass loss rate) in enclosure fires is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$ [3], which means that it is directly proportional to the vent width w and height h raised to the power 1.5, that is $h^{1.5}$. Thus, for the same size ventilation openings the same rate of burning is expected. The experimental program reported below investigated the effect of opening shape and size and enclosure shape on the rate of burning in an enclosure with fuel uniformly distributed through the enclosure. An extensive experimental program covering fires in enclosures with single ventilation openings with fuel limited to one area in the enclosure has been reported elsewhere[4].

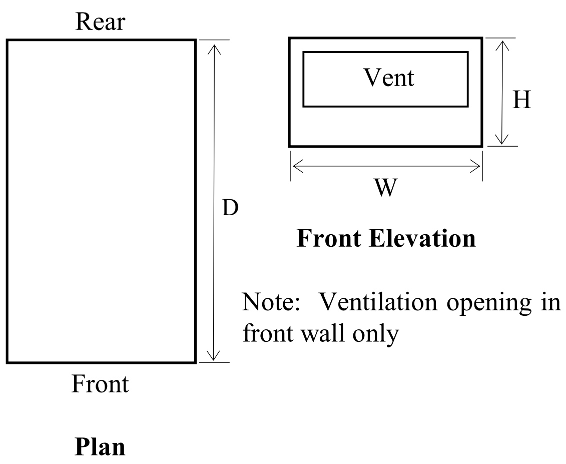


Figure 1 Enclosure Details

The following terminology and nomenclature is used for the clear internal dimensions of the enclosure (Figure 1):

- width (W) - horizontal dimension parallel to the plane of the ventilation opening
- depth (D) - horizontal dimension perpendicular to the plane of the ventilation opening
- height (H) - vertical dimension from the bottom surface to the top surface

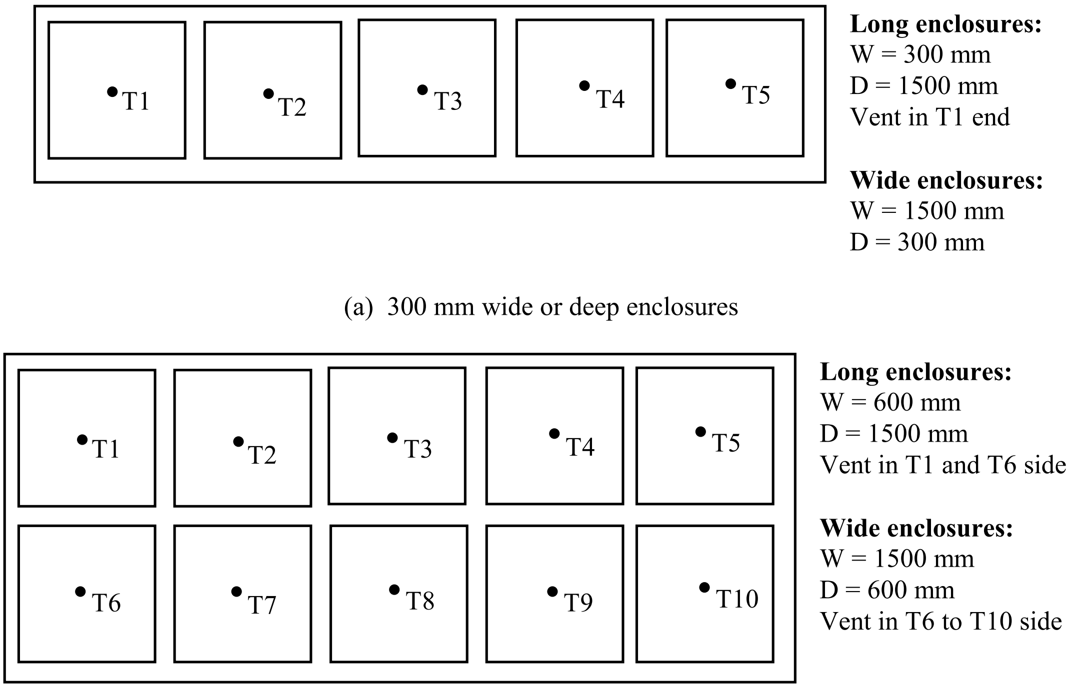
The following terminology and nomenclature is used for the dimensions of the ventilation opening:

- opening width (w) - the clear horizontal dimension
- opening height (h) - the clear vertical dimension
- sill height - the vertical dimension from the enclosure floor to the bottom of the opening

Experimental Program

The enclosures used in these tests were all 200 or 300 mm high (interior dimensions). In most tests the roof, floor and walls of made of 3 mm steel plate or 12 mm calcium silicate board. . In a number of tests one side wall of the steel enclosures was replaced by glass. This enabled viewing of the development of the fires and of the gas flows that developed. The effect of the glass wall on the fires in the steel enclosures is shown below to be was minor compared with the effects of changes in ventilation.

In these tests 500 ml of liquid fuel (96% ethanol and 4% methanol) was placed in one or more 250 mm square and 25 mm high steel trays. Each tray was placed in the centre of an area in the enclosure 300 mm square. Thus in enclosures 300 mm square one tray was used. In enclosures 300 mm by 600 mm two trays were used, and so on up to the maximum enclosure size of 600 mm by 1500 mm in which ten trays were used (Figure 2).



(b) 600 mm wide or deep enclosures

Figure 2 Tray and Thermocouple Positions and Numbers

Temperatures were recorded using five Type K mineral insulated thermocouples with the hot junction exposed. Each thermocouple was 20 mm from the roof and placed centrally over a tray of fuel (Figure 2). Temperature readings were taken every 15 seconds. The fuel mass loss was recorded by weighing the entire enclosure. The mass loss was recorded manually at 15 second intervals using a digital scale able to resolve to 0.01 kg. The vent and enclosure shapes and sizes tested are shown in Table 1.

Initially multiple tests were conducted for many of the enclosure and vent combinations. Due to great consistency in the results, in many later tests only single tests were conducted for each enclosure and vent combination.

Several arrangements of trays of fuel were also burned in the open to enable comparison of fires in the open with those in enclosures using the same fuel quantities and layouts.

Burning in the Open

Single trays of 250 ml and 500 ml of the liquid fuel (96% ethanol, 4% methanol) were burned in the open to establish the mode and duration of burning in the free-burn situation. When burned in the open the fuel burned on all sides of the tray with the flames covering the entire tray. The flames were generally symmetrical and central above the tray (Figure 3).

Figure 3 Burning of Single Tray in Open

In the open single trays containing 250 ml of this fuel burned in an average of 215 seconds (range 214 to 215, two tests) and 500 ml burned in an average of 418 seconds (range 394 to 460, nine tests).

When a tightly fitting steel shield 50 mm high was fitted on three sides of the tray (effectively an extension of the tray height of 25 mm on three sides) 500 ml of fuel burned in an average of 369 seconds (range 364 to 372, four tests). The only visible effect was simply to move the centre of the plume back slightly (away from the side that had not been "extended"). The burning appeared to take place over the entire surface of the tray and the flame height was unchanged. As the shielding of the three sides was extended in height in 50 mm steps to a maximum of 300 mm there was little further change. The flames still seemed to cover the entire surface, the flame height appeared unchanged and the centre of the plume moved only slightly further back (away from the unextended side).

When a **group of five trays** spaced as in the 300 mm by 1500 mm enclosures were burned in the open the burnout time for 500 ml of fuel averaged of 539 seconds (538 and 540, two tests), about 29% longer than for a single tray. Similarly, when a **group of ten trays** was placed in two rows spaced as in enclosures 1500 mm by 600 mm and burned in the open the burnout time for 500 ml of fuel averaged 502 seconds (497 and 507, two tests), about 20% longer than for a single tray. In both cases each tray appeared to burn over the entire surface of the tray and the flames from the individual trays converged and combined to become a reasonably stable single major flame a little above the level of the trays (Figures 4 and 5). Thus the flame was generally taller over the centre of the group and the flames from the end trays were slanted towards the centre of the group.

Single Row of Five Trays - arranged as for 1500 mm by 300 mm enclosure

Figure 4 Burning in the Open of Five Trays in a Row

Double Row of Five Trays Per Row - arranged as for 1500 mm by 600 mm enclosure

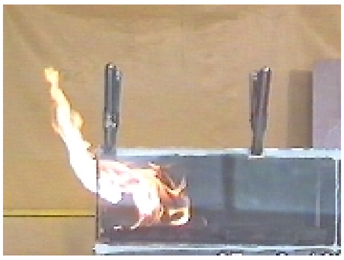
Figure 5 Burning in the Open of Ten Trays in Two Rows

Burning in Enclosures

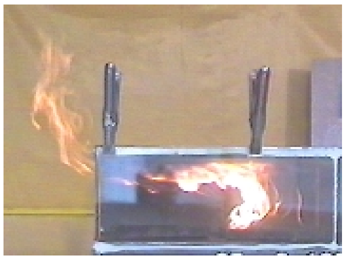
As reported elsewhere[1-3], when trays of liquid fuel were burned in enclosures the behaviour and appearance of the flames were substantially different from that described above.

The initial behaviour when a flame was introduced into an enclosure with trays of this liquid fuel depended on the ambient temperature. When the ambient temperature was about 15°C or above flames flashed briefly throughout the enclosure (above all of the trays) and then burning started in the tray or trays immediately adjacent to the opening. When the ambient temperature was below about 15°C it was possible to ignite a specific tray, in such cases the tray furthest from the ventilation opening was usually ignited. The behaviour in all such tests was then identical: the seat of combustion (and flames) rapidly made their way towards the ventilation opening, passing from tray to tray, with the flames in the previous tray being extinguished as combustion became established in the next forward tray. Once the tray (or trays) closest to the vent was ignited, combustion continued in those tray(s) alone until the fuel in those tray(s) was exhausted.

Generally when trays of liquid fuel were burned in an enclosure combustion took place (and flames formed) at the front of the burning tray(s) (Figure 6). Sometimes flames also extended for a short distance along the sides of the tray from the front edge because of the air in the space between the sides of the tray and the enclosure walls or adjacent trays. No flames were visible rising from the back of the tray and most of the fuel was clearly not (directly) covered by flames (in the same way it was when burning took place in the open).



(a) Flames from front of **front tray** shortly after ignition - flames rise mainly from front edge of tray, travel back and up, and then largely forward and out of the enclosure



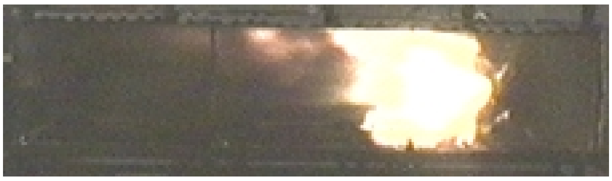
(b) Flames from front of **rear tray** after fuel in front tray exhausted - flames largely from front edge of tray, curve upward then towards vent (note obscuration of flames near vent due soot deposited on glass)

Figure 6 Side View of Fire in Enclosure 600 mm Deep and 200 mm High

Two basic modes of behaviour were observed when trays of liquid fuel were burned in enclosures[3]. In enclosures where the vent was the full width of the enclosure the behaviour was essentially two dimensional (Figures 6 to 9). In enclosures with the vent width less than the width of the enclosure the behaviour was (at least for the time burning remained near the vent) three dimensional (Figure 10). The behaviour of each of these situations will now be described in detail, dealing first with enclosures with full width vents and then those with partial width vents.

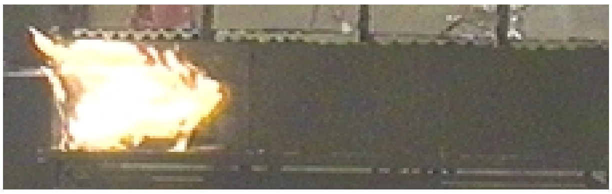
In enclosures with full width vents the origin of the flames was always the edge closest to the vent of the remaining tray(s) of fuel (Figures 6 and 7). If initially the fuel in the rear tray(s) was ignited strong burning occurred as the fire moved from tray to tray towards the vent. In all cases the fire moved towards the vent without burning much of the fuel in each tray. Combustion in the rear trays ceased once burning was established in a tray between it and the vent. Once the fire had settled at the front of the front tray(s) the form and stability of the flames depended on the size of the opening. In general, once the fire moved to the front tray(s) the rate of burning appeared to reduce and the fire become less stable. This situation was strongly influenced by the height of the opening. When the opening was at or close to the full height of the enclosure the fire remained reasonably strong and stable and a stable flow pattern was observed. This flow pattern consisted of cool air moving in at the bottom of the vent, contacting the leading edge of the fuel, taking part in combustion of the fuel and in the process being heated, rising towards the top of the enclosure, the flow splitting near the top of the enclosure with most of the flow moving towards the vent and thus out of the enclosure, and the remaining flow moving back into the rear of the enclosure.

(a) Just after ignition of trays furthest from vent (trays T5 and T10)



(b) Fire rapidly moves towards vent - rear trays extinguish

(c) Shortly after ignition, fire has moved to trays T2 and T7

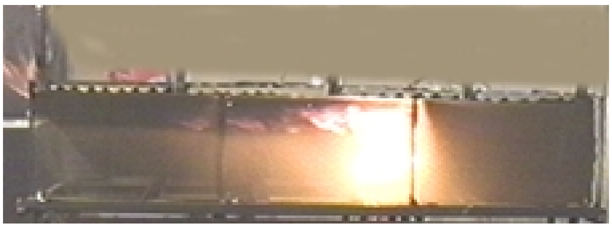


(d) Fire beginning to establish itself in trays T1 and T6

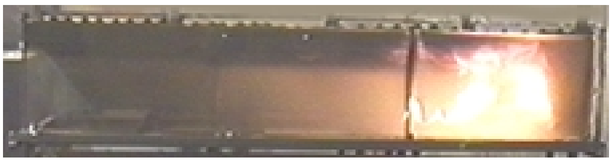
(e) Fire fully established in front trays. Flames largely from front of front trays - no burning in rear trays

(f) After fuel in tray T1 exhausted, fire moves to tray T2 360 seconds after ignition

(g) Fuel in tray T2 exhausted, fire moves to tray T3



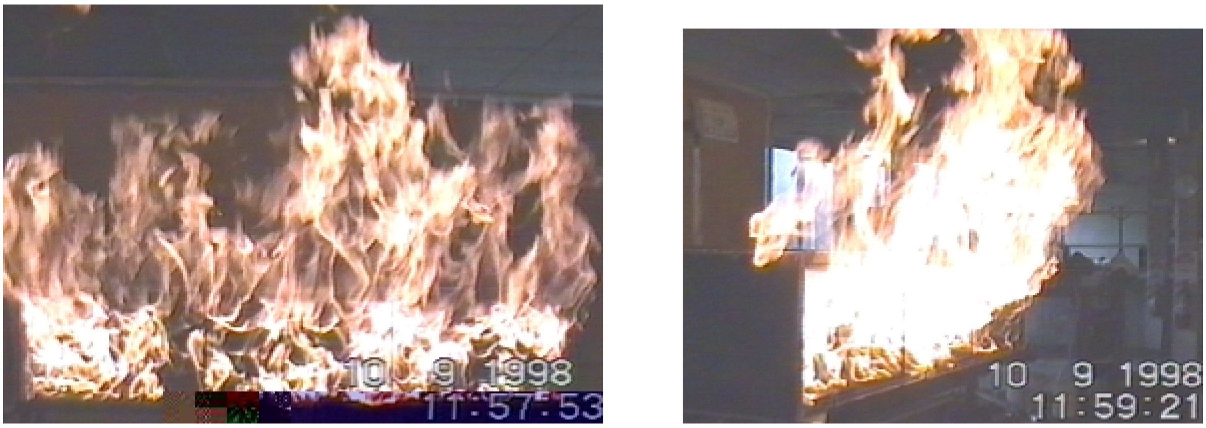
(h) Fuel in tray T3 exhausted, fire transferring to tray T4



(i) Finally fire returns to tray T5

Figure 7 Side View of Fire in Enclosure 600 mm Wide, 1500 mm Deep and 300 mm High Vent 600 mm Wide by 275 mm High

When the full width vent was substantially less than the height of the enclosure and placed at the top of the front wall the fire and flow pattern became unstable and in some cases went out. The instability seemed to come about because the in-flowing cool air moved into the enclosure over the sill in very close proximity to the out-flowing fire gases. In such cases, provided the fire remained alight long enough to burn all of the fuel in the front tray, when the fire progressed to the second and subsequent trays the fire became more stable, in some cases the mass loss rate increased, and the flows in the enclosure became stronger and more clearly defined. The flames always extended across the width of the enclosure but the thickness of the flames low in the enclosure (close to the tray) was quite small. There was thickening (spreading) of the flames as they rose in the enclosure and began to flow forward. Only the flow towards the vent was clearly identifiable as a stable flow because there were always flames (and generally some smoke) visible. The flow towards the rear appeared intermittent, but this may only be because there were few and intermittent flames visible in this region. Clearly the majority of the flames were directed towards the front of the enclosure. When the tray closest to the back wall began to burn, there was some thickening of the flames low in the enclosure and sometimes more burning took place over the surface of the fuel. Thus there seemed to be some effect of the rear wall on the fire and flow in the enclosure when the fire came close to it.



(a) View from directly in front - front trays burning, rear trays not burning

(b) Diagonal view from front left side, some front trays beginning to run low in fuel

Figure 8 Views of Fire in Enclosure 1500 mm Wide, 600 mm Deep and 300 mm High Vent 1500 mm Wide by 275 mm High

In **300 mm deep** enclosures with full width vents of height over half of the height of the enclosure, the flames appeared to virtually fill the enclosure as even those from the front edge of the tray initially moved towards the back of the enclosure, then vertically and then (near the top of the enclosure) towards the front to sometimes form large flame extensions outside the enclosure, occasionally with pronounced periodicity (Figure 9). However, in these enclosures the flames appeared to cover more of the surface of the fuel somewhat like the behaviour in the shielded tray tests described above.

Flames appear to fill enclosure

Figure 9 Side View of Fire in Enclosure 300 mm Wide, 300 mm Deep and 300 mm High, Vent 300 mm Wide by 275 mm High

In wide enclosures (from 600 mm to 1500 mm were tested) **300 mm deep**, all of the trays of fuel burned at once. In wide enclosures (again from 600 mm to 1500 mm were tested) **600 mm deep**, the front row of trays burned first and then the rear row. When a tray in the front row burned out the burning immediately transferred, but only to the tray directly behind. Looked at from the side the appearance of the fire in these enclosures was essentially the same as if the enclosure was only 300 mm wide except for occasional overlaps as burning moved from one row of trays to the next.

That is, the flows were two dimensional and a strip through the enclosure from front to back would accurately represent the appearance of the entire enclosure. In these enclosures there often seemed to be a slight "end effect" at each end of the enclosure with generally somewhat lower luminosity flames and lesser flame extensions near the end than the middle of the enclosure. Occasionally this was reversed and large flame extensions occurred at one end or the other. The "end effect" was reflected in the situation that generally the middle trays burnt out first and the end trays continued to blaze for a short time after the middle trays ran out of fuel.

In enclosures of **depth 600, 900, 1200 and 1500 mm,** when the fuel was ignited only the front tray (or row of trays) continued to burn - there was no sign of flames from the trays further from the ventilation opening (Figures 6 and 7). Once the fuel in the first tray (or row) was consumed and as the flames in that tray were going out the fuel in the second tray ignited. The fuel in this tray then burned until consumed when the third tray ignited and so on. Thus, in these enclosures, except for a brief time following first ignition and momentarily when the fuel in one tray was almost consumed and the fuel in the next tray ignited, burning only occurred in one tray (or row) at a time.

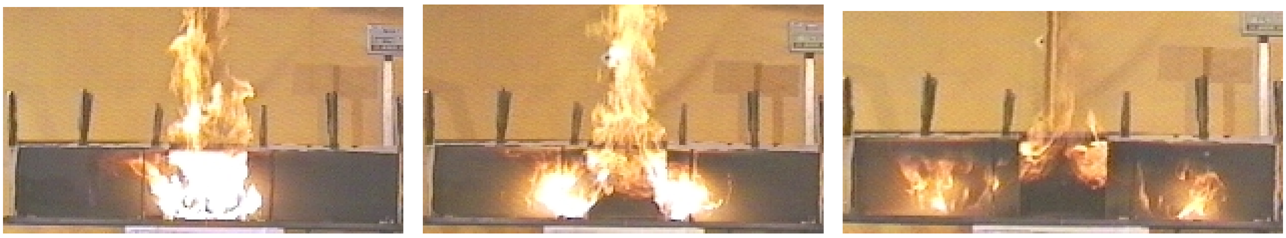
The flame extensions from the enclosures were often very high in the high ventilation (fast burning) tests, but were minimal in the lowest ventilation tests. In the **600, 900, 1200 and 1500 mm deep** enclosures flames from all of the trays when burning (including the rear trays) generally extended the full length of the enclosure and out of the opening. As mentioned above the flame front was generally thin, particularly when there was plenty of fuel in the burning tray. As fuel in a tray burned out the flames appeared to become thicker (but not uniformly over the full width of the enclosure) and as the flames in the nearly burned out tray contracted the fuel in the tray behind started flaming. In the new tray the flames were initially thick but as flaming became well established across the width of the tray the thickness of the flames decreased.

In enclosures with **full width vents** the outgoing flow of fire gases consistently occupied about the top third of the enclosure and vent. This was clearly observed in many tests and was also clearly defined in soot deposits on the glass side used in many tests.

In the enclosures with **partial width vents** the flows in the enclosures became more complex. When the fire was ignited the fire always settled immediately in or quickly migrated to the tray(s) directly adjacent to the vent. The appearance and behaviour of the fire was then essentially the same whether the enclosure was wide or long while ever the burning was taking place near the vent. However, in long enclosures once the fuel near the opening was burnt the behaviour except near the vent became very similar to that in similar enclosures with full width openings.

Once the fire in enclosures with **partial width openings** was established the flame front could clearly be seen to extend only over a width of the trays equal to the width of the opening (Figure 10). The flames could be seen to then spread laterally to some extent as they moved into the enclosure and upward. Other than this, the main flow was similar to that in the enclosures with full width vents in that the main flow consisted of flames and fire gases initially moving towards the top of the enclosure, then towards and out of the vent. When viewed from the side a small portion of the flow was observed to move (apparently intermittently) back into the rear of the enclosure. Because of the lateral spread of the fire gases as they moved through the enclosure towards the vent, they were wider than the vent when they arrived at the front wall (and vent). Consequently, while a substantial portion moved through the vent and out of the enclosure, the remainder were deflected back into the enclosure in the regions on either side of the vent. These flows appeared to circulate through the enclosure and then move back towards the vent colliding in the middle of the enclosure underneath the main outward flow mentioned above and then exiting through the vent under the main flow.

It was apparent in tests on enclosures with **partial width vents** that the flow through the vent generally occupied about a half to two-thirds of the height of the vent for most of the time.



(a) Flames the width of the vent at the front of the front tray

(b) The "tunnel" appearance with flames surrounding the incoming air

(c) Burning in the trays on each side of the vent, with flames colliding in the centre and spilling out of the vent

Figure 10 Front Views of Fire in Enclosure 1500 mm Wide, 600 mm Deep and 300 mm High Vent 300 mm wide by 275 mm High

When the fuel in the tray(s) closest to the vent was exhausted the burning then moved to the trays immediately behind them. At this stage it was generally possible to see virtually a "tunnel" through which the inward air flowed surrounded by flames from similar flows to those described above and some flames from the trays in the front row on either side of the vent.

Once the fuel from these trays was burnt the fire generally progressed to the trays adjacent to those already burnt, with the fire effectively splitting into two, on each side of the vent. Except for the area of the vent, each side, when viewed from the front was similar to a fire in a long enclosure viewed from the side. That is, the two dimensional flow described above. However, in this case there were two symmetrically opposite flows that collided in the middle and formed a combined "spiralling vortex" flow out of the vent, again generally filling the top two-thirds of the vent.

While the burning was taking place near the vent there was a large flare outside the enclosure. It appears that the lateral flows mentioned above were picking up large quantities of fuel and transporting them out of the enclosure where they burned. A somewhat similar behaviour occurred in long enclosures with full width vents at some ventilation levels, when a stable situation of burning of vapourised fuel in the vent (without oxygen entering the enclosure) occurred. This also occurred in larger scale low ventilation wood crib tests reported elsewhere[5,6]. Generally however, it appears that the three dimensional flows are more effective in transporting vapourised fuel out of the enclosure than the two dimensional flow as bigger flares were generally present in the former case.

Another form of behaviour that was observed was for the burning to continue to take place near trays near the vent even after they, and occasionally the adjacent trays, were empty. Again vapourised fuel was clearly being transported towards the vent but the burning was taking place just inside the vent rather than outside.

The order of burning (emptying) of the trays in the 1500 mm wide by 600 mm deep enclosures was generally (Figure 2) 8, 3, 2 and 4, 7 and 9, 1 and 5, and finally 6 and 10.

Experimental Results

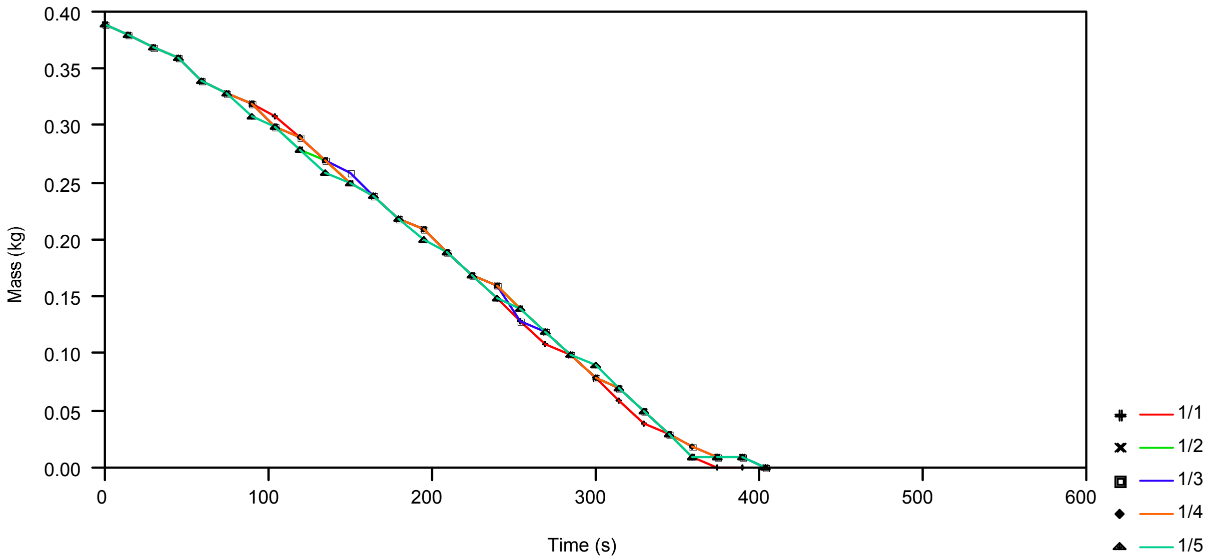
The remaining fuel mass was recorded throughout the tests for all of the tests in the open and for all enclosure tests with steel and steel and glass enclosures. It was not obtained in tests in calcium silicate board enclosures.

The variation in remaining fuel mass with time for trays burned in the open is shown in Figure 11. The responses are reasonably linear (Figure 11 (a) and (b)) apart from the beginning and end of each test. The response for the ten tray tests is considerably more non-linear than the single and five tray tests. Figure 11 (c) compares the mass history of the single trays with those of the five and ten tray tests on a "per tray" basis. It can be seen that on this basis the histories are essentially identical for the single and five tray tests but significantly different for the ten tray tests. The mass loss rate was considerably higher for the ten tray tests than for the others for much of the time. This is despite the fact that the burnout times reported above for the multiple tray tests were both longer than for the single tray tests.

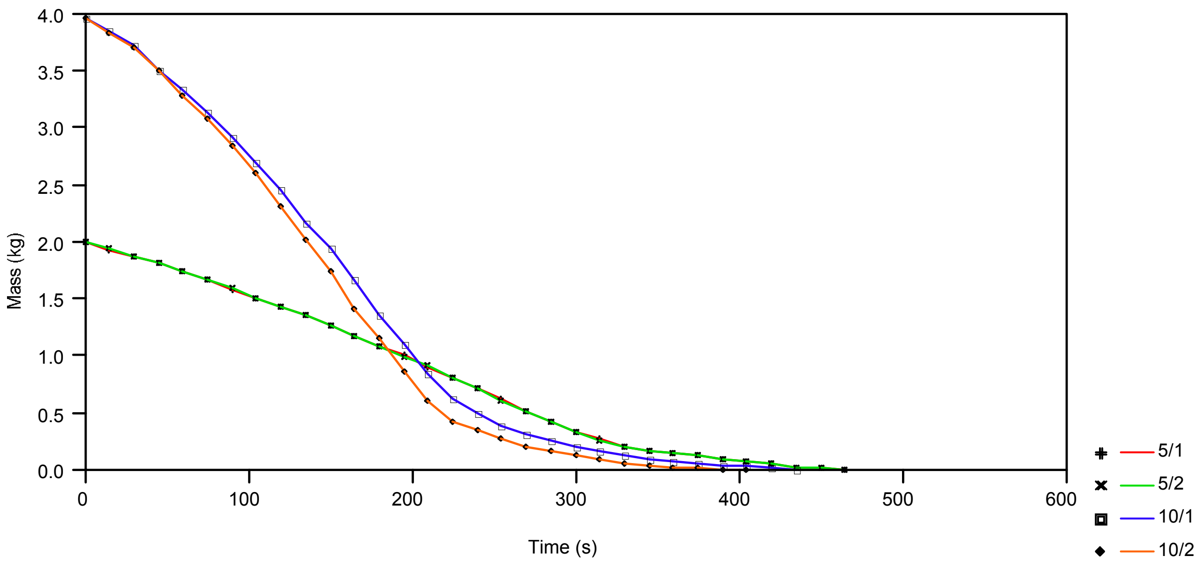
The results of the enclosure tests are summarised in Appendix A, Table A1. The table shows details of the geometry of the enclosure for each test, the construction materials and the maximum temperature and burnout time. The situations in which *stable* burning did not occur are not shown in the table. (The term *stable* is used herein to describe tests in which the fire did not self-extinguish before all the fuel was consumed. In *unstable* situations the fire self-extinguished before all of the fuel was burnt, generally soon after ignition.) Tests were initially attempted with vent widths equal to the width of the enclosure and vent heights of 100%, 75%, 50% and 25% of the height of the enclosure. If the fire self-extinguished at one of these ventilation levels intermediate vent heights were tried and if stable burning occurred the results appear in the table.

The fuel mass histories for the enclosure tests are shown in Figures 12 and 13. In Figures 12 and 13 when the vent is the full width of the enclosure the only vent dimension given is the height (mm), but when the vent width is less than the width of the enclosure both the width and height are given thus: width/height (both mm). Similarly, when the vent is at the bottom of the wall, a suffix "b" is added to the label, when the vent is at the top of the wall no suffix is given. The other letters in the label are simply to distinguish each tests.

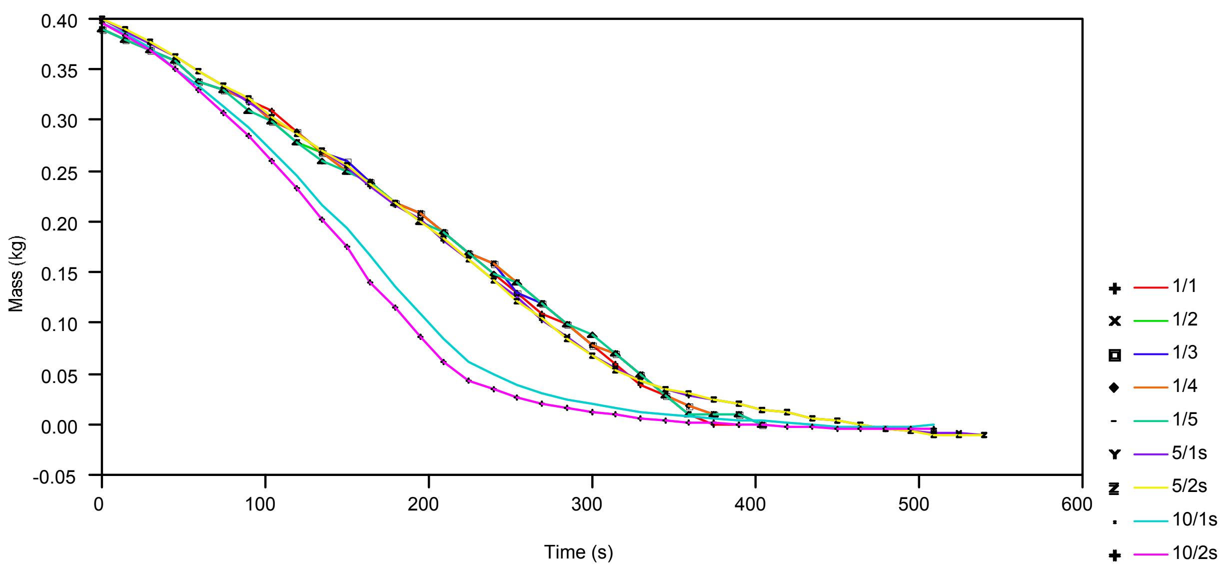
Inspection of these figures reveals that generally the response was quite linear, more-so than for the tests in the open (Figure 11) and also that there was generally extremely good reproducibility of the results for each enclosure and vent configuration. Because of the linearity of the response the overall burnout time provides a good basis for estimating the overall average rate of mass loss, although the estimate will be slightly lower than the actual rate because of the slow-down in mass loss rate just before burnout.



(a) Single Tray Tests

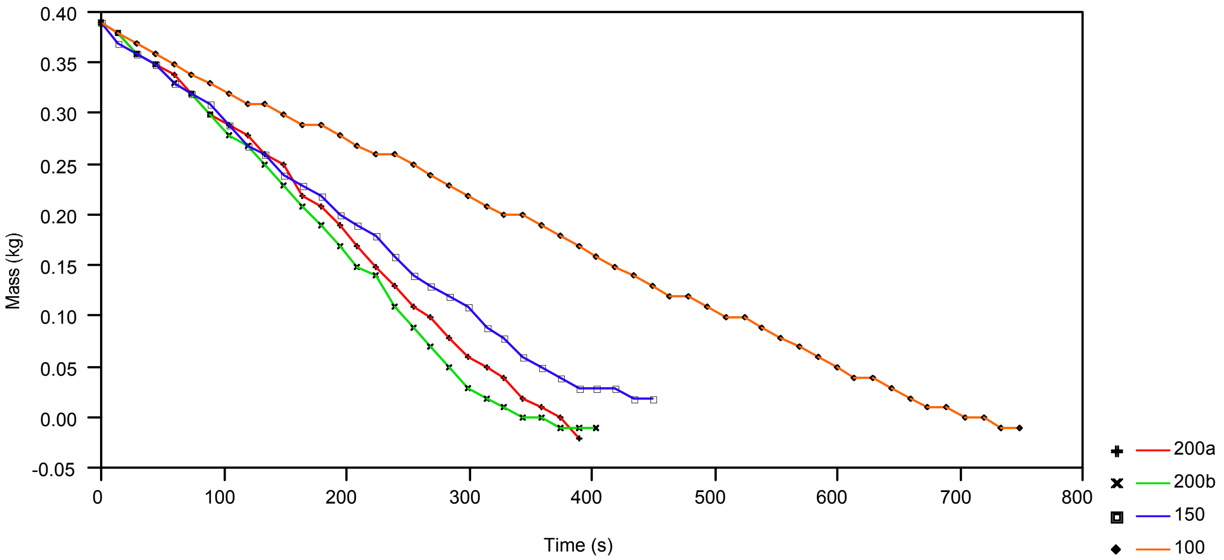


(b) Five and Ten Tray Tests

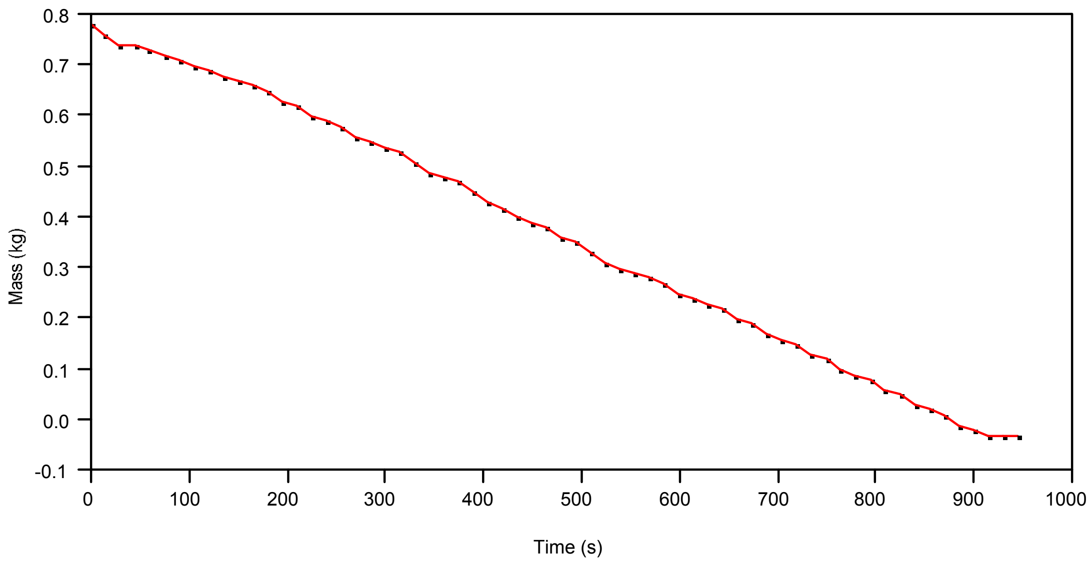


(c) Standardised Five and Ten Tray Tests Superimposed on Single Tray Test Results

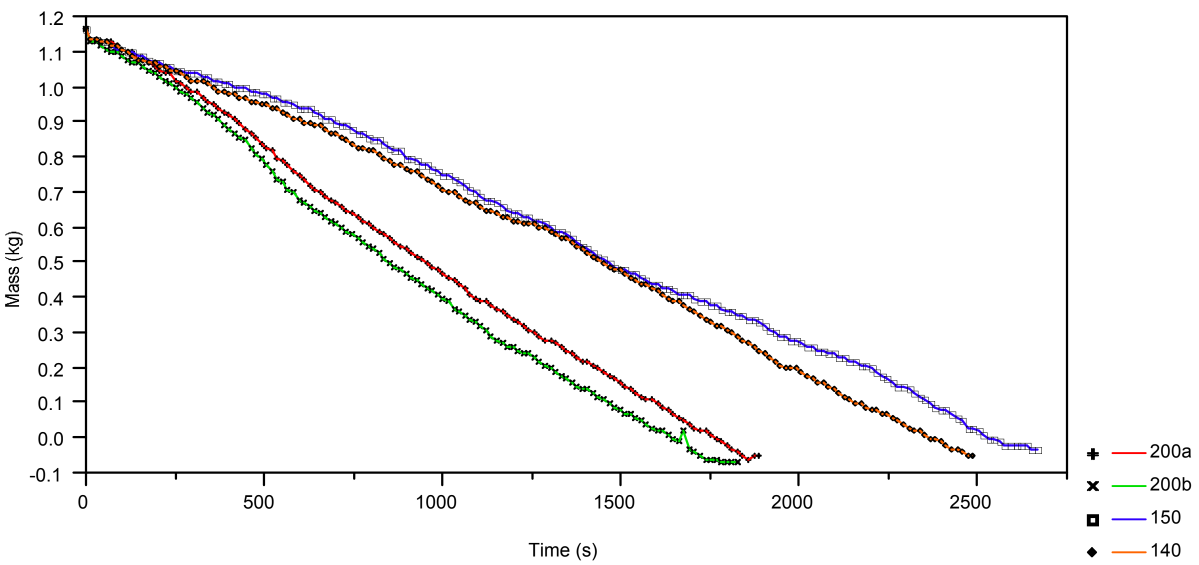
Figure 11 Fuel Mass Histories for Trays Burned in Open



(a) Enclosures 300 mm Wide by 300 mm Deep by Vent Height

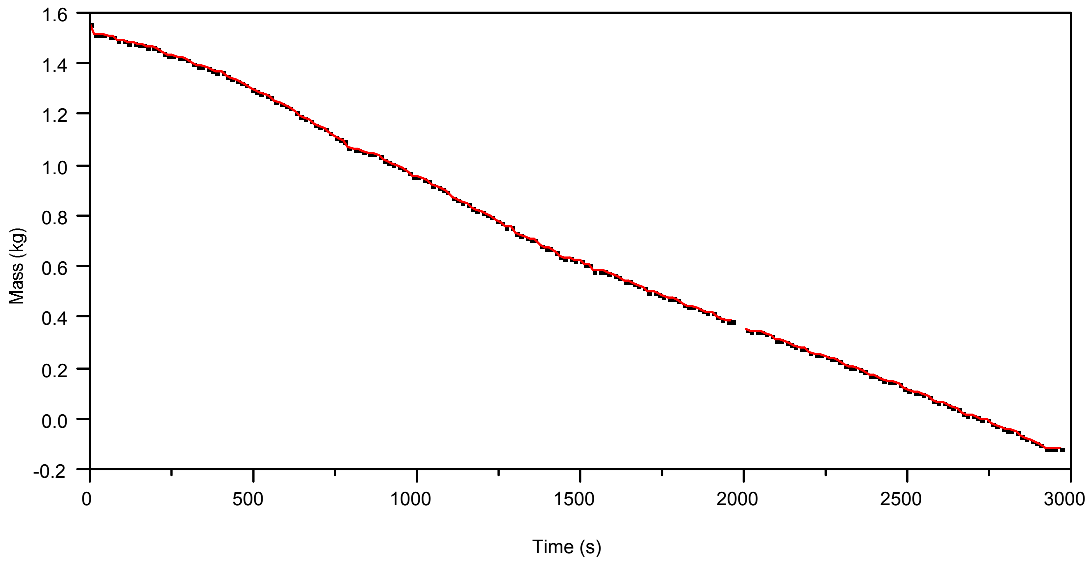


(b) Enclosures 300 mm Wide by 600 mm Deep (Vent 200 mm High)

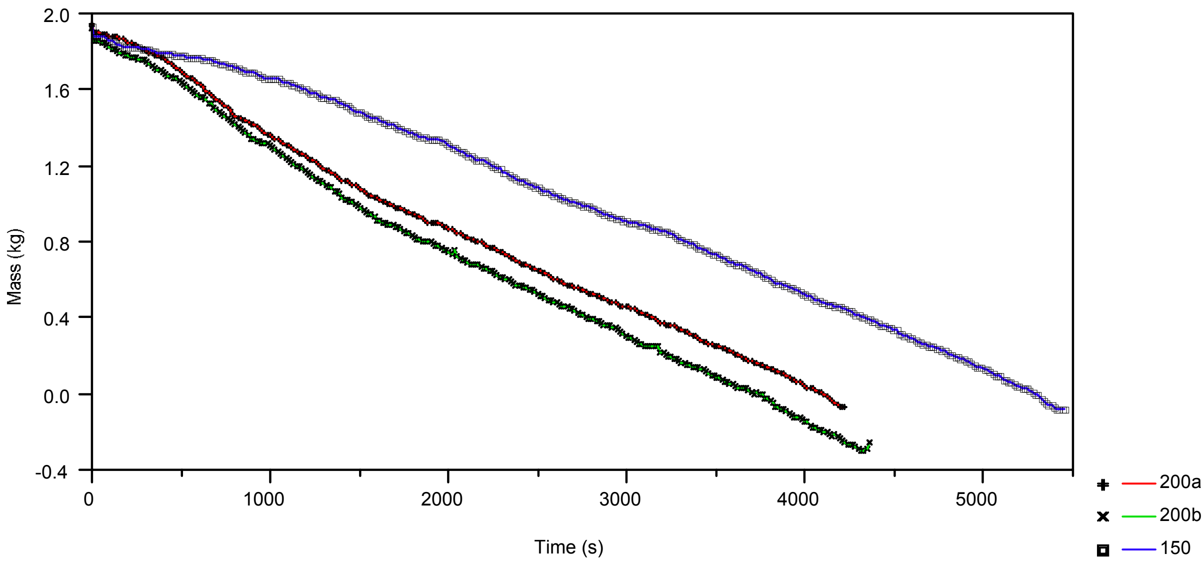


(c) Enclosures 300 mm Wide by 900 mm Deep by Vent Height

Figure 12 Fuel Mass Histories for Enclosures 200 mm High

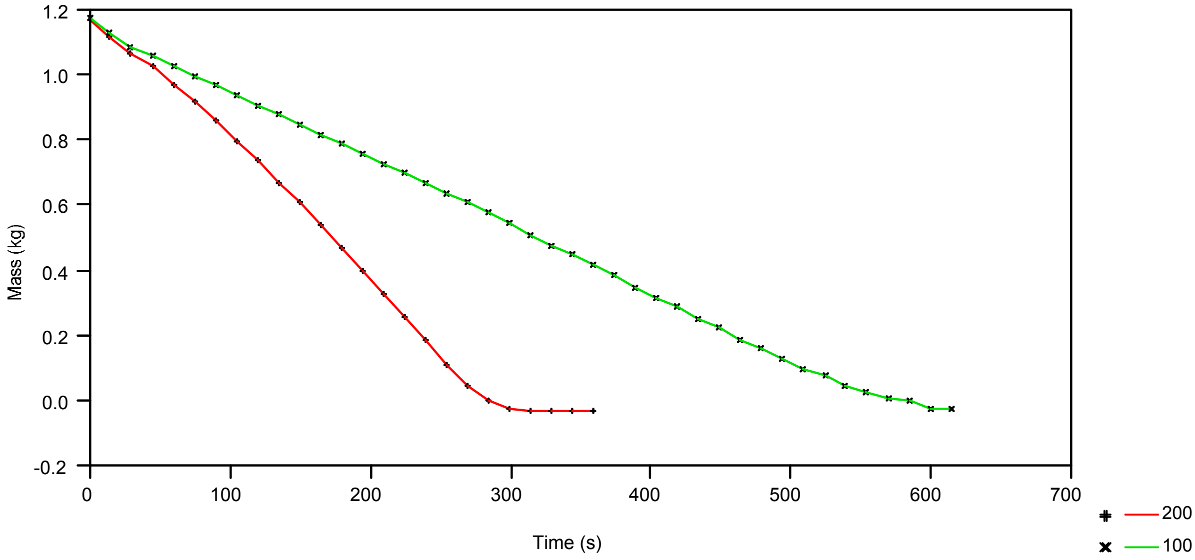


(d) Enclosures 300 mm Wide by 1200 mm Deep (Vent 200 mm High)

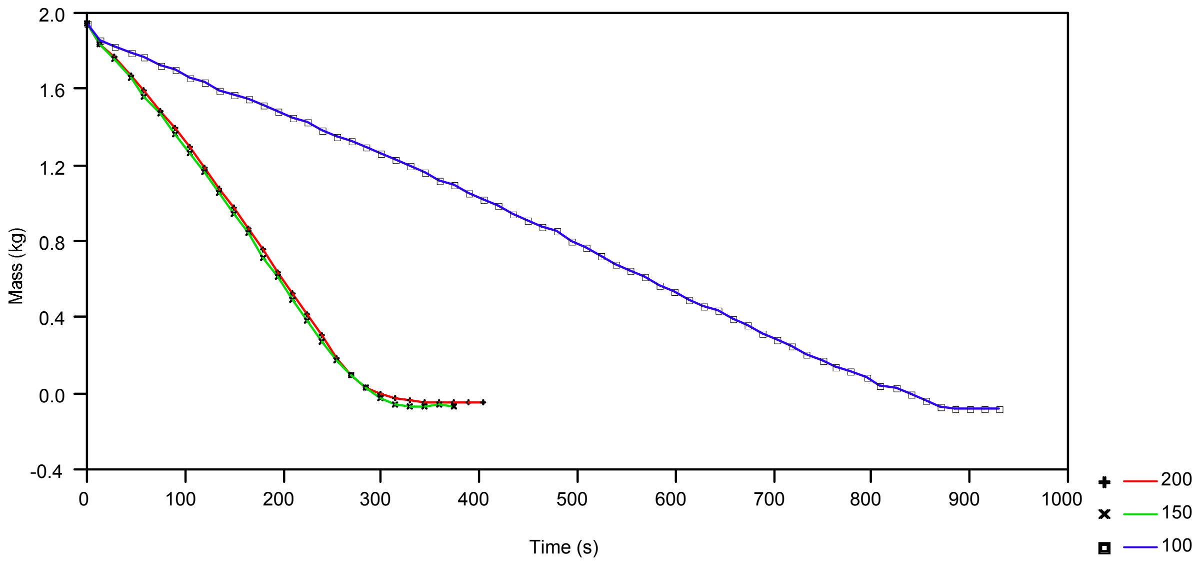


(e) Enclosures 300 mm Wide by 1500 mm Deep by Vent Height

Figure 12 Fuel Mass Histories for Enclosures 200 mm High (continued)

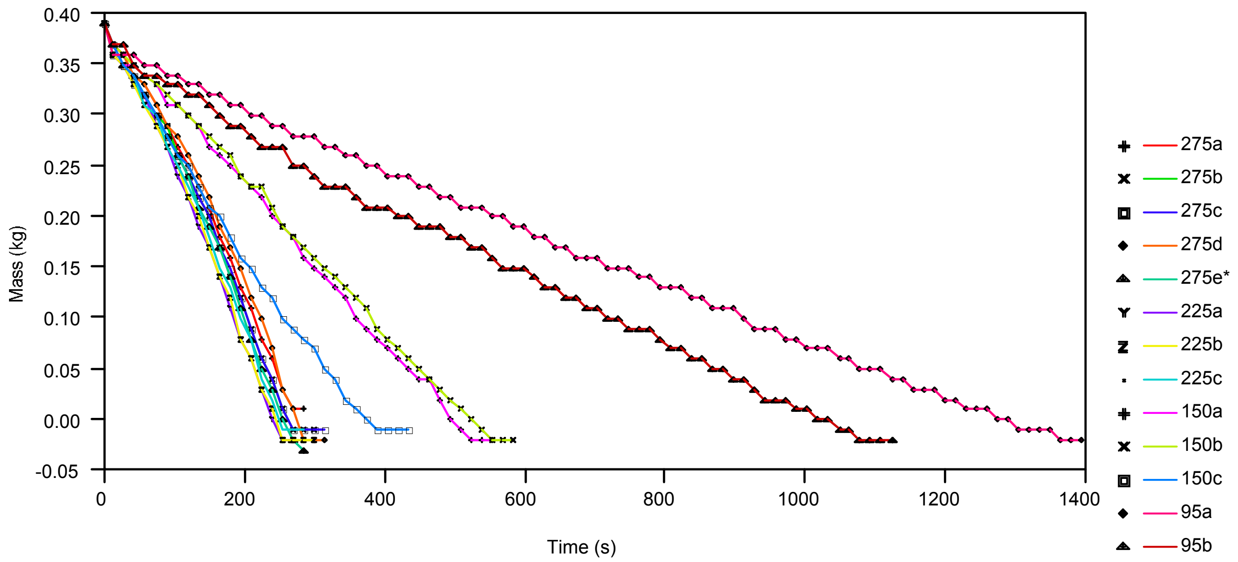


(f) Enclosures 900 mm Wide by 300 mm Deep by Vent Height

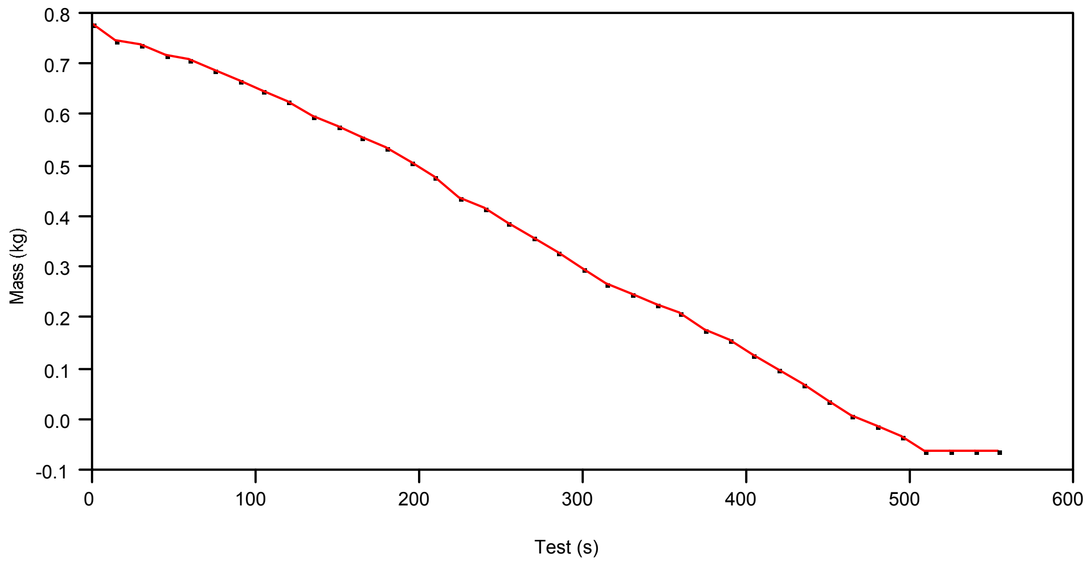


(e) Enclosures 1500 mm Wide by 300 mm Deep by Vent Height

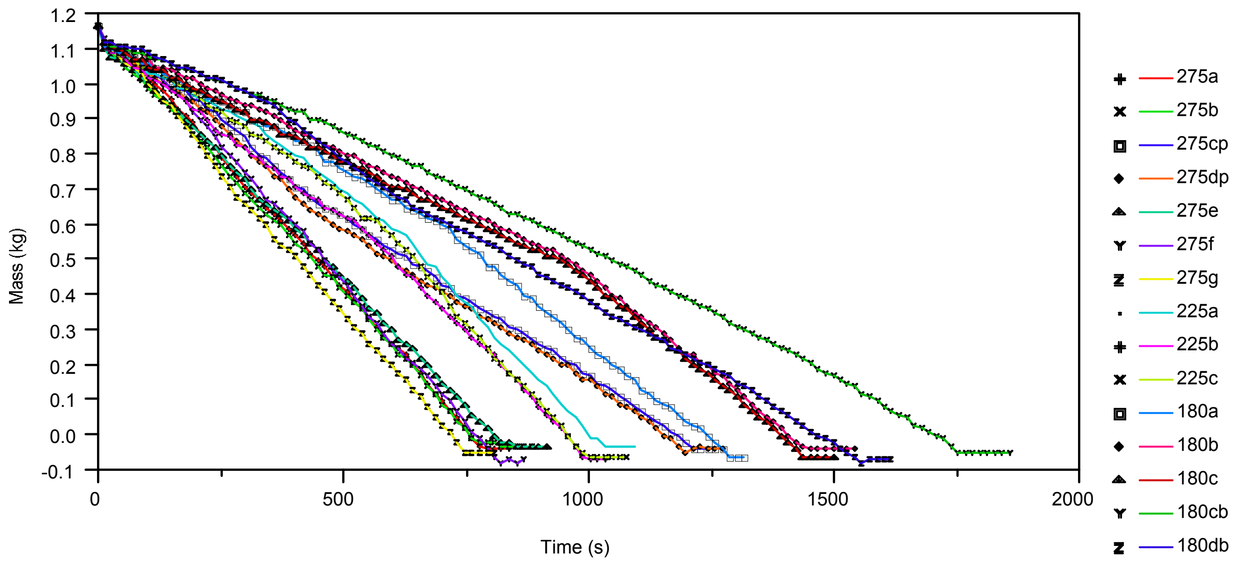
Figure 12 Fuel Mass Histories for Enclosures 200 mm High (continued)



(a) Enclosures 300 mm Wide by 300 mm Deep by Vent Height

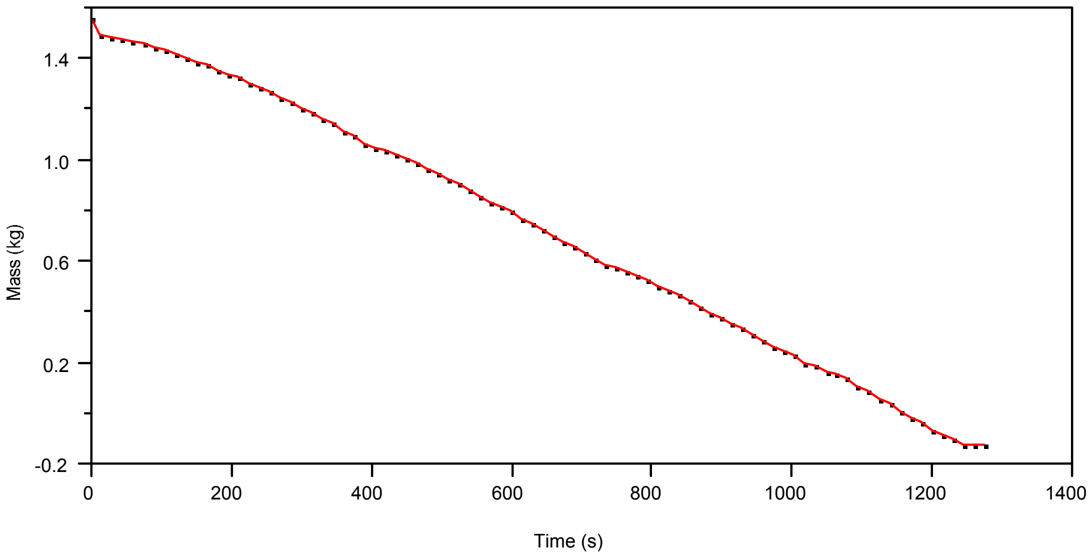


(b) Enclosures 300 mm Wide by 600 mm Deep (Vent 275 mm High)

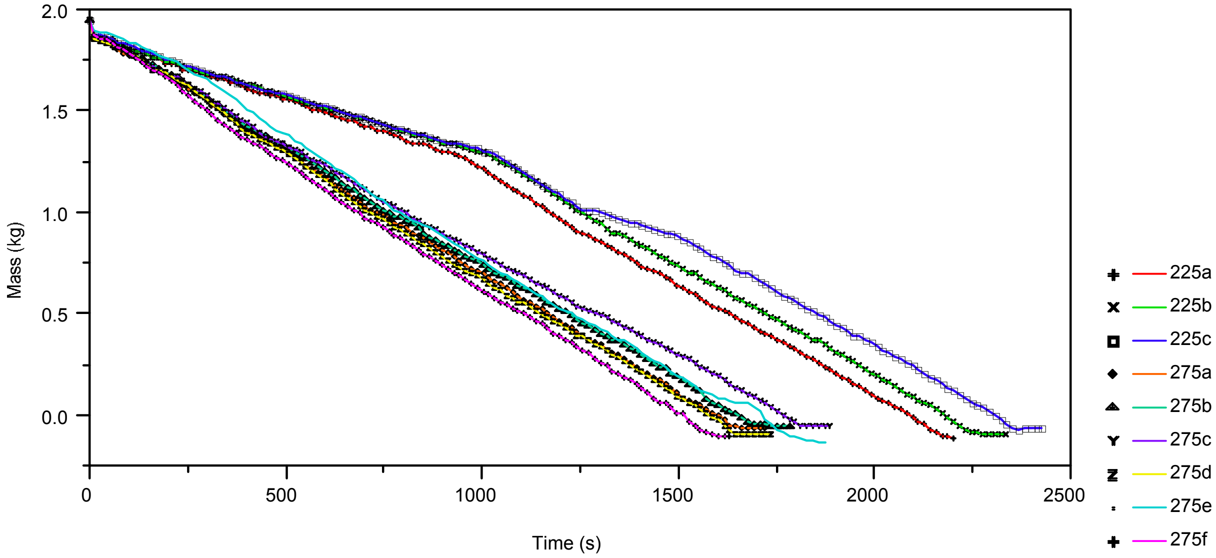


(c) Enclosures 300 mm Wide by 900 mm Deep by Vent Height

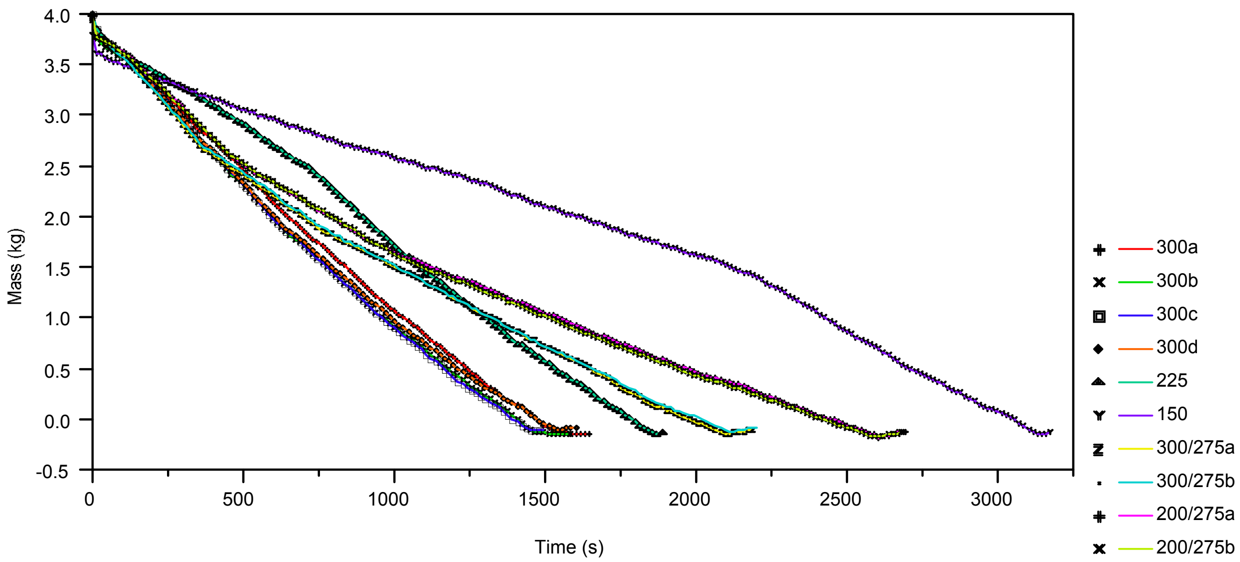
Figure 13 Fuel Mass Histories for Enclosures 300 mm High



(d) Enclosures 300 mm Wide by 1200 mm Deep (Vent 275 mm High)

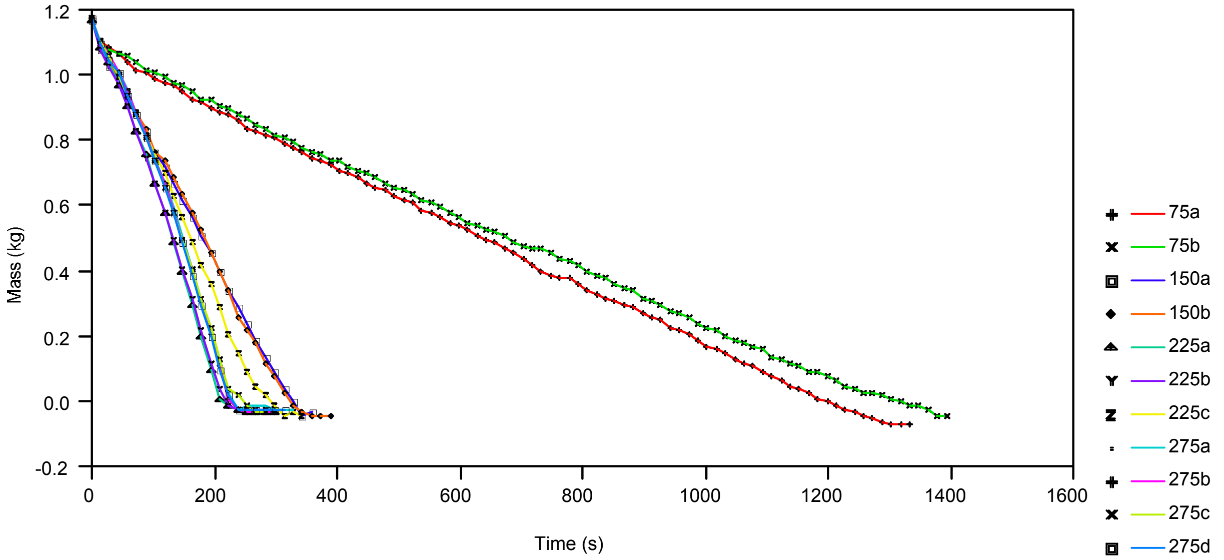


(e) Enclosures 300 mm Wide by 1500 mm Deep by Vent Height

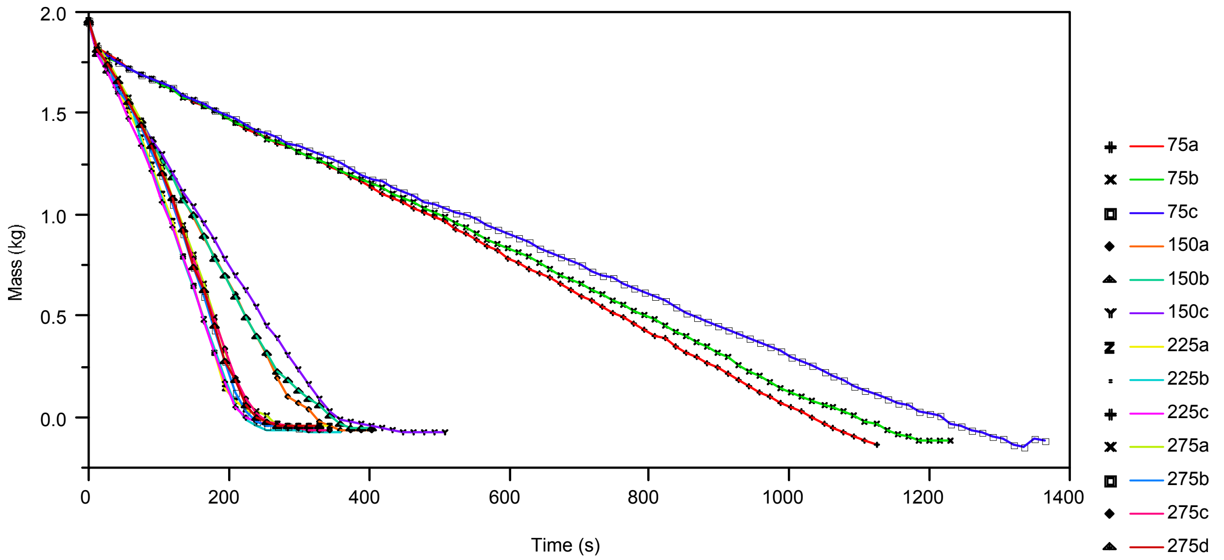


(f) Enclosures 600 mm Wide by 1500 mm Deep by Vent Height

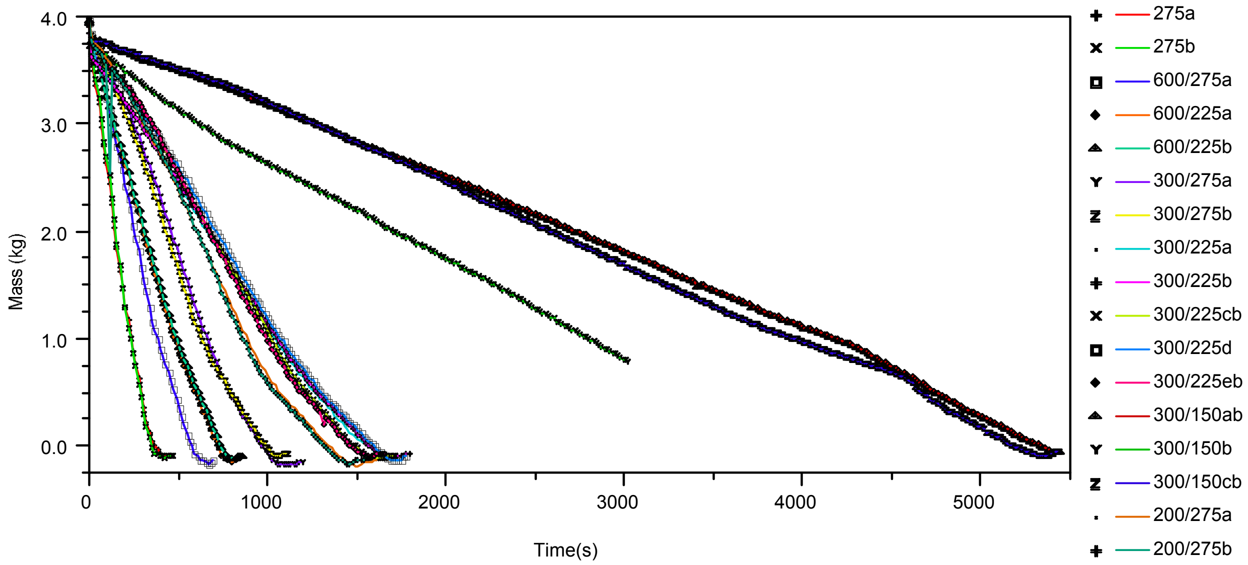
Figure 13 Fuel Mass Histories for Enclosures 300 mm High (continued)



(g) Enclosures 900 mm Wide by 300 mm Deep by Vent Height



(h) Enclosures 1500 mm Wide by 300 mm Deep by Vent Height



(i) Enclosures 1500 mm Wide by 600 mm Deep by Vent Height

Figure 13 Fuel Mass Histories for Enclosures 300 mm High (continued)

In Figure 12 (a) it can be seen that the mass loss for the 200 mm opening height is quicker than for the 150 mm opening height, which in turn is quicker than for the 100 mm opening height. The pattern is generally similar throughout Figures 12 and 13, although in Figures 12 (a) and (e) the lines for the 150 and 200 mm vent heights are very close compared with the lines for the 100 mm vent heights. Similarly in Figures 13 (a), (g) and (h) the lines for 275 and 225 mm vent heights are very close compared with those for smaller opening heights.

Also notable in several graphs of Figure 13 is the non-linearity of the responses for enclosures with partial width vents. This is shown more clearly in Reference 1, and reflects the phases of burning that occur in enclosures with this vent configuration[1].

The temperature responses in representative tests are shown in Figure 14. In Figure 14(a) the single thermocouple trace shows the typically rapid rise and fall in temperature following ignition and burnout in the 300 mm cube shaped enclosure.

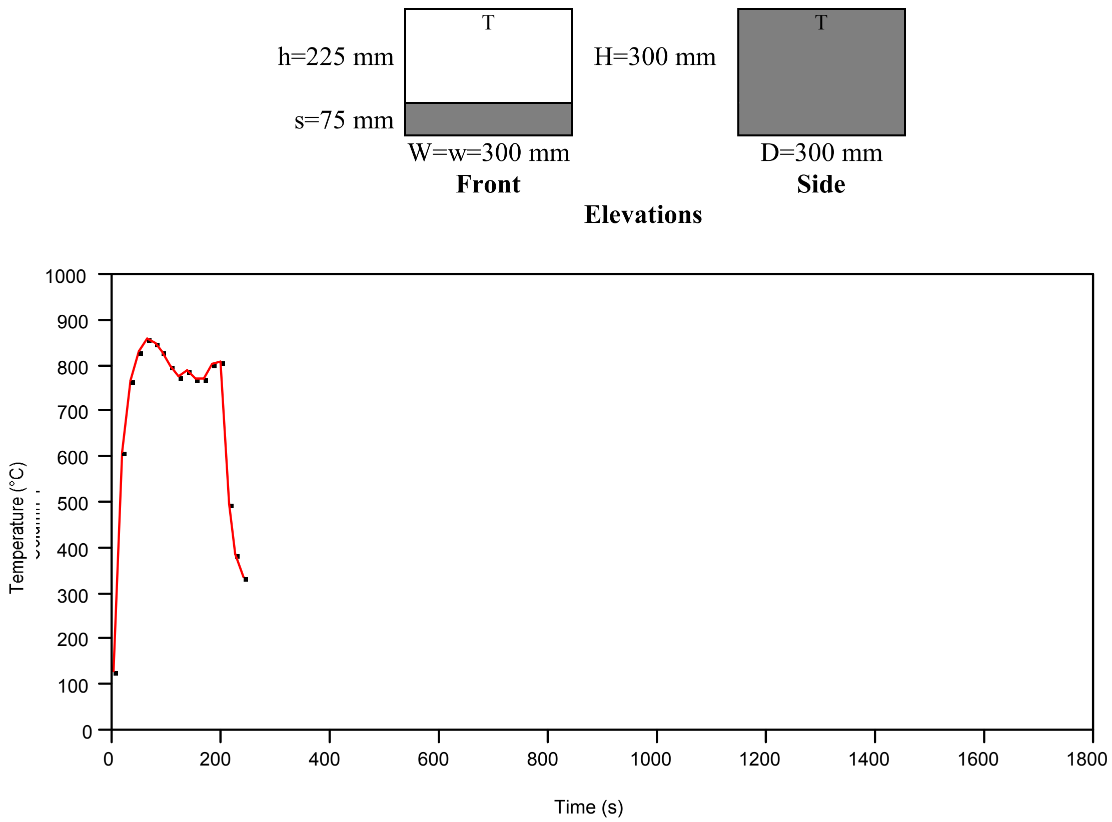
Figure 14(b) shows the traces for the two thermocouples in a 600 mm long enclosure. Both thermocouples initially rise quickly, the thermocouple at the front of the enclosure more to a higher temperature than that at the rear. The temperatures at both positions remain relatively constant while the front tray burns, then both rise when the second tray burns. Again they are both relatively constant while this tray burns and then fall rapidly when the fuel is exhausted. It is notable that the front thermocouple “sees” higher temperatures and high temperatures for much longer than the rear thermocouple. Thus, the severity of the fire is much greater in the front of the enclosure than in the rear.

The three traces in Figure 14 (c) show the very similar temperatures recorded through most of the fire by the three thermocouples in the 900 mm wide by 300 mm deep enclosure. It shows that there is little variation in temperature across the width of a wide enclosure with full width variation, and none of the systematic variation shown in Figure 14 (d) through the depth of an enclosure 300 mm wide by 900 mm deep. The three quite distinct traces in Figure 14(d) for the 900 mm deep enclosure show the four phases in burning in deep enclosures with full width openings:

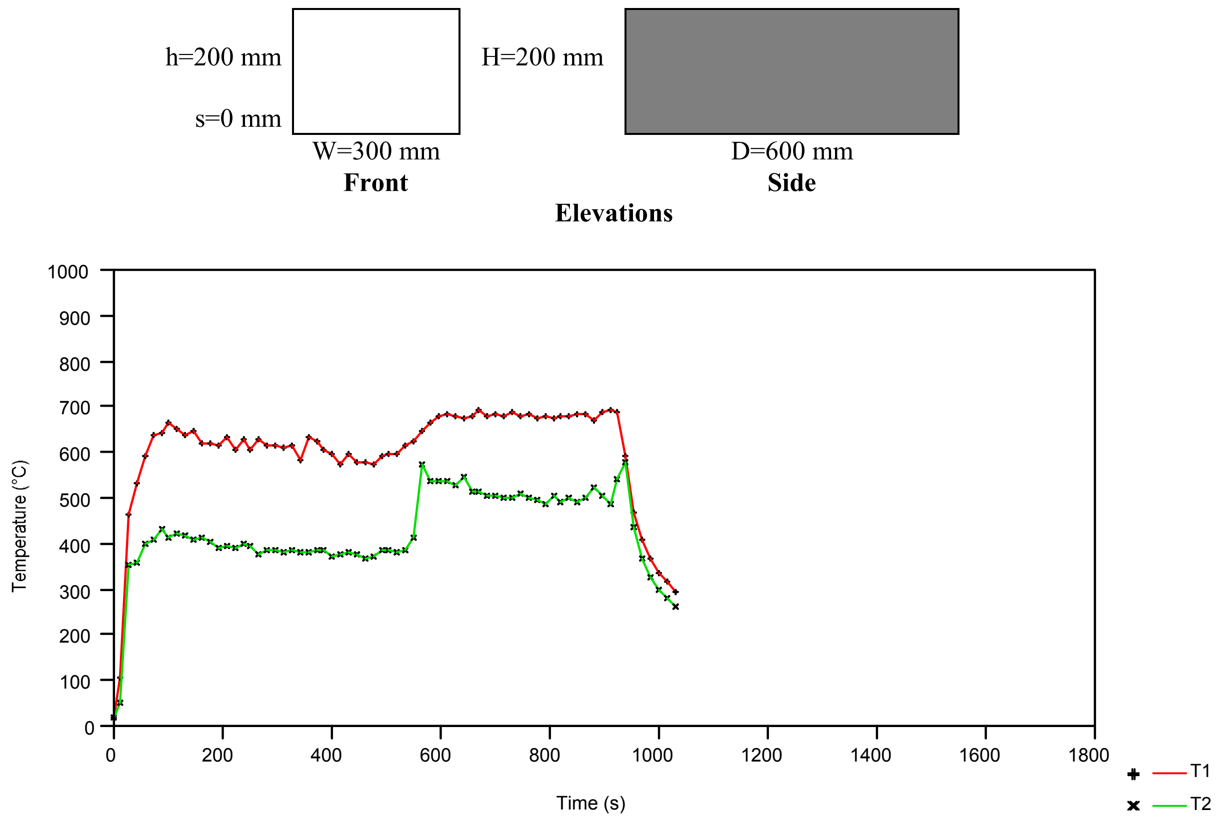
1. the initial rapid temperature rise of all three thermocouples reflects the initial, very short, ignition of all three trays of fuel which happened in this test and usually happens if the ambient temperature is high enough
2. the distinctly higher temperature in thermocouple T1 early in the test reflects the continued burning of tray 1 (closest to the ventilation opening)
3. the rise in temperature of thermocouple 2 about one-third of the way through the test reflects the burnout of tray 1 and the ignition of tray 2
4. the rise in temperature of thermocouple 3 about two-thirds of the way through the test reflects the burnout of tray 2 and the ignition of tray 3

The temperature of the thermocouple closest to the opening (thermocouple 1) remains higher than the others for most of the test, only falling slightly below the others close to the end of the test.

The thermocouple traces shown in Figures 14(e) and (f) show similar stages of burning in 1500 mm deep enclosures, with, after an initial brief ignition of all five trays, burning progressing from the ventilated end of the enclosure to the closed end. Note that in Figure 14(f) the time of burning for the front tray is much greater than for the other trays, and that the burning time for each tray gets progressively less moving from the front to the rear of the enclosure. The previous figures (Figure 14(b) to (e) are similar in this respect but the successive reductions in burning time are less than in Figure 14(f).

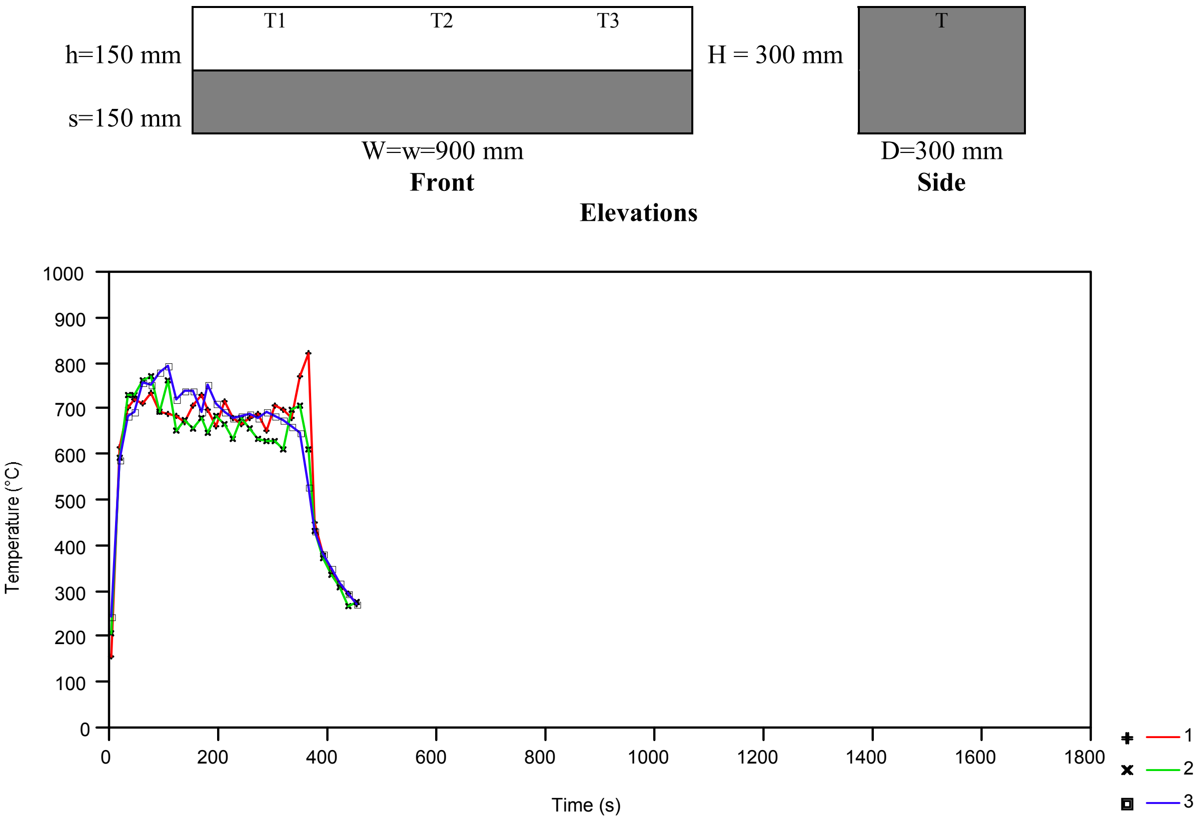


(a) Test C3Q86: material = calcium silicate board

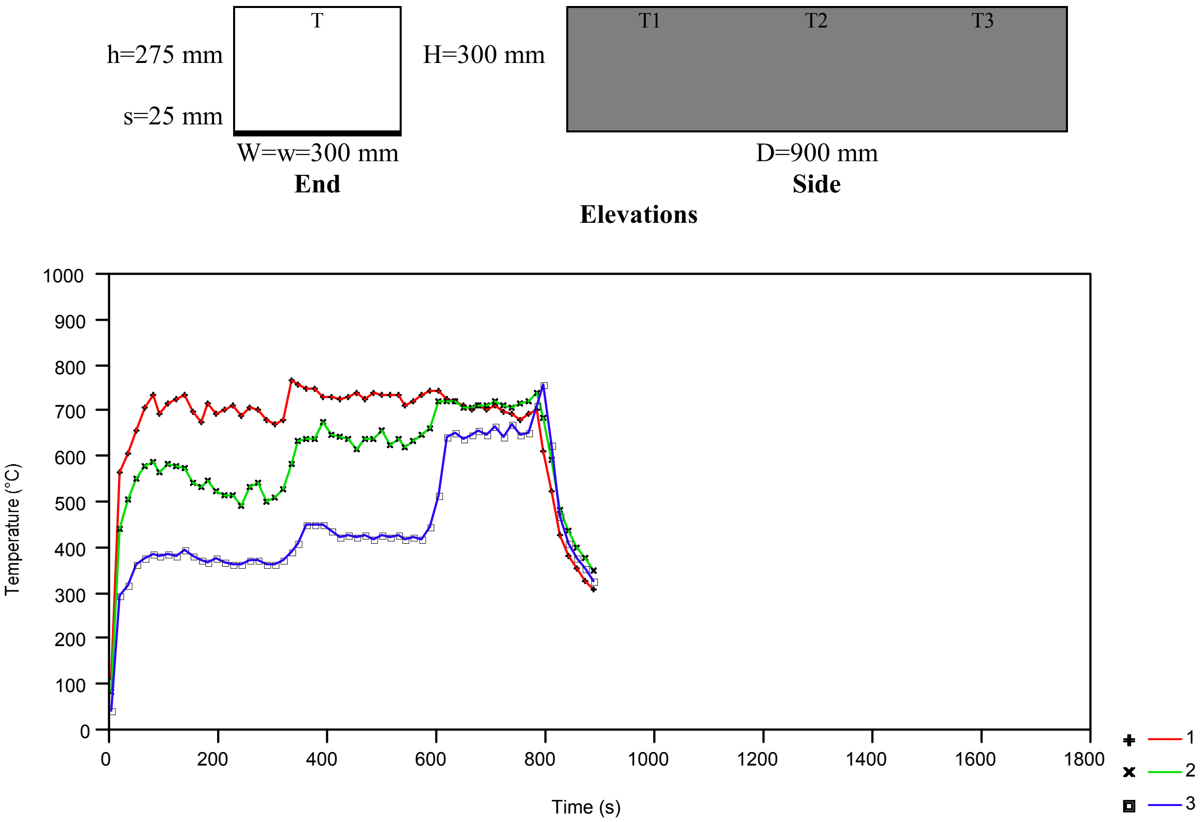


(b) Test SGFOE216: material = steel and glass

Figure 14 Examples of Temperature - Time Curves for Various Enclosure Configurations

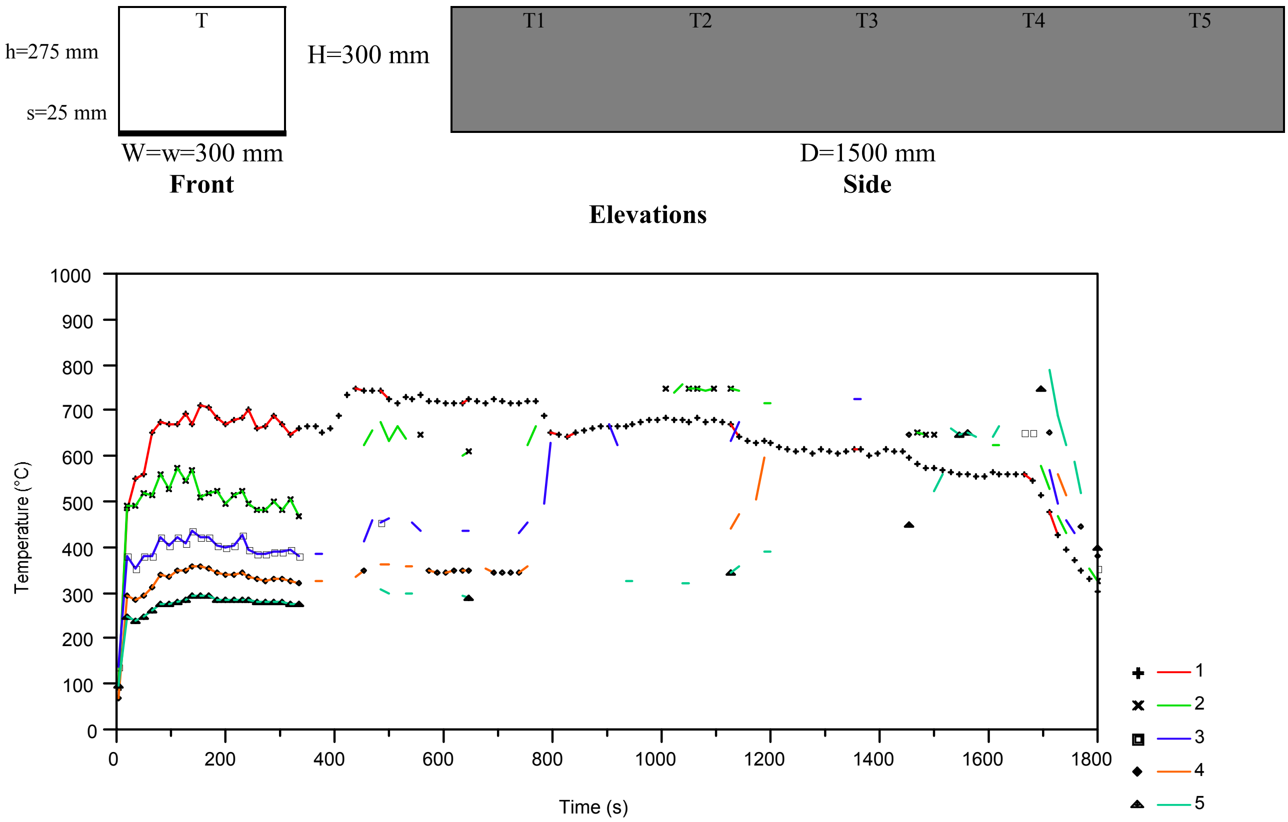


(c) Test SH21: material = steel

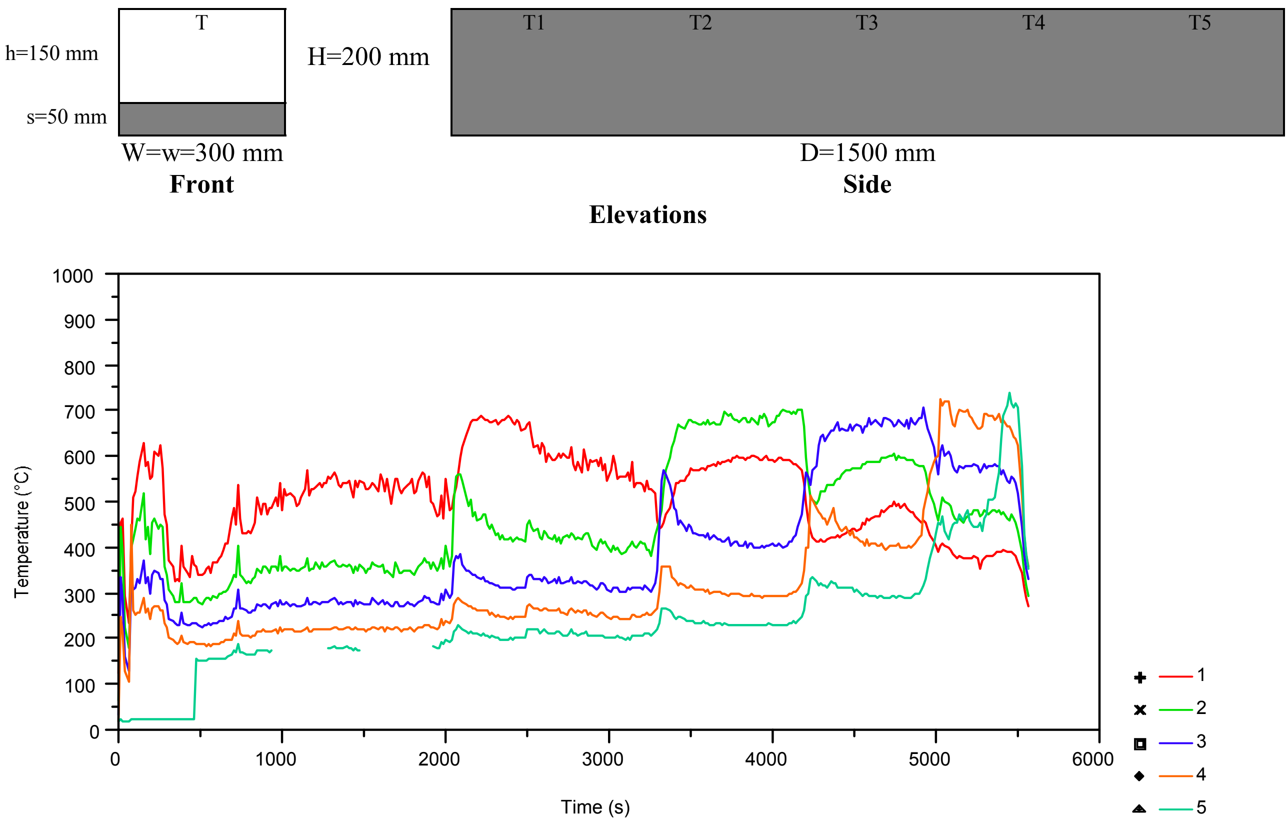


(d) Test SO74: material = steel

Figure 14 Examples of Temperature - Time Curves for Various Enclosure Configurations (continued)

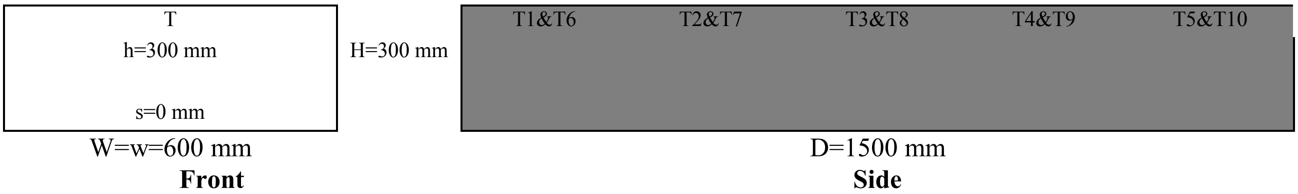


(e) Test SO55: material = steel

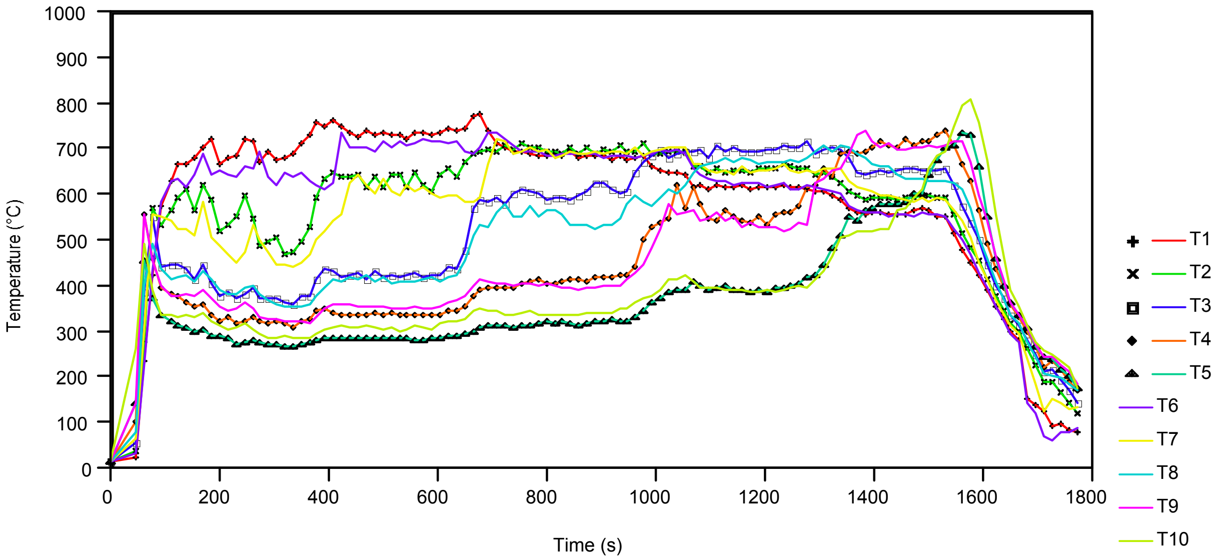


(f) Test S3Q108: material = steel (Note change of time scale compared with (a) to (d))

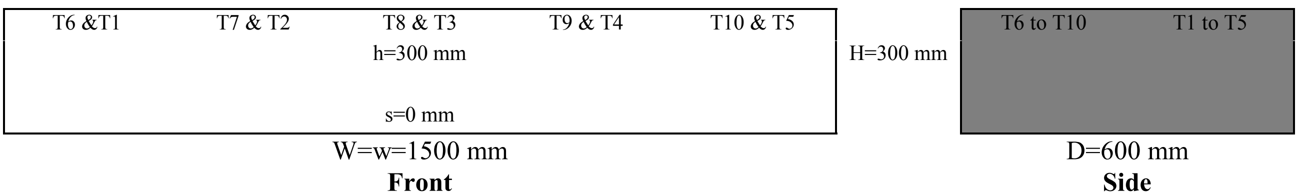
Figure 14 Examples of Temperature - Time Curves for Various Enclosure Configurations (continued)



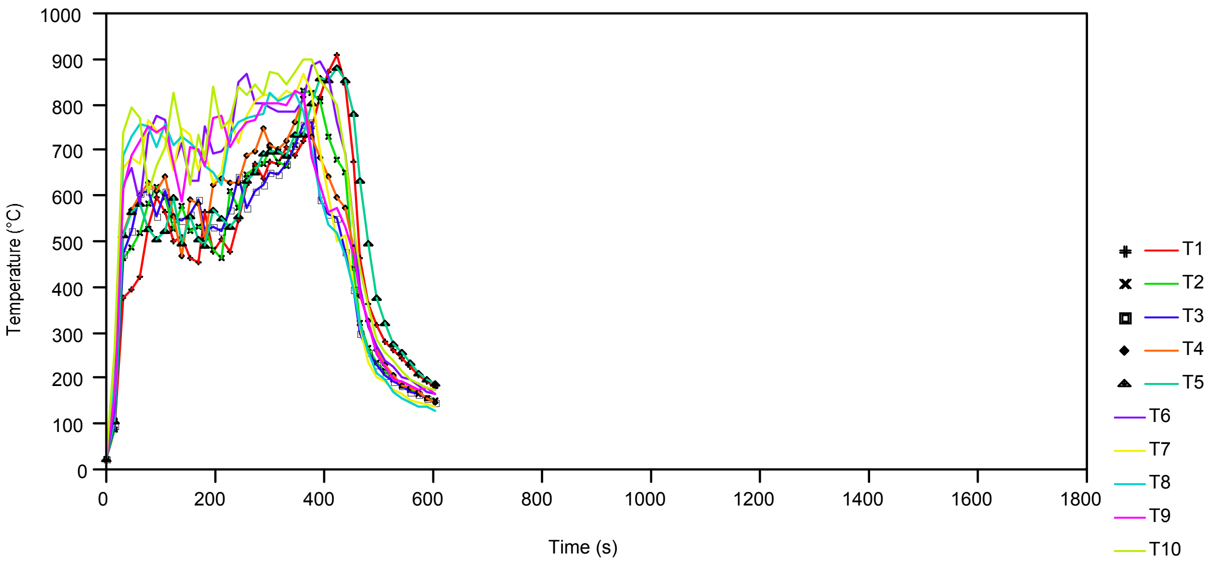
Elevations



(g) Test SFOE119: material = steel and glass

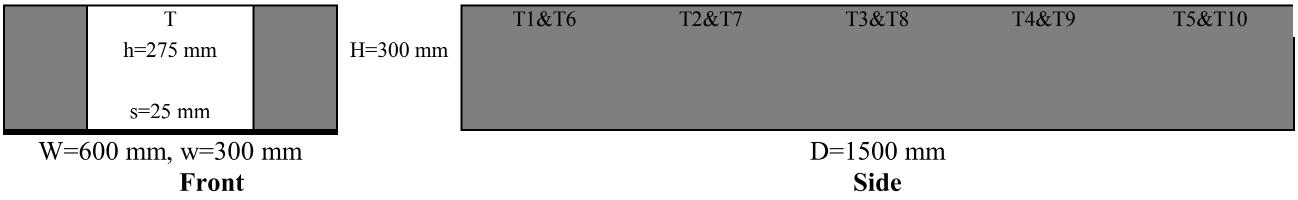


Elevations

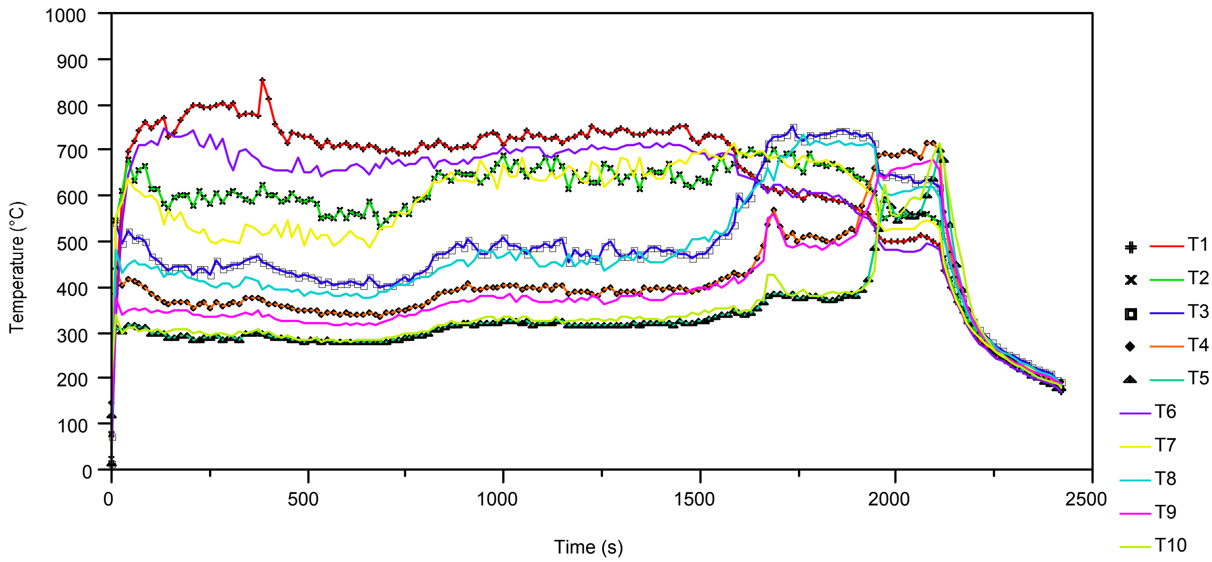


(h) Test SFOS137: material = steel

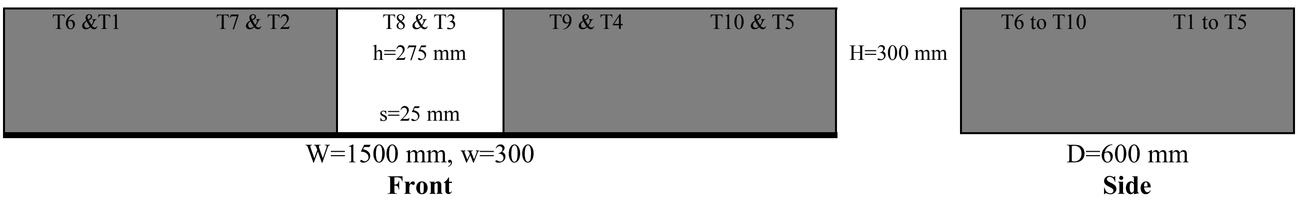
Figure 14 Examples of Temperature - Time Curves for Various Enclosure Configurations (continued)



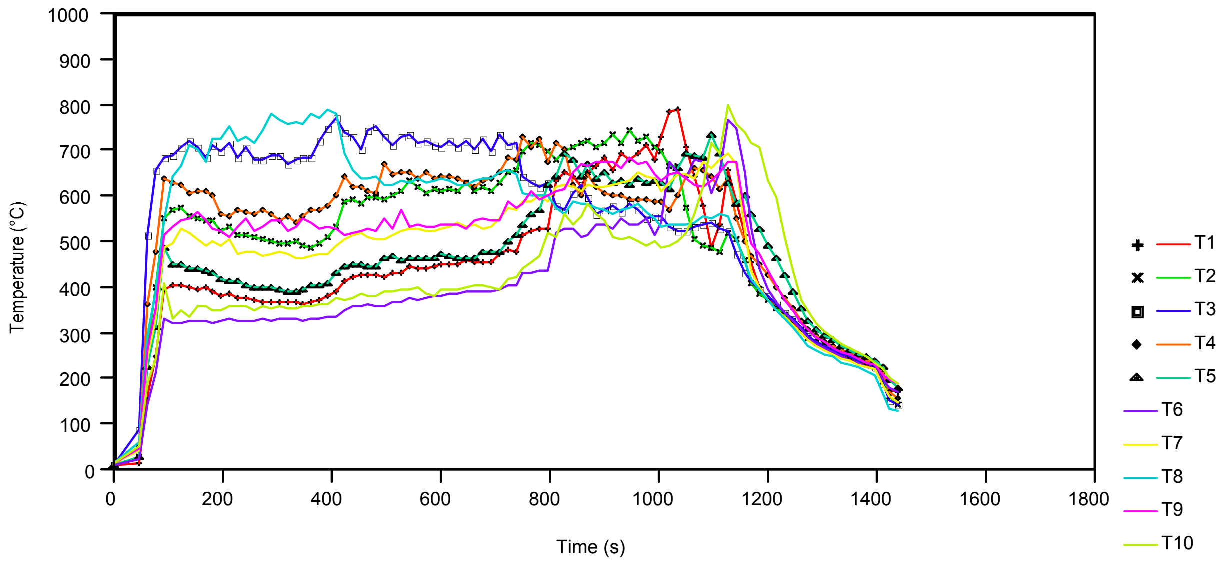
Elevations



(i) Test SPOE141: material = steel and glass



Elevations

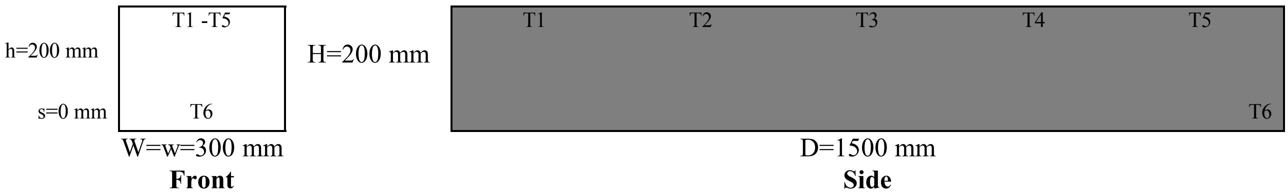


(j) Test SPOST126: material = steel and glass

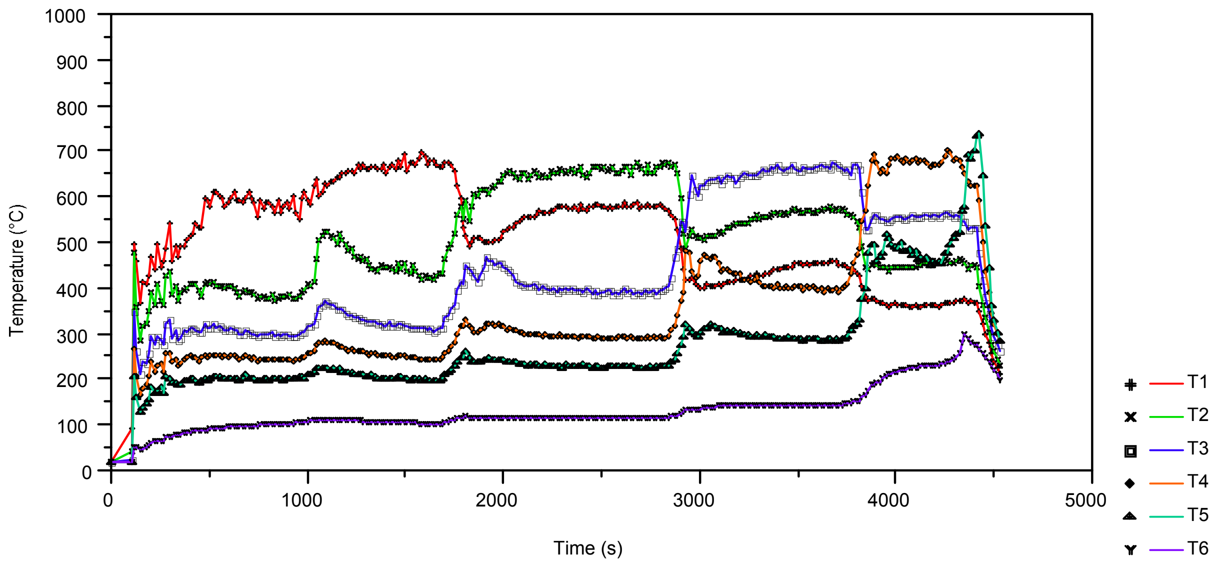
Figure 14 Examples of Temperature - Time Curves for Various Enclosure Configurations (continued)

In Figures 14 (g) and (h) both show the thermocouple traces for enclosures 600 mm by 1500 mm in plan. The first is 1500 mm deep, the second 1500 mm wide. In Figure 14 (g) comparison of the traces for each of the pairs of thermocouples equal distances from the vent shows that they always remain very similar, and overall the pattern of change through the test is very similar to that for the 300 mm wide by 1500 mm deep enclosure (Figure 14 (e)). In Figure 14 (h) it is clear that the temperatures of the rear thermocouples remain well below those of the front thermocouples for the first part of the test while the front trays were burning, and then they were all very similar while the rear trays were burning.

The enclosures in Figures 14 (i) and (j) both had partial width vents, rather than the full width vents in Figures 14 (a) to (h). The thermocouple traces are notably different from those for the similar size enclosures in Figures 14 (g) and (h). Firstly, the durations of the fires were longer with the partial width openings, but not nearly as much longer as might be expected from a simple comparison of the vent widths (the vent heights being very similar)[1]. Secondly, the thermocouple traces for other than the front thermocouples are lower for much longer in the enclosures with the partial width vents than in the enclosures with full width vents. This reflects greater transportation of the fuel to towards the vent and it being burned in the region close to the vent in these enclosures[1]. However the basic pattern is identical: the fuel closest to the ventilation opening burns first, with the fuel furthest from the vent (and those with the most "difficult" gas flows in the case of the wide partial width vent enclosures) burn last. Thus, in Figure 14 (i), the remaining fuel in trays T3 and T8, then T4 and T9, and finally T5 and T10 burn after the fuel in trays T1, T2, T6 and T7 is exhausted. In Figure 14 (j) the traces confirm the visual observations that burning takes place in the regions of tray T8 first, then T3 and T8, then T2 and T4, followed by T7 and T9, then T1 and T5 and finally T6 and T10.



Elevations



Test SFGOE210: material = steel and glass

Figure 15 Temperature - Time Curves Near Top and Bottom of Enclosure

In none of the enclosures represented by these graphs was the temperature anything like uniform throughout even the upper level of the enclosure represented by these traces. Even greater temperature differences exist in such enclosures when temperatures near the floor are considered. This is illustrated in Figure 15 which shows the temperatures measured by the usual thermocouples near the top of an enclosure and the temperature measured near the floor at the rear of the enclosure (25 mm from floor, 20 mm from rear wall on centreline).

The temperature differential between the top of the enclosure and the bottom even at the rear of the enclosure was very substantial for most of the test. This indicates a strong driving force for a circulation cell between the fire front and the rear of the enclosure as well as the observed strong flow between the vent and the fire.

Discussion

In considering fire severity there are two basic parameters - the temperatures reached and the duration of the high temperatures. In these tests the simplest time measure reflecting the duration of high temperatures is simply the burnout time - that is the time from ignition to final flame out. As mentioned above it also represents a good measure of the burning rate when used in conjunction with the total mass of fuel in the enclosure.

Thus a useful measure of the overall average burning rate in the tests represented by Table A1 is given by R (MJ/s), defined as follows:

$$R = \frac{F_l \times 27}{t_b}$$

where:

F_l is the total fire load in the enclosure (kg), and

t_b is the burnout time (s)

The only input variables throughout these tests have been the geometry of the enclosure and vent, and the wall materials. Considering a relationship of the form

$$R = c \times W^{c_W} \times D^{c_D} \times H^{c_H} \times w^{c_w} \times h^{c_h}$$

a least squares regression may be used to evaluate the terms c, c_W, c_D, c_H, c_w and c_h.

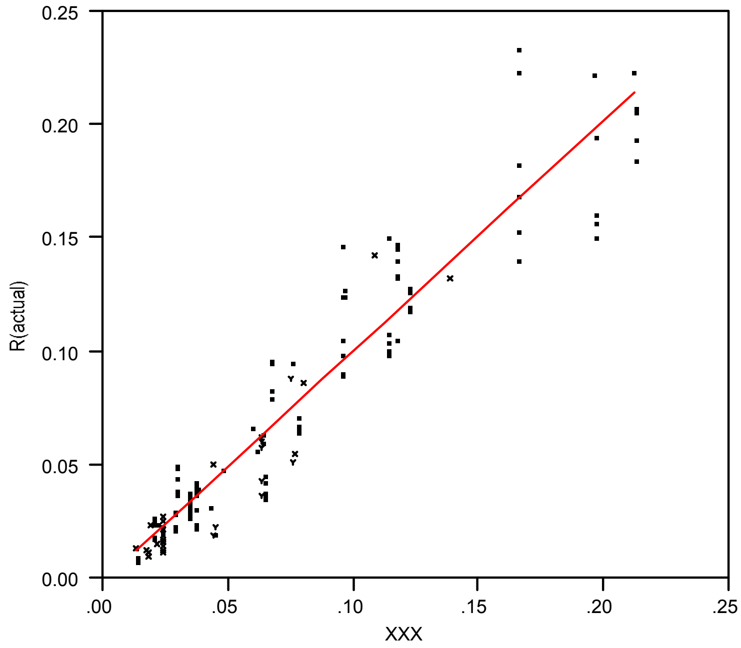
If this is done on the data as a whole a good correlation between the actual and predicted R results:

$$R = 0.476 \times W^{0.485} \times D^{-0.006} \times H^{0.180} \times w^{0.591} \times h^{0.858}$$

Figure 16 shows a comparison of the actual values of and that predicted by this expression.

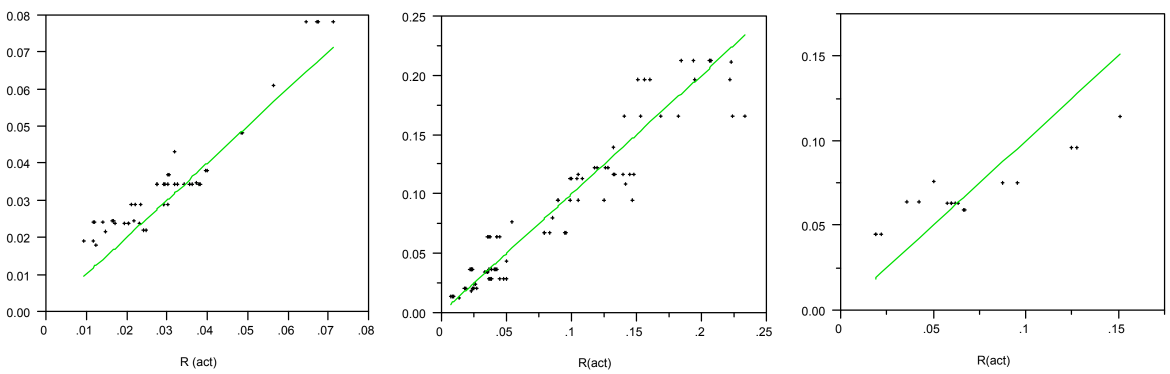
However, close examination of this figure reveals that in some regions this expression does not provide a good representation of the data, although the overall representation is adequate. Consequently, the data has been analysed using this expression in three distinct regions which have been identified after extensive analysis of the data:

1. $D/W \geq 2$
2. $D/W < 2$ and $w/W = 1$
3. $D/W < 2$ and $w/W < 1$



(Correlation coefficient ($R^2 = 0.91$))

Figure 16 Scatter Diagram of Actual and Predicted Average Mass Loss Rate



(a) $D/W \geq 2$ (b) $D/W < 2$ and $w/W = 1$ (c) $D/W < 2$ and $w/W < 1$

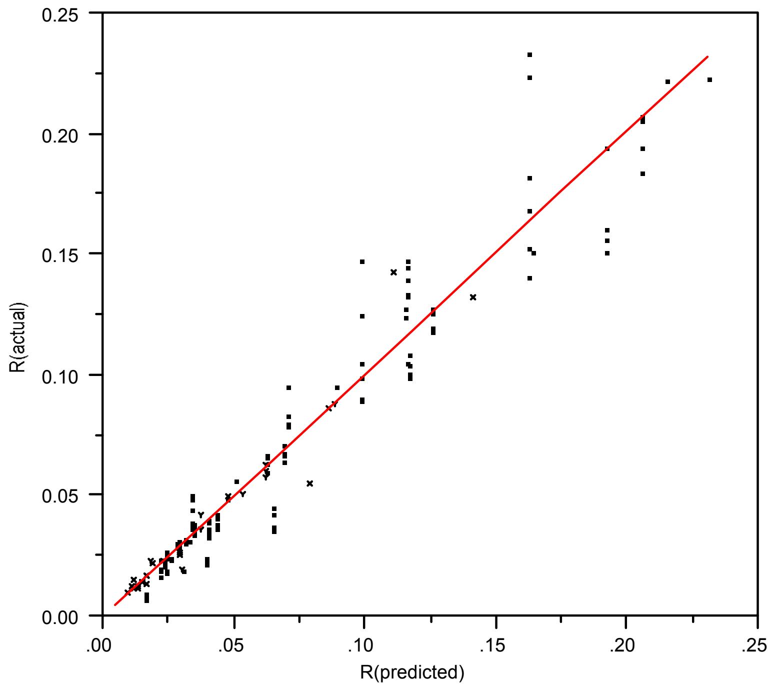
Figure 17 Scatter Diagram of Actual and Predicted Average Mass Loss Rate

The following combination of formulae provides a good correlation with the data:

If $D/W \geq 2$ $\quad R = 1.601 \times W^{0.715} \times D^{-0.367} \times H^{0.952} \times w^{0.404} \times h^{1.06}$

If $D/W < 2$ and $w/W = 1$ $\quad R = 0.517 \times D^{0.166} \times H^{0.0973} \times w^{0.968_w} \times h^{0.827}$

If $D/W < 2$ and $w/W < 1$ $\quad R = 3.56 \times D^{0.727} \times w^{0.879} \times h^{1.75}$

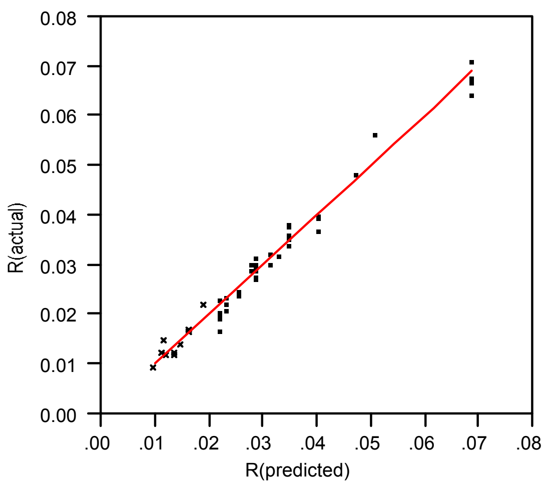


(Correlation coefficient ($R^2 = 0.93$))

Figure 18 Scatter Diagram of Actual and Predicted Average Mass Loss Rate

Looking at each region separately:

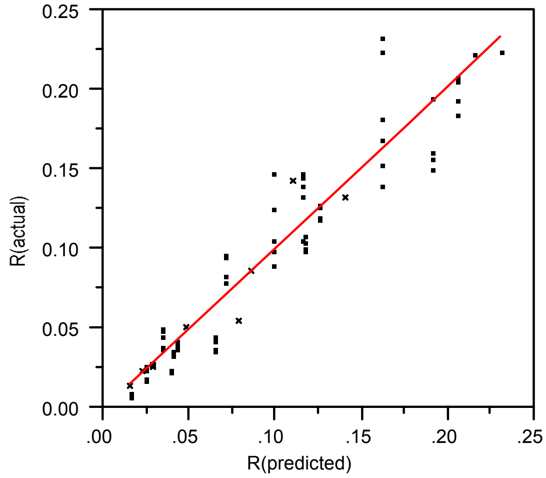
- $D/W \geq 2$



(Correlation coefficient ($R^2 = 0.98$))

Figure 18 Scatter Diagram of Actual and Predicted Average Mass Loss Rate

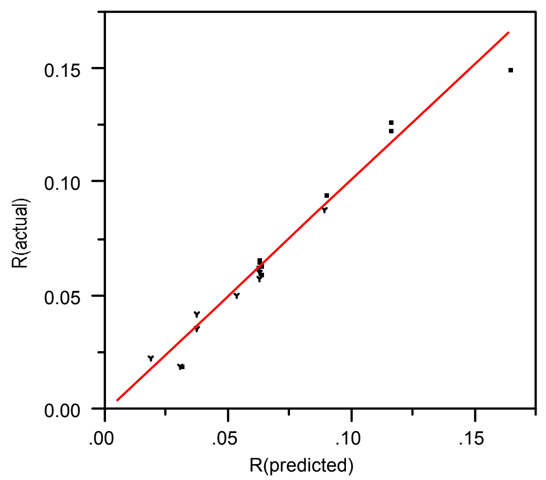
- $D/W < 2$ and $w/W = 1$



(Correlation coefficient ($R^2 = 0.91$))

Figure 20 Scatter Diagram of Actual and Predicted Average Mass Loss Rate

- $D/W < 2$ and $w/W < 1$



(Correlation coefficient ($R^2 = 0.97$))

Figure 21 Scatter Diagram of Actual and Predicted Average Mass Loss Rate

It is of note that only in the last of these do the powers of the vent width (0.879) and the vent height (1.75) approximate the usually adopted figures of 1 and 1.5 respectively. It is, of course, possible to incorporate the usual (that is,) term in the expressions but all that this does is result in compensating values of the powers for and , or alternatively compromises the fit of the expressions.

The maximum temperature shows a large amount of variability as shown in Figure 22 where it is plotted against the burnout time. A log-linear relationship represented by the plotted line provides a reasonable estimate, somewhat better than a straight line fit. Complex relationships of the variables as used in the correlations for the rate of burning provide only a slightly better fit.

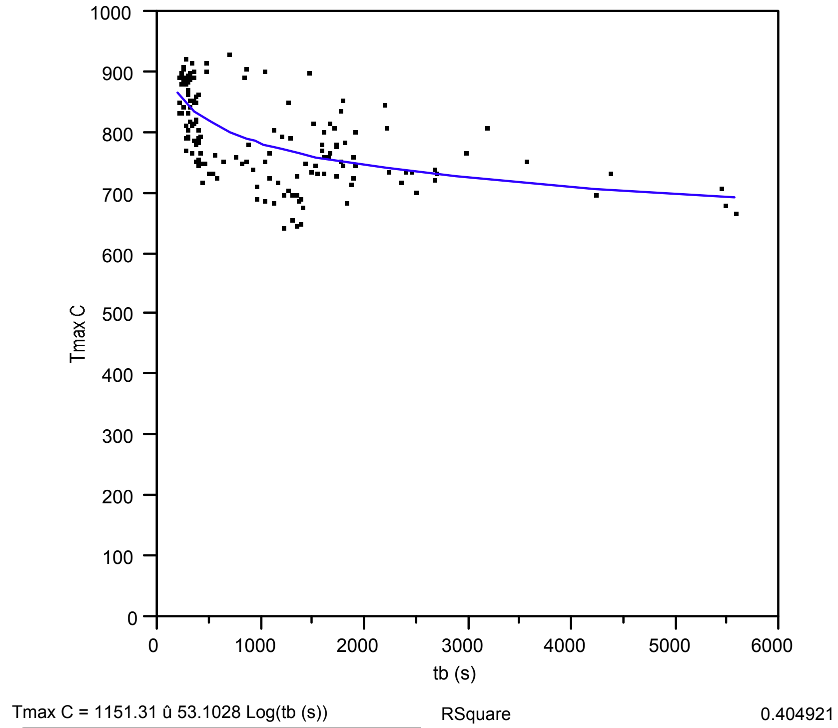
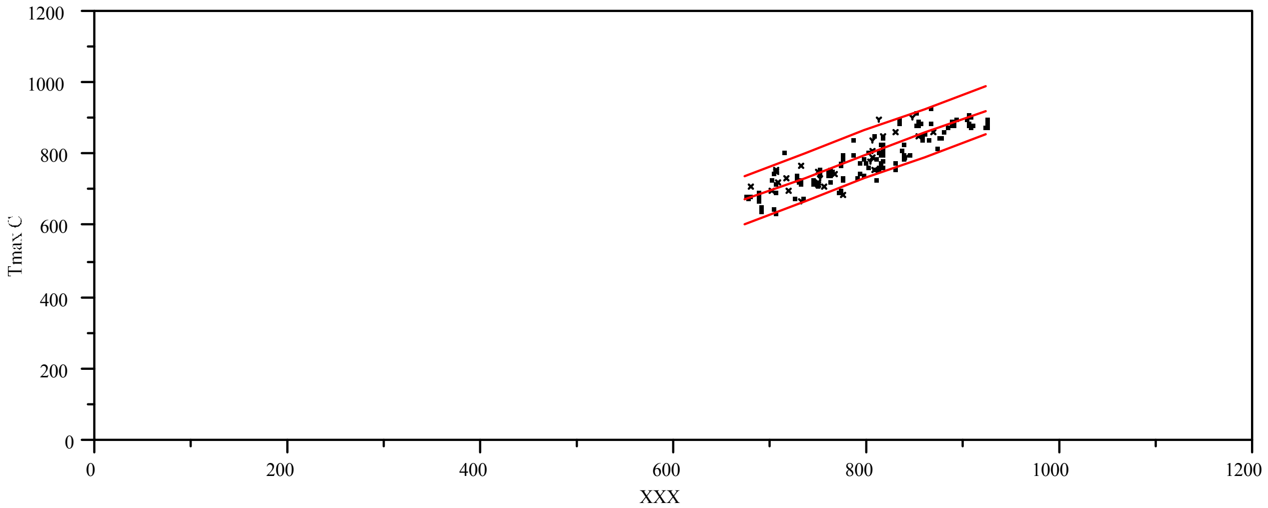


Figure 21 Maximum Temperature Variation with Burnout Time

The main feature of the fires in these enclosures is that "flashover" does not occur and that uniform conditions do not occur, indeed, cannot occur if the flows necessary to sustain the supply of oxygen to the fire are to exist.



Acknowledgments

The author is grateful to Rob Ralph, Michael Culton and Paul Tisch for carrying out the experimental program and to Ian Bennetts for support and valuable discussions.

References

1. Thomas, I.R. and Bennetts, I.D., *Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures, Submitted for IAFSS Symposium 1999.*
2. Drysdale, D., *An Introduction to Fire Dynamics*, Wiley (1985).

Appendix A

H (mm)	W (mm)	D (mm)	w (mm)	h (mm)	s (mm)	Material	t_b (s)	T_m (°C)	Test
200	300	300	300	100	100	Steel	765	765	SH104
200	300	300	300	150	50	Steel	453	755	S3Q96
200	300	300	300	200	0	Steel	411	802	SO92
200	300	300	300	200	0	Steel & glass	392	764	SGFOE217HT
200	300	600	300	200	0	Steel & glass	956	695	SGFOE216
200	300	900	300	140	60	Steel	2505	707	SH106
200	300	900	300	150	50	Steel	2669	729	S3Q103
200	300	900	300	200	0	Steel	1860	720	SO100
200	300	900	300	200	0	Steel & glass	1896	731	SGFOE214
200	300	1200	300	200	0	Steel & glass	2975	775	SGFOE211
200	300	1500	300	150	50	Steel	5455	714	S3Q108
200	300	1500	300	175	25	CaSi	3562	758	CFOE224
200	300	1500	300	200	0	Steel	4238	703	SO110
200	300	1500	300	200	0	Steel & glass	4375	739	SGFOE210
200	900	300	900	100	100	Steel	630	760	SH109
200	900	300	900	200	0	Steel	367	857	SO111
200	1500	300	1500	100	100	Steel	955	719	SH105
200	1500	300	1500	150	50	Steel	369	868	S3Q99
200	1500	300	1500	200	0	Steel	397	871	SO95
300	300	300	300	95	205	CaSi	1035	694	CQ31
300	300	300	300	95	205	Steel	1129	689	SQ85
300	300	300	300	95	205	Steel	1393	695	SQ30
300	300	300	300	150	150	CaSi	383	760	CH75
300	300	300	300	150	150	CaSi	414	772	CH17
300	300	300	300	150	150	CaSi	420	755	CH48
300	300	300	300	150	150	Steel	427	723	SH84
300	300	300	300	150	150	Steel	546	739	SH13
300	300	300	300	150	150	Steel	573	730	SH35
300	300	300	300	225	75	CaSi	208	856	C3Q86
300	300	300	300	225	75	CaSi	215	840	C3Q58
300	300	300	300	225	75	CaSi	235	840	C3Q6
300	300	300	300	225	75	Steel	269	778	S3Q12
300	300	300	300	225	75	Steel	274	819	S3Q36
300	300	300	300	225	75	Steel	284	799	S3Q71
300	300	300	300	275	25	Steel	291	813	SO41
300	300	300	300	275	25	Steel	293	803	S1
300	300	300	300	275	25	Steel	295	839	SO11
300	300	300	300	275	25	Steel	315	825	SO66
300	300	300	300	275	25	Steel & glass	297	799	SGFOE215HT

H (mm)	W (mm)	D (mm)	w (mm)	h (mm)	s (mm)	Material	t_b (s)	T_m (°C)	Test
300	300	300	300	300	0	CaSi	243	902	C5
300	300	300	300	300	0	CaSi	243	906	CO33
300	300	300	300	300	0	CaSi	255	893	C6
300	300	300	300	300	0	CaSi	270	892	CO5
300	300	300	300	300	0	CaSi	283	932	CO82
300	300	600	300	275	25	Steel & glass	564	770	SGFOE213
300	300	900	140	275	25	Steel	1266	712	SV54
300	300	900	140	275	25	Steel	1300	704	SV64
300	300	900	300	180	0	Steel	1612	740	SQ102
300	300	900	300	180	0	Steel	1838	690	SQ52
300	300	900	300	180	120	Steel	1343	735	SQ51
300	300	900	300	180	120	Steel	1517	751	SH62
300	300	900	300	180	120	Steel	1538	740	SQ101
300	300	900	300	225	75	Steel	1039	761	S3Q61
300	300	900	300	225	75	Steel	1075	732	SQ60
300	300	900	300	225	75	Steel	1075	772	S3Q83
300	300	900	300	275	25	Steel	817	756	SO74
300	300	900	300	275	25	Steel	828	756	S7
300	300	900	300	275	25	Steel	864	759	SO47
300	300	900	300	275	25	Steel	920	745	SO59
300	300	900	300	275	25	Steel & glass	885	787	SGFOE212
300	300	1200	300	275	25	Steel & glass	1287	799	SGFOE209
300	300	1500	300	225	75	Steel	2224	743	S3Q63
300	300	1500	300	225	75	Steel	2355	726	S3Q65
300	300	1500	300	225	75	Steel	2451	742	S3Q79
300	300	1500	300	275	25	Steel	1648	765	S8
300	300	1500	300	275	25	Steel	1734	736	SO70
300	300	1500	300	275	25	Steel	1772	758	SO46
300	300	1500	300	275	25	Steel	1786	753	SO55
300	300	1500	300	275	25	Steel	1907	754	SO57
300	300	1500	300	275	25	Steel & glass	1887	766	SGFOE207
300	300	1500	300	300	0	CaSi	1724	787	CFOE223
300	300	1500	300	300	0	CaSi	1737	784	CSFOE220
300	600	1500	200	275	25	Steel & glass	2684	744	SPOE144
300	600	1500	200	275	25	Steel & glass	2688	740	SPOE143
300	600	1500	300	275	25	Steel & glass	2200	853	SPOE141
300	600	1500	300	275	25	Steel & glass	2208	814	SPOE142
300	600	1500	600	150	150	Steel	3190	817	SFOE97
300	600	1500	600	225	75	Steel	1903	810	SFOE96
300	600	1500	600	300	0	Steel	1515	823	SFOE95
300	600	1500	600	300	0	Steel	1592	776	SFOE94
300	600	1500	600	300	0	Steel	1605	809	SFOE119
300	600	1500	600	300	0	Steel	1669	822	SFOE93

H (mm)	W (mm)	D (mm)	w (mm)	h (mm)	s (mm)	Material	t_b (s)	T_m (°C)	Test
300	900	300	900	75	225	CaSi	1305	662	CQ19
300	900	300	900	75	225	CaSi	1335	653	CQ45
300	900	300	900	75	225	CaSi	1357	694	CQ81
300	900	300	900	75	225	Steel	1350	703	SQ23
300	900	300	900	75	225	Steel	1401	682	SQ38
300	900	300	900	150	150	CaSi	328	818	CH16
300	900	300	900	150	150	CaSi	330	773	CH78
300	900	300	900	150	150	CaSi	377	787	CH32
300	900	300	900	150	150	Steel	395	752	SH37
300	900	300	900	150	150	Steel	400	798	SH21
300	900	300	900	225	75	CaSi	214	898	C3Q72
300	900	300	900	225	75	CaSi	254	851	C3Q4
300	900	300	900	225	75	CaSi	349	862	C3Q53
300	900	300	900	225	75	Steel	302	872	S3Q10
300	900	300	900	225	75	Steel	317	851	S3Q26
300	900	300	900	225	75	Steel	351	900	S3Q113
300	900	300	900	275	25	Steel	291	891	SO67
300	900	300	900	275	25	Steel	302	903	S2
300	900	300	900	275	25	Steel	316	896	SO9
300	900	300	900	275	25	Steel	318	906	SO40
300	900	300	900	300	0	CaSi	246	888	C4
300	900	300	900	300	0	CaSi	246	917	C073
300	900	300	900	300	0	CaSi	252	892	CO3
300	900	300	900	300	0	CaSi	262	916	CO34
300	900	300	900	300	0	CaSi	264	899	C1
300	1500	300	300	75	25	Steel & glass	.	.	SPOSB125
300	1500	300	300	150	25	Steel & glass	2385	743	SPOSB124
300	1500	300	300	225	25	Steel	1270	858	SPOSB123
300	1500	300	300	225	75	Steel	1465	908	SPOST121
300	1500	300	300	275	25	Steel	1041	909	SPOS120
300	1500	300	1500	75	225	CaSi	1225	648	CQ49
300	1500	300	1500	75	225	CaSi	1419	756	CQ80
300	1500	300	1500	75	225	CaSi	1476	743	CQ20
300	1500	300	1500	75	225	Steel	1168	726	SQ24
300	1500	300	1500	75	225	Steel	1232	704	SQ42
300	1500	300	1500	75	225	Steel	1379	656	SQ97
300	1500	300	1500	150	150	CaSi	357	796	CH15
300	1500	300	1500	150	150	CaSi	361	824	CH77
300	1500	300	1500	150	150	CaSi	375	827	CH44
300	1500	300	1500	150	150	Steel	395	790	SH25
300	1500	300	1500	150	150	Steel	395	813	SH56
300	1500	300	1500	150	150	Steel	499	739	SH94
300	1500	300	1500	225	75	CaSi	226	889	C3Q14
300	1500	300	1500	225	75	CaSi	235	888	C3Q43
300	1500	300	1500	225	75	CaSi	288	879	C3Q76
300	1500	300	1500	225	75	Steel	313	860	S3Q8
300	1500	300	1500	225	75	Steel	345	857	S3Q27
300	1500	300	1500	225	75	Steel	374	831	S3Q91

H (mm)	W (mm)	D (mm)	w (mm)	h (mm)	s (mm)	Material	t_b (s)	T_m (°C)	Test
300	1500	300	1500	275	25	Steel	270	894	S3
300	1500	300	1500	275	25	Steel	328	900	SO39
300	1500	300	1500	275	25	Steel	335	925	SO68
300	1500	300	1500	275	25	Steel	350	910	SO7
300	1500	300	1500	300	0	CaSi	254	898	CO1
300	1500	300	1500	300	0	CaSi	254	914	CO69
300	1500	300	1500	300	0	CaSi	255	890	C2
300	1500	300	1500	300	0	CaSi	272	889	CO2
300	1500	300	1500	300	0	CaSi	285	.	C1?
300	1500	600	200	275	25	Steel & glass	1595	787	SPOS146
300	1500	600	200	275	25	Steel & glass	1615	768	SPOS145
300	1500	600	300	150	25	Steel & glass	5483	687	SPOSB138
300	1500	600	300	150	25	Steel & glass	5587	673	SPOSB130
300	1500	600	300	150	150	Steel & glass	.	.	SPOST135
300	1500	600	300	225	25	Steel & glass	1672	772	SPOSB136
300	1500	600	300	225	25	Steel & glass	1710	815	SPOSB129
300	1500	600	300	225	75	Steel & glass	1770	845	SPOST127
300	1500	600	300	225	75	Steel & glass	1780	862	SPOST134
300	1500	600	300	225	75	Steel & glass	1808	790	SPOST128
300	1500	600	300	275	25	Steel & glass	1125	813	SPOS133
300	1500	600	300	275	25	Steel & glass	1212	802	SPOS126
300	1500	600	600	75	25	Steel & glass	.	.	SPOS131
300	1500	600	600	225	75	Steel & glass	840	898	SPOST139
300	1500	600	600	225	75	Steel & glass	860	912	SPOST140
300	1500	600	600	275	25	Steel & glass	707	939	SPOS132
300	1500	600	1500	275	25	Steel	475	909	SFOS137
300	1500	600	1500	300	0	Steel	480	925	SPOS147

In Table A1, apart from the dimensions mentioned above the following quantities are tabulated for each test:

- material type (CaSi = calcium silicate board, steel = steel plate, steel and glass = steel enclosure with one wall of glass)
- time from ignition to burnout (t_b) in seconds
- maximum temperature (T_m) in °C

Attachment 3

Investigation of the Effect of Fuel Position on Fire Severity in Long Enclosures

by

I R Thomas
BHP Research Melbourne Laboratories

Introduction

The severity of possible fires in a building must be estimated in order to properly develop an engineering design of the fire safety system for the building. The *severity* of a fire in an enclosure is dependent on a number of factors including the size, shape and ventilation of the enclosure and the fire load in the enclosure. In investigating the severity of fires to be considered in estimating the fire resistance requirements for barrier and structural elements for buildings it became apparent that the rate of burning (as measured by the mass loss rate) varied with the position of the burning fuel in long enclosures.

A comparison of fire severity in long and wide enclosures with single vents has been reported previously[1]. Another factor of importance that has previously been reported is the effect of the position of the openings in each end of enclosures with two vents[2]. Reference 2 included a comparison of the cross ventilation (two vent) cases with single vent cases in identical shape and size enclosures. The severity of fires in small enclosures with uniform fire load (that is, fire load uniformly distributed over the floor area of the enclosures) has previously been reported[3].

The rate of burning (as measured by heat release rate or mass loss rate) in enclosure fires is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$ [4], which means that it is directly proportional to the vent width w and height h raised to the power 1.5, that is $h^{1.5}$. Thus, for the same size ventilation openings the same rate of burning is expected. The experimental program reported below investigated the effect of opening shape and size and enclosure shape on the rate of burning in an enclosure with fuel uniformly distributed through the enclosure.

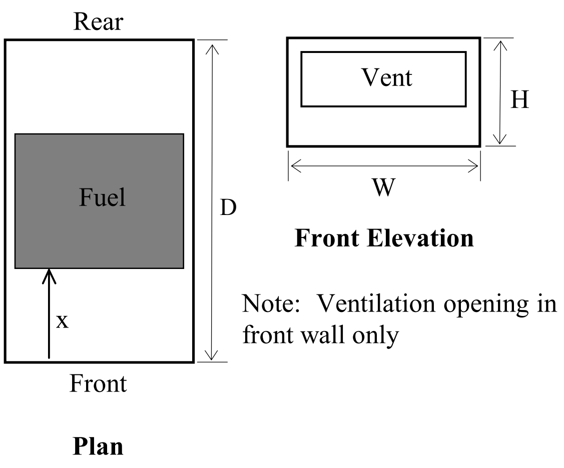


Figure 1 Enclosure Details

The following terminology and nomenclature is used for the clear internal dimensions of the enclosure (Figure 1):

- width (W) - horizontal dimension parallel to the plane of the ventilation opening
- depth (D) - horizontal dimension perpendicular to the plane of the ventilation opening
- height (H) - vertical dimension from the bottom surface to the top surface

The following terminology and nomenclature is used for the dimensions of the ventilation opening:

- opening width (w) - the clear horizontal dimension
- opening height (h) - the clear vertical dimension
- sill height - the vertical dimension from the enclosure floor to the bottom of the opening

The distance from the front of the enclosure (vent) to the front edge of the tray of fuel is denoted by the dimension "x" as in Figure 1.

Experimental Program

The enclosures used in these tests were all 200 or 300 mm high (interior dimensions). In these tests the roof, floor and walls of made of 3 mm steel plate.

In each of these tests 500 ml of liquid fuel (96% ethanol and 4% methanol) was placed in one 250 mm square and 25 mm high steel tray which was placed equidistant from the side walls at a specified distance (x) from the front of the enclosure (Figure 1).

Temperatures were recorded using five Type K mineral insulated thermocouples with the hot junction exposed. Five thermocouples were placed 20 mm from the roof on the centreline of the enclosure (Figure 2). Thermocouple T1 was placed 150 mm from the front of the enclosure and the remainder at 300 mm centres from there. In some tests an additional thermocouple (T6) was also placed in the enclosure 25 mm from the floor and 20 mm from the rear of the enclosure. Temperature readings were taken every 15 seconds.

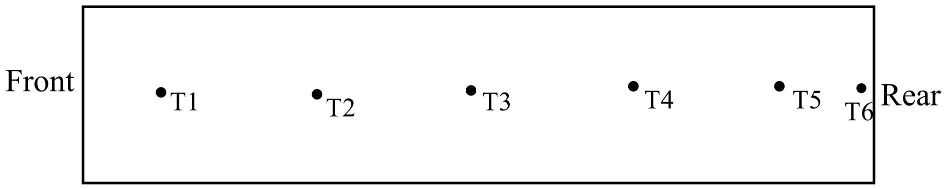


Figure 2 Thermocouple Positions and Numbers

The fuel mass loss was recorded by weighing the entire enclosure. The mass loss was recorded manually at 15 second intervals using a digital scale able to resolve to 0.01 kg. The vent and enclosure shapes and sizes tested are shown in Table A1 in Appendix A.

Most of these tests were conducted in the 300 mm wide by 1500 mm deep enclosures, but tests were also conducted in 300, 600, 900 and 1200 mm deep enclosures. Enclosure widths of 300 mm and 600 mm and enclosure heights of 200 and 300 mm were tested.

Trays of fuel were also burned in the open to enable comparison of the burning of a tray of fuel in the open with a tray of fuel at various positions in the enclosures.

Burning in the Open

Single trays of 500 ml of the liquid fuel (96% ethanol, 4% methanol) were burned in the open to establish the mode and duration of burning in the free-burn situation. When burned in the open the fuel burned on all sides of the tray with the flames covering the entire tray. The flames were generally symmetrical and central above the tray (Figure 3).

Figure 3 Burning of Single Tray in Open

In the open single trays containing 500 ml burned in an average of 418 seconds (range 394 to 460, nine tests).

When a tightly fitting steel shield 50 mm high was fitted on three sides of the tray (effectively an extension of the tray height of 25 mm on three sides) 500 ml of fuel burned in an average of 369 seconds (range 364 to 372, four tests). The only visible effect was simply to move the centre of the plume back slightly (away from the side that had not been "extended"). The burning appeared to take place over the entire surface of the tray and the flame height was unchanged. As the shielding of the three sides was extended in height in 50 mm steps to a maximum of 300 mm there was little further change. The flames still seemed to cover the entire surface, the flame height appeared unchanged and the centre of the plume moved only slightly further back (away from the unextended side).

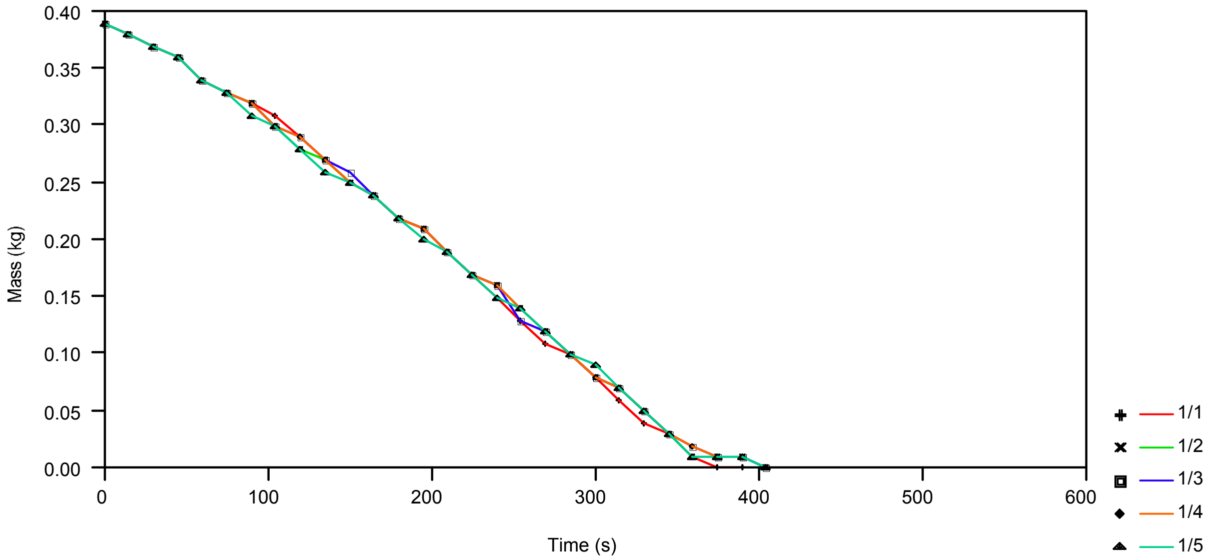


Figure 4 Fuel Mass Histories for Single Trays Burned in Open

Tests in Enclosures

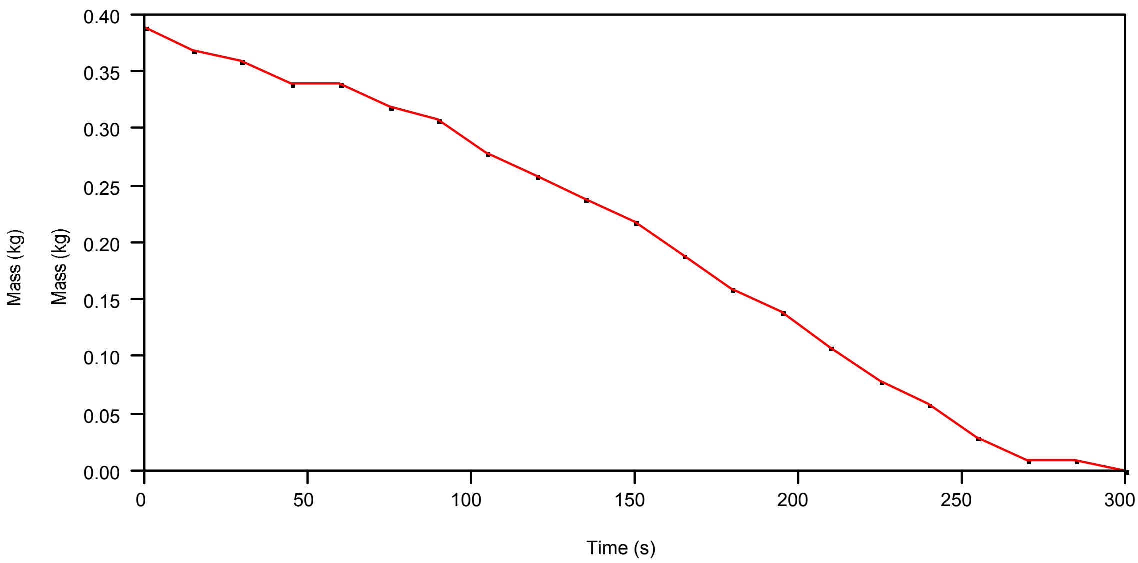
In the single tray tests in the 200 mm high and 1500 mm deep enclosures considerable differences were noted between the tests where the tray was placed close to the ventilation opening and those where the tray was placed well back in the enclosure. Some differences were noted in the tests in the 300 mm high and 1500 mm deep enclosures but these were not as significant as for the 200 mm high enclosures.

(a) Flames from front of tray 25 mm from vent (b) Flames from front of tray 325 mm from vent

Figure 5 Side View of Fire in Enclosure 600 mm Deep and 200 mm High

In the 200 mm high enclosures when the edge of the tray was placed right at the end of the enclosure (x = 0) the flames consistently reached the ceiling but appeared perhaps slightly “lazy”. However, when the tray was moved 50 mm into the enclosure (x = 50) the flames were much more variable, changing in luminosity, sometimes almost appearing to extinguish and not to reach the top of the enclosure. When the tray was moved back a further 50 mm (x = 100) the flames were similar to those described above for x = 0, and when moved a further 50 mm back (x = 150) the flames were similar to x = 0 but stronger, more vigorous, and flames were more often emitted from the enclosure. As the tray was moved further back into the enclosure the flames appeared more vigorous, with a well established flow along the top of the enclosure towards the opening. This flow clearly had strong circular vortices in each top corner of the enclosure with the circulation of the gas and flames being towards the walls at the top and down the walls. Flames were emitted from the opening intermittently as the tray position moved towards the back of the enclosure and consistently when the tray was near the back of the enclosures.

In the case of the 300 mm high enclosures there was much less variation in the appearance of the flames, with the flames for tray positions 0 < x < 100 all appearing quite vigorous. Again, as the tray was positioned further back in the enclosure strong flows along the top of the enclosure with similar vortices, and more consistent flame emission from the opening when the tray was near the back of the enclosure.

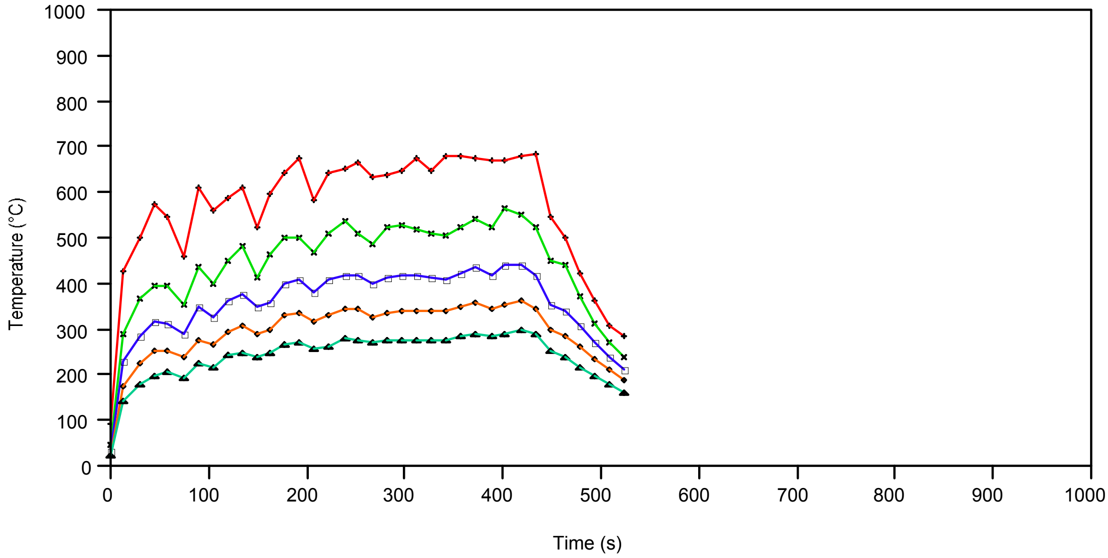


(b) 300W 300D 300H

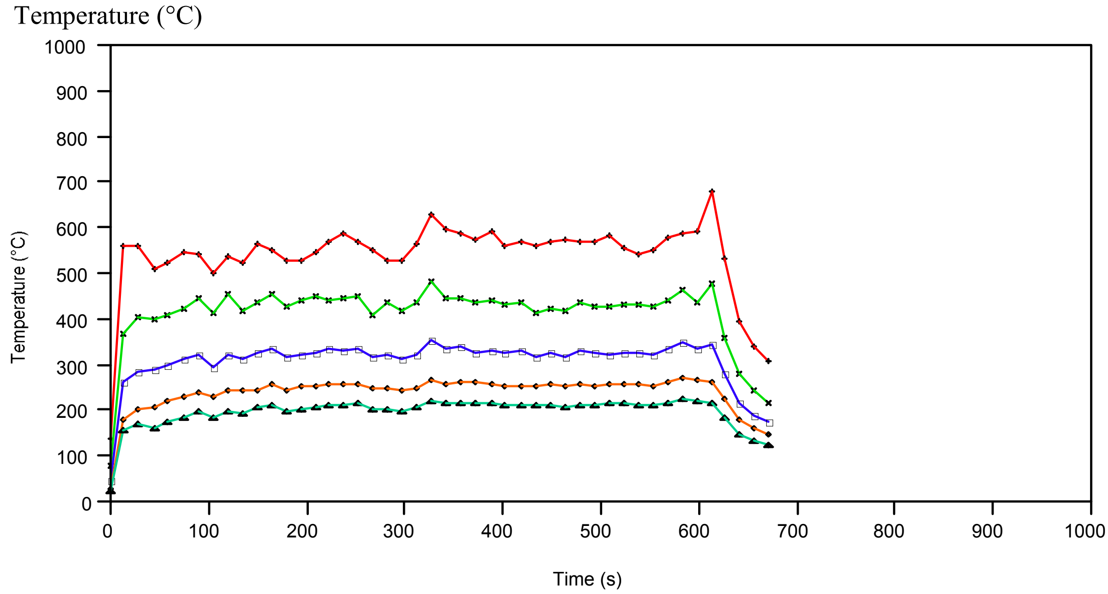
Figure 6 Typical Reduction in Fuel Mass with Time - Trays of Liquid Fuel

Time-temperature traces for enclosures of various shapes are shown in Figure 7.

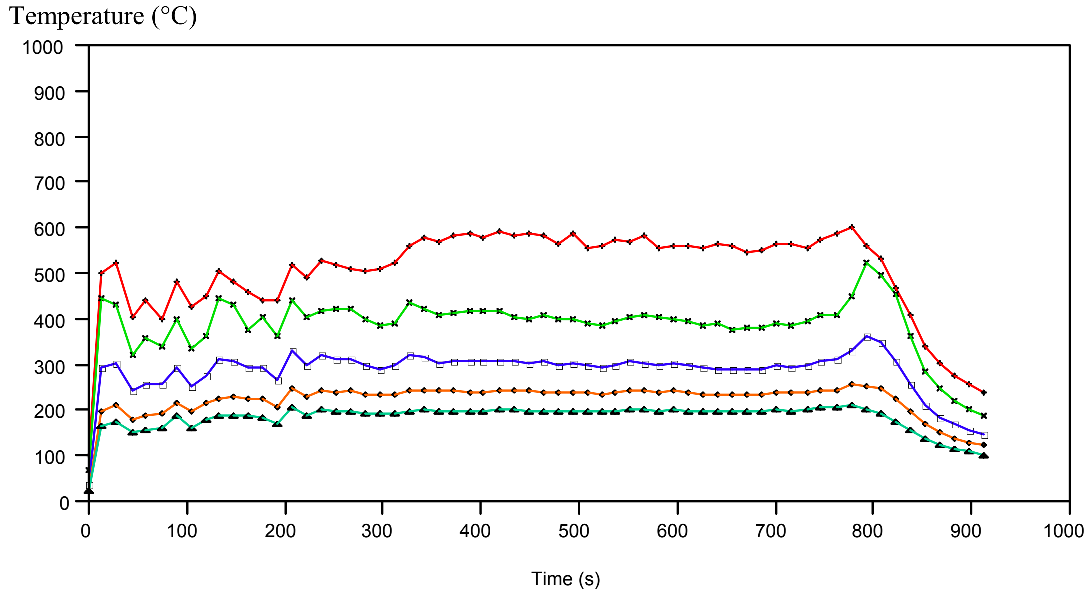
Temperature (°C)



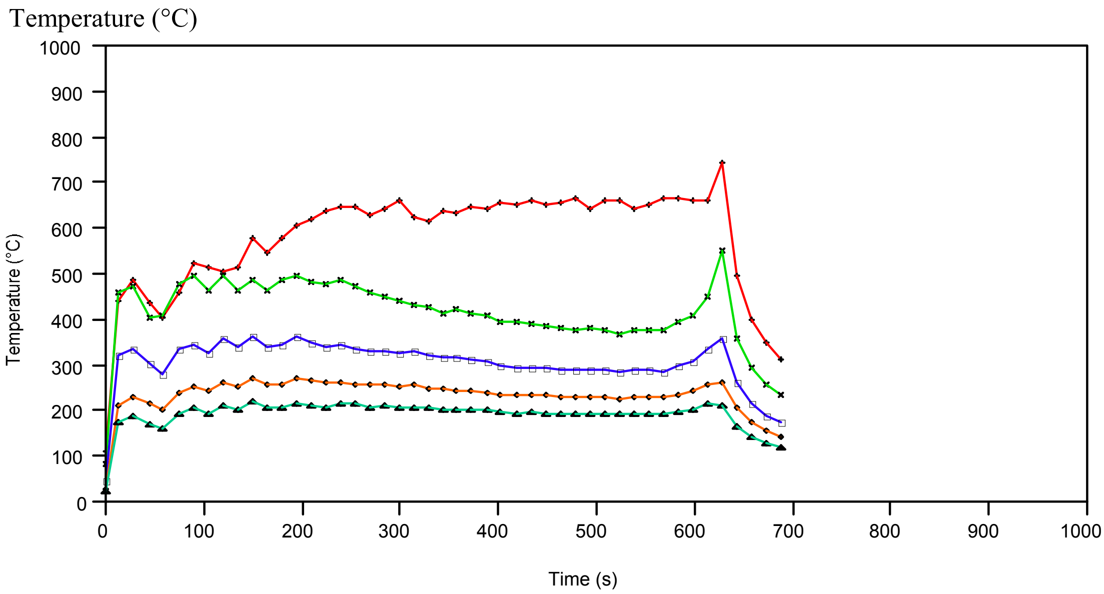
300 mm wide, 1500 mm deep, 300 mm high, wall material = steel, x = 0 mm



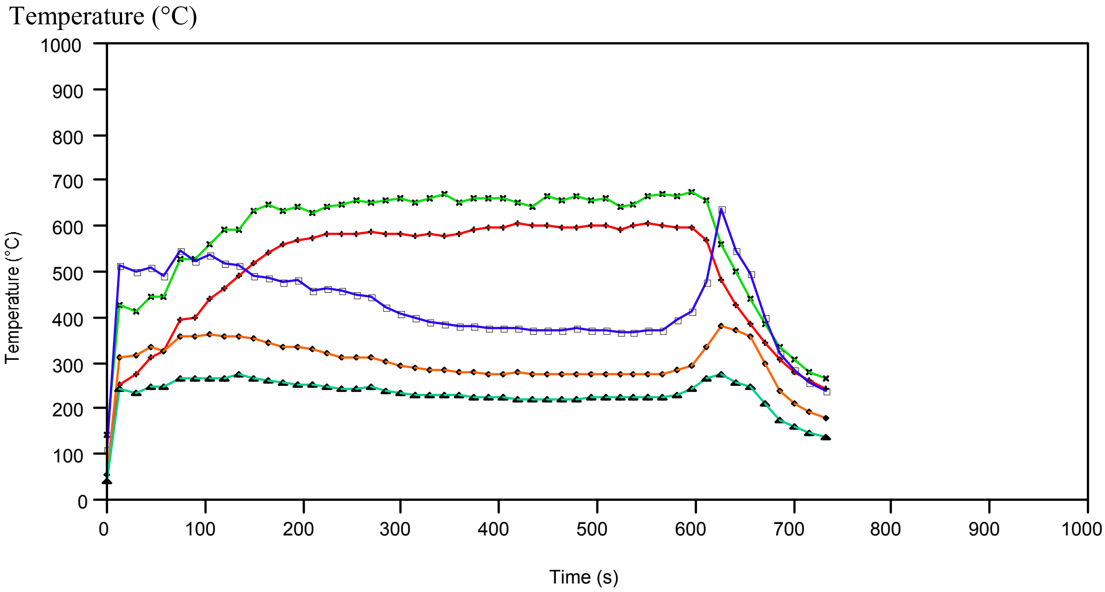
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 0 mm



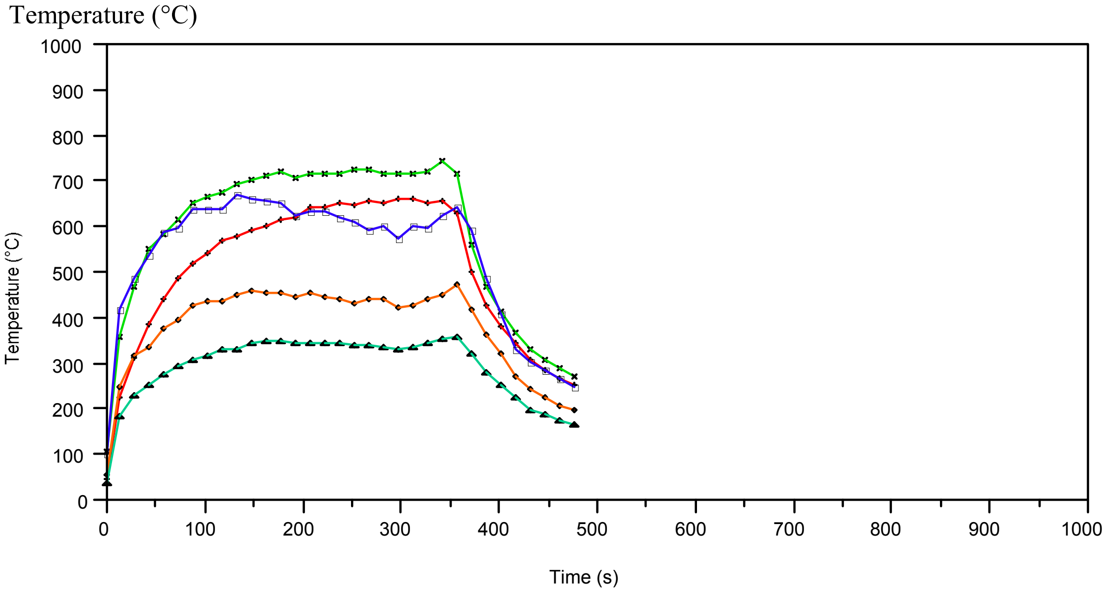
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 50 mm



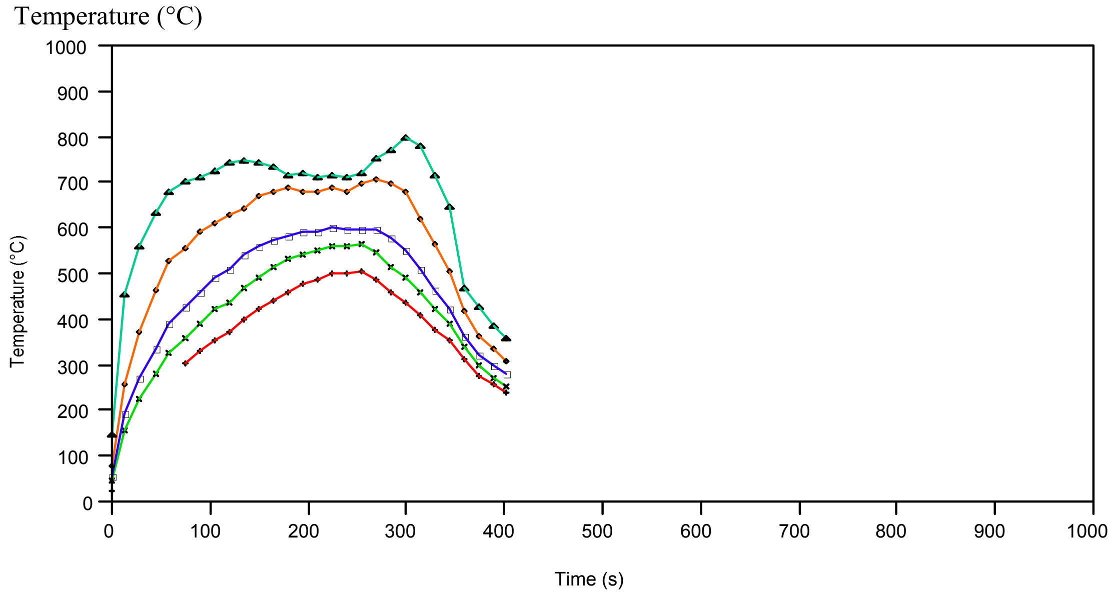
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 150 mm



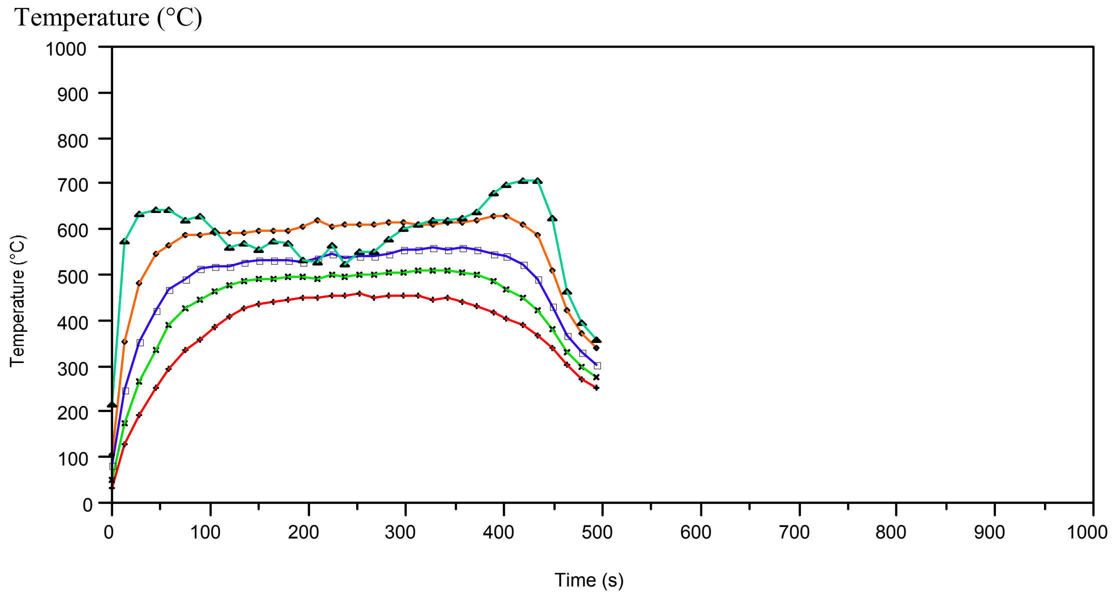
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 500 mm



300 mm wide, 1500 mm deep, 300 mm high, wall material = steel, x = 500 mm

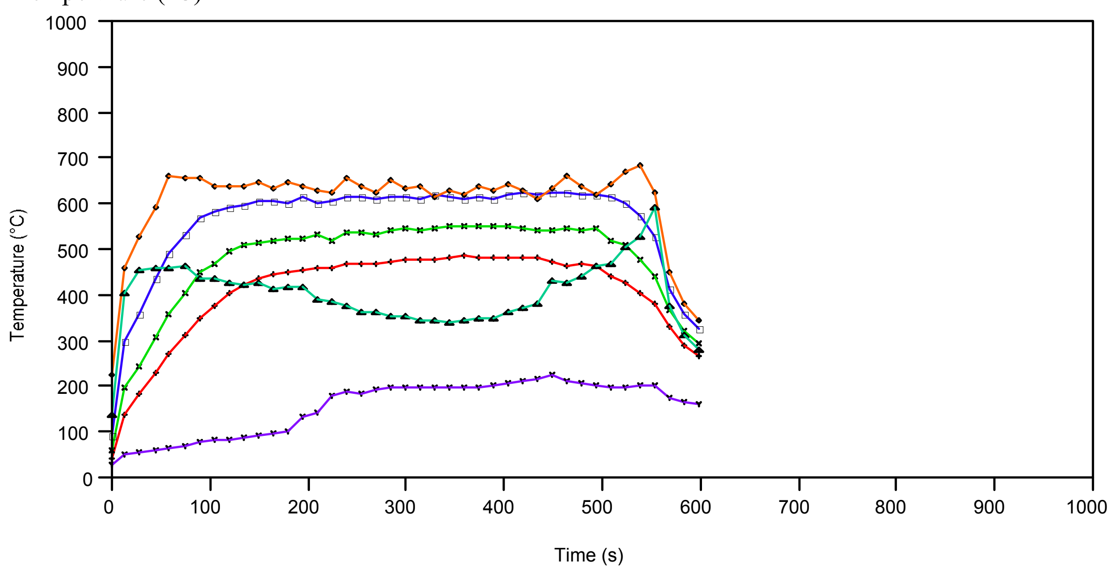


300 mm wide, 1500 mm deep, 300 mm high, wall material = steel, x = 1200 mm



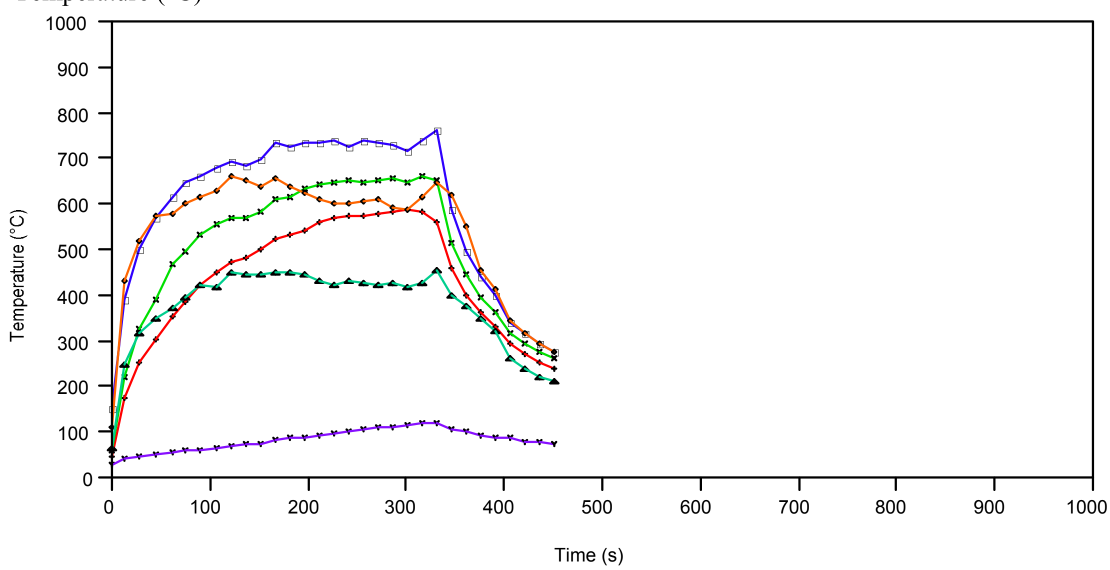
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 1200 mm

Temperature (°C)



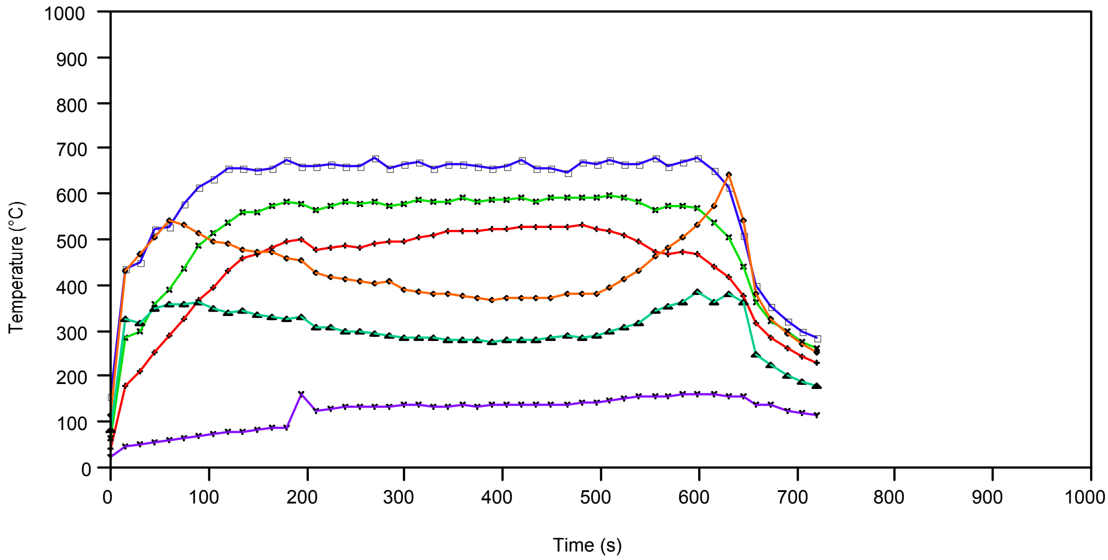
300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 1000 mm
extra thermocouple 20 mm from floor, ??? mm from rear of enclosure on centreline

Temperature (°C)



300 mm wide, 1500 mm deep, 300 mm high, wall material = steel, x = 800 mm
extra thermocouple 20 mm from floor, ??? mm from rear of enclosure on centreline

Temperature (°C)



300 mm wide, 1500 mm deep, 200 mm high, wall material = steel, x = 800 mm
extra thermocouple 20 mm from floor, ??? mm from rear of enclosure on centreline

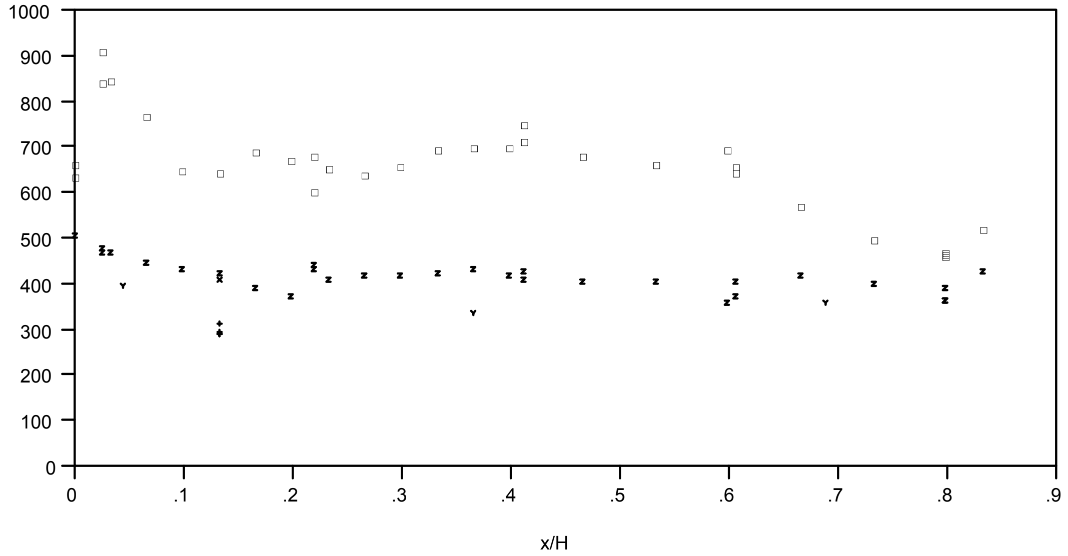
Figure 7 Examples of Temperature - Time Curves for Various Enclosure Configurations and Tray Positions

The variation in burnout time (tb) with distance between the front face of the tray and the ventilation opening is shown in Figure 8. It is apparent from this figure that there is a considerable difference between results for the two enclosure heights.

In the case of enclosure height 300 mm there is a fairly smooth progression from about 500 seconds when the tray is right at the ventilation opening to about 400 seconds when the tray is as far back in the enclosure as possible. There appears to be some systematic variation as the tray is moved from the front of the enclosure to the back, but this variation is minor in comparison with the variation apparent in the 200 mm height enclosure.

In the 200 mm height enclosure there is a great deal of variation particularly in the region close to the ventilation opening. In this region with the tray right against the opening the tray takes 600+ seconds to burnout, but 50 mm into the enclosure it takes between 850+ and 900+ seconds. As the tray is progressively moved into the enclosure the burnout time rapidly falls to about 650 seconds at 150 mm into the enclosure. It then remains reasonably constant until it is about 800 mm into the enclosure where it begins to decrease, reaching a minimum of 450 seconds at 1200 mm.

Burnout Time (s)

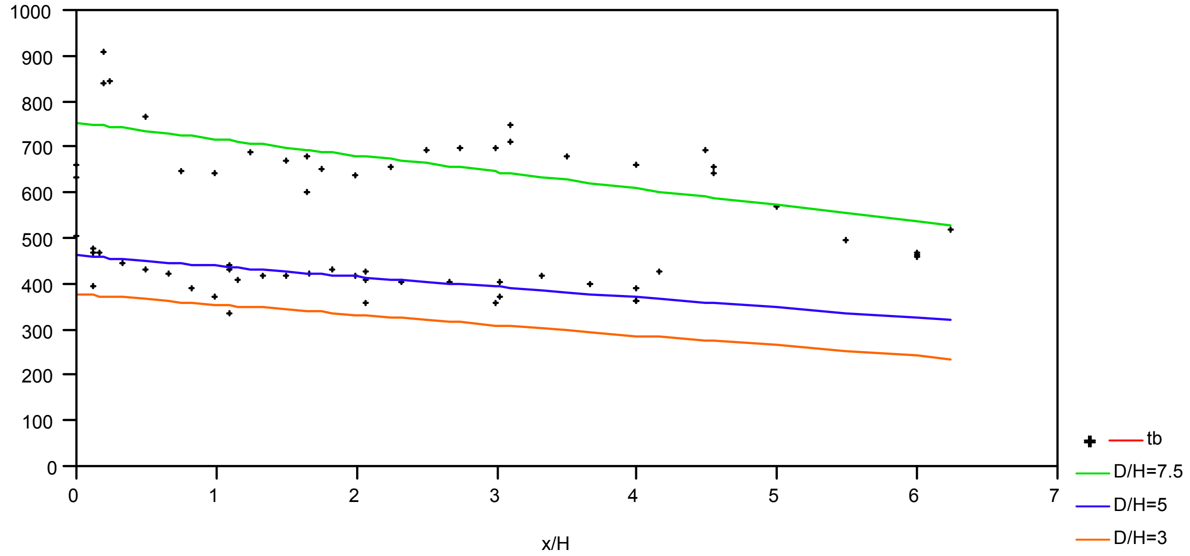


+ : D/H = 1.0, X : D/H = 1.5, Y : D/H = 3.0, Z : D/H = 5.0, : D/H = 7.5

Figures 7 (200 and 300H)

Although this complex behaviour indicates that there are complex mechanisms affecting the delivery of oxygen to the fuel it is worthwhile trying to obtain some insight into the overall trends. However, it is obvious that no simple relationships are going to explain or define the variations apparent in Figures ? and ?.

Burnout Time (s)



Figures 8 (200 and 300H)

A regression analysis has been conducted on the data represented by Figures ? and ? using combinations of the following ratios: $\left(\frac{L}{wh^{1.5}}\right)$, $\left(\frac{L}{wh^{1.5}}\right)\left(\frac{x}{H}\right)$ and $\left(\frac{x}{H}\right)$.

The best fit to the data was obtained with the expression:

$$t_b = 289 + \left(\frac{L}{wh^{1.5}}\right)\left(0.193\left(\frac{D}{H}\right) - 0.0762\left(\frac{x}{H}\right)\right), \ r^2 = 0.87$$

The variation in the maximum temperature with position of the tray is shown in Figure ??. Examination of Figure ?? reveals that there is some systematic variation of the maximum temperature with the enclosure height and depth (or D/H). There appears to be little variation with position of the tray in the enclosure.

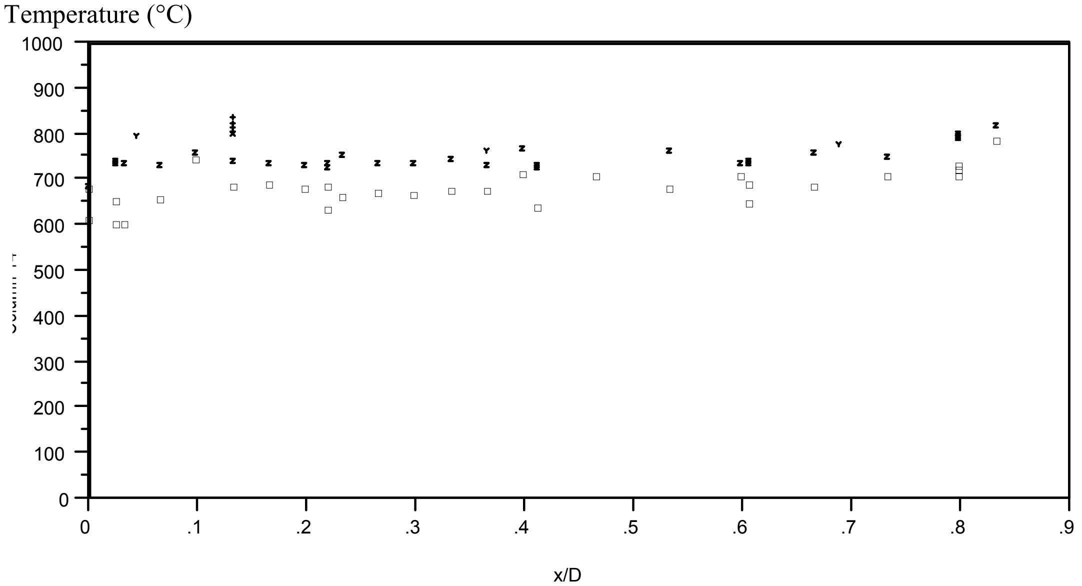


Figure ?? Variation of Maximum Temperature with x/H
(Line is mean of all values)
+ : D/H = 1.0, X : D/H = 1.5, Y : D/H = 3.5, Z : D/H = 5.0, : D/H = 7.5

$$T_b = 837 - 24.4\left(\frac{D}{H}\right) + 76.9\left(\frac{x}{D}\right),\ r^2 = 0.77$$

Discussion

The significant variation in burnout time with position in the enclosure (particularly for the 200 mm deep enclosure) obviously requires further testing and analysis.

Overall there does seem to be a systematic variation as the fuel is moved further back in the enclosure but the degree of this effect does appear to be related to enclosure height (or perhaps D/H ratio).

Conclusions

This study is not conclusive, but it appears that the mass loss rate varies significantly with tray position

Acknowledgments

The author is grateful to Rob Ralph, Michael Culton and Paul Tisch for carrying out the experimental program and to Ian Bennetts for support and valuable discussions.

References

1. Thomas, I.R. and Bennetts, I.D., *Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures, Submitted for IAFSS Symposium 1999.*
2. Drysdale, D., *An Introduction to Fire Dynamics*, Wiley (1985).

Appendix A

Table A1 Data from Single Tray Tests

Width (mm)	Depth (mm)	Height (mm)	Opening Width (mm)	Opening Height (mm)	Sill Height (mm)	x (mm)	Burnout Time (s)	Maximum Temperature (°C)
300	300	200	300	200	0	40	411	802
300	300	300	300	275	25	40	295	839
300	300	300	300	275	25	40	293	803
300	300	300	300	275	25	40	291	813
300	300	300	300	275	25	40	315	825
300	900	300	300	275	25	40	396	795
300	900	300	300	275	25	330	337	765
300	900	300	300	275	25	620	360	780
300	1500	200	300	200	0	330	679	686
300	1500	200	300	200	0	620	712	642
300	1500	200	300	200	0	910	645	650
300	1500	200	300	200	0	40	843	603
300	1500	200	300	200	0	1200	467	709
300	1500	200	300	200	0	40	910	652
300	1500	200	300	200	0	1200	463	724
300	1500	200	300	200	0	330	603	636
300	1500	200	300	200	0	620	748	642
300	1500	200	300	200	0	910	660	690
300	1500	200	300	200	0	0	635	683
300	1500	200	300	200	0	50	848	604
300	1500	200	300	200	0	100	770	659
300	1500	200	300	200	0	150	650	747
300	1500	200	300	200	0	200	645	685
300	1500	200	300	200	0	250	691	692
300	1500	200	300	200	0	300	672	682
300	1500	200	300	200	0	350	655	662
300	1500	200	300	200	0	400	640	672
300	1500	200	300	200	0	450	658	666
300	1500	200	300	200	0	500	693	675
300	1500	200	300	200	0	550	699	678
300	1500	200	300	200	0	600	701	713
300	1500	200	300	200	0	700	680	707
300	1500	200	300	200	0	800	663	682
300	1500	200	300	200	0	900	695	711
300	1500	200	300	200	0	1000	570	684
300	1500	200	300	200	0	1100	498	709
300	1500	200	300	200	0	1200	471	734
300	1500	200	300	200	0	1250	522	789
300	1500	200	300	200	0	0	665	612
300	1500	300	300	275	25	40	470	740
300	1500	300	300	275	25	330	442	727
300	1500	300	300	275	25	620	413	726
300	1500	300	300	275	25	910	405	738
300	1500	300	300	275	25	1200	363	800
300	1500	300	300	275	25	910	372	740
300	1500	300	300	275	25	40	480	738

Width (mm)	Depth (mm)	Height (mm)	Opening Width (mm)	Opening Height (mm)	Sill Height (mm)	x (mm)	Burnout Time (s)	Maximum Temperature (°C)
300	1500	300	300	275	25	330	435	736
300	1500	300	300	275	25	620	431	731
300	1500	300	300	275	25	1200	363	791
300	1500	300	300	275	25	50	471	735
300	1500	300	300	275	25	0	506	688
300	1500	300	300	275	25	100	446	732
300	1500	300	300	275	25	150	434	758
300	1500	300	300	275	25	200	426	740
300	1500	300	300	275	25	250	393	735
300	1500	300	300	275	25	300	372	733
300	1500	300	300	275	25	350	412	755
300	1500	300	300	275	25	400	418	735
300	1500	300	300	275	25	450	418	735
300	1500	300	300	275	25	500	424	746
300	1500	300	300	275	25	550	433	731
300	1500	300	300	275	25	600	422	768
300	1500	300	300	275	25	700	405	.
300	1500	300	300	275	25	800	405	765
300	1500	300	300	275	25	900	360	735
300	1500	300	300	275	25	1000	420	759
300	1500	300	300	275	25	1100	403	749
300	1500	300	300	275	25	1200	393	796
300	1500	300	300	275	25	1250	429	818

Attachment 4

CIB Tests of Fire Severity in Single Vent Enclosures with Uniform Fire Load

by

I R Thomas
CESARE
Victoria University of Technology

Introduction

The severity of possible fires in a building must be estimated in order to properly develop an engineering design of the fire safety system for the building. The *severity* of a fire in an enclosure is dependent on a number of factors including the size, shape and ventilation of the enclosure and the fire load in the enclosure. In investigating the severity of fires to be considered in estimating the fire resistance requirements for barrier and structural elements for buildings it became apparent that the estimates obtained using available fire models and correlation formulae were unreliable for the broad range of enclosure sizes, shapes and ventilation arrangements that are possible.

A comparison of fire severity in long and wide enclosures with single vents has been reported previously[1].

The rate of burning (as measured by heat release rate $\dot{Q}$ or mass loss rate R) in fully developed enclosure fires is usually assumed to be proportional to the ventilation factor $A\sqrt{h}$ [2] where A is the area of the vent and h the vent height. This means that it is assumed that the burning rate is directly proportional to the vent width w and vent height raised to the power 1.5:

$$R_{8030} = a_1 w h^{1.5} \qquad (1)$$

Thus, for the same size ventilation openings the same rate of burning is expected.

This paper examines data from an international test program conducted under the auspices of CIB by eight laboratories in several countries[3]. Wood cribs with a variety of wood species, stick thicknesses and spacings were burned in enclosures of various shapes and sizes. A variety of relationships between the mean rate of burning, mean intensity of radiation and mean temperatures were developed based on the experimental results and others have been published since, largely based on this data.

The original data have not been available for this study. This study and the analysis that follows have been based on summary data[3]. This data consists of results of individual tests and results that are the average of a number of tests. Unfortunately, for such groups of tests, only the average results are known - there was no data on the variability or range of results within the group. Consequently, in what follows, each result for a specific combination of the input variables is treated as though it represented a single test.

The following terminology and nomenclature is used for the clear internal dimensions of the enclosure (Figure 1):

- width (W) - horizontal dimension parallel to the plane of the ventilation opening
- depth (D) - horizontal dimension perpendicular to the plane of the ventilation opening

- height (H) - vertical dimension from the bottom surface to the top surface

The following terminology and nomenclature is used for the dimensions of the ventilation opening:

- opening width (w) - the clear horizontal dimension
- opening height (h) - the clear vertical dimension
- sill height - the vertical dimension from the enclosure floor to the bottom of the opening

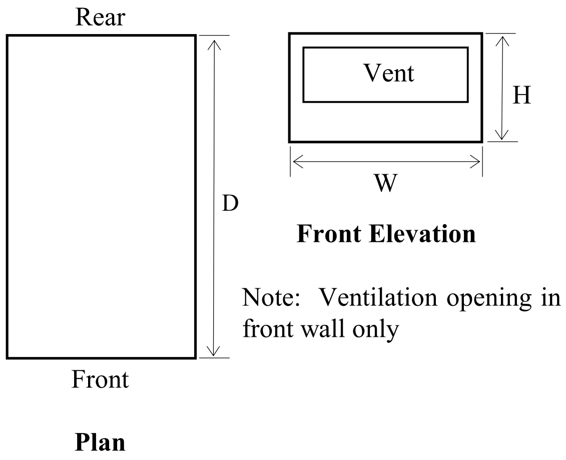


Figure 1 Enclosure Details

Experimental Program

The dimensions of the ventilation openings, the enclosure dimensions, and the stick thickness and spacing along with summary results of the tests conducted in still air are shown in Table A1 (Appendix A). In summary the enclosures were 0.5, 1.0 and 1.5 m high and the single ventilation opening in each enclosure was the full height of the enclosure and either 25%, 50%, 75% or 100% of the width of the front of the enclosure. The fire load density was equivalent to 10, 20, 30 or 40 kg/m^2 of wood over the floor area. The same materials were used for the boundaries of all of the enclosures.

During tests the mass of the remaining fuel was recorded along with the temperatures at the centre of the enclosure at heights of 25% and 75% of the ceiling height (T_b and T_c respectively) and the intensity of radiation at two points. The record of fuel mass was used to calculate the mean rate of burning during the period when the fuel mass went from 80% of the original mass to 30%, and this is recorded in Table A1 as R_{8030} (g/s). The temperature records were used to determine average temperatures during the same time period and are shown in Table A1 as T_{b8030} and T_{c8030} (°C).

A single centrally located crib was used in each enclosure, with the plan dimensions of the crib being 0.833 of the plan dimensions of the enclosure. The sticks used in the cribs were 10, 20 and 40 mm thick and were spaced 0.33, 1.0 or 3.0 stick thicknesses apart as noted for each test in Table A1. The fires were lit using kerosene soaked strips between every pair of the lowest layer of sticks over the front third of each crib.

Experimental Results

Burning Rates

The data in Table A1 are ordered by ventilation opening width, opening height and by R_{8030}. Examination of the data reveals that for the same ventilation opening there are gross discrepancies in the mean burning rates (R_{8030}) (and also the temperatures T_{b8030} and T_{c8030}). A summary of the range of R_{8030} for each ventilation opening size is given in Table 1.

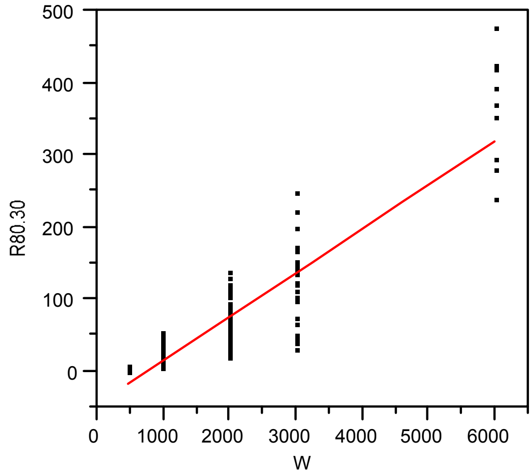
It can be seen in Table 1 that there are very wide variations in both mass loss rate and temperatures. For example, for an opening 250 mm wide by 500 mm deep the maximum mass loss rate is 4.4 times the minimum. This degree of variation is not exceptional, the maximum multiplier on mass loss rate being over 50 for the 500 mm by 500 mm size vent.

Table 1 Range of R_{8030} for Each Ventilation Opening Size

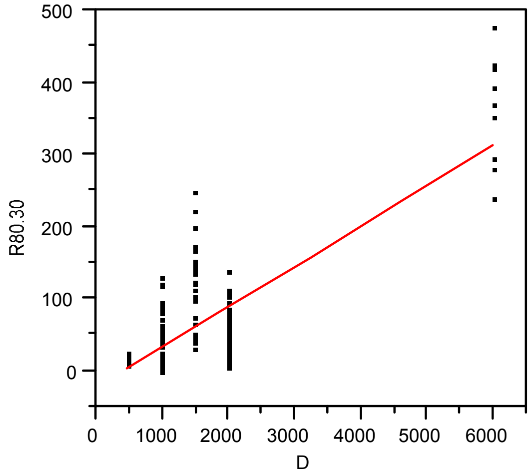
Vent Size w x h (mm)	Number of Tests	Range of R_{8030} (g/s)	Range of Maximum of T_{b8030} and T_{c8030} (°C)
125 x 500	5	3.5 to 4.7	399 to 643 511 to 712
250 x 500	15	2.8 to 12.2	273 to 952 521 to 945
250 x 1000	15	13.5 to 25	393 to 869 609 to 937
500 x 500	17	0.5 to 27.8	139 to 934 118 to 921
500 x 1000	29	30.5 to 72.8	286 to 1036 568 to 1058
750 x 1500	15	48 to 168	529 to 1054 643 to 1145
1000 x 500	12	11.2 to 36.8	187 to 888 556 to 868
1000 x 1000	22	5.7 to 93.8	234 to 1015 190 to 1035
1500 x 1000	1	119	587 783
1500 x 1500	3	240 to 283	546 to 698 825 to 919
2000 x 500	2	47.3 to 48	357 to 564 625 to 643
2000 x 1000	29	28.2 to 139	252 to 948 451 to 998
3000 x 1500	18	32 to 425	336 to 873 251 to 987
4500 x 1500	1	370	768 961
6000 x 1500	3	355 to 479	816 to 940 918 to 1047

Reviewing the data in Table A1 it becomes obvious that the variables that appear to have the greatest systematic effect on the mass loss rate R_{8030} are the enclosure width, the stick spacing (0.3333 particularly, there seems little difference in effect for stick spacings of 1 and 3) and the vent or enclosure height (the two were identical in this test program). It appears that the fire load density and the stick thickness have very little effect.

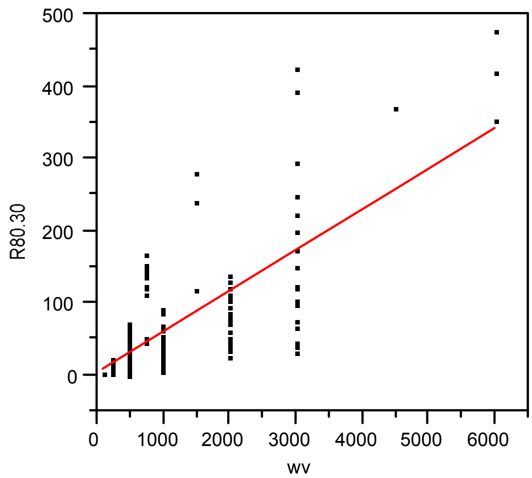
Figure 2 shows the variation of R_{8030} against the enclosure width, enclosure depth, vent width, vent height (= enclosure height in this data), fire load density stick thickness and stick spacing. It can be seen that R_{8030} correlates best with the enclosure width W (r^2 = 0.81), reasonably well with the enclosure depth D (r^2 = 0.59), vent width w (r^2 = 0.54), and vent height h (r^2 = 0.46), but poorly with the fire load density, stick thickness and stick spacing (all with $r^2 < 0.01$).



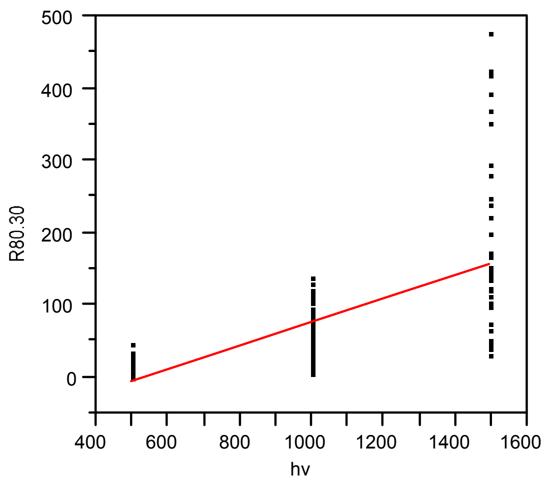
(a) Enclosure Width



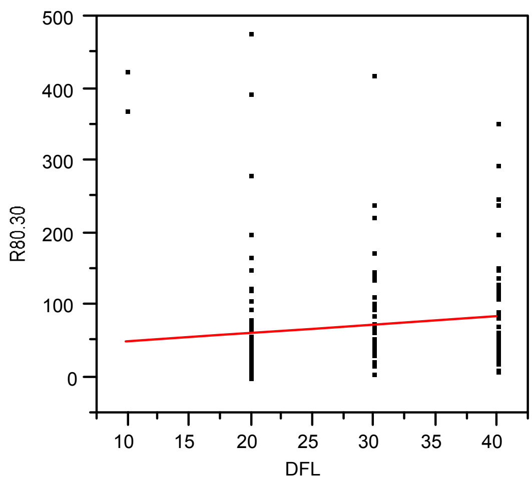
(b) Enclosure Depth



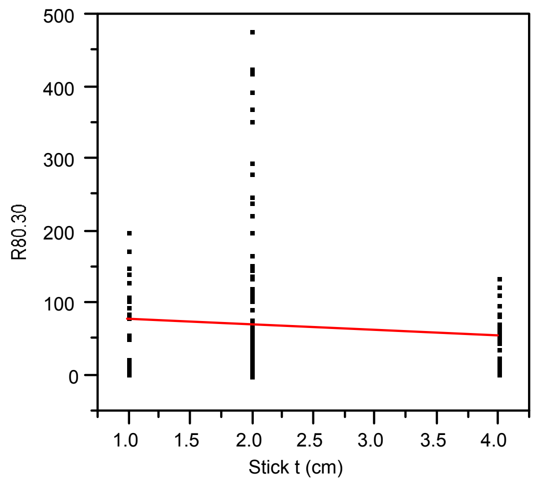
(c) Vent Width



(d) Vent Height (= Enclosure Height)

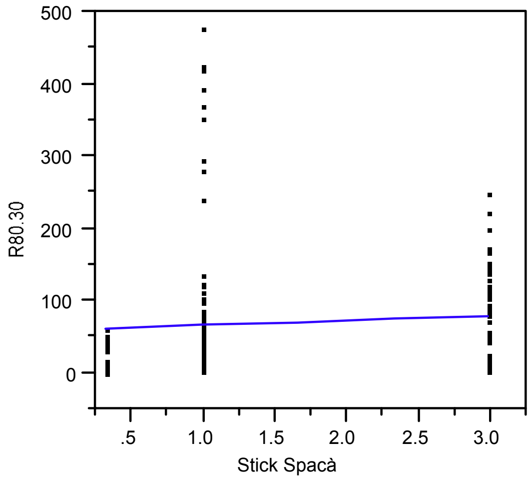


(e) Fire Load Density



(f) Stick Thickness

Figure 2 Correlation of Mass Loss Rate with Various Variables



(g) Stick Spacing (stick thicknesses)

Figure 2 Correlation of Mass Loss Rate with Various Variables (continued)

A least squares regression analysis using an expression of the form:

$$R_{8030} = a_1 w^{a2} h^{a3} W^{a4} D^{a5} t_{st}^{a6} s_{st}^{a7} L_d^{a8}$$

where

R_{8030} = mass loss rate (g / s)
a_1, a_2, etc = regression parameters
t_{st} = stick thickness (m)
s_{st} = stick spacing (stick thicknesses)
L_d = fire load density (kg/m^2)

results in the following expression:

$$R_{8030} = 60.4 w^{0.24} h^{0.45} W^{1.00} D^{0.24} t_{st}^{0.16} s_{st}^{0.51} L_d^{-0.09} \quad (r^2 = 0.94) \qquad (2)$$

Or, if $\dot{Q}_{8030}$ = heat release rate (MW) based on a heat of combustion of 17 MJ/kg of wood

$$\dot{Q}_{8030} = 1.03 w^{0.24} h^{0.45} W^{1.00} D^{0.24} t_{st}^{0.16} s_{st}^{0.51} L_d^{-0.09} \quad (r^2 = 0.94) \qquad (2A)$$

The terms in equations 2 and 2A involving the enclosure depth, stick thickness and fire load density have very little effect in improving the correlation and the following simpler expression provides almost as good a fit:

$$R_{8030} = 20.0 w^{0.24} h^{0.12} W^{1.42} s_{st}^{0.441} \quad (r^2 = 0.94) \qquad (3)$$

or

$$\dot{Q}_{8030} = 0.34 w^{0.24} h^{0.12} W^{1.42} s_{st}^{0.441} \quad (r^2 = 0.94) \qquad (3A)$$

In this expression the majority of the variation in the mass loss rate is associated with variation of the width of the enclosure, with minor adjustments provided by the other terms. Figure 3 is a scatter diagram showing a comparison of the experimental mass loss rate with that predicted by Equation 3. It can be seen that 95% of the experimental points are within about ±40 g/s of the line.

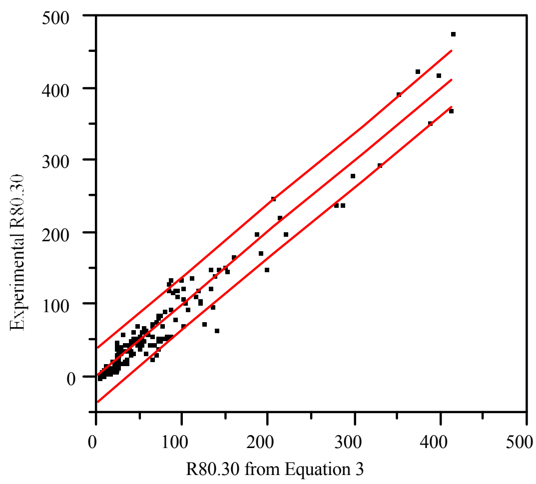


Figure 3 Comparison of Estimated and Experimentally Determined Mass Loss Rates

If only the vent dimensions and stick spacing are included in the expression then the relationship in Equation 4 results, but the correlation is not nearly as good, as shown in Figure 4. This implies that the mass loss rate is not simply a function of the vent dimensions as is usually assumed.

$$R_{8030} = 53.5 w^{0.543} h^{1.90} s_{st}^{0.217} \quad (r^2 = 0.70) \qquad (4)$$

or

$$\dot{Q}_{8030} = 0.91 w^{0.543} h^{1.90} s_{st}^{0.217} \quad (r^2 = 0.70) \qquad (4A)$$

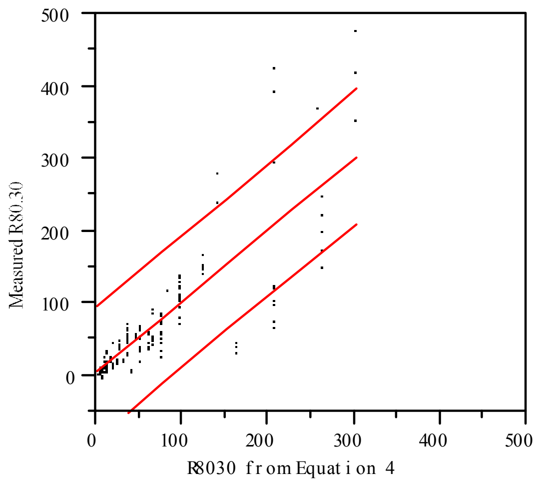


Figure 4 Comparison of Estimated and Experimentally Determined Mass Loss Rates Estimate Based on Vent Dimensions and Stick Spacing (Equation 4) Only

It is noteworthy that the correlation of the burning rate with the pair of variables h and w ($r^2 = 0.70$) is also clearly not as good as with the single variable W ($r^2 = 0.81$) and that the correlation of any pair of variables incorporating W is much better than the pair of variables h and w ($r^2 > 0.90$ compared with $r^2 = 0.70$).

In a previous report[1] it has been shown that there is a difference in the rate of burning (mass loss) and in the burning behaviour in enclosures with $w/W = 1$ compared with those where $w/W < 1$. This was done by direct comparison of long and wide enclosures of the same shapes and with identical openings, but in one case with the openings in the long side and in the other with the openings in the short side. In this (CIB) data there limited opportunities for such comparisons, but those that are possible are set out in Table 2.

Table 2 Comparison of Enclosures with the Same Vent Sizes and w/W = 1 and w/W < 1

w	h	W	D	H	StSp	$\dot{Q}$ (w/W < 1)	$\dot{Q}$ (w/W = 1)
500	500	1000 or 500	500 or 1000	500	0.33	0.20	0.01
					1	0.20, 0.22	0.10, 0.13
					3	0.27, 0.31	0.13, 0.15
1000	1000	2000 or 1000	1000 or 2000	1000	1	0.70, 0.88, 0.95	0.36, 0.60, 0.63, 0.63, 0.65, 0.67
					3	1.51, 1.59	0.77, 0.83, 0.88, 0.91, 0.93, 0.97

Examination of Table 2 shows that there is clearly a similar trend in this data. In cases with *w/W < 1* the mass loss rate is always greater than for similar cases with *w/W = 1* even though the range of *W/D* in this case is quite limited in comparison with that in Reference 1.

An alternative way of looking at the effect of *w/W* is to compare the ratios of the measured burning rates to those calculated using Equation 1 (the Kawagoe formula). Table 3 shows these ratios for the major w/W and stick spacing cases covered by the data.

Table 3 Ratio of Measured Burning Rate to Rate Calculated Using Equation 1

w/W	Stick Spacing (stick thicknesses)	Ratio	
		Mean	Range
0.25	1	1.15	0.80 - 1.7
	3	1.17	0.90 - 1.5
0.5	1	0.76	0.45 - 1.1
	3	0.94	0.84 - 1.1
1.0	1	0.37	0.13 - 0.74
	3	0.55	0.30 - 0.81

Examination of Table 3 reveals that for each of the *w/W* ratios there are comparatively small differences between the means and ranges of the ratio for the stick spacings of 1 and 3. There are much larger and obviously systematic differences in the means and ranges of the ratio as *w/W* increases from 0.25 to 1.0. Thus it is clear that for this data:

- there is a substantial and systematic decrease in the ratio of the measured burning rate to the burning rate calculated using Equation 1 with increase in w/W ratio
- there is comparatively little variation in this ratio with increase in stick spacing from 1 to 3 stick thicknesses

Thus, it is of interest to note the results when regression analysis is applied to the data if the whole data set is divided into the two groups, *w/W = 1* and *w/W < 1*. The results are as follows:

w/W = 1

When all of the variables are taken into account

$$R_{8030} = 0.67 w^{0.23} h^{0.24} W^{1.00} D^{0.40} t_{st}^{0.17} s_{st}^{0.64} L_d^{0.00} \quad (r^2 = 0.96) \tag{5}$$

Without the less important terms

$$R_{8030} = 0.27 w^{0.88} h^{-0.27} W^{1.00} s_{st}^{0.55} \quad (r^2 = 0.94) \tag{6}$$

As w = W

$$R_{8030} = 0.27 w^{1.88} h^{-0.27} s_{st}^{0.55} \quad (r^2 = 0.94) \tag{7}$$

w/W < 1

When all of the variables are taken into account

$$R_{8030} = 1.73 w^{0.30} h^{0.77} W^{1.00} D^{-0.02} t_{st}^{0.20} s_{st}^{0.35} L_d^{-0.14} \quad (r^2 = 0.97) \tag{8}$$

Without the less important terms

$$R_{8030} = 0.52 w^{0.34} h^{0.69} W^{1.00} s_{st}^{0.31} \quad (r^2 = 0.97) \tag{9}$$

Without *W* and the less important terms (to make comparable with Equation 7)

$$R_{8030} = 1.22 w^{0.71} h^{1.89} s_{st}^{0.23} \quad (r^2 = 0.94) \tag{10}$$

It is notable that in both cases when all of the variables are incorporated in the analysis that the rate is directly proportional to the enclosure width *W* as it was in the overall case (Equations 2 and 2A). It is also noteworthy that in the case for *w/W = 1*, when the less important terms are dropped from the analysis, that the resulting negative power for the opening height h implies that the rate reduces as the opening height increases, which is intuitively incorrect and is opposite from the evident trend found experimentally (Figure 2(D)). This occurs because *w* and *h* are quite highly correlated and in the resulting regression expression the main variation of the rate is modelled using the opening width w, with the opening height h providing a minor correction. This situation emphasises once more the fact that correlation equations such as those above do not necessarily reflect any direct relationship between the variables, nor is the form of the expression a reflection of any overall relationship between the variables.

Temperatures

The two recorded maximum temperatures (T_{b8030} and T_{c8030}) for each test often differ considerably. However, the temperature at the higher position is usually, but not always, the maximum of the two as Figure 5 shows. In Figure 5 the maximum of T_{b8030} and T_{c8030} is compared with T_{c8030}. Those points above the line of the majority of points are those for the tests in which $T_{b8030} > T_{c8030}$.

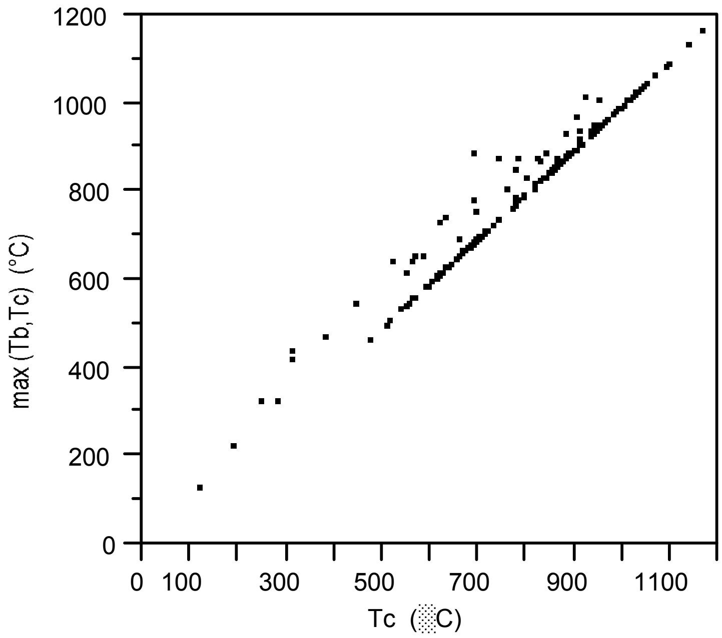
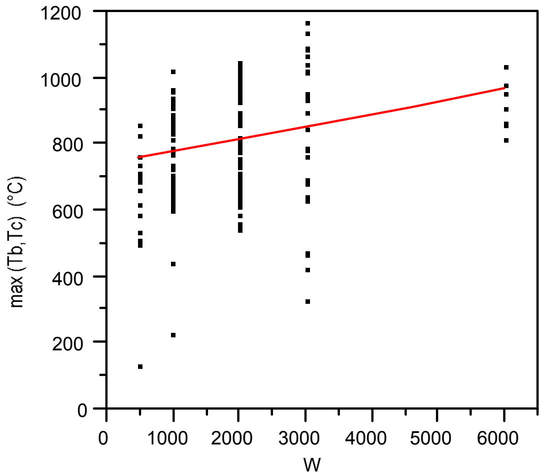
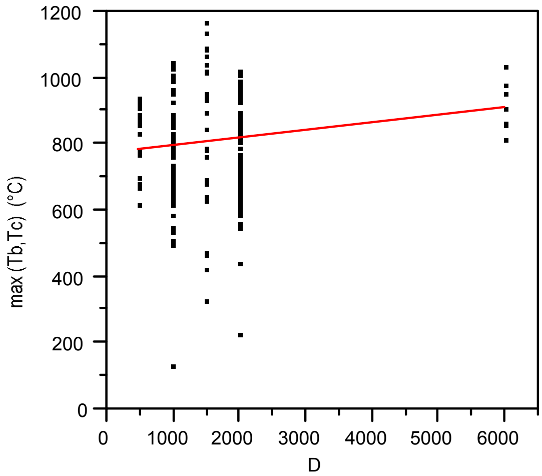


Figure 5 Maximum Temperature in Enclosure

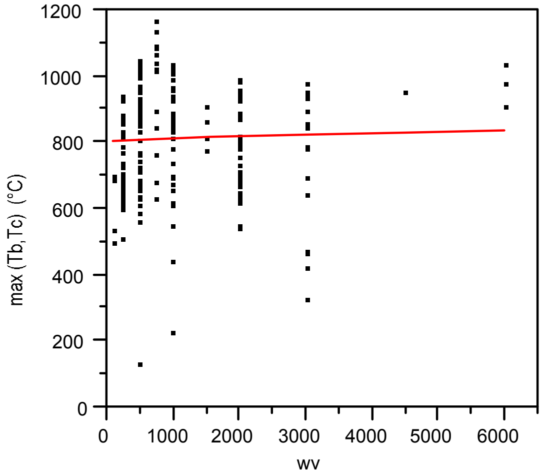
In examining Table A1 in detail it is difficult to see that there is any systematic variation of T_{b8030} and T_{c8030} with any of the recorded test variables. This observation is confirmed in Figure 5 where the maximum of T_{b8030} and T_{c8030} is plotted against each of these variables and the mass loss rate R_{8030}. In these plots the variation in temperature at any particular value of each variable is generally nearly as great as the overall variation in the temperature.



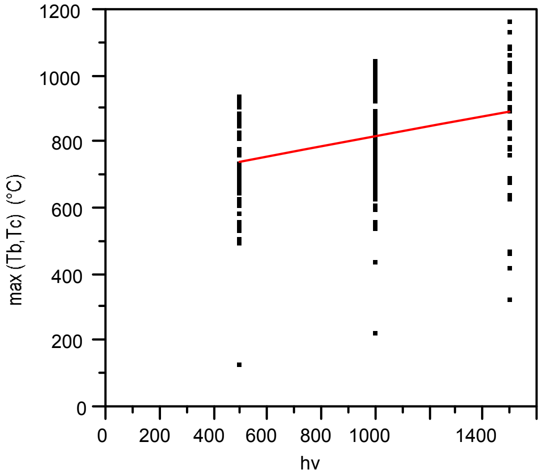
(a) Enclosure Width



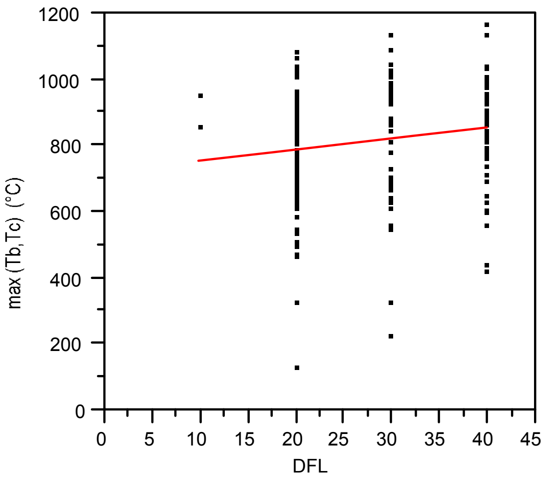
(b) Enclosure Depth



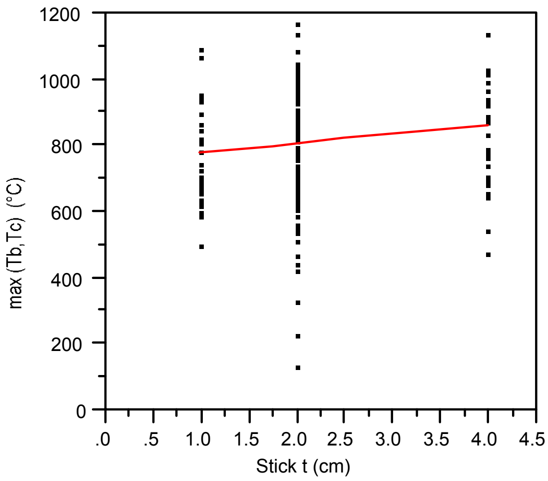
(c) Vent Width



(d) Vent Height

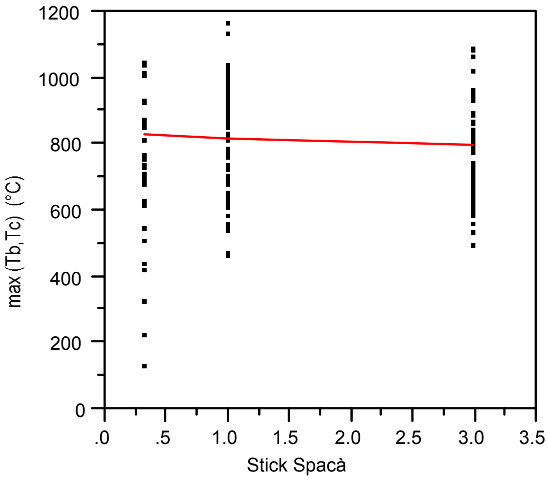


(e) Fire load Density

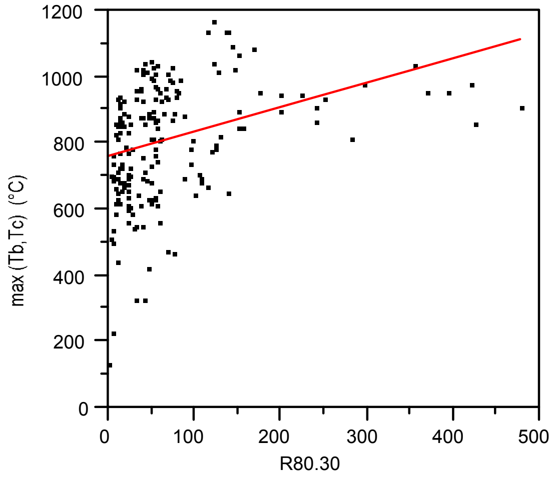


(f) Stick Thickness

Figure 6 Correlation of Maximum Temperature with Various Variables



(g) Stick Spacing (stick thicknesses)



(h) Mass Loss Rate

Figure 6 Correlation of Maximum Temperature with Various Variables (continued)

A least squares regression analysis using an expression of the form used in Equation 1 results in the following expression

$$T_{8030} = 1002 w^{-0.067} h^{0.11} W^{0.15} D^{-0.053} t_{st}^{0.10} s_{st}^{0.03} L_d^{0.03} \quad (r^2 = 0.18) \qquad (11)$$

The estimate of the maximum temperature using this expression along with the estimates of the 95 percentiles of individual results are plotted in Figure 7 along with the experimental points. It can be seen that the variation is extremely large and that the temperature estimate for any particular situation is subject to very large uncertainties (±300 °C).

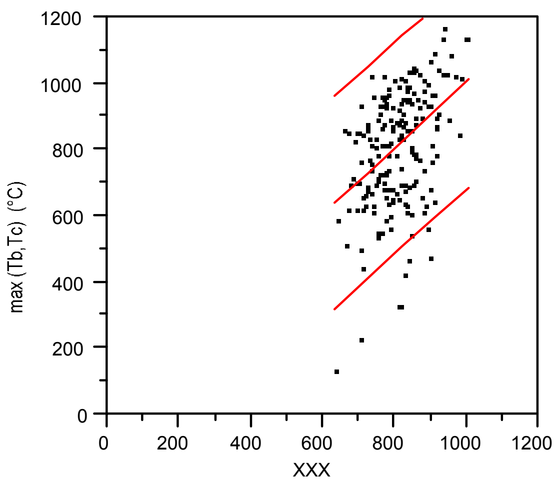


Figure 7 Measured Maximum Temperature Compared with Estimated Maximum

A similar regression incorporating the total surface area of the enclosure and the variables incorporated in Equation 11 except for W and D results in a slightly lower correlation coefficient (r^2 = 0.14) and thus a slightly greater spread in the estimated temperature.

Discussion

In the discussions above of the previous sets of experimental data the time that the temperature in the test has been above 500 °C or the burnout time has been used as a basis for estimating the length of time the fire has lasted. Because of the limited data available for this data set it is not possible to obtain such time data. An estimate of the burnout time may be obtained by dividing the total mass of fuel by R_{8030}.

Thus

$$\tau = \frac{L_f}{R_{8030}} \text{ (s)}$$

where L_f = total fire load (g)

R_{8030} = mass loss rate (g / s)

provides an estimate of burnout time.

References

1. Thomas, I.R. and Bennetts, I.D., *Fires in Enclosures with Single Ventilation Openings - Comparison of Long and Wide Enclosures, Submitted for IAFSS Symposium 1999.*
2. Drysdale, D., *An Introduction to Fire Dynamics*, Wiley (1985).
3. Thomas, P.H. and Heselden, A.J.M., *Fully Developed Fires in Single Compartments. A Cooperative Research Programme of the CIB,* CIB Report No 20, Fire Research Note 923.

Appendix A

Table A1 Data from CIB Tests[6]

Row	w (mm)	h = H (mm)	R_{8030} (mm)	W (mm)	D (mm)	FLD	St t (mm)	St spac	N	T_b (°C)	T_c (°C)
1	125	500	3.5	500	1000	20	2	0.3333	1	643	712
2	125	500	3.7	500	1000	20	2	1	1	594	695
3	125	500	4.2	500	1000	20	4	1	1	613	708
4	125	500	4.2	500	1000	20	1	3	1	399	511
5	125	500	4.7	500	1000	20	2	3	1	412	543
6	250	500	2.8	500	1000	20	2	0.3333	1	491	521
7	250	500	5.7	500	1000	20	4	1	1	643	747
8	250	500	7	500	1000	20	1	3	1	468	629
9	250	500	7.3	500	1000	20	2	3	1	435	672
10	250	500	7.5	500	1000	20	2	1	1	774	836
11	250	500	9	1000	1000	20	1	3	1	273	638
12	250	500	10	1000	1000	20	2	0.3333	1	725	825
13	250	500	10.5	1000	500	20	2	0.3333	1	865	945
14	250	500	10.7	1000	1000	20	2	3	1	425	659
15	250	500	10.8	1000	1000	20	4	1	1	705	662
16	250	500	11	1000	500	20	4	1	1	952	918
17	250	500	11	1000	1000	20	2	1	2	638	736
18	250	500	11.2	1000	500	20	1	3	1	645	689
19	250	500	11.5	1000	500	20	2	1	2	817	880
20	250	500	12.2	1000	500	20	2	3	1	842	808
21	250	1000	13.5	1000	2000	40	2	0.3333	1	736	746
22	250	1000	14.8	1000	2000	20	2	0.3333	1	845	873
23	250	1000	16.7	1000	2000	30	2	0.3333	1	823	937
24	250	1000	18.5	1000	2000	20	4	1	1	722	801
25	250	1000	20.7	1000	2000	30	4	1	1	630	716
26	250	1000	20.7	1000	2000	30	1	3	1	393	647
27	250	1000	22	1000	2000	20	2	3	1	628	684
28	250	1000	22	1000	2000	40	1	3	1	554	609
29	250	1000	22.2	1000	2000	40	4	1	1	685	779
30	250	1000	22.7	1000	2000	30	2	3	1	428	623
31	250	1000	22.7	1000	2000	40	2	1	10	770	842
32	250	1000	22.8	1000	2000	30	2	1	2	869	892
33	250	1000	23.3	1000	2000	40	2	3	1	532	617
34	250	1000	24	1000	2000	20	2	1	10	831	867
35	250	1000	25	1000	2000	20	1	3	1	573	736
36	500	500	0.5	500	1000	20	2	0.3333	1	139	118
37	500	500	5.8	500	1000	20	4	1	1	666	775
38	500	500	7.5	500	1000	20	2	1	1	733	866
39	500	500	7.7	500	1000	20	1	3	1	377	597
40	500	500	9	500	1000	20	2	3	1	373	720

Row	w (mm)	h = H (mm)	R_{8030} (mm)	W (mm)	D (mm)	FLD	St t (mm)	St spac	N	T_b (°C)	T_c (°C)
41	500	500	10.8	1000	1000	20	2	0.3333	1	859	784
42	500	500	12	1000	500	20	2	0.3333	1	733	782
43	500	500	12	1000	500	20	4	1	1	934	914
44	500	500	12.7	1000	500	20	2	1	2	865	921
45	500	500	13.3	1000	1000	20	2	1	2	712	845
46	500	500	13.7	1000	1000	20	1	3	1	274	665
47	500	500	13.8	1000	1000	20	2	3	1	530	733
48	500	500	15.8	1000	500	20	1	3	1	678	672
49	500	500	15.8	1000	1000	20	4	1	1	689	.
50	500	500	18.2	1000	500	20	2	3	1	902	693
51	500	500	21.8	2000	2000	30	2	1	1	487	572
52	500	500	27.8	2000	2000	20	2	1	1	596	598
53	500	1000	30.5	1000	2000	40	2	1	1	655	971
54	500	1000	31.7	1000	2000	20	2	1	1	947	941
55	500	1000	32.2	1000	2000	30	2	1	1	986	1031
56	500	1000	38.3	2000	2000	40	2	0.3333	1	1020	956
57	500	1000	40	2000	2000	20	2	0.3333	1	885	828
58	500	1000	41	2000	1000	40	2	0.3333	1	820	1051
59	500	1000	42.7	2000	1000	20	2	0.3333	1	478	699
60	500	1000	43.8	2000	2000	30	2	0.3333	1	1029	927
61	500	1000	47.8	2000	1000	40	2	1	11	887	1008
62	500	1000	48.8	2000	1000	30	2	0.3333	1	956	1058
63	500	1000	50	2000	1000	20	2	1	12	921	1042
64	500	1000	50.2	2000	1000	30	4	1	1	961	1039
65	500	1000	51.3	2000	2000	40	2	1	8	832	908
66	500	1000	52.7	2000	1000	30	2	1	3	916	1018
67	500	1000	52.7	2000	2000	40	1	3	1	286	643
68	500	1000	54	2000	2000	30	1	3	1	518	646
69	500	1000	54.2	2000	2000	30	2	1	3	980	913
70	500	1000	55.8	2000	2000	40	4	1	1	883	835
71	500	1000	56	2000	1000	20	2	3	1	837	977
72	500	1000	56.2	2000	2000	30	2	3	1	607	620
73	500	1000	57	2000	2000	20	1	3	1	753	635
74	500	1000	58	2000	2000	20	2	1	9	961	948
75	500	1000	58	2000	2000	40	2	3	1	381	568
76	500	1000	58.7	2000	1000	20	1	3	1	690	820
77	500	1000	59.2	2000	2000	20	2	3	1	664	591
78	500	1000	63.5	2000	1000	40	4	1	1	902	847
79	500	1000	65.7	2000	2000	30	4	1	1	968	975
80	500	1000	68.3	2000	2000	20	4	1	1	943	885
81	500	1000	72.8	2000	1000	20	4	1	1	1036	1033

Row	w (mm)	h = H (mm)	R_{8030} (mm)	W (mm)	D (mm)	FLD	St t (mm)	St spac	N	T_b (°C)	T_c (°C)
82	750	1500	48	3000	1500	20	2	0.3333	1	614	643
83	750	1500	48	3000	1500	30	2	0.3333	1	547	691
84	750	1500	53	3000	1500	40	2	0.3333	1	529	775
85	750	1500	115	3000	1500	40	4	1	1	988	1145
86	750	1500	121	3000	1500	20	2	1	1	966	1052
87	750	1500	122	3000	1500	40	2	1	1	1054	1175
88	750	1500	126	3000	1500	20	4	1	1	1002	1027
89	750	1500	136	3000	1500	30	4	1	1	1044	1145
90	750	1500	138	3000	1500	30	2	1	1	976	1144
91	750	1500	144	3000	1500	30	1	3	1	929	1101
92	750	1500	147	3000	1500	30	2	3	1	876	1035
93	750	1500	151	3000	1500	40	1	3	1	662	906
94	750	1500	152	3000	1500	20	1	3	1	862	1077
95	750	1500	155	3000	1500	40	2	3	1	773	853
96	750	1500	168	3000	1500	20	2	3	1	1036	1095
97	1000	500	11.2	1000	500	20	4	1	1	888	787
98	1000	500	11.3	1000	500	20	2	0.3333	1	627	556
99	1000	500	13.3	1000	500	20	2	1	2	790	868
100	1000	500	14.2	1000	1000	20	2	0.3333	1	807	859
101	1000	500	16	1000	1000	20	2	1	2	606	862
102	1000	500	21.8	1000	1000	20	1	3	1	187	702
103	1000	500	22	1000	1000	20	2	3	1	341	687
104	1000	500	22.2	1000	1000	20	4	1	1	810	845
105	1000	500	23.7	1000	500	20	1	3	1	306	710
106	1000	500	26.5	1000	500	20	2	3	1	780	790
107	1000	500	32.8	2000	2000	30	2	1	1	480	560
108	1000	500	36.8	2000	2000	20	2	1	1	573	622
109	1000	1000	5.7	1000	2000	30	2	0.3333	1	234	190
110	1000	1000	9	1000	2000	40	2	0.3333	1	452	313
111	1000	1000	21.3	1000	2000	20	4	1	1	666	570
112	1000	1000	35.5	1000	2000	20	2	1	10	887	872
113	1000	1000	36.8	1000	2000	40	2	1	10	790	969
114	1000	1000	37.3	1000	2000	30	4	1	1	847	974
115	1000	1000	38.2	1000	2000	30	2	1	2	996	1035
116	1000	1000	39.7	1000	2000	40	4	1	1	558	938
117	1000	1000	41.3	2000	1000	20	2	1	1	750	870
118	1000	1000	45.3	1000	2000	20	2	3	1	744	899
119	1000	1000	49	1000	2000	30	2	3	1	567	825
120	1000	1000	51.5	1000	2000	40	2	3	1	648	823
121	1000	1000	51.8	2000	1000	30	2	1	1	932	1003
122	1000	1000	53.3	1000	2000	20	1	3	1	715	947
123	1000	1000	54.7	1000	2000	40	1	3	1	304	874

Row	w (mm)	h = H (mm)	R_{8030} (mm)	W (mm)	D (mm)	FLD	St t (mm)	St spac	N	T_b (°C)	T_c (°C)
124	1000	1000	56	2000	1000	40	2	1	2	636	1045
125	1000	1000	57	1000	2000	30	1	3	1	561	856
126	1000	1000	65.5	2000	2000	40	2	1	1	554	950
127	1000	1000	68.7	2000	2000	20	2	1	1	1015	1022
128	1000	1000	69.7	2000	2000	30	2	1	1	956	1000
129	1000	1000	88.7	2000	1000	40	1	3	1	681	704
130	1000	1000	93.8	2000	1000	40	2	3	2	725	747
131	1500	1000	118.7	2000	1000	40	2	3	1	587	783
132	1500	1500	240	6000	6000	30	2	1	1	698	872
133	1500	1500	240	6000	6000	40	2	1	1	641	919
134	1500	1500	283	6000	6000	20	2	1	1	546	825
135	2000	500	47.3	2000	2000	30	2	1	1	357	643
136	2000	500	48	2000	2000	20	2	1	2	564	625
137	2000	1000	28.2	2000	1000	20	4	1	1	375	555
138	2000	1000	34.8	2000	1000	20	2	1	12	653	567
139	2000	1000	38.2	2000	1000	20	2	0.3333	1	560	451
140	2000	1000	39.5	2000	2000	30	2	0.3333	1	706	701
141	2000	1000	39.7	2000	2000	20	2	0.3333	1	766	702
142	2000	1000	41.8	2000	2000	40	2	0.3333	1	685	723
143	2000	1000	47.2	2000	1000	30	4	1	1	890	746
144	2000	1000	48	2000	1000	30	2	0.3333	1	741	626
145	2000	1000	51.8	2000	1000	40	2	1	12	739	885
146	2000	1000	54	2000	1000	30	2	1	3	790	784
147	2000	1000	61.5	2000	1000	40	4	1	1	786	939
148	2000	1000	61.7	2000	1000	40	2	0.3333	1	762	824
149	2000	1000	72.2	2000	1000	20	2	3	1	740	882
150	2000	1000	74.2	2000	2000	40	2	1	9	760	993
151	2000	1000	74.3	2000	2000	20	4	1	1	902	891
152	2000	1000	76.8	2000	2000	30	2	1	3	948	942
153	2000	1000	77.5	2000	2000	20	2	1	9	940	970
154	2000	1000	81	2000	1000	20	1	3	1	595	965
155	2000	1000	83.7	2000	2000	40	4	1	1	937	998
156	2000	1000	88.8	2000	2000	30	4	1	1	894	888
157	2000	1000	95	2000	1000	30	1	3	1	475	790
158	2000	1000	96.7	2000	2000	20	1	3	1	818	763
159	2000	1000	104	2000	2000	30	1	3	1	268	718
160	2000	1000	107.3	2000	2000	20	2	3	1	581	694
161	2000	1000	111.5	2000	2000	40	1	3	1	.	.
162	2000	1000	114.3	2000	2000	30	2	3	1	391	679
163	2000	1000	123.5	2000	1000	40	2	3	1	563	802
164	2000	1000	129.8	2000	1000	40	1	3	1	832	820
165	2000	1000	139	2000	2000	40	2	3	1	252	660

Row	w (mm)	h = H (mm)	R_{8030} (mm)	W (mm)	D (mm)	FLD	St t (mm)	St spac	N	T_b (°C)	T_c (°C)
166	3000	1500	32	3000	1500	30	2	0.3333	1	336	251
167	3000	1500	42	3000	1500	20	2	0.3333	1	337	282
168	3000	1500	46	3000	1500	40	2	0.3333	1	429	315
169	3000	1500	68	3000	1500	20	4	1	1	483	381
170	3000	1500	75	3000	1500	20	2	1	1	462	476
171	3000	1500	100	3000	1500	30	4	1	1	650	523
172	3000	1500	106	3000	1500	30	2	1	1	705	666
173	3000	1500	123	3000	1500	40	2	1	1	796	782
174	3000	1500	125	3000	1500	40	4	1	1	790	693
175	3000	1500	150	3000	1500	20	1	3	1	758	853
176	3000	1500	174	3000	1500	30	1	3	1	786	963
177	3000	1500	199	3000	1500	40	1	3	1	649	954
178	3000	1500	200	3000	1500	20	2	3	1	873	905
179	3000	1500	223	3000	1500	30	2	3	1	824	958
180	3000	1500	250	3000	1500	40	2	3	1	756	946
181	3000	1500	296	6000	6000	40	2	1	1	748	987
182	3000	1500	395	6000	6000	20	2	1	1	710	960
183	3000	1500	425	6000	6000	10	2	1	2	626	871
184	4500	1500	370	6000	6000	10	2	1	2	768	961
185	6000	1500	355	6000	6000	40	2	1	1	940	1047
186	6000	1500	421	6000	6000	30	2	1	1	858	988
187	6000	1500	479	6000	6000	20	2	1	1	816	918

Note: Sill height is zero for all tests.

APPENDIX I

COMPARISON OF FIRE SEVERITY BETWEEN IDEALISED FIRE CURVES AND STANDARD FIRE TEST

Comparison of Fire Severity
Between Idealised Fire Curves and Standard Fire Test

Introduction

The determination of appropriate fire resistance levels for fires in enclosures requires:

1. knowledge of the severity of the fires that are likely to occur, and
2. knowledge of the relationship between the severity of fires in enclosures and the fire resistance level (FRL) determined by the standard fire resistance test to AS1530.4

The severity of fires may be thought of in a variety of ways but probably the most common used when considering FRLs is the **temperature - time** relationship, perhaps because the most carefully specified aspect of the standard fire test is the required variation of the temperature in the furnace with time.

An alternative way of thinking of fire severity (fire "size") is through the heat release rate. In many cases (when using fire models for example) the fire is specified by the **heat release rate - time** relationship.

In real fires in enclosures the temperature - time and heat release rate - time relationships vary widely. Factors that are usually assumed to affect these relationships are the type, form and quantity of fuels; the materials used in the walls, roof and floor of the enclosure; the ventilation of the enclosure and the manner of ignition, but many other factors can also lead to significant variations in these relationships.

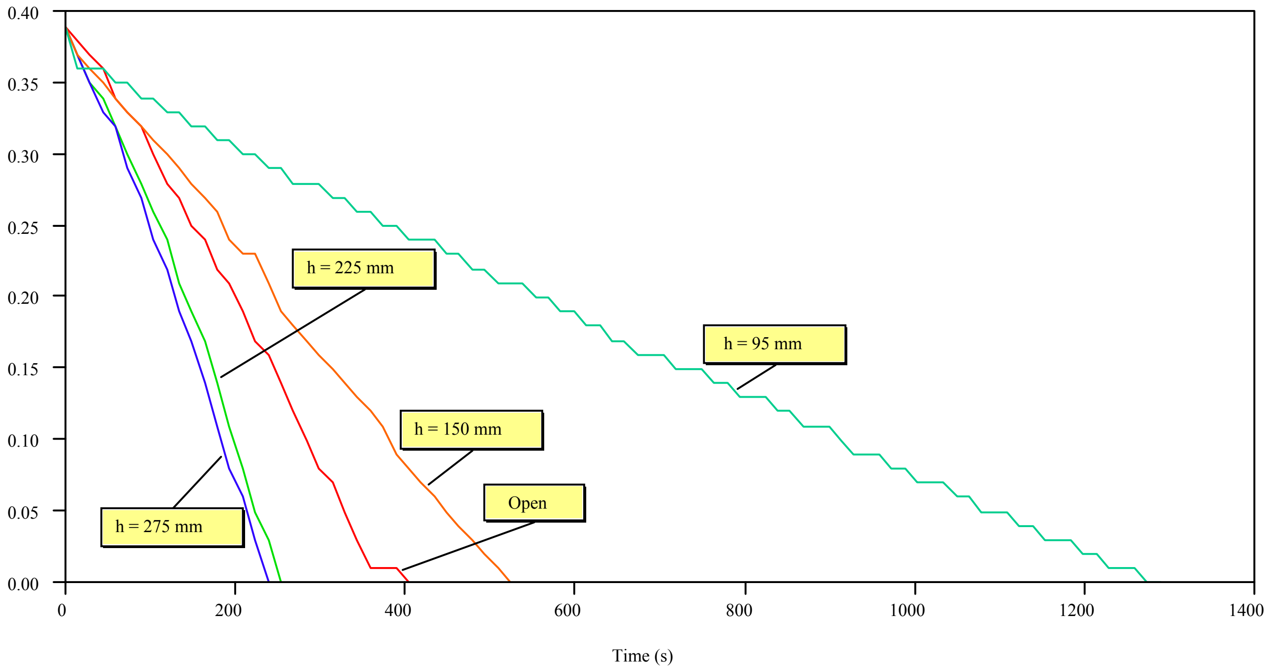


Figure 1 Reduction of Fuel Mass with Time for Trays of Methylated Spirits in the Open and in Enclosures with Opening Height as Shown

Figures 1 and 2 illustrate some of these factors. Figure 1 shows fuel mass - time curves for trays of methylated spirits burned in the open and in an enclosure with various sizes of opening. The burning in the open is at a very steady rate virtually from the time of ignition until almost all the fuel is consumed. In the enclosure again the burning rate is fairly constant but slight non-linearity does occur in some cases. The amount of ventilation also has a very great effect. Figure 2 is similar, but is for wooden cribs. In the open the burning rate is highly dependent on whether a small quantity of accelerant (methylated spirits) is poured over the crib before ignition. The burning rate is very much greater if it is than otherwise. Even when the accelerant is used, but also when it is not used, the burning rate increases much more slowly than in the liquid fuel case. It eventually reaches a fairly steady maximum and then decreases again as the fuel is exhausted. There are similar effects on the burning rate in the enclosure, and as for the liquid fuel, the ventilation has a significant effect.

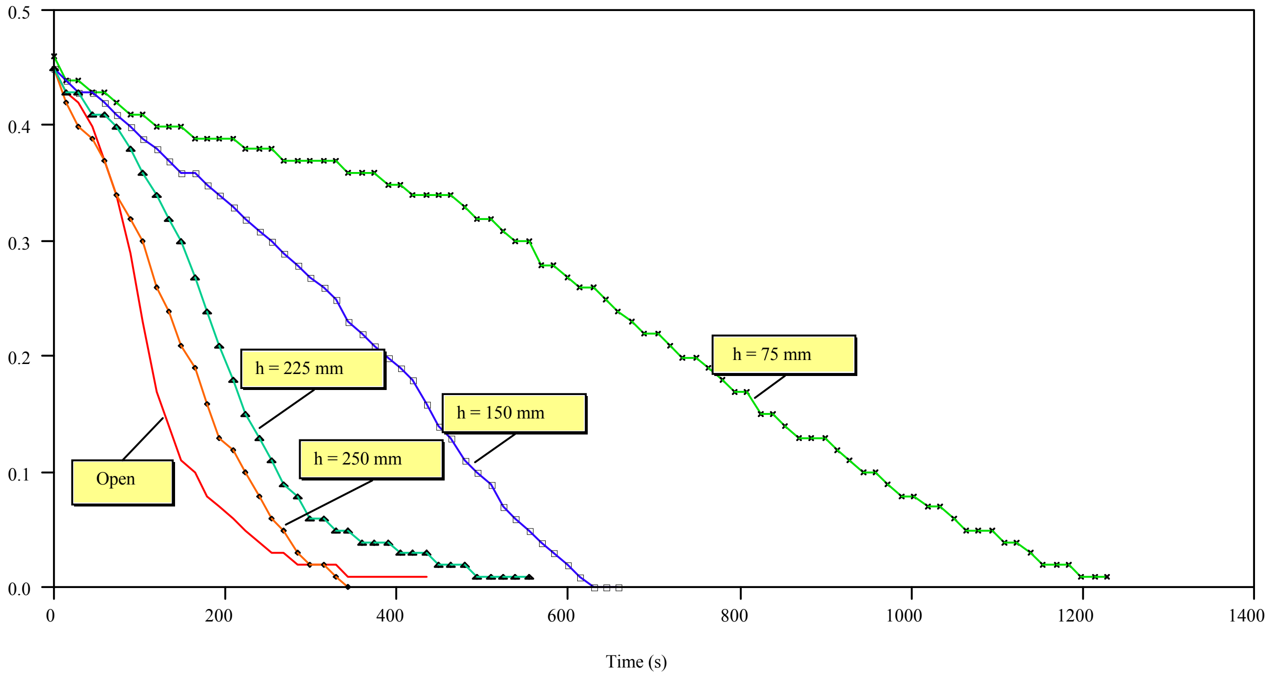


Figure 2 Reduction of Fuel Mass with Time for Wooden Cribs in the Open and in Enclosures with Opening Height as Shown

In real fires in buildings the rate of development of the fire can vary greatly, with the development being very rapid or very slow, sometimes with virtually no increase in burning rate occurring for a long period, followed by a sudden very rapid increase in the burning rate. This is reflected in great variations in the resulting increase in temperature with time. Once burning at a high rate is established the period over which this is sustained also varies greatly, though generally more systematically. The duration of rapid burning may be affected by many factors but two obvious factors are the quantity of fuel in the enclosure and the ventilation available to the fire. Once most or all of the fuel is consumed the burning rate decreases, but again the time over which the burning rate of the fire decreases can vary greatly, depending on such things as the type and form of the fuel and many other factors.

Discussion

In this report the fire severity is generally specified by the temperature - time relationship, although the fuel mass - time relationship will also be used in some cases. When applied to discussion or estimation of fire resistance levels the fire severity will generally be discussed in simplified form in terms of the maximum temperature and the duration of high temperatures. The duration used is the estimated time for which temperatures in the enclosure are estimated to be greater than 500°C. The forms of some of the idealised temperature - time relationships that may be considered are shown in Figure 5. In this figure the duration in each case is arbitrarily shown as 180 minutes (3 hours), but this can of course vary very widely; similarly the maximum temperature is also arbitrarily chosen as 1100°C, and again this can vary greatly. The shapes shown are a constant temperature of 1100°C, an initial temperature of 1100°C falling linearly to 500°C, an initial temperature of 500°C rising linearly to 1100°C, and finally an initial temperature of 500°C rising linearly to 1100°C at 90 minutes and then falling linearly to 500°C at 180 minutes. Clearly the first mentioned is the most conservative. In this case the temperature at the surface of any exposed structural member would rise from ambient to close to 1100°C at a rate depending on the structural material, the type and thickness of any insulation material applied to the structural element and the size and shape of the structural element.

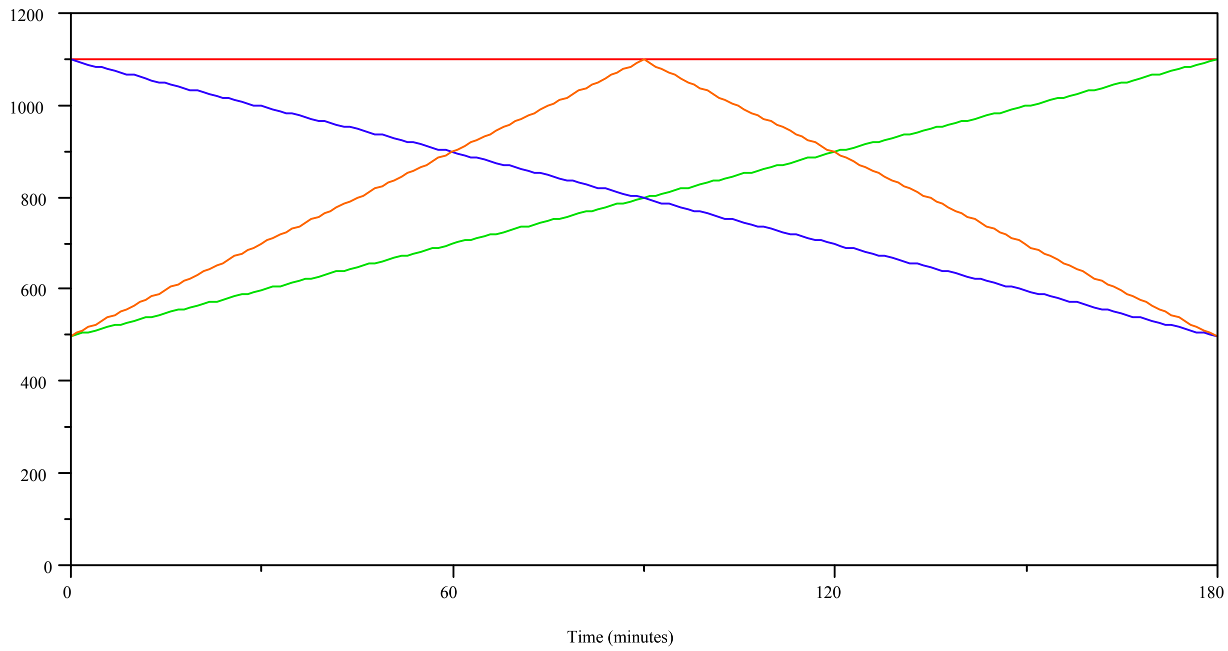


Figure 5 Idealised Temperature - Time Relationships

Two cases to illustrate this are shown in Figure 6 for the constant enclosure temperature idealisation: the case of a smaller less protected element (StrucElem 2) which rises quickly and by 90 minutes is at temperatures close to 1100°C; and the case of a larger or more protected element (StrucElem 1) which after 180 minutes is at about 900°C, substantially below the gas temperature of 1100°C.

If the assumed enclosure temperature is 1100°C and falls linearly to 500°C the temperatures reached by similar structural elements are as shown in Figure 7. In this case the temperatures of StrucElem 1 reaches a maximum of about 950°C at about 50 minutes and the temperature of StrucElem 2 peaks at about 600°C at about 120 minutes. In this case the temperatures never reach those reached in the previous case, although initially the rate of temperature rise is similar. However, it gradually reduces and eventually the temperatures begin to fall once the gas temperature falls below the element temperature.

In the case where the enclosure temperature is assumed to start at 500°C and rise to 1100°C at 180 minutes the temperatures reached by the structural elements are as shown in Figure 8. In this case they both continue to rise, StrucElem 1 reaching about 1000°C at 180 minutes and StrucElem 2 about 700°C at this time.

The case where the temperature starts at 500°C and rises to 1100°C at 90 minutes then falls to 500°C at 180 minutes is shown in Figure 9. In this case the temperature of StrucElem 1 peaks at about 1000°C at about 100 minutes and StrucElem 2 at about 650°C at about 140 minutes.

For comparison, the temperature rise of the same elements when subjected to the temperature - time regime of the standard fire test is shown in Figure 10. In this case both elements peak at 180 minutes, StrucElem 1 at about 1000°C and StrucElem 2 at about 800°C.

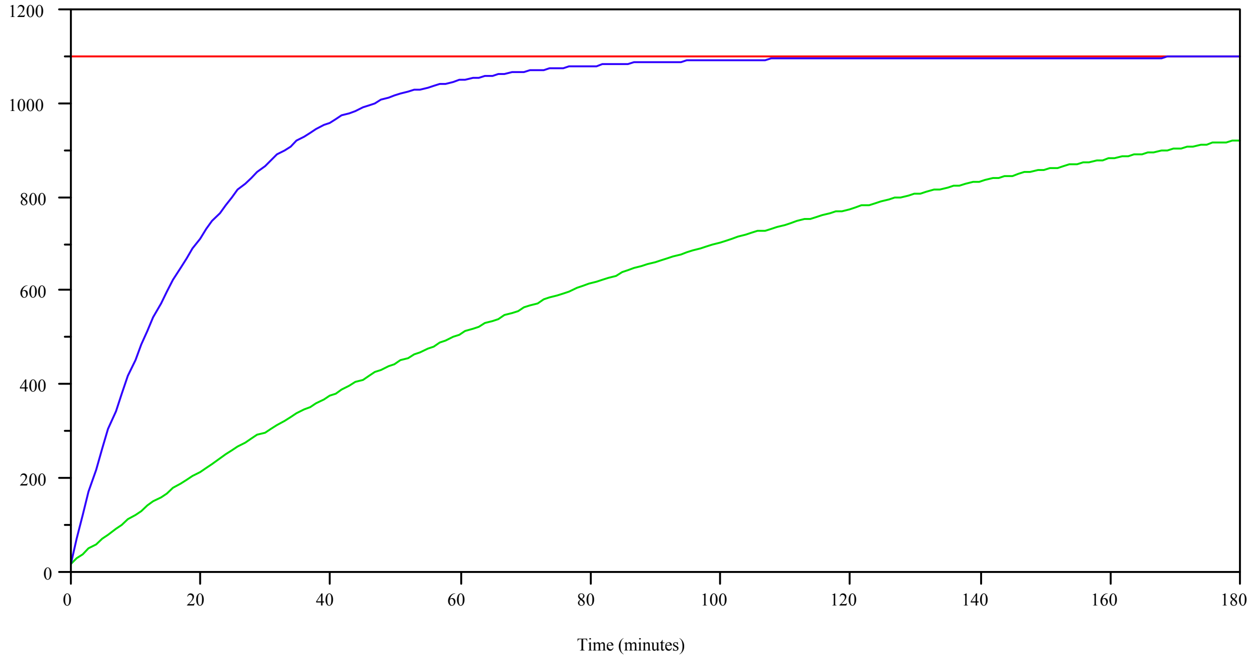


Figure 6 Constant Temperature Enclosure and Resulting Element Temperature - Time Relationships

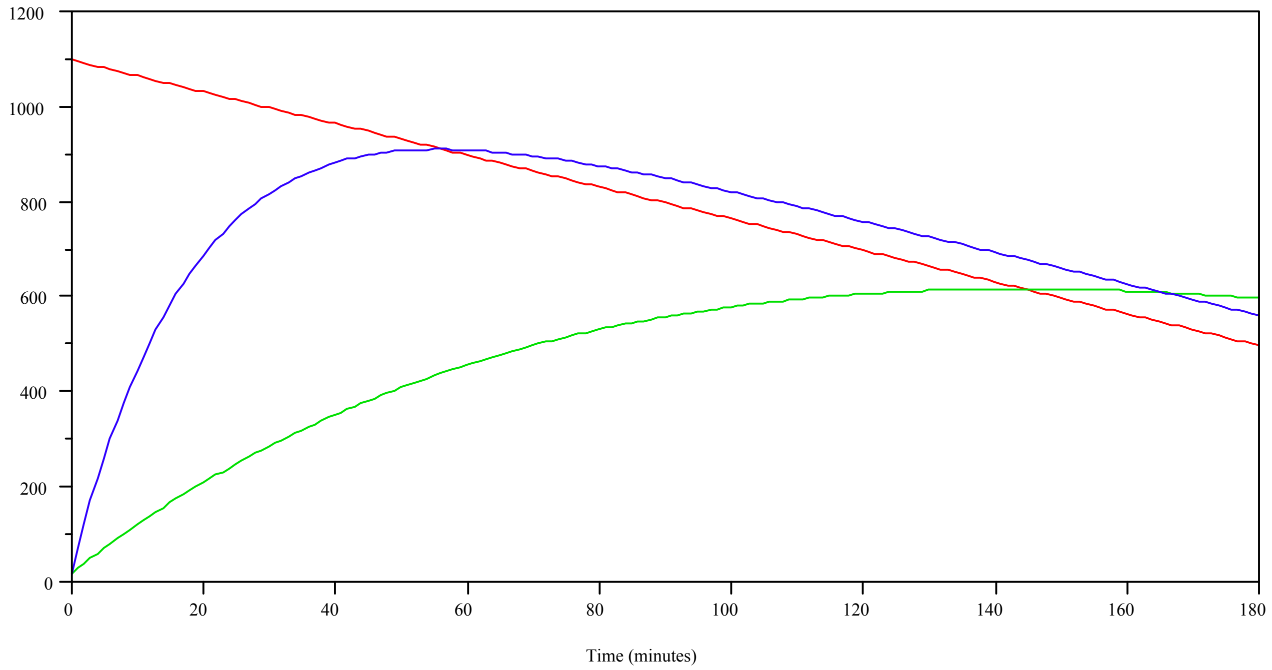


Figure 7 Temperature Enclosure and Resulting Element Temperature - Time Relationships

Thus, as expected the constant temperature regime of Figure 6 is the most severe with the highest temperatures being reached quickest in both elements. The constant rise regime of Figure 8 and the standard fire test regime of Figure 10 are the next most severe in terms of the maximum temperature reached, but in both cases this occurs at 180 minutes.

The constant temperature fall regime of Figure 7 generally produces quite high maximum element temperatures quickly, but the maximum temperature reached for slowly responding elements is generally lower than for the other regimes.

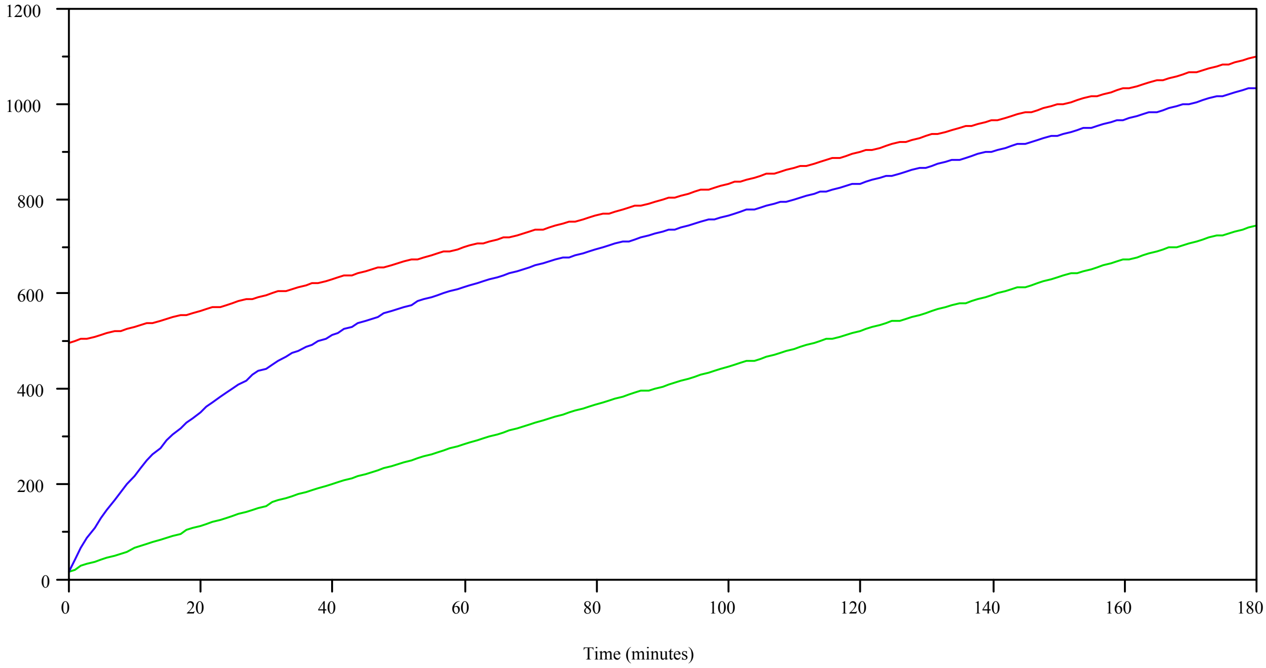


Figure 8 Temperature Enclosure and Resulting Element Temperature - Time Relationships

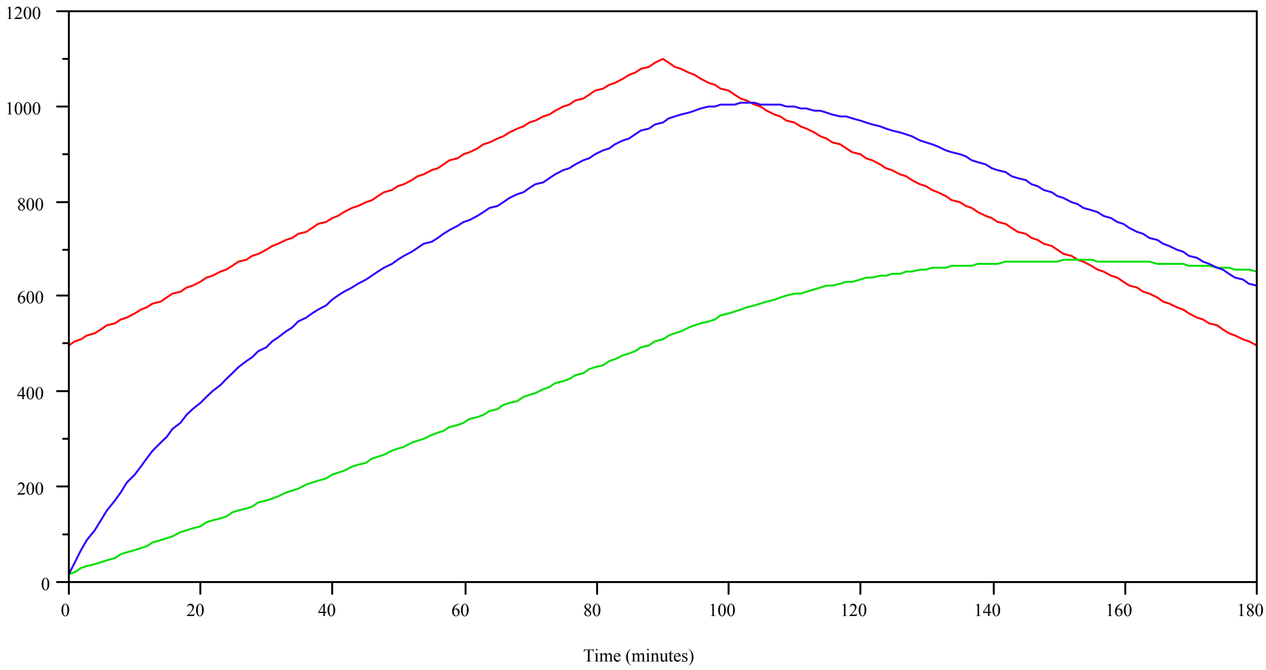


Figure 9 Temperature Enclosure and Resulting Element Temperature - Time Relationships

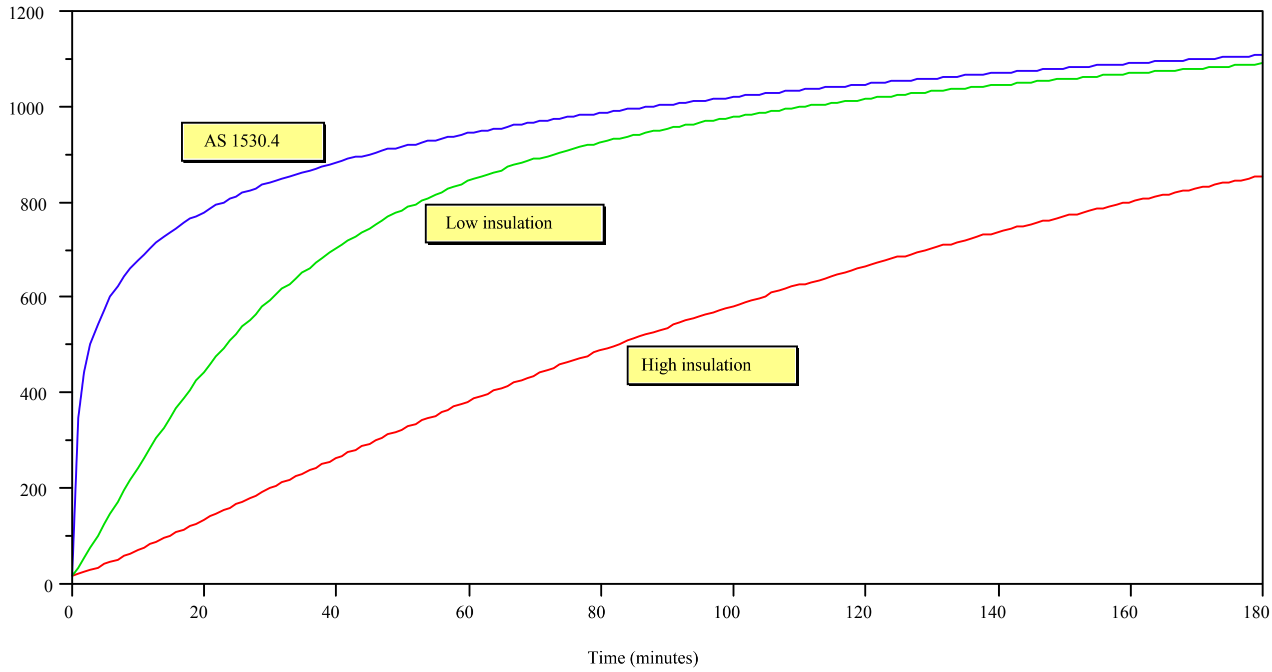


Figure 10 Standard Temperature-Time Response in Enclosure and Resulting Element Temperature - Time Relationships

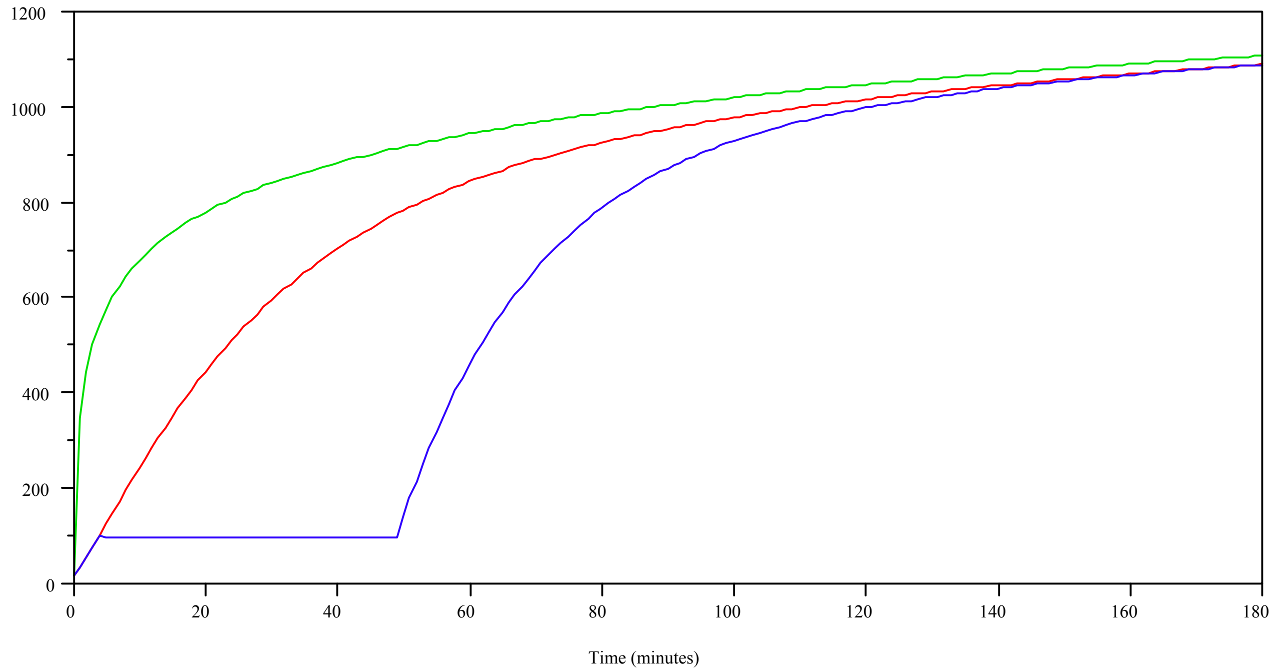


Figure 11 Standard Temperature-Time Response in Enclosure and Resulting Element Temperature - Time Relationships for Low Insulation Element and Element with Protection Material with Significant Water Content

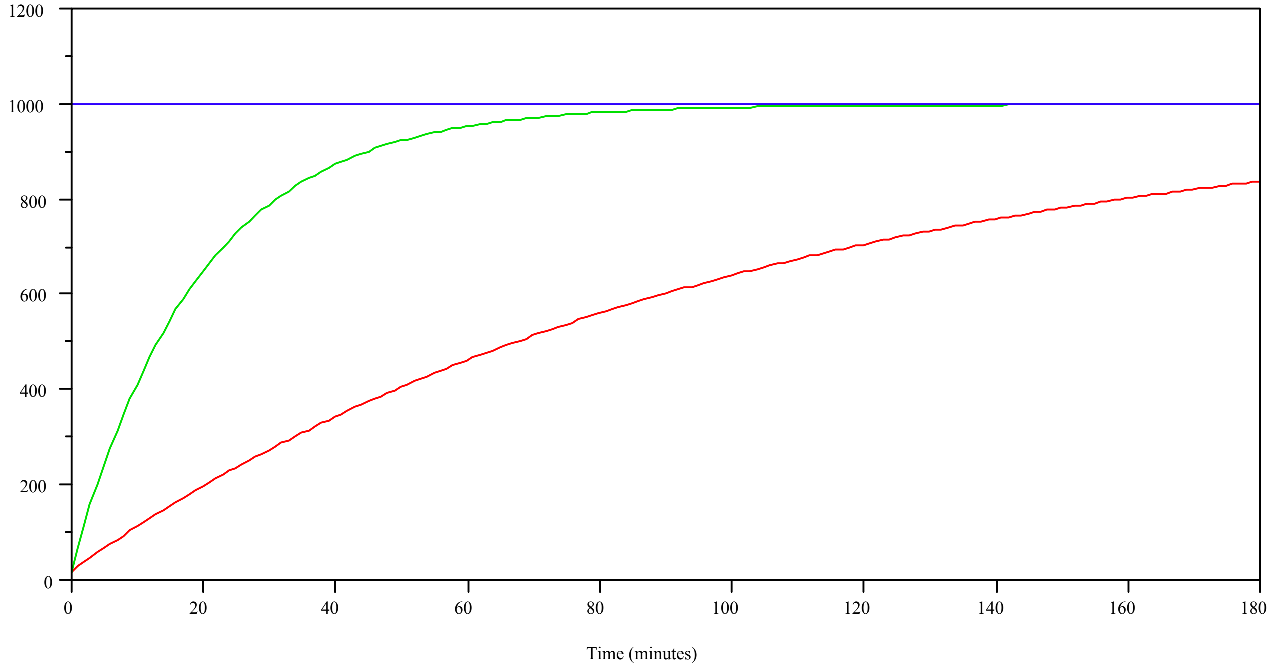


Figure 12 Constant 1000°C Temperature-Time Response in Enclosure and Resulting Element Temperature - Time Relationships

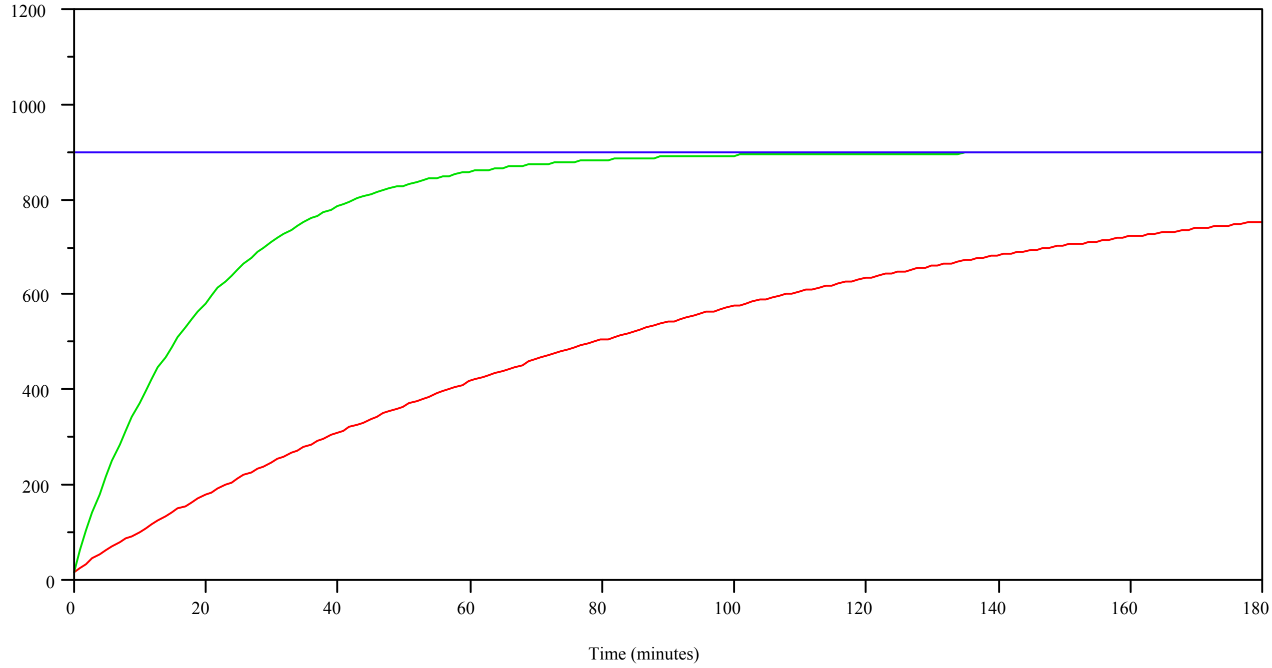


Figure 13 Constant 900°C Temperature-Time Response in Enclosure and Resulting Element Temperature - Time Relationships

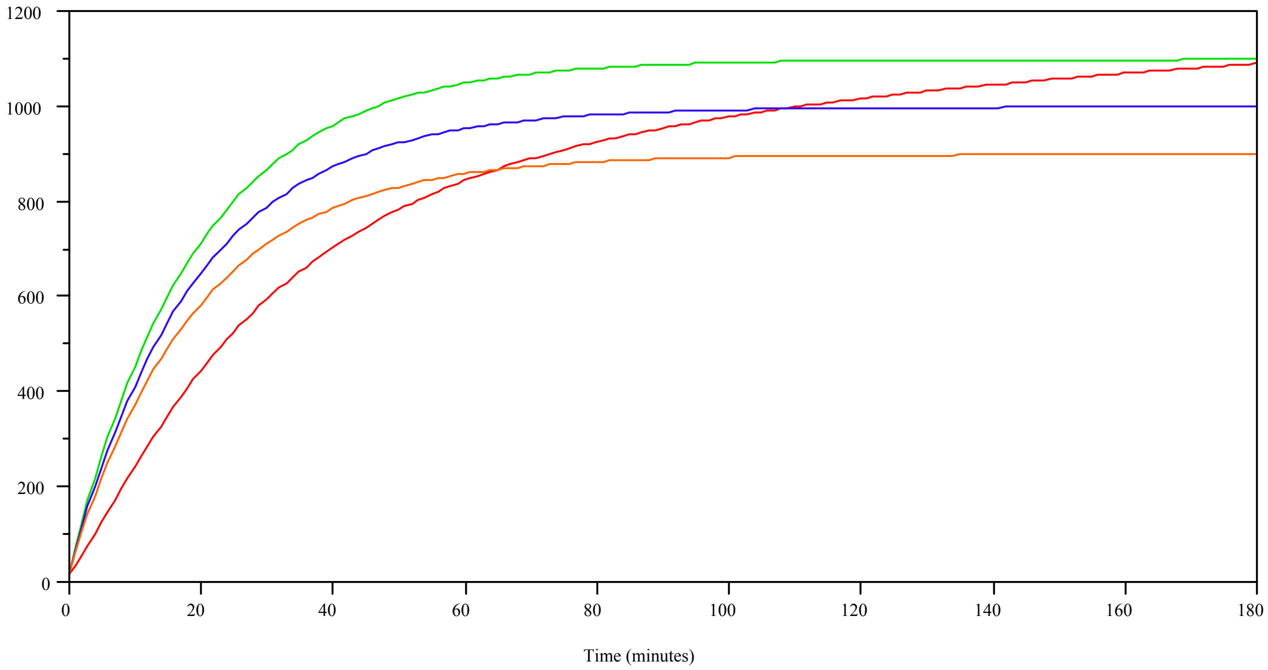


Figure 14 Comparison of Resulting Element Temperatures for Constant 900, 1000 and 1100°C and Standard Temperature-Time Regimes in Enclosure for StrucElem 1

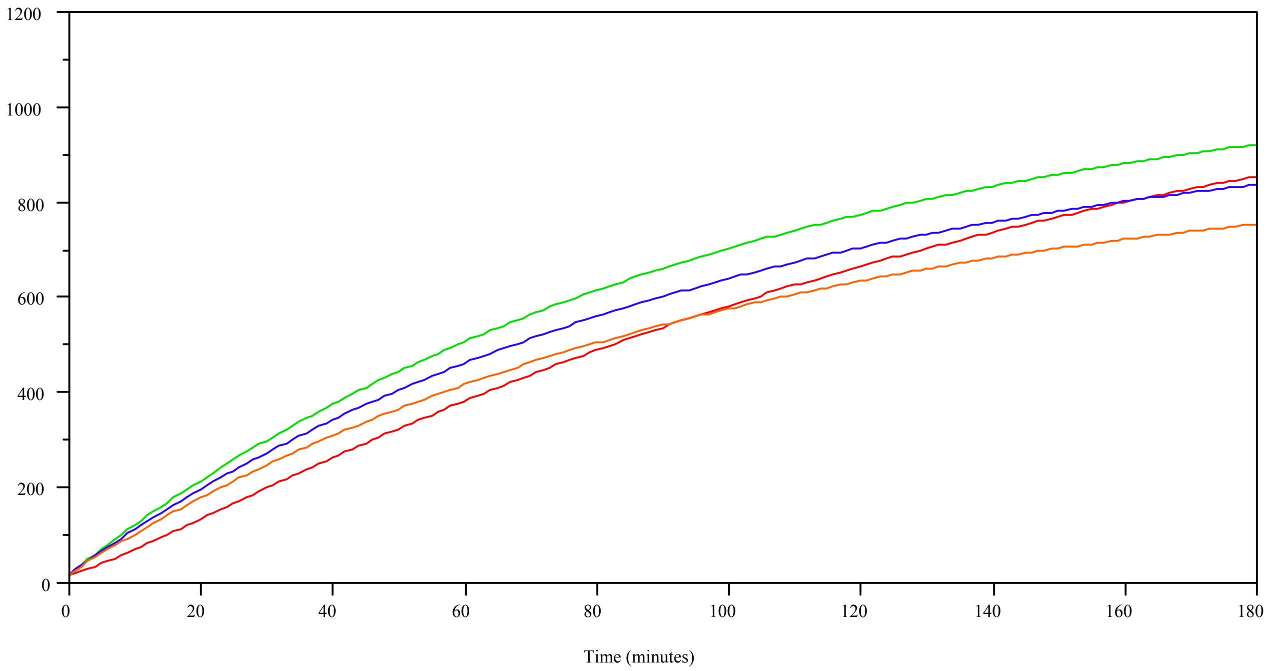


Figure 15 Comparison of Resulting Element Temperatures for Constant 900, 1000 and 1100°C and Standard Temperature-Time Regimes in Enclosure for StrucElem 2

APPENDIX J

CALCULATION OF FIRE RESISTANCE LEVELS FOR ENCLOSURES

CALCULATION OF FIRE RESISTANCE LEVELS FOR ENCLOSURES

by

I R Thomas, P Beever and J Blackmore

Introduction

A rational method for the calculation of fire resistance levels (FRLs) for enclosures has been developed. The method recognises that there are three bases which may be appropriate for the determination of durations that the barriers and/or structure of enclosures and buildings may be required to function satisfactorily in the event of a fire. These are:

- occupant avoidance
- fire brigade intervention
- burnout

Determination of which of these are appropriate is the first step in determining the appropriate FRL for and enclosure or building.

The second step is determination of the severity of the fire. In this context fire severity can be thought of as the time-temperature history of the fire. This can be represented in a simplified manner by two parameters, the maximum temperature that occurs during the fire and the length of time for which high temperatures exist in the enclosure.

A methodology has been developed for estimating these parameters which is based on three factors

- the size of the enclosure
- the fire load density in the enclosure
- the ventilation of the enclosure

(Alternatively, it can be said that the estimate is based on only two quantities, the quantity of fuel in the enclosure and the ventilation of the enclosure, but this approach ignores the way in which this problem is normally approached by using the actual dimensions of the enclosure and estimating from surveys and other available data the fire load density.)

It has been found that the thermal properties of the boundaries have no significant influence on the temperatures or the duration of high temperatures, and thus these properties are not considered in making the estimate.

It is assumed that the enclosure has a single ventilation opening. Multiple openings can either be treated as an equivalent single opening or the largest opening treated as though it were the only opening (this should generally be conservative). It is known that in many multiple opening configurations the duration of high temperatures will be much shorter than with a single opening of the same size, but that this is very dependent on the arrangement of the openings.

The duration of burning (or the approximate inverses, the burning rate or mass loss rate) has been found to be significantly influenced by the width of the opening compared with the width of the enclosure. It has been found that the longest duration occurs for an opening that is across the full width of the enclosure, with little or no change in the maximum temperatures reached. Thus in the following the openings considered extend across the full width of the enclosure, and thus for a given ventilation condition (ratio of ventilation factor to total surface area, see ???) the opening is the widest but shallowest possible.

Maximum enclosure sizes have previously been determined for each occupancy in the BCA and are shown in Table 1. Also shown in Table 1 are the range of ventilation and fire load density considered appropriate. The basis for determination of these has been documented elsewhere.

The following calculation of FRLs is based on the mean fire load density for each enclosure size and ventilation condition.

The FRL is determined from the fire severity on the basis of the fire resistance level that is required for all representative elements to survive the fire, either for the required period (in cases where occupant avoidance or fire brigade control are the governing criterion) or burnout.

The estimated survival times for the representative elements for FRL's of 30, 45, 60, 90, 120 and 180 minutes are given in Table 2 for several maximum temperatures. For each maximum temperature the estimated survival times are tabulated for durations of high temperatures from ten minutes (600 s) to three hours (10800 s). In Table 2 it is assumed that the maximum temperature of 1100 °C occurs at the start of the period considered and that the temperature reduces linearly to 500 °C over the nominated duration of high temperatures.

It should be noted that, although often assumed otherwise, it has been observed for many of the enclosures for which test data is available that uniform temperature conditions do not occur throughout the enclosure - the duration of high temperatures near the vent generally lasts throughout the fire, but at locations remote from the fire the duration of high temperatures is often shorter. This has implications for FRL requirements (for example, possible reductions away from the opening) but these have not been taken into account in the following recommendations.

In the modelling of barriers and structural elements on which the relationship between the design fire and the standard fire resistance test is based, the model for masonry is for a single leaf wall only and is based on very limited standard test data only. It is not possible to predict the behaviour of realistic walls with an FRL of 90, 120 or 180. Also, with the sudden heating implied by the form of the temperature-time relationship used in this report such walls are predicted to fail very early in the fire, but in reality the temperature rise will be slower. Consequently, the results of the model for masonry walls have been ignored in the following recommendations.

In addition, it should be noted that the structural and barrier details used in the following are not necessarily realistic systems, in that thicknesses of protective coatings, insulation or wall boards are not necessarily commercially available or generally used in practice. The systems are otherwise similar to those used in practice. This has been necessary to achieve the desired FRLs. Even the minimum systems used in practice would generally achieve higher FRLs than 30, 45 and sometimes 60 minutes. However this procedure is necessary to ensure that systems developed in the future specifically for low FRLs are covered as best is possible with current information.

Evacuation Times

The derivation of the evacuation times has been reported elsewhere. The times for each building class are given below.

	Evacuation Time (minutes)						
Class	**1 Storey**	**2 to 5 Storeys**	**➢ 5 Storeys (n storeys)**	**10 Storeys**	**20 Storeys**	**30 Storeys**	**50 Storeys**
2	16	21	1.3n + 13	26	39	52	78
3a	extended	extended	extended	-	-	-	-
3b	16	21	1.3n + 13	26	39	52	78
4	16	21	1.3n + 13	26	39	52	78
5	16	21	1.5n + 13	28	43		
6	16	21	-	-	-	-	-
7 carpark	-	-	-	-	-	-	-
7 other	-	-	-	-	-	-	-
8 purpose built	-	-	-	-	-	-	-
8 general purpose	-	-	-	-	-	-	-
9a	extended	extended	extended	-	-	-	-
9b school	16	21	-	-	-	-	-
9b disco or nightclub	16	21	-	-	-	-	-
9b exhibition hall	16	21	-	-	-	-	-
9b theatre or public hall with stage	16	21	-	-	-	-	-
9b theatre or public hall without stage	16	21	-	-	-	-	-
9b other	16	21	-	-	-	-	-

Fire Brigade Access Time

The figure agreed for this is **84 minutes** which is the 95%ile of the available Australian data. This figure is considered to be conservative (that is, excessively long) but no better basis for determining a figure has been found.

Determination of FRL

In cases where occupant evacuation time governs:

The FRLs below would be required unless a lesser FRL is required for the burnout time criterion below.

For cases where the occupant evacuation time is 16 minutes (and assuming the maximum temperature is 1100 °C) an FRL of 60 minutes would result in an estimated failure time of greater than 16 minutes for almost all fire durations.

For cases where the occupant evacuation time is over 20 minutes (and again assuming the maximum temperature is 1100 °C) an FRL of 60 minutes could produce failures in less than the required time but an FRL of 90 minutes would produce no failures in over 60 minutes.

On the same basis, for the case where the occupant evacuation time is 78 minutes an FRL of 120 minutes would produce no failure in less than 80 minutes.

In cases where fire brigade control time governs:

In cases where fire brigade control time governs an FRL of 120 minutes would produce no failures in 84 minutes (again assuming the maximum temperature is 1100 °C).

In cases where burnout time governs:

Classes 2 and 4

The maximum enclosure size for classes 2 and 4 is 10 m by 20 m by 2.4 m high. The minimum ventilation for this case is by a single opening 10 m wide by 1.87 m high in the end wall. It is estimated (Table A2) that with a fire load density of 58.8 kg/m^2 (wood equivalent) the fire duration is 321 minutes. From Table 2 for a maximum temperature of 1100°C no element with an FRL of 180 minutes would be satisfactory. By extrapolation an FRL of over 300 minutes would be required, but no requirement is stated because of the degree of extrapolation required.

Alternative vents are 20 m by 1.37 m high and 2.10 m high, and for these cases the fire durations are estimated as 104 and 50 minutes respectively. With a maximum temperature of 1100°C an FRL of 120 minutes would be satisfactory for the smaller ventilation case. Some elements with an FRL of 60 minutes would be expected to have failed at 50 minutes (with a maximum temperature of 1100 °C), but no elements with an FRL of 90 minutes would be expected to have failed by this time. Thus an FRL of 90 minutes would suffice for the larger ventilation case.

Classes 3a and 3b

The maximum enclosure size for class 3a and the smaller enclosure size for class 3b is 4 m by 8 m by 2.4 m high. The maximum larger enclosure size for class 3b is 30 m by 50 m by 5 m high. Considering only the smaller of these, the minimum ventilation for Class 3a is by a single opening 4 m wide by 1.14 m high in the end wall and for Class 3b by a similar opening 0.72 m high. It is estimated (Table A2) that with a fire load density of 29.4 kg/m^2 (wood equivalent) the fire duration is 156 minutes for the class 3a case and 343 minutes for the class 3b case. With a maximum temperature of 1100 °C for both classes it is obvious (from the classes 2 and 4 case) that a FRL of 180 minutes would be required for the first and (by extrapolation) over 300 minutes for the second.

Alternative vents sizes are 8 m by 1.58 m high and 2.4 m high for class 3a and 0.94 and 1.49 m high for class 3b, and for these cases the fire durations are estimated as 39, 19, 94 and 43 minutes respectively. With a maximum temperature of 1100 °C and an FRL of 60 minutes no elements would be expected to fail by 43 minutes, so this would be satisfactory for the 19, 39 and 43 minute cases. An FRL of 120 minutes would be required for no failures to be predicted by 94 minutes.

The FRLs required for the larger enclosures considered appropriate for Class 3b are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

Class 5

The enclosure sizes for classes 5 is 4 m by 8 m by 3 m high and 60 m by 60 m by 3 m high. Considering initially the smaller of these, the minimum ventilation for Class 5 is by a single opening 4 m wide by 0.77 m high in the end wall. It is estimated (Table A2) that with a fire load density of 47.1 kg/m^2 (wood equivalent) the fire duration is 484 minutes and the temperature 1100 °C. An FRL of about 480 minutes is estimated for this case, but no requirement is stated because of the degree of extrapolation required.

Alternative vents sizes are 8 m by 1.23 m high and 2.34 m high with fire durations estimated as 96 and 32 minutes respectively. With an assumed maximum temperature of 1100 °C FRLs of 120 and 60 minutes would suffice.

The FRLs required for the larger enclosures considered appropriate for Class 5 are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

Class 6

The enclosure sizes for class 6 are 5 m by 20 m by 3 m high and 50 m by 100 m by 5 m high.

The minimum ventilation of the smaller enclosure is by a single opening 5 m wide by 1.64 m high in the end wall. It is estimated that with a fire load density of 58.8 kg/m^2 the fire duration is 402 minutes. It is estimated an FRL of about 420 minutes would be required, but no requirement is stated because of the degree of extrapolation required.

Alternative vents are 20 m by 1.35 m high and 2.31 m high, and for these cases the fire durations are estimated as 106 and 43 minutes respectively. With an assumed maximum temperature of 1100°C FRLs of 120 and 60 minutes suffice.

The FRLs required for the larger enclosures considered appropriate for Class 5 are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

Classes 7a and 7b

The enclosure sizes for classes 7a and 7b are 5 m by 20 m by 2.4 m high and 50 m by 100 m by 2.4 m high.

Considering only the smaller of these, the minimum ventilation for Class 7a is by a single opening 5 m wide by 1.18 m high in the end wall. It is estimated (Table A2) that with a fire load density of 11.8 kg/m^2 (wood equivalent) the fire duration is 141 minutes. With an assumed maximum temperature of 1100 °C an FRL of 180 minutes would be required.

Alternative vents sizes for the class 7a case are 20 m by 1.37 and 2.4 m high with estimated fire durations of 21 and 8 minutes respectively. With an assumed maximum temperature of 1100 °C FRLs of 60 and 30 minutes respectively would be required.

For class 7b, again considering only the smaller enclosures, the minimum ventilation is by a single opening 5 m wide by 1.79 m high in the end wall. It is estimated (Table A2) that with a fire load density of 324 kg/m^2 (wood equivalent) the fire duration would be 1902 minutes. No FRL can be estimated for such an extended duration fire. Alternative vents sizes for the class 7b case are 20 m by 1.37 and 2.4 m high with estimated fire durations of 499 and 202 minutes respectively. No FRL estimate can be made for the first of these because of the extended duration, while, with an assumed maximum temperature of 1100 °C an FRL of 240 minutes respectively would be required for the second.

The FRLs required for the larger enclosures are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

Class 8

The enclosure sizes for class 8 are 5 m by 20 m by 4 m high and 50 m by 100 m by 6 m high.

The minimum ventilation of the smaller enclosure is by a single opening 5 m wide by 1.79 m high in the end wall. It is estimated that with a fire load density of 35.3 kg/m^2 the fire duration is 208 minutes. Thus an FRL of 240 minutes would be required.

Alternative vents are 20 m by 1.48 and 2.52 m high, and for these cases the fire durations are estimated as 54 and 22 minutes respectively. With an assumed maximum temperature of 1100 °C elements with an FRL of 90 and 60 minutes respectively would be expected to suffice.

The FRLs required for the larger enclosures considered appropriate for Class 8 are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

Classes 9a and 9b

The maximum enclosure size for class 9a is 6 m by 20 m by 3.0 m high and those for class 9b are 5 m by 20 m by 3.0 m high and 30 m by 50 m by 5 m high.

The minimum ventilation for Class 9a is by a single opening 6 m wide by 1.58 m high in the end wall. The corresponding estimated fire duration is 145 minutes which would require an FRL of 180 minutes.

Alternative vent sizes for class 9a are 20 m by 1.47 and 2.50 m high, and for these cases the fire durations are estimated as 39 and 16 minutes respectively. With an assumed maximum temperature of 1100 °C an estimated FRL for both cases is 60 minutes.

The minimum ventilation for Class 9b by an opening 5.0 m wide by 1.64 m high is estimated (Table A2), with a fire load density of 44.1 kg/m^2 (wood equivalent), to have a fire duration of 302 minutes. No FRL estimate can be made because of the degree of extrapolation required.

Alternative vents sizes are 20 m by 1.35 and 2.31 m high for class 9b, and for these cases the fire durations are estimated as 79 and 32 minutes respectively. With an assumed maximum temperature of 1100 °C elements with an FRL of 90 minutes for the first case and 60 minutes for the second case are estimated to be satisfactory.

The FRLs required for the larger enclosures considered appropriate for Class 9b are not able to be estimated because the severity of the fires in these enclosures are not able to be estimated.

These results are summarised in the following tables.

Table 3 Required FRL to Cover Evacuation Time

Class	1 Storey	2 to 5 Storeys	➢ 5 Storeys (n storeys)	10 Storeys	20 Storeys	30 Storeys	50 Storeys
2	60	90	90	90	90	90	120
3a	extended	extended	extended	-	-	-	-
3b	60	90	90	90	90	90	120
4	60	90	90	90	90	90	120
5	60	90	90	90	90		
6	60	90	-	-	-	-	-
7 carpark	-	-	-	-	-	-	-
7 other	-	-	-	-	-	-	-
8 purpose built	-	-	-	-	-	-	-
8 general purpose	-	-	-	-	-	-	-
9a	extended	extended	extended	-	-	-	-
9b school	60	90	-	-	-	-	-
9b disco or nightclub	60	90	-	-	-	-	-
9b exhibition hall	60	90	-	-	-	-	-
9b theatre or public hall with stage	60	90	-	-	-	-	-
9b theatre or public hall without stage	60	90	-	-	-	-	-
9b other	60	90	-	-	-	-	-

Table 4 Required FRL to Cover Burnout

Class	W (m)	D (m)	H (m)	w (m)	h (m)	FLD (kg/m^2)	t500 (minutes)	FRL (minutes)
2 & 4	10	20	2.4	10	1.87	58.8	321	-
2 & 4	20	10	2.4	20	1.37	58.8	104	120
2 & 4	20	10	2.4	20	2.10	58.8	50	90
3a	4	8	2.4	4	1.14	29.4	156	180
3a	8	4	2.4	8	1.58	29.4	39	60
3a	8	4	2.4	8	2.40	29.4	19	60
3b	4	8	2.4	4	0.72	29.4	343	-
3b	8	4	2.4	8	0.94	29.4	94	120
3b	8	4	2.4	8	1.49	29.4	43	60
3b	30	50	5	30	1.13	29.4		-
3b	50	30	5	50	2.04	29.4		-
3b	50	30	5	50	4.08	29.4		-
5	4	8	3	4	0.77	47.1	484	-
5	8	4	3	8	1.23	47.1	96	120
5	8	4	3	8	2.34	47.1	32	60
5	60	60	3	60	1.52	47.1		-
5	60	60	3	60	3	47.1		-
5	60	60	3	60	3	47.1		-
6	5	20	3	5	1.64	58.8	402	-
6	20	5	3	20	1.35	58.8	106	120
6	20	5	3	20	2.31	58.8	43	60
6	50	100	5	50	3.09	58.8		-
6	100	50	5	100	4.63	58.8		-
6	100	50	5	100	5	58.8		-
7a	5	20	2.4	5	1.18	11.8	141	180
7a	20	5	2.4	20	1.37	11.8	21	60
7a	20	5	2.4	20	2.40	11.8	8	30
7a	50	100	2.4	50	2.4	11.8		-
7a	100	50	2.4	100	2.4	11.8		-
7a	100	50	2.4	100	2.4	11.8		-
7b	5	20	4	5	1.79	323.5	1902	-
7b	20	5	4	20	1.37	323.5	499	-
7b	20	5	4	20	2.40	323.5	202	240
7b	50	100	6	50	2.89	323.5		
7b	100	50	6	100	4.34	323.5		
7b	100	50	6	100	6	323.5		
8	5	20	4	5	1.79	35.3	208	240
8	20	5	4	20	1.48	35.3	54	90
8	20	5	4	20	2.52	35.3	22	60
8	50	100	6	50	2.89	35.3		
8	100	50	6	100	4.34	35.3		
8	100	50	6	100	6	35.3		
9a	6	20	3	6	1.58	20.6	145	180
9a	20	6	3	20	1.47	20.6	39	60
9a	20	6	3	20	2.50	20.6	16	60
9b	5	20	3	5	1.64	44.1	302	-
9b	20	5	3	20	1.35	44.1	79	90
9b	20	5	3	20	2.31	44.1	32	60
9b	30	50	5	30	1.70	44.1		
9b	50	30	5	50	3.06	44.1		
9b	50	30	5	50	5	44.1		

Conclusion

The FRLs required in the cases considered are highly dependent on the three factors considered in their derivation (fire load density, enclosure area and vent size) and on the temperature assumed to occur. In addition, the assumption of an 1100 °C temperature (which it is acknowledged is in the upper range of temperatures measured in realistic fire tests in enclosures) results in a quite severe fire when compared with the standard fire test as the furnace temperature only gets to this level nearly three hours after the commencement of the test.

The three factors considered in the derivation are all important but the size of the enclosure is possibly most important. There are two (possibly three, if the 1100 °C temperature is considered also) extreme factors involved in the calculations on which the FRLs are based: the enclosures are the largest considered likely for the occupancies and the ventilation is the minimum considered likely. Both of these lead to longer durations, and therefore the durations estimated must be towards the upper extreme of those that might occur in practice.

For a specific building design a calculation using the methods used above but with the actual enclosure size and ventilation conditions would lead to considerably lower requirements. This can be accomplished by calculating the fire duration and then using Table 4.

The following table is an example of a possible presentation to cover a range of enclosure sizes and ventilation conditions. It is for Classes 2&4 and includes the values in Table 4.

Table 5 Example Table Covering a Range of Enclosure and Vent Sizes

Enclosure Size	Ventilation	
	Small (10m x 1.2m)	Large (10m x 2.4m)
Large (10 m x 20 m)	771 (FRL)	223 (FRL)
Medium (5 m x 10 m)	386 (FRL)	112 (FRL 120)
Small 3 m x 5 m)	193 (FRL)	56 (FRL 90)

This estimate may also be made slightly more approximately by using the following formulae:

$$t = \frac{FLD \times D}{18.7 \times h^{1.79}} \qquad (1)$$

$$FRL \geq \frac{(t + 1230)}{67} \qquad (2)$$

For the same example as in Table 5 above these formulae would lead to the results in the following table (Table 6). In this table the FRLs are expressed in the calculated number of minutes rather than in the standard FRL periods (60, 90, 120, etc)

Table 6 Example Covering a Range of Enclosure and Vent Sizes Based on Equations

Enclosure Size	Ventilation	
	Small (10m x 1.2m)	Large (10m x 2.4m)
Large (10 m x 20 m)	770 (FRL 708)	221 (FRL 216)
Medium (5 m x 10 m)	385 (FRL 363)	111 (FRL 117)
Small 3 m x 5 m)	192 (FRL 191)	55 (FRL 68)

(Note in this table that for fire durations up to about 160 minutes the FRL period is slightly greater than the fire duration, but for those above about 200 minutes the FRL period is less than the fire duration. This is because the standard fire test temperature is about 1100 °C at 180 minutes.)

It can be seen that the results in the two tables are very similar.

It should be noted that many of the FRLs recommended above are greater than those currently required by the BCA. It is not recommended that FRLs in the BCA be increased as there is no indication in the fire record that the current FRLs are unsatisfactory. Indeed, the general opinion seems to be that, if anything, FRLs are too high. As the estimates above are highly dependent on the enclosure size, fire load density and ventilation assumed it may be that reduced values of these parameters might be appropriate, and that further consideration of these values by ABCB would be sensible.

Table 1

Class	W (m)	D (m)	H (m)	w (m)	h (m)	FL (kg/m^2)
2 & 4	5	20	2.4	5	1.87	34.7
2 & 4	5	20	2.4	5	1.87	58.8
2 & 4	5	20	2.4	5	1.87	94.1
2 & 4	20	5	2.4	20	1.37	34.7
2 & 4	20	5	2.4	20	1.37	58.8
2 & 4	20	5	2.4	20	1.37	94.1
2 & 4	20	5	2.4	20	2.10	34.7
2 & 4	20	5	2.4	20	2.10	58.8
2 & 4	20	5	2.4	20	2.10	94.1
3a	4	8	2.4	4	1.14	17.6
3a	4	8	2.4	4	1.14	29.4
3a	4	8	2.4	4	1.14	45.9
3a	8	4	2.4	8	1.58	17.6
3a	8	4	2.4	8	1.58	29.4
3a	8	4	2.4	8	1.58	45.9
3a	8	4	2.4	8	2.40	17.6
3a	8	4	2.4	8	2.40	29.4
3a	8	4	2.4	8	2.40	45.9
3b	4	8	2.4	4	0.72	17.6
3b	4	8	2.4	4	0.72	29.4
3b	4	8	2.4	4	0.72	45.9
3b	8	4	2.4	8	0.94	17.6
3b	8	4	2.4	8	0.94	29.4
3b	8	4	2.4	8	0.94	45.9
3b	8	4	2.4	8	1.49	17.6
3b	8	4	2.4	8	1.49	29.4
3b	8	4	2.4	8	1.49	45.9
3b	30	50	5	30	1.86	17.6
3b	30	50	5	30	1.86	29.4
3b	30	50	5	30	1.86	45.9
3b	50	30	5	50	2.75	17.6
3b	50	30	5	50	2.75	29.4
3b	50	30	5	50	2.75	45.9
3b	50	30	5	50	4.37	17.6
3b	50	30	5	50	4.37	29.4
3b	50	30	5	50	4.37	45.9

Class	W (m)	D (m)	H (m)	w (m)	h (m)	FL (kg/m²)
5	4	8	3	4	0.77	16.5
5	4	8	3	4	0.77	47.1
5	4	8	3	4	0.77	100.0
5	8	4	3	8	1.23	16.5
5	8	4	3	8	1.23	47.1
5	8	4	3	8	1.23	100.0
5	8	4	3	8	2.34	16.5
5	8	4	3	8	2.34	47.1
5	8	4	3	8	2.34	100.0
5	60	60	3	60	1.91	16.5
5	60	60	3	60	1.91	47.1
5	60	60	3	60	1.91	100.0
5	60	60	3	60	3.00	16.5
5	60	60	3	60	3.00	47.1
5	60	60	3	60	3.00	100.0
5	60	60	3	60	3.00	16.5
5	60	60	3	60	3.00	47.1
5	60	60	3	60	3.00	100.0
6	5	20	3	5	1.64	24.1
6	5	20	3	5	1.64	58.8
6	5	20	3	5	1.64	111.8
6	20	5	3	20	1.35	24.1
6	20	5	3	20	1.35	58.8
6	20	5	3	20	1.35	111.8
6	20	5	3	20	2.31	24.1
6	20	5	3	20	2.31	58.8
6	20	5	3	20	2.31	111.8
6	50	100	5	50	3.69	24.1
6	50	100	5	50	3.69	58.8
6	50	100	5	50	3.69	111.8
6	100	50	5	100	4.84	24.1
6	100	50	5	100	4.84	58.8
6	100	50	5	100	4.84	111.8
6	100	50	5	100	6.00	24.1
6	100	50	5	100	6.00	58.8
6	100	50	5	100	6.00	111.8

Class	W (m)	D (m)	H (m)	w (m)	h (m)	FL (kg/m²)
7a	5	20	2.4	5	1.18	7.1
7a	5	20	2.4	5	1.18	11.8
7a	5	20	2.4	5	1.18	18.2
7a	20	5	2.4	20	1.37	7.1
7a	20	5	2.4	20	1.37	11.8
7a	20	5	2.4	20	1.37	18.2
7a	20	5	2.4	20	2.40	7.1
7a	20	5	2.4	20	2.40	11.8
7a	20	5	2.4	20	2.40	18.2
7a	50	100	2.4	50	2.40	7.1
7a	50	100	2.4	50	2.40	11.8
7a	50	100	2.4	50	2.40	18.2
7a	100	50	2.4	100	2.40	7.1
7a	100	50	2.4	100	2.40	11.8
7a	100	50	2.4	100	2.40	18.2
7a	100	50	2.4	100	2.40	7.1
7a	100	50	2.4	100	2.40	11.8
7a	100	50	2.4	100	2.40	18.2
7b	5	20	4	5	1.79	94.1
7b	5	20	4	5	1.79	323.5
7b	5	20	4	5	1.79	764.7
7b	20	5	4	20	1.48	94.1
7b	20	5	4	20	1.48	323.5
7b	20	5	4	20	1.48	764.7
7b	20	5	4	20	2.52	94.1
7b	20	5	4	20	2.52	323.5
7b	20	5	4	20	2.52	764.7
7b	50	100	6	50	3.69	94.1
7b	50	100	6	50	3.69	323.5
7b	50	100	6	50	3.69	764.7
7b	100	50	6	100	4.84	94.1
7b	100	50	6	100	4.84	323.5
7b	100	50	6	100	4.84	764.7
7b	100	50	6	100	6.00	94.1
7b	100	50	6	100	6.00	323.5
7b	100	50	6	100	6.00	764.7
8	5	20	4	5	1.79	10.0
8	5	20	4	5	1.79	35.3
8	5	20	4	5	1.79	82.4
8	20	5	4	20	1.48	10.0
8	20	5	4	20	1.48	35.3
8	20	5	4	20	1.48	82.4
8	20	5	4	20	2.52	10.0
8	20	5	4	20	2.52	35.3
8	20	5	4	20	2.52	82.4
8	50	100	6	50	3.69	10.0
8	50	100	6	50	3.69	35.3
8	50	100	6	50	3.69	82.4
8	100	50	6	100	4.84	10.0
8	100	50	6	100	4.84	35.3
8	100	50	6	100	4.84	82.4
8	100	50	6	100	6.00	10.0
8	100	50	6	100	6.00	35.3
8	100	50	6	100	6.00	82.4

Class	W (m)	D (m)	H (m)	w (m)	h (m)	FL (kg/m^2)
9a	6	20	3	6	1.58	11.8
9a	6	20	3	6	1.58	20.6
9a	6	20	3	6	1.58	32.4
9a	20	6	3	20	1.47	11.8
9a	20	6	3	20	1.47	20.6
9a	20	6	3	20	1.47	32.4
9a	20	6	3	20	2.50	11.8
9a	20	6	3	20	2.50	20.6
9a	20	6	3	20	2.50	32.4
9b	5	20	3	5	1.64	25.9
9b	5	20	3	5	1.64	44.1
9b	5	20	3	5	1.64	70.6
9b	20	5	3	20	1.35	25.9
9b	20	5	3	20	1.35	44.1
9b	20	5	3	20	1.35	70.6
9b	20	5	3	20	2.31	25.9
9b	20	5	3	20	2.31	44.1
9b	20	5	3	20	2.31	70.6
9b	30	50	5	30	2.44	25.9
9b	30	50	5	30	2.44	44.1
9b	30	50	5	30	2.44	70.6
9b	50	30	5	50	3.61	25.9
9b	50	30	5	50	3.61	44.1
9b	50	30	5	50	3.61	70.6
9b	50	30	5	50	5.00	25.9
9b	50	30	5	50	5.00	44.1
9b	50	30	5	50	5.00	70.6

Table 2

The figures in the following table are the estimated failure time in seconds for the idealised temperature - time relationships of the temperatures and durations shown, for elements of the specified FRLs.

The temperature profile for the design fires are the specified (maximum) temperature (Tmax) at the start of the fire with the temperature falling linearly to 500 °C at the time corresponding to the duration.

The duration, in seconds, is given in the column marked t500.

An entry of “Nil” means no failure is predicted.

The remaining columns represent each of the structural and barrier elements considered as follows:

SSW	Steel stud wall
MW	Masonry wall
CW	Concrete wall
CB	Concrete beam
CC	Concrete column
SB	Steel beam
SC	Steel column
MSD	Insulated steel duct

FRL 30

Tmax 1200

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
1200	360	120	1080	Nil	840	Nil	Nil	Nil
1800	**360**	**120**	**660**	**600**	**600**	**1140**	**1140**	**660**
2400	360	120	600	540	540	1020	1020	660
3000	360	120	600	540	540	1020	1020	600
3600	300	120	540	540	540	960	960	600
4200	300	120	540	540	480	960	960	600
4800	300	120	540	540	480	960	960	600
5400	300	120	540	480	480	960	960	600
6000	300	120	540	480	480	960	960	600
6600	300	120	540	480	480	960	960	600
7200	300	120	540	480	480	900	900	600
7800	300	120	540	480	480	900	900	600
8400	300	120	540	480	480	900	900	540
9000	300	120	540	480	480	900	900	540
9600	300	120	540	480	480	900	900	540
10200	300	120	480	480	480	900	900	540
10800	300	120	480	480	480	900	900	540

Tmax 1100

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
1800	**420**	**180**	**900**	**780**	**780**	**1320**	**1320**	**900**
2400	360	180	780	720	660	1200	1200	780
3000	360	120	720	660	660	1140	1140	720
3600	360	120	720	660	660	1080	1080	720
4200	360	120	660	660	600	1080	1080	720
4800	360	120	660	600	600	1080	1080	660
5400	360	120	660	600	600	1020	1020	660
6000	360	120	660	600	600	1020	1020	660
6600	360	120	660	600	600	1020	1020	660
7200	360	120	660	600	600	1020	1020	660
7800	360	120	660	600	600	1020	1020	660
8400	360	120	660	600	600	1020	1020	660
9000	360	120	660	600	600	1020	1020	660
9600	360	120	660	600	600	1020	1020	660
10200	360	120	660	600	600	1020	1020	660
10800	360	120	600	600	600	1020	1020	660

FRL 30

Tmax **1000**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	**Nil**	**300**	**1380**	**Nil**	**Nil**	**1620**	**1620**	**Nil**
2400	1560	240	1080	1080	1080	1380	1380	1080
3000	1440	240	1020	900	900	1260	1260	960
3600	1380	240	960	900	840	1260	1260	900
4200	480	240	900	840	840	1200	1200	840
4800	480	240	900	840	780	1200	1200	840
5400	420	240	840	780	780	1200	1200	840
6000	420	240	840	780	780	1200	1200	840
6600	420	240	840	780	780	1200	1200	840
7200	420	240	840	780	780	1140	1140	840
7800	420	240	840	780	780	1140	1140	780
8400	420	240	840	780	780	1140	1140	780
9000	420	240	840	780	780	1140	1140	780
9600	420	240	840	780	780	1140	1140	780
10200	420	240	840	780	780	1140	1140	780
10800	420	240	840	780	720	1140	1140	780

Tmax **900**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	1740	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	1560	Nil	Nil	1620	1620	Nil
3000	1740	Nil	1380	Nil	Nil	1500	1500	Nil
3600	1620	Nil	1260	1440	1500	1440	1440	Nil
4200	1560	Nil	1260	1320	1320	1440	1440	1260
4800	1560	600	1200	1260	1260	1380	1380	1200
5400	1500	540	1200	1200	1200	1380	1380	1140
6000	1500	540	1140	1140	1140	1380	1380	1140
6600	1500	540	1140	1140	1140	1380	1380	1080
7200	1500	480	1140	1140	1140	1320	1320	1080
7800	1440	480	1140	1080	1140	1320	1320	1080
8400	1440	480	1140	1080	1080	1320	1320	1080
9000	1440	480	1080	1080	1080	1320	1320	1080
9600	1440	480	1080	1080	1080	1320	1320	1080
10200	1440	480	1080	1080	1080	1320	1320	1020
10800	1440	480	1080	1080	1080	1320	1320	1020

FRL 45

Tmax **1200**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
1800	540	120	1800	Nil	Nil	Nil	Nil	Nil
2400	**480**	**120**	**1680**	**1440**	**1440**	**2400**	**Nil**	**Nil**
3000	480	120	1620	1140	1200	1980	2040	1560
3600	480	120	1620	1080	1140	1860	1860	1380
4200	480	120	1560	1020	1080	1800	1800	1320
4800	480	120	1560	960	1080	1740	1740	1320
5400	480	120	1560	960	1020	1740	1680	1260
6000	480	120	1560	960	1020	1680	1680	1260
6600	480	120	1560	960	1020	1680	1620	1260
7200	480	120	1560	900	1020	1680	1620	1200
7800	480	120	1560	900	1020	1680	1620	1200
8400	480	120	1500	900	1020	1620	1560	1200
9000	480	120	1500	900	1020	1620	1560	1200
9600	480	120	1500	900	960	1620	1560	1200
10200	480	120	1500	900	960	1620	1560	1200
10800	480	120	1500	900	960	1620	1560	1200

Tmax **1100**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
2400	**Nil**	**180**	**1860**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
3000	600	180	1800	Nil	1740	2280	2520	Nil
3600	540	180	1740	1440	1500	2100	2160	1860
4200	540	180	1740	1320	1380	2040	2040	1620
4800	540	180	1680	1260	1320	1980	1980	1560
5400	540	180	1680	1200	1260	1920	1920	1500
6000	540	180	1680	1200	1260	1920	1860	1500
6600	540	180	1680	1200	1260	1860	1860	1440
7200	540	180	1680	1140	1200	1860	1860	1440
7800	540	180	1680	1140	1200	1860	1800	1440
8400	540	180	1680	1140	1200	1860	1800	1440
9000	540	180	1680	1140	1200	1800	1800	1380
9600	540	180	1680	1140	1200	1800	1800	1380
10200	540	180	1620	1140	1200	1800	1740	1380
10800	540	180	1620	1140	1200	1800	1740	1380

FRL 45

Tmax **1000**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	**Nil**	**420**	**2160**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
3000	Nil	360	2040	Nil	Nil	2820	Nil	Nil
3600	Nil	300	1980	Nil	Nil	2460	2700	Nil
4200	Nil	300	1920	Nil	2100	1340	2460	Nil
4800	2340	300	1920	1920	1860	2220	2340	2220
5400	2280	300	1860	1740	1740	2220	2220	2040
6000	2220	300	1860	1680	1680	2160	2220	1920
6600	2160	300	1860	1620	1620	2100	2160	1860
7200	2100	300	1860	1560	1620	2100	2100	1800
7800	2100	300	1860	1560	1560	2100	2100	1800
8400	2040	300	1860	1560	1560	2040	2100	1740
9000	780	300	1800	1500	1560	2040	2040	1740
9600	720	300	1800	1500	1560	2040	2040	1740
10200	720	300	1800	1500	1500	2040	2040	1680
10800	720	300	1800	1500	1500	2040	2040	1680

Tmax **900**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	2400	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	2280	Nil	Nil	3000	Nil	Nil
4200	Nil	Nil	2220	Nil	Nil	2760	3060	Nil
4800	Nil	Nil	2220	Nil	Nil	2640	2820	Nil
5400	Nil	4800	2160	Nil	Nil	2580	2700	Nil
6000	Nil	4800	2160	Nil	2940	2520	2640	Nil
6600	2700	4740	2100	3120	2640	2460	2580	Nil
7200	2640	4680	2100	2700	2460	2460	2520	Nil
7800	2580	4680	2100	2580	2400	2400	2520	2760
8400	2520	4620	2100	2460	2340	2400	2460	2580
9000	2460	4620	2100	2340	2280	2400	2460	2460
9600	2460	4620	2100	2280	2220	2340	2460	2400
10200	2460	4560	2100	2280	2160	2340	2400	2400
10800	2400	4560	2040	2220	2160	2340	2400	2340

FRL 60

Tmax **1200**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	120	2820	Nil	Nil	Nil	Nil	Nil
3600	**900**	**120**	**2700**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
4200	840	120	2640	2100	2220	3000	3120	Nil
4800	840	120	2580	1920	2040	2820	2880	2520
5400	840	120	2520	1860	1980	2700	2700	2340
6000	780	120	2520	1800	1920	2580	2640	2220
6600	780	120	2520	1740	1860	2580	2580	2160
7200	780	120	2460	1740	1800	2520	2520	2160
7800	780	120	2460	1680	1800	2460	2460	2100
8400	780	120	2460	1680	1800	2460	2460	2100
9000	780	120	2460	1680	1740	2400	2460	2040
9600	780	120	2460	1680	1740	2400	2400	2040
10200	780	120	2460	1620	1740	2400	2400	2040
10800	780	120	2460	1620	1740	2400	2400	1980

Tmax **1100**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
3600	**Nil**	**180**	**3000**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
4200	Nil	180	2880	Nil	Nil	3660	3960	Nil
4800	Nil	180	2820	2760	3120	3300	3420	Nil
5400	Nil	180	2760	2460	2640	3120	3180	3300
6000	1080	180	2760	2280	2460	3000	3060	2880
6600	1020	180	2700	2220	2340	2880	2940	2700
7200	960	180	2700	2160	2280	2820	2880	2580
7800	960	180	2700	2100	2220	2820	2820	2520
8400	960	180	2700	2100	2160	2760	2820	2460
9000	960	180	2640	2040	2160	2760	2760	2460
9600	960	180	2640	2040	2100	2700	2760	2400
10200	900	180	2640	1980	2100	2700	2700	2400
10800	900	180	2640	1980	2100	2700	2700	2340

FRL 60

Tmax **1000**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	360	Nil	Nil	Nil	Nil	Nil	Nil
3600	**Nil**	**360**	**3420**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
4200	Nil	300	3240	Nil	Nil	Nil	Nil	Nil
4800	Nil	300	3180	Nil	Nil	3960	4320	Nil
5400	Nil	300	3120	Nil	Nil	3660	3840	Nil
6000	Nil	300	3060	3960	Nil	3480	3600	Nil
6600	Nil	300	3000	3180	36900	3360	3480	Nil
7200	Nil	300	3000	3000	3240	3300	3360	Nil
7800	Nil	300	3000	2880	3060	3240	3300	3540
8400	Nil	300	2940	2760	2940	3180	3240	3300
9000	Nil	300	2940	2700	2880	3120	3180	3180
9600	Nil	300	2940	2640	2820	3120	3180	3120
10200	Nil	300	2940	2580	2760	3060	3120	3060
10800	Nil	300	2940	2580	2700	3060	3120	3000

Tmax **900**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	3840	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	3720	Nil	Nil	Nil	Nil	Nil
5400	Nil	4860	3600	Nil	Nil	4560	4980	Nil
6000	Nil	4800	3540	Nil	Nil	4260	4500	Nil
6600	Nil	4800	3480	Nil	Nil	4080	4260	Nil
7200	Nil	4740	3420	Nil	Nil	3900	4080	Nil
7800	Nil	4740	3420	Nil	Nil	3840	3960	Nil
8400	Nil	4680	3360	5100	Nil	3780	3900	Nil
9000	Nil	4680	3360	4440	5400	3720	3840	Nil
9600	Nil	4620	3360	4140	4620	3660	3780	Nil
10200	Nil	4620	3300	3960	4320	3600	3720	Nil
10800	Nil	4620	3300	3780	4140	3600	3660	Nil

FRL 90

Tmax **1200**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	180	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	120	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	120	4260	Nil	Nil	Nil	Nil	Nil
5400	**Nil**	**120**	**4140**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
6000	Nil	120	4020	Nil	Nil	5700	5820	Nil
6600	Nil	120	3960	4260	4500	5100	5100	Nil
7200	Nil	120	3960	3900	3960	4860	4800	4740
7800	Nil	120	3900	3720	3720	4680	4560	4260
8400	Nil	120	3900	3600	3540	4560	4440	4080
9000	Nil	120	3840	3480	3480	4440	4320	3900
9600	Nil	120	3840	3420	3420	4380	4260	3840
10200	2280	120	3840	3360	3360	4320	4200	3720
10800	2160	120	3780	3300	3300	4260	4140	3660

Tmax **1100**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	300	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	240	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	180	4800	Nil	Nil	Nil	Nil	Nil
5400	**Nil**	**180**	**4560**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
6000	Nil	180	4440	Nil	Nil	Nil	Nil	Nil
6600	Nil	180	4380	Nil	Nil	6300	6480	Nil
7200	Nil	180	4320	Nil	Nil	5700	5700	Nil
7800	Nil	180	4260	5220	Nil	5400	5400	Nil
8400	Nil	180	4200	4740	5100	5220	5160	Nil
9000	Nil	180	4200	4500	4620	5100	4980	5400
9600	Nil	180	4140	4320	4440	4980	4860	4920
10200	Nil	180	4140	4200	4260	4860	4800	4680
10800	Nil	180	4140	4080	4140	4800	4740	4560

FRL 90

Tmax **1000**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	4800	Nil	Nil	Nil	Nil	Nil	Nil
5400	**Nil**	**4740**	**5280**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
6000	Nil	540	5040	Nil	Nil	Nil	Nil	Nil
6600	Nil	540	4920	Nil	Nil	Nil	Nil	Nil
7200	Nil	480	4860	Nil	Nil	Nil	Nil	Nil
7800	Nil	480	4740	Nil	Nil	6540	6600	Nil
8400	Nil	480	4680	Nil	Nil	6180	6180	Nil
9000	Nil	480	4680	Nil	Nil	5940	5940	Nil
9600	Nil	480	4620	6900	Nil	5820	5760	Nil
10200	Nil	420	4620	6000	Nil	5640	5640	Nil
10800	Nil	420	4560	5640	6540	5580	5520	Nil

Tmax **900**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	5400	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	5340	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	5280	5880	Nil	Nil	Nil	Nil	Nil
7200	Nil	5280	5700	Nil	Nil	Nil	Nil	Nil
7800	Nil	5220	5580	Nil	Nil	Nil	Nil	Nil
8400	Nil	5160	5460	Nil	Nil	7800	8040	Nil
9000	Nil	5160	5400	Nil	Nil	7320	7440	Nil
9600	Nil	5160	5340	Nil	Nil	7020	7080	Nil
10200	Nil	5100	5280	Nil	Nil	6780	6840	Nil
10800	Nil	5100	5220	Nil	Nil	6660	6660	Nil

FRL 120

Tmax **1200**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	6000	6240	Nil	Nil	Nil	Nil	Nil
7200	**Nil**	**6000**	**6060**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
7800	Nil	5940	5940	Nil	Nil	Nil	Nil	Nil
8400	Nil	5940	5880	Nil	Nil	8280	Nil	Nil
9000	Nil	5880	5760	Nil	Nil	7560	7980	Nil
9600	Nil	5880	5700	Nil	Nil	7200	7440	Nil
10200	Nil	5880	5700	Nil	6240	6900	7080	Nil
10800	Nil	5880	5640	Nil	5820	6720	6840	7860

Tmax **1100**

t500	SSW	MW	CW	CB	CC	SB	SC	MSD
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	**Nil**	**6480**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
7800	Nil	6420	6660	Nil	Nil	Nil	Nil	Nil
8400	Nil	6420	6480	Nil	Nil	Nil	Nil	Nil
9000	Nil	6360	6360	Nil	Nil	Nil	Nil	Nil
9600	Nil	6360	6300	Nil	Nil	8580	9360	Nil
10200	Nil	6300	6240	Nil	Nil	8100	8520	Nil
10800	Nil	6300	6180	Nil	Nil	7800	8100	Nil

FRL 120

Tmax **1000**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	**Nil**	**7140**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**
7800	Nil	7080	7740	Nil	Nil	Nil	Nil	Nil
8400	Nil	7020	7440	Nil	Nil	Nil	Nil	Nil
9000	Nil	7020	7260	Nil	Nil	Nil	Nil	Nil
9600	Nil	6960	7140	Nil	Nil	Nil	Nil	Nil
10200	Nil	6960	7020	Nil	Nil	10200	Nil	Nil
10800	Nil	6900	6960	Nil	Nil	9480	10260	Nil

Tmax **900**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
8400	Nil	7980	Nil	Nil	Nil	Nil	Nil	Nil
9000	Nil	7980	8880	Nil	Nil	Nil	Nil	Nil
9600	Nil	7920	8580	Nil	Nil	Nil	Nil	Nil
10200	Nil	7860	8340	Nil	Nil	Nil	Nil	Nil
10800	Nil	7800	8160	Nil	Nil	Nil	Nil	Nil

FRL 180

Tmax **1200**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9600	Nil	9360	Nil	Nil	Nil	Nil	Nil	Nil
10200	Nil	9360	Nil	Nil	Nil	Nil	Nil	Nil
10800	**Nil**	**9300**	**10380**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**

Tmax **1100**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
10200	Nil	10140	Nil	Nil	Nil	Nil	Nil	Nil
10800	**Nil**	**10080**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**

FRL 180

Tmax **1000**

t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
10800	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**	**Nil**

Tmax **900**

	t500	**SSW**	**MW**	**CW**	**CB**	**CC**	**SB**	**SC**	**MSD**
	600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	1800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	2400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	3000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
1 hr	3600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	4800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	5400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	6600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2 hr	7200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	7800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	8400	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9000	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	9600	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	10200	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
3 hr	10800	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil