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Department for Communities and Local Government Project Final Work Stream report:

BD 2887

Compartment sizes, resistance to fire and fire safety project

Work stream 1 –
Periods of fire resistance

286855 (D23V2)

CPD/04/102

Prepared for:

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FIRE

BD 2887

Compartment sizes, resistance to fire and fire safety project

Final Work Stream Report for Work Stream 1 Periods of fire resistance

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Executive Summary

Building Regulations and Standards Division, Department for Communities and Local Government (DCLG) commissioned BRE to carry out a project titled "Compartment sizes, resistance to fire and fire safety". The main aim of this project was to produce robust evidence and data based on research, experimental fire testing, computer modelling and laboratory testing, where necessary, on a number of linked work streams in relation to fire safety and associated provisions in Schedule 1 of Part B of the Building Regulations 2010.

This Final work stream report describes the findings of the research for Work stream 1 – Periods of fire resistance. The aim of this work stream was to produce robust evidence and data to explore the potential to adopt a more flexible approach to the specification of fire resistance periods in Approved Document B[1].

The work conducted under this work stream has considered the background to the current guidance in relation to periods of fire resistance. New performance based methods for characterising fire severity and specifying fire resistance periods have been evaluated through a consideration of data from a large series of full scale fire experiments. In order to consider the impact of the levels of insulation typical of modern forms of construction on fire growth and development, a number of new fire experiments have been undertaken. Alternative methodologies for determining compartment fire severity and specifying fire resistance periods have been evaluated and validated as part of this work stream.

This work stream has also involved the participation of an industry Steering Group.

The conclusions of this work stream are as follows:

- The fire tests undertaken as part of this work stream have demonstrated that enhanced levels of thermal insulation result in higher peak temperatures within the compartment and higher levels of thermal radiation from the compartment to adjacent buildings. It is important that this issue is considered in any future revision of regulatory guidance for fire safety.
- The calculation methods set out in BS EN 1991-1-2 and used to develop the alternative tables in BS 9999 provide an accurate prediction of compartment peak temperature and overall fire duration for a range of different parameters and are capable of taking into account the impact of high levels of thermal insulation on fire growth and development as represented by the thermal diffusivity present in modern buildings which typically range from 300 to 1500 $J/m^2s^{1/2}K$. The conclusion is based on comparison with experimental results covering a number of different compartment sizes, geometries, ventilation conditions and fuel loads. However, the scope of validation only covers fire compartments with a floor area up to 378 m^2. Beyond this value, the parametric fire calculations may still be used but will tend to yield unduly conservative results. This is because the parametric approach assumes a single zone temperature distribution with the maximum value present throughout the compartment when, in reality, there will be significant spatial temperature variations throughout any large fire compartment.

[1] Department for Communities and Local Government. The Building Regulations 2010 (England). Approved Document B: Fire safety. Volume 1: Dwelling houses (2006 edition incorporating 2010 and 2013 amendments). Volume 2: Buildings other than dwelling houses (2006 edition incorporating 2010 and 2013 amendments).

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- The calculation methods in BS EN 1991-1-2 and BS 9999 are currently in the public domain and are widely used as an alternative approach to the guidance set out in Table A2 of AD B. Consideration could be given to making a specific reference to these approaches as part of an overall fire engineering strategy within any subsequent revision of AD B.

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1 Introduction and Objectives

This Final work stream report is delivered as part of the Department for Communities and Local Government (DCLG) project BD 2887, titled "Compartment sizes, resistance to fire and fire safety", DCLG Contract reference CPD/04/102/010. The main aim of this project was to produce robust evidence and data based on research, experimental fire testing, computer modelling and laboratory testing (where necessary) on a number of linked work streams in relation to fire safety and associated provisions in Schedule 1 of Part B of the Building Regulations 2010. The project has been broken down into specific work streams.

This report describes the findings of the research for Work stream 1 – Periods of fire resistance.

Resistance to fire is specified in terms of time periods that relate to a standard furnace test. The period specified for a particular building is based on assumptions about expected fire severity and the consequences of failure. Approved Document B (AD B)[1] does this with a table which specifies minimum periods of fire resistance against the intended purpose of a building and its height.

The table is, to some extent, based on the conclusions of the "fire grading of buildings" report which was originally published in 1946. Since then, the table has been modified in a piecemeal fashion. In more recent years, deterministic approaches to specifying fire resistance, have been developed and have become codified in engineering standards such as Eurocode 1[2] (EN 1991-1-2) and in BS 9999: 2008[3]. This approach can offer a more cost effective approach to fire protection than the traditional prescriptive approach but the use of BS EN 1991-1-2 requires specialist expertise to apply it.

The principal objective of this work stream was to produce robust evidence and data to explore the potential to adopt a more flexible approach to the specification of fire resistance periods in Approved Document B.

The Work stream 1 tasks were:

- Task 1.1 Identification and engagement of stakeholders
- Task 1.2 Review of background to existing AD B requirements
- Task 1.3 Review of existing fire load survey information
- Task 1.4 Review of large-scale fully developed fires
- Task 1.5 Experimental programme
- Task 1.6 Analysis and Cost Benefit Analysis
- Task 1.7 Reporting.

2 Programme of work

2.1 Stakeholder engagement

This work stream has involved the participation of an industry Steering Group, Satellite Steering Group A. This group provided input during the course of the work, giving feedback on the research methodology as well as key deliverables and milestones. This group met three times.

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The organisations represented at the Steering Group are as follows.

Organisations represented at the Steering Group
• Building Regulations Division, Department for Communities and Local Government (DCLG) • BRE Project team • British Constructional Steelwork Association (BCSA) • Association of Specialist Fire Protection (ASFP) • Association of Building Engineers (ABE) • British Automatic Fire Sprinkler Association (BAFSA) • Business Sprinkler Alliance (BSA) • Chief Fire Officers Association (CFOA) • The Chartered Institute of Building (CIOB) • The Concrete Centre • Fire Brigades Union (FBU) • Fire Industry Association (FIA) • Institution of Fire Engineers (IFE) • LABC • National Register of Access Consultants (NRAC) • Passive Fire Protection Federation (PFPF) • RICS Building Control Professional Group (RICS) • RISCAuthority • Scottish Building Standards (SBS) • Shore Engineering • Structural Timber Association (STA) • Warwickshire FRS • Welsh Government (WG)

2.2 Review of background to existing AD B requirements

A review has been undertaken of the principal document underpinning the current regulatory guidance with respect to fire resistance to understand the methodology and background to the current guidance. The current guidance in AD B is based largely on the findings from the *Post-War Building Studies No. 20 Fire Grading of Buildings Part 1 General Principles and Structural Precautions*[4] published in 1946. The current provisions are largely based on this pioneering document with fire load density (i.e. fire load divided by floor area) forming the principal hazard categories set alongside the type of construction requiring elements of structure to achieve a specified period of fire resistance. Three hazard categories are identified corresponding to 'low', 'moderate' and 'high' fire loads. The values corresponding to these categories are significantly higher than the corresponding figures used for the performance based design of buildings suggesting that performance based approaches are based on more recent information such as the fire load densities tabulated in the CIB W14 design guide for structural fire safety[5] (See Section 2.3).

In the Post-War Building Studies No. 20 report three categories of occupancy are identified principally on the basis of the fire load expected in each case as illustrated in Table 1.

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Category	Fire load density (BTU/ft²)	Fire load density (MJ/m²)	Example occupancies
Low fire load	≤ 100,000	≤ 1134	Flats, offices, hotels etc.
Moderate fire load	100,000 ≤ 200,000	1134 ≤ 2269	Shops, factories etc.
High fire load	200,000 ≤ 400;000	2269 ≤ 4538	Warehouses and storage
Note. For conversion from BTU/ft² to MJ/m² x 0.001054/0.092903)			

Table 1 - Occupancy characteristics from Post-War Building Studies No. 20

The concept of 'normal' and 'abnormal' fire loads is used to quantify the additional risk related to ignitability, burning rate and products of combustion of certain materials as well as the impact that certain activities may have on the risk of fire initiation. This concept recognises that situations involving identical fire loads may create additional risks in relation to fire initiation and propagation.

Those familiar with fire load densities used for modern performance based fire engineering design solutions would be surprised to see that fire load densities up to 1134 MJ/m² are classified as low fire load. Typical design values for offices and residential buildings would be of the order of 570 and 780 MJ/m², respectively.

The relationship between fire load density and fire resistance period for cellulosic fires was identified based on USA data as shown in Table 2.

Weight (lb/ft²)	Weight (kg/m²)	Fire load (BTU/ft²)	Fire load (MJ/m²)	Equivalent fire severity (hours)
10	48.8	80,000	907.6	1
15	73.2	120,000	1361.4	1.5
20	97.6	160,000	1815.2	2
30	146.4	240,000	2722.8	3
40	195.2	320,000	3630.4	4.5
50	244	380,000	4538	6
60	292.8	43,200	5445.6	7
Note. For conversion from lb/ft² to kg/m² x 0.453592/0.092903.				

Table 2 - Relationship between fire load density and fire resistance period from Post-War Building Studies No. 20

The relationship in Table 2 was used to develop the categories in the Fire Grading of Buildings report, as shown in Table 3.

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Fire load (BTU/ft²)	Fire load (MJ/m²)	Category	Equivalent fire severity (hours)
< 100000	< 1134	Low fire load	1
100000 – 200000	1134 – 2269	Moderate fire load	2
200000 - 400000	2269 – 4538	High fire load	4

Table 3 - Categorisation in Fire Grading of Buildings report

The concept of 'fully protected' construction was developed to cover those buildings designed to withstand a complete burn out i.e. the protection provided equals the severity anticipated.

Special requirements are included in relation to separating and division walls. It is recommended that separating walls i.e. walls which separate different buildings should provide at least 4 hours fire resistance (loadbearing capacity, integrity and insulation, as appropriate) regardless of the fire load. Division walls separating different fire risks within the same building should be related to the fire load category although it is recommended that at least 2 hours fire resistance is provided even where a low fire load is present. External walls of 1 hour fire resistance are restricted to buildings of up to 15 m (50 ft). Above this height, external walls should be of at least 2 hours fire resistance and 4 hours in the case of high fire loads.

Other categories were defined with a fire resistance less than that required to survive complete burn out as shown in Table 4.

Seven categories of construction are identified ranging from fully protected structures designed to survive a complete burn out of all combustible material through to combustible materials without any specific fire resistance requirement.

Type of construction	Fire resistance required (hours)	Description	Examples
1	≥ 4	Fully protected	Large warehouses, large shops, factories, office blocks, blocks of flats
2	≥ 2	Fully protected	
3	≥ 1	Fully protected	
4	≥ 0.5	Partially protected	Small shops or factories, apartment houses
5	≥ 2 (external walls only)	Externally protected	
6	0 but incombustible materials	Unprotected incombustible	Single storey factories, garages
7	0	Combustible	Timber houses, factories etc.

Table 4 - Categories of construction from Post-War Building Studies report

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Strict restrictions on the use of combustible material apply for Types 1-3. With the exception of fire-rated timber doors, it is recommended that all structural parts of fully protected buildings requiring fire resistance should be of incombustible (nowadays referred to as non-combustible – see Table A6 of AD B for definition) material. This has important implications when considering limitations in relation to allowable heights of buildings. The criteria in relation to fire resistance for each type of construction is summarised in Table 5.

Type of building		
Fully protected	Design for burn out based on fire load density	Type 1, 2 and 3
Partially protected construction	Not capable of surviving a complete burn out	Type 4
Externally protected	Internal construction has no specified fire resistance but external walls have ≥ 2 hours	Type 5
Unprotected incombustible construction	No specified fire resistance (other than separating walls) but incombustible material e.g. portal frames	Type 6
Combustible construction	No fire resistance	Type 7

Table 5 - Relationship between fire resistance performance and form of construction

A summary of the grading recommendations giving the fire resistance requirements of the various elements of structure for each type of construction is presented in Table 6.

Grading	**Minimum fire resistance for elements of structure (hours)**				
	Walls and columns or beams supporting walls				Floors and roofs and columns and beams supporting floors and roofs
	External	Separating	Division	Other fire resisting or loadbearing	
Type 1	4	4	4	4	4
Type 2	2	4	2/4+	2	2
Type 3	2/1*	4	2/4+	1	1
Type 4	2/1*	4	2/4+	1	0.5
Type 5	2	4	2/4+	1	-
Type 6	-	4	2/4+	-	-
Type 7	-	4	2/4+	-	-

* 1 hour for low fire load occupancies in framed buildings below 50 ft (15 m)

+ If occupancy is of high fire load

Table 6 - Summary of grading recommendations

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Restrictions on maximum height/floor area/cubic capacity apply depending on the type of occupancy as defined by the nature of the anticipated fire load and the accessibility of the building or compartment. The restrictions on maximum compartment size in relation to height, floor area or cubic capacity were defined based on a study of existing requirements.

The principle of establishing an appropriate fire resistance period for a particular occupancy and height of building is the same in the current guidance as the approach used in the 1946 document. The fire severity is assumed to be a function principally of the type and magnitude of the fire load. The size of the building in terms of height, floor area and cubic capacity is related to the consequences of failure and the accessibility for means of escape and fire fighter access.

The basic methodology underpinning the fire grading of buildings is summarised in Figure 1. There is an acknowledged acceptance that there may be cases where buildings will need to exceed the proposed limits on floor area, cubic capacity and height. It is therefore clear that the recommendations were never intended to cover all forms of construction just as the guidance in AD B does not cover all types of building.

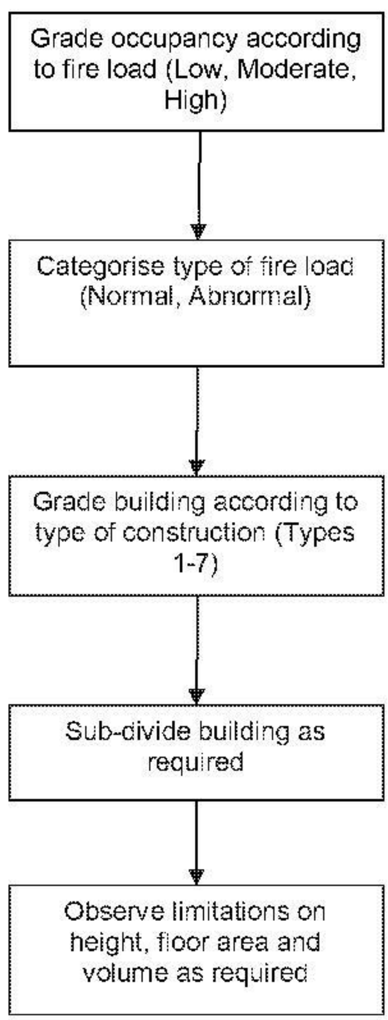

Figure 1 - Methodology underpinning Fire Grading of Buildings

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To illustrate the similarities between the approach adopted in the Post-War Building Studies Report and the current guidance, a fire resistance period will be derived using both the recommendations of the Post-War Building Studies and the current guidance in relation to the following cases:

- Case A, an 8-storey office building 32 m high
- Case B, a 5-storey residential building 15 m high

Case A, an office building with a 'normal' fire load type and distribution, would be classed as low fire load. Assuming the building will need to be fully protected i.e. protected to withstand a burn out then the structure (excluding external walls) could be designed using incombustible material to provide a fire resistance of one hour (Type 3). However, the external walls and any internal compartment walls would require two hours fire resistance.

Using Approved Document B guidance, the required period of fire resistance for such a building would be two hours but the building would require an automatic sprinkler system. Elements not forming part of the structural frame would only require 90 minutes fire resistance. The results are summarised in Table 7.

Design approach	**Minimum fire resistance of elements of structure for 32 m office building (hours)**				
	Walls and columns or beams supporting walls				Floors and roofs and columns and beams supporting floors and roofs
	External	Separating	Division	Other fire resisting or loadbearing	
Fire Grading of buildings Type 3	2	4	2	1	1
AD B	2	2	1.5	2	0

Table 7 - Comparison between fire grading of buildings approach and AD B guidance for Case A

Case B, a residential building (apartment block) with a 'normal' fire load type and distribution, would be classed as low fire load. Assuming the building will need to be fully protected i.e. protected to withstand a burn out, then the structure (excluding external walls) could be designed using incombustible material to provide a fire resistance of one hour (Type 3). However, the external walls and any internal compartment walls would require two hours fire resistance.

There is also a possibility to construct the building from Type 4 or Type 5 construction. Where Type 4 construction is used, then fire resisting construction is required but it does not need to be incombustible. Where Type 5 construction is used, the external walls need to be incombustible, but the internal construction may be combustible.

Using AD B guidance, the required period of fire resistance for such a building would be one hour. The results are summarised in Table 8.

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Design approach	Minimum fire resistance of elements of structure for 15 m residential building (hours)				
	Walls and columns or beams supporting walls				Floors and roofs and columns and beams supporting floors and roofs
	External	Separating	Division	Other fire resisting or loadbearing	
Fire grading of buildings Type 3	2	4	2	1	1
Fire grading of buildings Type 4	1	4	2	1	0.5
Fire Grading of buildings Type 5	2	4	2	1	-
AD B	1	1	1	1	-

Table 8 - Comparison between Fire Grading of Buildings approach and AD B Guidance for Case B

The review has established that the guidance in the Approved Document in relation to periods of fire resistance is strongly influenced by the recommendations of the Post-War Building Studies research. The current values are a combination of statistical data (fire loads), experimental data (calorific values), engineering calculations supported by empirical observations (time equivalence) and engineering judgement influenced by experience of real fires, commercial considerations and political decisions.

One area which is completely absent in the work of the Post-War Building Studies research is the impact of ventilation on fire growth and development. Fire severity is assumed to be purely a function of the fire load and the floor area of the compartment. This is clearly a major simplification of real fire behaviour.

2.3 Review of existing fire load survey information

The relationship between fire load and fire severity established in the Post-War Building Studies Fire Grading of Buildings was based on unpublished work from the Building Research Station which indicated that the fire load of residential buildings, hotels, hospitals, schools and similar occupancies does not exceed 100,000 BTU/ft^2 (1,134 MJ/m^2). The fire load of shops and factories is generally greater than this value and the fire load of warehouses may be as much as 1,000,000 BTU/ft^2 (11,345 MJ/m^2).

The most comprehensive set of data relating to fire load densities yet produced was compiled as part of the CIB W14 guide to structural fire safety[5]. The tabulated values from this document are summarised in Table 9 with respect to variable fire load densities for various occupancies. The values given are approximate

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averages for each data set. The source document should be consulted for the detailed breakdown according to the type of occupancy and for the reference to the original data source.

Occupancy type	Source data	Fractile value (MJ/m²)			Average (MJ/m²)
		80%	90%	95%	
Dwelling	Swedish	820	-	-	750
	European	796	860	890	642
	Swiss (flat)	-	-	-	330
	USA	-	-	-	320
Office	Swedish	675-720	-	-	411
	European	570	740	950	420
	European	520	770	920	410
	European	-	-	-	330
	Swiss	-	-	-	580-750
	USA	-	-	-	555
	USA	-	-	-	580
Shops	European	-	-	-	478
	Swiss	-	-	-	564
Hospitals	European	350	-	670	230
	Swiss	-	-	-	330
	USA	108	-	-	
Hotels	Swedish	380	-	-	
	European	400	470	510	310
	Swiss				330
Industrial buildings	German (storage < 150kg/m²)	2560	3490	4490	1780
	German (storage > 150kg/m²)	23190	33110	44330	15360
	German (manufacture and storage < 150kg/m²)	1820	2640	3590	1180
	German (manufacture and storage > 150kg/m²)	14180	19810	26040	9920
Schools	Swedish	340	-	-	285
	European	350	389	435	240
	Netherlands	365	-	550	215
	Swiss	-	-	-	250

Table 9 - Summary of variable fire load data from CIB W14 Design Guide

These values should be considered alongside tabulated values from national and European standards as summarised in Table 10.

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Occupancy type	**Source data**	**Fractile value (MJ/m²)**			**Average (MJ/m²)**
		80%	**90%**	**95%**	
Dwelling	PD 7974-1[6]	870	920	970	780
Offices		570	670	760	420
Shops		900	1100	1300	600
Hospitals		350	440	520	230
Hotels		400	460	510	310
Manufacturing and storage (< 150 kg/m²)		1800	2240	2690	1180
Manufacturing		470	590	720	300
Schools		360	410	450	285
Libraries		2250	2550	-	1500
Dwelling	BS EN 1991-1-2[2]	948	-	-	780
Offices		511	-	-	420
Shops		730	-	-	600
Hospitals		280	-	-	230
Hotels		377	-	-	310
Schools		347	-	-	285
Libraries		1824	-	-	1500

Table 10 - Tabulated characteristic fire load densities from national and European fire engineering codes

The codified values are very similar. The average values for each occupancy type are exactly the same suggesting that they are both based on the same data set. PD 7974-1 specifically acknowledges the CIB Design Guide as the source of the tabulated values. It is therefore reasonable to assume that both the national and European tabulated fire load densities are based on these values. The values suggest that the principal source of information is the Swedish data referenced in the CIB design guide.

More recent fire load surveys support the values above in relation to shopping malls and offices. Four shopping malls were surveyed by Carmen and Chow[7]. The results in terms of the range of fire load densities encountered are summarised in Table 11.

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Shopping mall	Estimated floor area (m^2)	Range of fire load density (MJ/m^2)
A	4500	320-1670
B	12300	190-2440
C	6100	100-2530
D	12500	75-1730

Table 11 - Range of fire load densities found by Carmen and Chow

A comprehensive survey of fire load densities was undertaken by the Fire Protection Research Association in the USA[8] based on a sample size of 103 offices which compared different survey methods. The results are summarised in Table 12.

	Inventory method (MJ/m^2)	Weighing method (MJ/m^2)	Combination method (MJ/m^2)
Mean	852	530	557
80% fractile	1572	871	1077
90% fractile	1805	996	1182
95% fractile	2090	1188	1282

Table 12 - Survey data for offices by the Fire Protection Research Association, USA

The results indicate a higher fire load density than that provided in the national and European standards. The combination methodology (weighing and inventory) is thought to provide the most accurate results.

Fourteen clothing stores in Canada were surveyed as part of a research project to characterise design fires for such premises[9]. The results indicated a spread of fire load density between 142 and 755 MJ/m^2 with a 95% fractile of 661 MJ/m^2 which is considerably lower than the tabulated values in the codes. This study was based on a comprehensive survey of 168 stores of all types conducted in Canada. The survey indicated a mean value of 750 MJ/m^2 which is higher than the codified values.

Bukowski[10] presented historic data from the USA and provided a comparison with Swiss data. He concluded that the numbers were reasonably consistent even though they covered a time span of almost 50 years and were based on survey data from different continents. He also mentions that fire engineering guideline documents recommend that the 90% or 95% fractile values are in the design. In the UK the 80% fractile value is usually adopted for fire engineering design calculations.

More up to date survey data was presented in relation to hotels at a SFPE keynote presentation in October 2012[11]. The data is summarised with respect to mean, 80% and 95% fractile values in Table 13.

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Variable fire load density (MJ/m²)			Total fire load density (MJ/m²)		
Mean	80% fractile	95% fractile	Mean	80% fractile	95% fractile
388	453	539	535	632	753

Table 13 - Fire load survey data for hotels

While the variable fire load densities are in line with the figures from published codes and standards, the total fire load densities are well in excess of these figures. With modern forms of construction, increasing amounts of combustible material are incorporated within the fabric or frame of the building.

Hietaniemi and Mikkola[12] have argued that increasing prosperity may result in an increase in fire load density within dwellings. The theory is supported by comparative data from the USA in 1970 and Canada in 2004 which suggests an increase of around 30% to 40% over this thirty year period which is at odds with the conclusions drawn by Bukowski. Based on their observations they provided an estimate for fire load densities for apartments in Finland with an average value of 509 MJ/m² and an 80% fractile value of 575 MJ/m². These values are averaged with significant differences between the various rooms comprising the dwelling. It should be noted that these increased values are significantly lower than the corresponding design values from national and European fire engineering codes.

Based on a review of available fire load survey data the following conclusions can be drawn:

- The current guidance in relation to periods of fire resistance is partly based on fire load survey information which is out of date.
- The design values of fire load density adopted in fire engineering codes and standards are based on the survey data contained within the CIB W14 Design Guide: Structural Fire Safety. A comparison between the CIB W14 fire load survey data and the tabulated data from the codes suggest that the values contained within national and European standards appear to be based, in particular, on survey results from Sweden.
- The values in the national (PD 7974-1) and European (BS EN 1991-1-2) codes are very similar. It is currently recommended within the National Annex to BS EN 1991-1-2 that the PD 7974-1 values are adopted for design within the UK. These values are set out in the background paper (PD 6688-1-2) that provides non-contradictory complementary information (NCCI) for use in the UK with BS EN 1991-1-2 and its UK National Annex.
- The available data indicate a significant variation in data sets from individual countries. This is to be expected as fire load density will be influenced by factors such as economic prosperity, availability and cost of land for development and cultural factors.
- The data in national and European codes and standards are based on survey data related to variable (moveable) fire load density and do not incorporate combustible material which is itself part of the fabric or structure of the building.

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2.4 Review of large-scale fully developed fires

A review of large-scale fire tests was undertaken to consider how the results (in relation to peak temperature, overall duration and equivalent period of fire severity) tie in with predictive methods from performance based fire engineering codes and standards such as the parametric approach set out in BS EN 1991-1-2 or the time equivalent methodology underpinning the alternative approach to specifying fire resistance periods in BS 9999. In order to consider the accuracy of the various design methods, it is necessary to have access to a great deal of information on the fire including magnitude and distribution of fire load, compartment geometry, ventilation conditions and type of construction involved. BRE has access to a large database of full scale fire tests which has been used to 'calibrate' the performance based design approaches identified above. The majority of fire tests considered either formed part of a series of tests undertaken by the Joint Fire Research Organisation in conjunction with the British Iron and Steel Federation (BISF) in the 1960s or formed part of a series of large-scale fire tests undertaken at the BRE's Large Building Test Facility at Cardington. The tests included in the review are listed in Table 14.

Test ref.	Description	Fire load density q_{fd} (MJ/m²)	Thermal properties b ($J/m^2s^{½}K$)	Opening factor (m^{-1})	Floor area (m²)
1	BRE corner[13]	720	720	0.183	54
2	BS corner[13]	810	1600	0.05	76
3	BRE large compartment[13]	720	720	0.164	342
4	BS Demo[13]	828	1600	0.07	136
5	European robustness[14]	720	714	0.043	77
6	Slimdek[15]	900	720	0.03-0.04	144
7	Hollow core (x2)[16]	540	945	0.065	36
8	Concrete building[17]	720	1104	0.08	225
9	NFSC 2 & 3[18]	720	720	0.1	144
10	NFSC 1 & 8[18]	720	1600	0.1	144
11	NFSC 4 & 5[18]	720	720	0.07	144
12	NFSC 6 & 7[18]	720	1600	0.07	144
13	Steel house 1[19]	648	650	0.037	29.6
14	Steel house 2[19]	648	650	0.048	28.8
15	Large compartment 1[20]	360	415	0.062	138
16	Large compartment 2[20]	360	415	0.062	138
17	Large compartment 3[20]	720	415	0.022	138

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Test ref.	Description	Fire load density q_{fd} (MJ/m²)	Thermal properties b (J/m²s^{½}K)	Opening factor (m^{-1})	Floor area (m²)
18	Large compartment 4[20]	360	415	0.022	138
19	Large compartment 5[20]	360	415	0.012	138
20	Large compartment 6[20]	360	415	0.003	138
21	Large compartment 7[20]	360	377	0.05	36
22	Large compartment 8[20]	360	732	0.057	138
23	Large compartment 9[20]	360	415	0.058	138
24	Large hollow core (x2)[21]	585	1060	0.03	125
25	TF2000[22]	414	720	0.038	21.5
26	SIPS (x4)[23]	450	520	0.026	12
27	BISF A[24]	135	1768	0.06	28.7
28	BISF B[24]	135	1768	0.06	28.7
29	BISF C[24]	1080	1768	0.06	28.7
30	BISF D[24]	270	1768	0.12	28.7
31	BISF E[24]	540	1768	0.12	28.7
32	BISF F[24]	540	1768	0.12	28.7
33	BISF G[24]	270	1768	0.06	28.7
34	BISF H[24]	540	1768	0.06	28.7
35	BISF I[24]	540	1768	0.06	28.7
36	BISF J[24]	135	1768	0.12	28.7
37	BISF K[24]	135	1768	0.12	28.7
38	BISF L[24]	1080	1768	0.12	28.7
39	BISF M[24]	540	1768	0.06	28.7
40	BISF N[24]	540	1768	0.12	28.7
41	BISF O[24]	135	553	0.06	28.7
42	BISF P[24]	135	553	0.12	28.7

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Test ref.	Description	Fire load density q_{fd} (MJ/m²)	Thermal properties b (J/m²s^{½}K)	Opening factor (m^{-1})	Floor area (m²)
43	BISF Q[24]	540	553	0.06	28.7
44	BISF R[24]	540	553	0.12	28.7
45	BISF S[24]	135	677	0.06	28.7
46	BISF U[24]	1080	1768	0.06	28.7
47	BISF V[24]	1080	1768	0.03	28.7
48	BISF W[24]	135	1768	0.12	28.7
49	BISF X[24]	270	1768	0.06	28.7
50	BISF Y[24]	135	1768	0.12	28.7

Table 14 – Large-scale fire tests included in review together with relevant parameters

For all the tests in Table 14, atmosphere temperatures have been recorded allowing a comparison between measured and predicted values of peak temperature. For many tests, indicative specimens were included to allow a comparison with an equivalent period of fire exposure to the standard fire curve. Where this data is available, a comparison is made with predicted and measured values of time equivalence. All available large-scale fire test information has been reviewed. In certain cases, such as test references 1, 2, 6 and 8, there were changes to the ventilation condition over the course of the fire test. However, this is to be expected in real situations where glazing will break over the course of the fire. Estimates representative of the range of ventilation conditions have been used in all cases where there have been changes over the course of the test.

The comparisons in terms of peak temperature and time to peak temperature as predicted using the parametric approach are illustrated graphically in Figures 2 to 6. In order to make interpretation of the data a little easier, the BISF fire tests are considered separately. For both the parametric and time equivalent approaches, there are limits to specific parameters outside of which the calculation is no longer valid. Where the parameters of a particular fire test lie outside the scope of validation for the predictive equation this is identified. Figure 2 shows the value of the measured to predicted temperature for a total of 35 large-scale fire tests. All parameters were within the allowable scope of the parametric equation and the complementary information contained within the UK National Annex with the exception of test reference 21 where the opening factor is lower than the minimum value permitted. Values above unity mean that the parametric equation under predicts peak temperature while values below unity mean that the parametric equation over predicts peak temperature.

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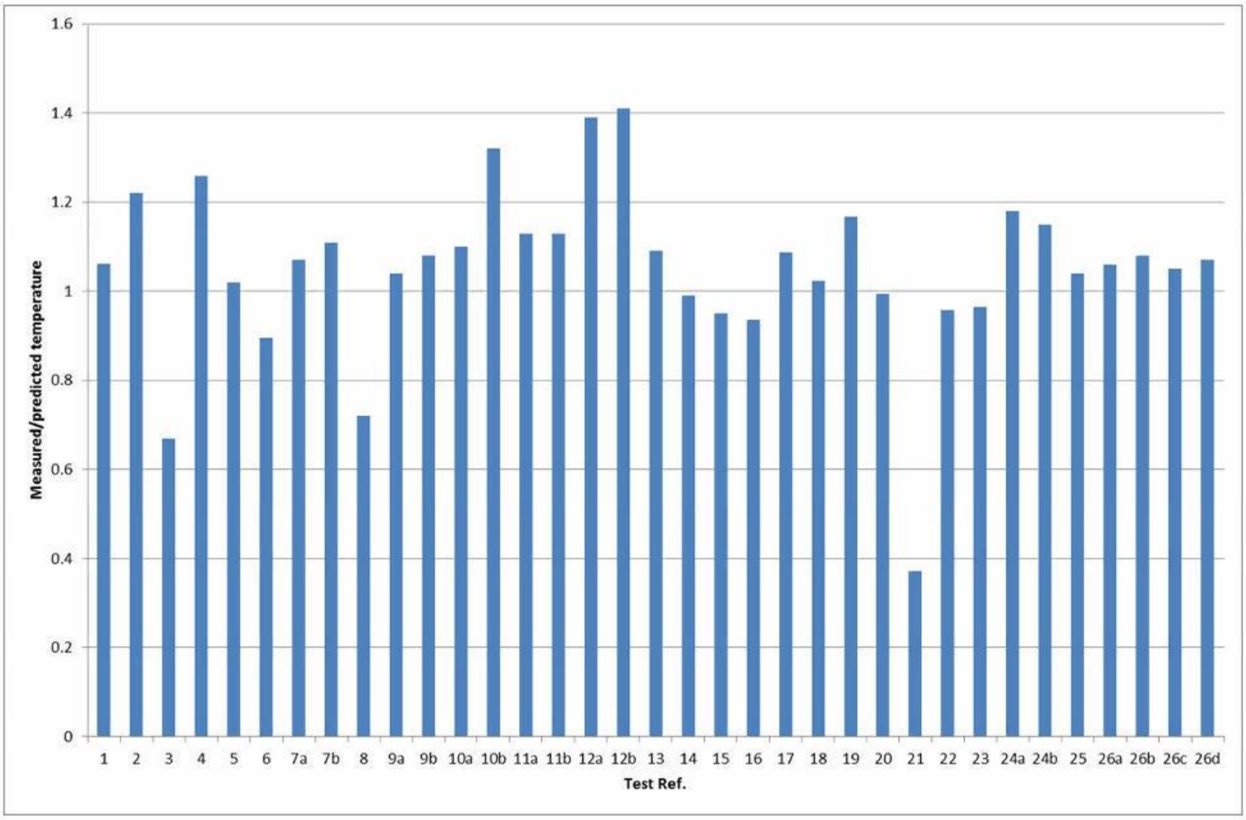

Figure 2 - Comparison between measured and peak temperatures for a range of large-scale fire tests

Figure 3 shows the same relationship for the BISF tests.

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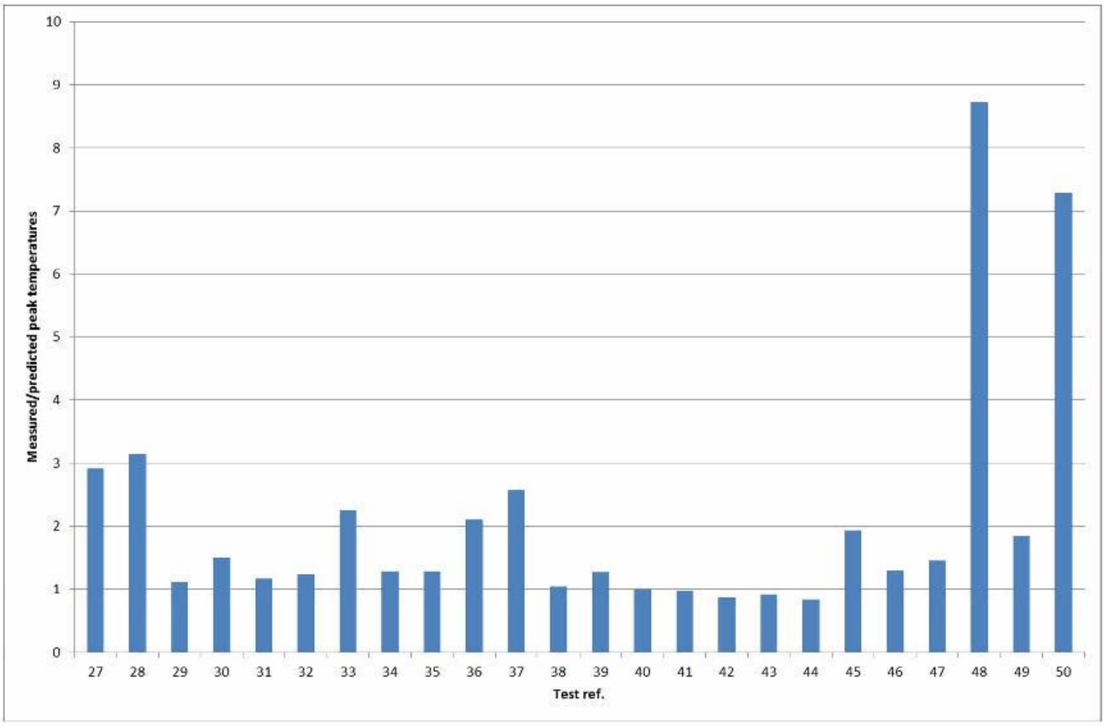

Figure 3 - Comparison between measured and predicted peak temperatures for BISF tests

Although all the test parameters satisfy the criteria for use of the parametric equation in relation to opening factor and thermal properties of the compartment linings, a number of the tests [27, 28, 36, 37, 41, 42, 45, 48 and 50] have low fire loads that do not satisfy the requirement for the fire load density related to total surface area q_{td} to lie between 50 and 1000 MJ/m². If these values are removed from the comparison, the parametric approach provides a reasonable agreement between measured and predicted peak temperature in line with Figure 2. Figure 4 shows the correlation with the low fire load values removed.

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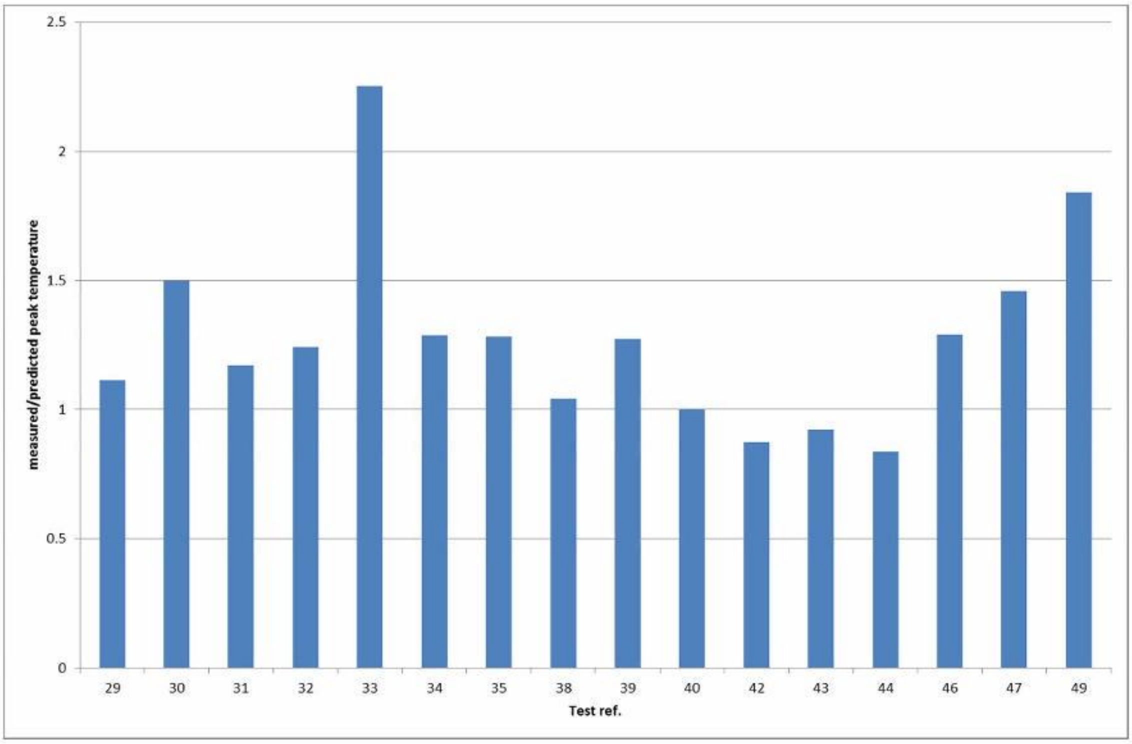

Figure 4 - Comparison between measured and predicted peak temperatures for BISF tests with low fire load values removed

Figure 5 shows the comparison between measured and predicted times to peak temperature for the range of fire tests covered in Figure 2.

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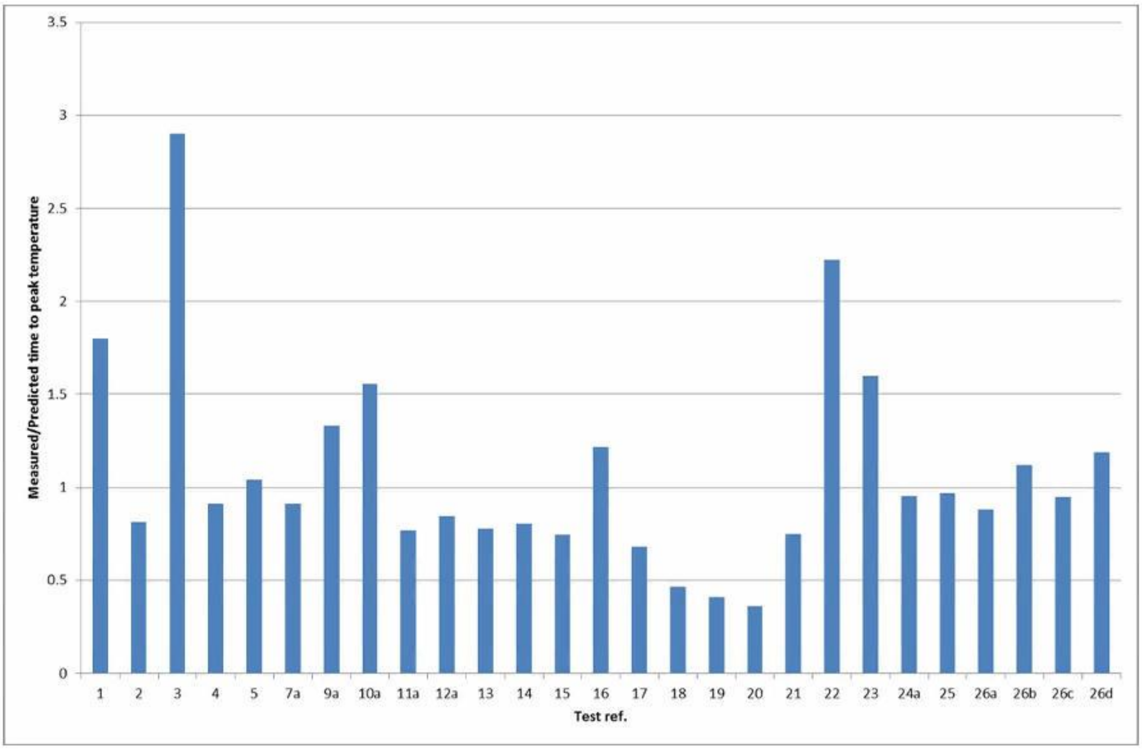

Figure 5 - Comparison between measured and predicted time to peak temperatures for a range of large fire tests

The correlation is generally very good. Where the parametric approach under predicts time to peak temperatures this is generally due to a pre-flashover phase. Figure 6 is a similar comparison for the BISF experimental programme.

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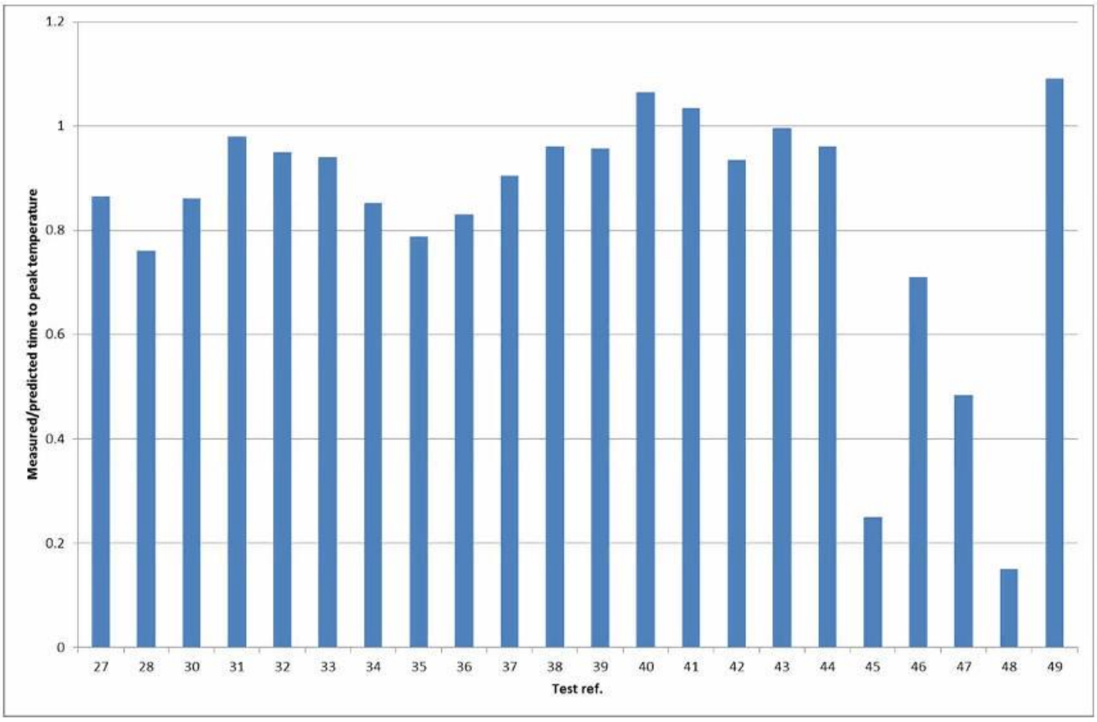

Figure 6 - Comparison between measured and predicted time to peak temperature for BISF fire tests

The results show that the parametric approach provides a reasonable estimate of peak compartment temperature and time to peak temperature for a wide range of different parameters.

Figure 7 shows the relationship between measured and predicted values of time equivalence for the fire experiments shown in Figure 2. The measured values are based on instrumented steel sections placed within the fire compartment for which standard fire test data is available. The predicted values are based on the time equivalence formulation set out in BS EN 1991-1-2 and associated National Annex and NCCI.

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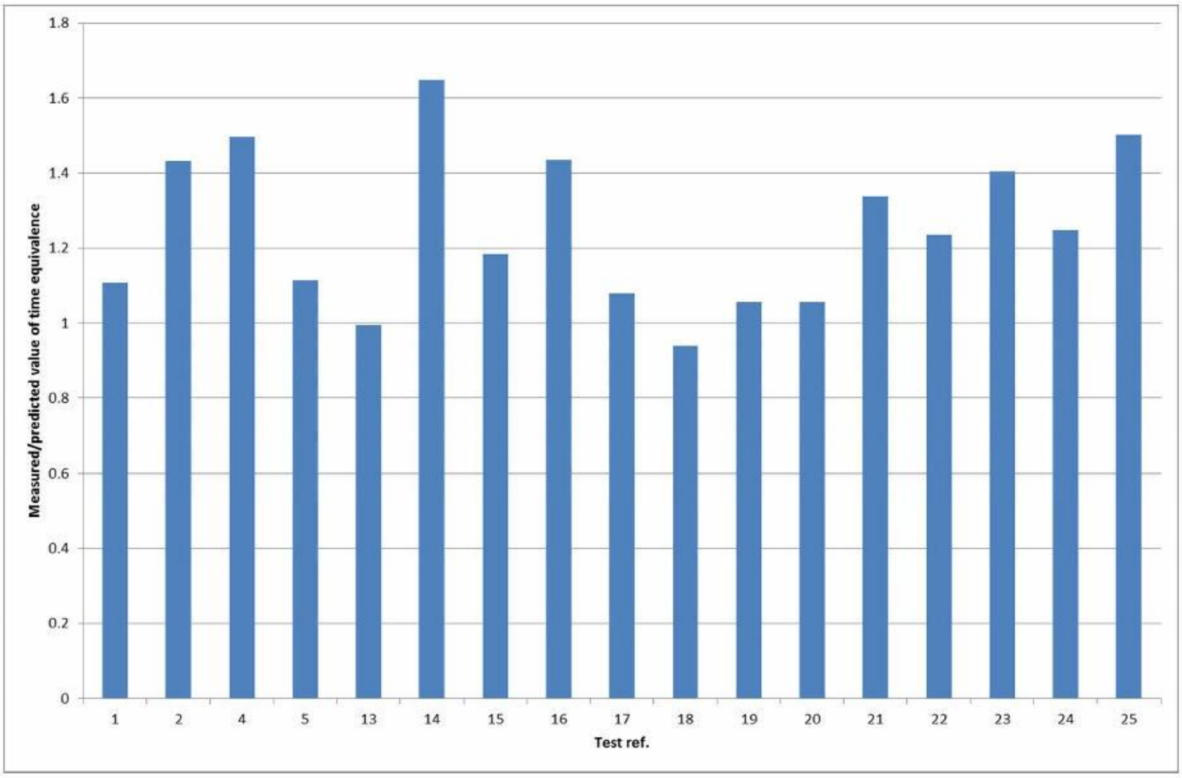

Figure 7 - Comparison between measured and predicted values of time equivalence for a range of large-scale fire tests

Figure 8 shows the corresponding relationship for the BISF tests.

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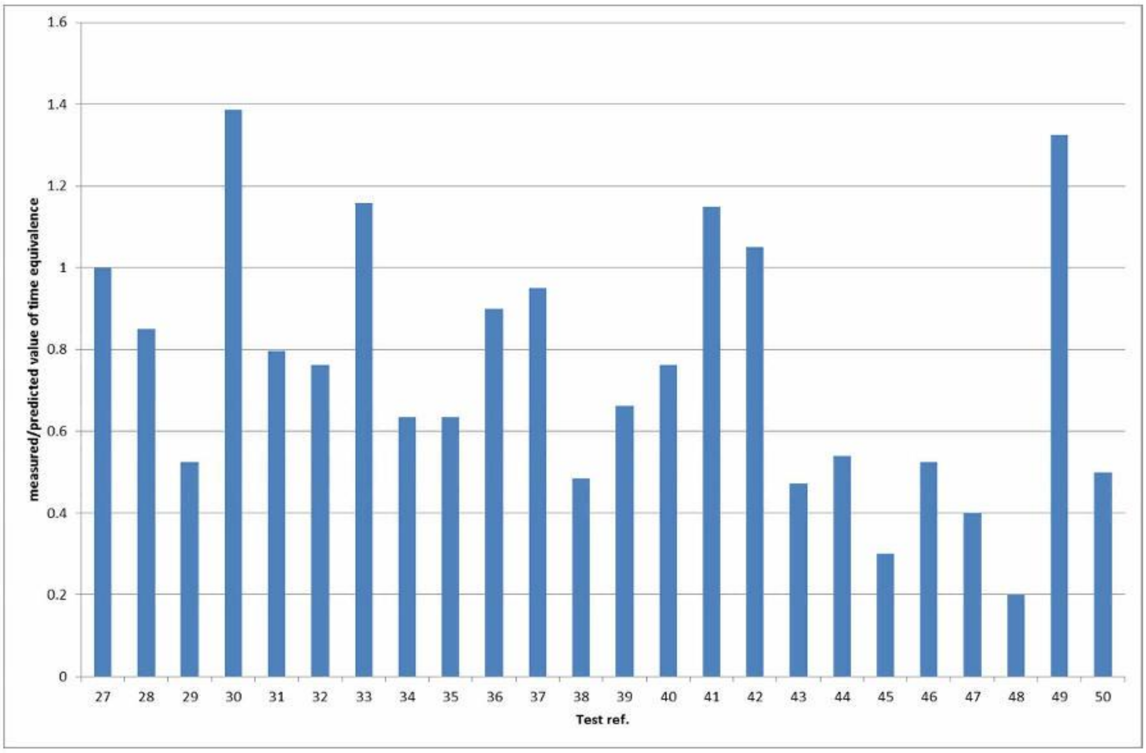

Figure 8 - Comparison between measured and predicted values of time equivalence for BISF tests

In Figure 8, a minimum period of 20 minutes has been assumed for the predicted period of fire resistance. This is consistent with observed behaviour in real fires and takes into account inconsistent values due to low fire load densities.

The results show that the time equivalent approach provides a reasonable estimate of equivalent severity for a wide range of different parameters.

2.5 Experimental programme

The database of fire tests reviewed above incorporates a wide range of different parameters with compartment floor area ranging from 12 m² to 378 m², fire load densities ranging from 135 MJ/m² to 1080 MJ/m² and opening factors ranging from 0.002 m^{-1} to 0.18 m^{-1}. While a number of the fire tests have considered the impact of the thermal properties of compartment linings on fire growth and development, this remains an area where further work is required.

Modern methods of construction incorporate large quantities of thermal insulation within the wall, floor and roof construction to provide the energy efficiency performance required by modern regulations. More information is required on the impact of the thermal properties of compartment linings on fire growth and development.

Three fully-developed post flashover fire experiments were conducted in this project in support of Work Stream 1. A specially designed compartment was used to carry out the experiments relevant to this work stream as well as providing additional information for other work streams within the research project. The compartment had internal dimensions of 3.6 m long, 3.6 m deep and 2.4 m high with provision for a 2.0 m

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high, 2.0 m wide opening in one wall. The walls of the compartment were built from medium density load bearing concrete blocks 100 mm thick (density 1400 kg/m^3). The roof of the compartment was constructed from a reinforced concrete beam and block system supported on two of the block walls. The floor of the laboratory was protected by either plasterboard sheets or sand.

To provide alternative levels of thermal insulation to the rig, non-combustible linings were selected to give thermal performance equivalent to walls and ceilings used in modern buildings. The insulation options and experimental programme are given in Table 15.

Experiment number	Work stream	Ventilation	Insulation	Roof structure	Date
1	1, 6	Wall 1.5 m^2	Very high	Closed	28th November 2013
2	1, 6	Wall 1.5 m^2	High	Closed	11th December 2013
3	1, 6	Wall 1.5 m^2	Low	Closed	17th December 2013

Table 15 – Experimental programme for Work stream 1

The 2 m by 2 m opening provided access to the rig to change lining materials, construct the fire and to remove debris. During each fire, the opening was partly blocked to provide the required wall ventilation.

The basic structure, prior to Experiment 1 is shown in Figure 9.

Figure 9 - View of the fire compartment looking in from front ventilation opening

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To assist with the location of instrumentation and other items in the rig, a reference grid was devised. This is shown in Figure 10.

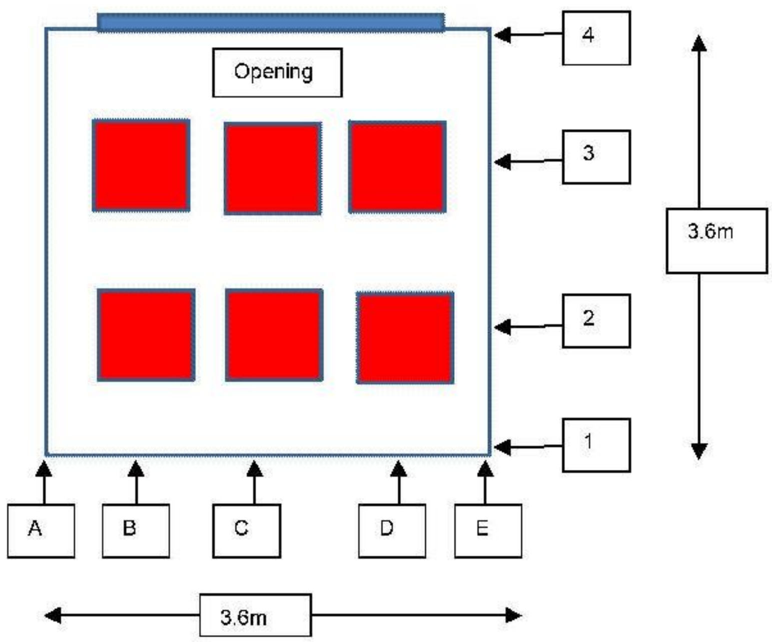

Figure 10 - Plan of rig showing reference grid and location of cribs

To provide alternative levels of thermal insulation, the rig included a non-combustible lining selected to give thermal performance equivalent to walls and ceilings used in modern buildings. The three options are given in Table 16.

Level	Relative degree of insulation	Construction	Thermal properties	U value (W/m²K)
1	Low	Walls: Block work, no lining	Conductivity 0.42 W/mK Thermal inertia 660 $J/m^2s^{1/2}K$	3.33
		Roof: Precast concrete beam and block floor	Conductivity 1.0 W/mK Thermal inertia 1100 $J/m^2s^{1/2}K$	2.36
2	High	Walls: Block work, lined with plasterboard	Conductivity 0.24 W/mK Thermal inertia 520 $J/m^2s^{1/2}K$	1.84
		Roof: Precast concrete beam and block floor lined with plasterboard	Conductivity 0.24 W/mk Thermal inertia 520 $J/m^2s^{1/2}K$	1.90
3	Very high	Walls: Block work lined with ceramic blanket	Conductivity 0.02 W/mK Thermal inertia 54 $J/m^2s^{1/2}K$	0.36
		Roof: Precast concrete beam and block floor lined with ceramic blanket	Conductivity 0.02 W/mK Thermal inertia 54 $J/m^2s^{1/2}K$	0.59

Table 16 - Thermal insulation

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Although it is true that higher levels of insulation produce more severe fires in terms of peak temperature and time to flashover there is no simple correlation between the impact of U values and the thermal properties of compartment linings. U values are used to determine heat transfer over a long period of time under steady state conditions where all constituent layers will play a role in providing insulation. In a fire situation the interaction between the compartment linings and the development of the fire is primarily influenced by those materials in direct contact with the fire compartment with materials on the non-fire side playing a less important role.

The key dimensions and material properties of the experimental rig are summarised as follows.

Internal dimensions:

Width 3.6 m

Depth 3.6 m

Height 2.4 m

Wall block thickness: 100 mm

Insulation thickness:

Ceramic fibre: 25 mm

Plasterboard: 12.5 mm

Wall opening: 2.0 m by 2.0 m

Blocked to 1.5 m wide by 1.0 m high opening in Experiments 1, 2 and 3

Material properties:

Material	**Density (ρ)**	**Conductivity (k)**	**Specific heat capacity (c)**	**Thermal inertia ($b = \sqrt{k\rho c}$)**
	kg/m^3	W/m/K	J/kg/K	$J/m^2s^{1/2}K$
Block work	1375	0.42	753	660
Plasterboard	900	0.24	1250	520
Sand	1750	1.0	800	1185
Ceramic fibre	128	0.02	1130	54

Table 17 - Thermal properties for compartment linings

For each experiment, a fire load of 570 MJ/m^2 (averaged over the entire floor area) has been used.

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For Experiments 1 to 3, the fire load was distributed across six wooden cribs made up of 1 m long 50 mm square section Scots pine timber sticks with a moisture content of less than 13%. The sticks were arranged in seven layers of ten sticks as shown in Figure 11. Figure 10 shows the locations of the cribs centred at locations B2, C2, D2, B3, C3, and D3. The crib at location C2 was constructed on a weighting platform; this raised its upper surface from the floor by approximately 150 mm (see Figure 11).

Figure 11 - View of cribs inside rig prior to Experiment 1

The common instrumentation for all the experiments was:

- Six thermocouple columns at locations B2, C2, D2, B3, C3, and D3.
- Each column had thermocouples at distances of 100, 400, 600, 1000 and 1400 mm from the ceiling.
- Weighting platform under crib C3.
- Two sets of three wall thermocouples (exposed side, middle, unexposed side) at grid lines A and 4.

Experiments 1 to 3 with a wall opening included heat flux meters at 4 m from the centre of the opening (1.4 m from the floor).

Experiments 1 to 3 included indicative protected steel sections suspended from the ceiling to provide information on the severity of the fires relative to an equivalent period in a standard fire test. Each sample had three thermocouples to measure the temperature of the steel flanges and web. It has not been possible to obtain standard fire test data corresponding to the instrumented sections so it is not possible to obtain measured values of time equivalence. However, the results indicate that the severity of the compartment fires was in excess of the design fire resistance of the protected steel sections.

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Experiments 1 to 3 included an array of six velocity measurement probes and thermocouples as shown in Figure 11. The instruments were located at on the centre line of the opening at 1/5, 2/5, 3/5 and 4/5 of the depth from the top of the opening and one at ¼ and ¾ width of the opening and 1/5 from the top of the opening.

The data were recorded using a data logger scanning each channel every 2.5 seconds.

Each experiment was recorded with at least one fixed video camera and observers took still and video images together with visual observation notes.

Experiment 1 - details and observations

Date and time: 28th November 2013 at 14:00

Ventilation: Wall opening 1.5 m wide, 1.0 m high, sill 0.9 m above floor.

Ventilation factor ($A\sqrt{H}$) = 1.5 $m^{3/2}$

Opening Factor ($A\sqrt{H}/A_T$) = 1.5/47.5 = 0.032 $m^{1/2}$

Insulation: Very high (see Table 15)

Thermal inertia, b = 54 $J/m^2s^{1/2}K$

Fire load: Six wood cribs, fire load = 570 MJ/m^2

Observations: Laboratory ambient temperature = 10°C prior to ignition

Time (mins: secs)	**Observation**
-5:00	Ignition countdown started: data logging begins
0:00	Ignition started
1:30	Ignition established, lower section of opening in place
3:00	Flames tips at sill level
7:00	Flame tips reach compartment ceiling
7:50	Flames leave compartment
7:50	Intumescent on indicative specimen activated
8:00	Flashover
10:00	Strong external flaming black smoke. Smoke from Target 1
12:00	Smoke from Target 2
17:00	Mass loss instrumentation fails
30:30	Target 1 falls from stand
40:00	Frame over sill falls away
53:00	Spalling of roof – test terminated
57:00	Explosive failure of lintel
90:00	Data logging stopped

Table 18 - Experiment 1 observations

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Experiment 1 – results

Figure 12 shows the spatially-averaged temperature of the six thermocouples mounted 1 m below the ceiling (at approximately the centre height of the opening) and some of the key events during the experiment.

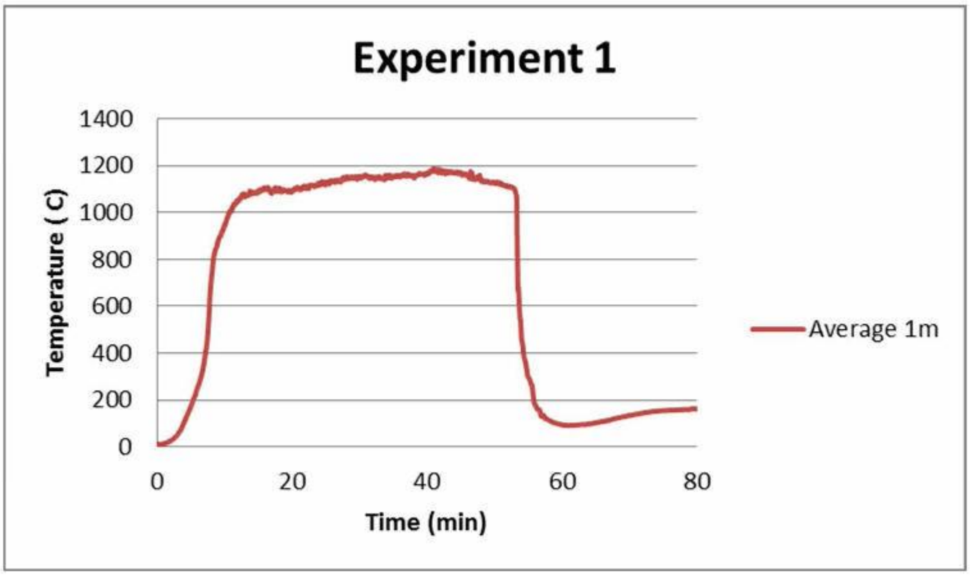

Figure 12 - Average temperature 1 m below ceiling and key events for Experiment 1

To illustrate the severity of the conditions in the compartment, Figure 13 shows a comparison between the average temperature 1 m below the ceiling and the standard "fire resistance" curves[1].

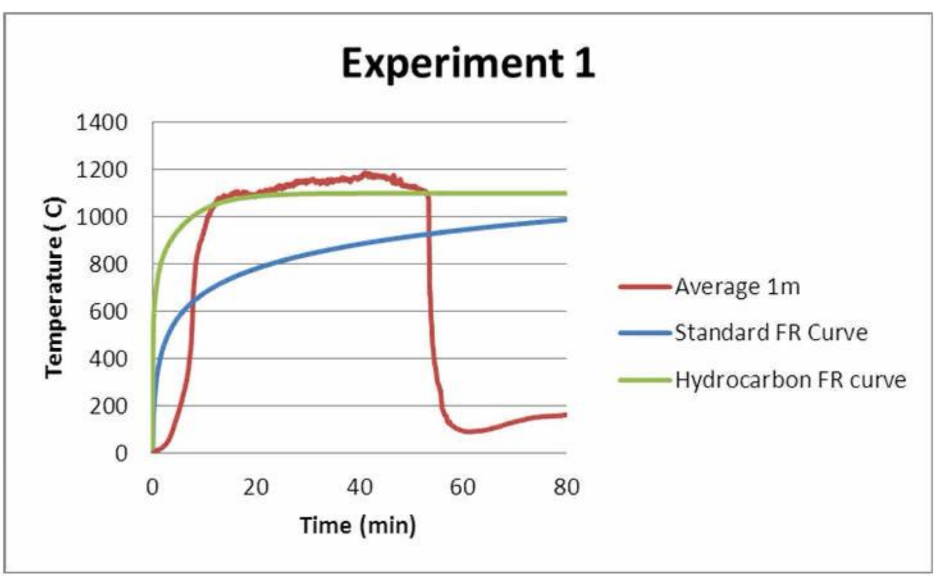

Figure 13 - Average temperature 1 m below ceiling and "fire resistance curves" for Experiment 1

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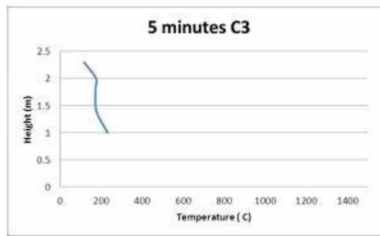
Figure 14 summarises the development of the fire using a series of “snapshots” of the data at key times during the experiment. These show an image of the fire, the vertical temperature profile at location C3 (above the back centre crib), a calculation of heat release rate based on the weighing platform data, maximum temperature recorded and the radiation intensity 4 m from the centre of the opening. The heat release rate data is calculated from the mass loss rate obtained for crib C2. The assumption is that the mass loss rate from the other cribs is identical and that the heat release rate is given by a two minute time averaged mass loss rate multiplied by the heat of combustion for timber (17.5 MJ/kg).

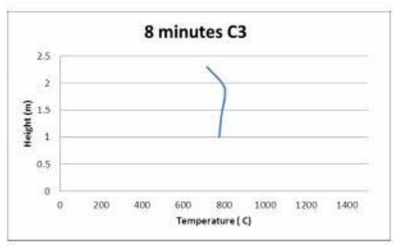


Heat release rate 0.8 MW

Maximum Temperature 247°C

Radiation intensity at 4 m, 0.05 kW/m^2

5 minutes (Pre flashover)

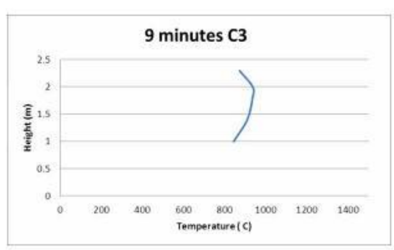


Heat release rate 3.5 MW

Maximum Temperature 830°C

Radiation intensity at 4 m, 2.7 kW/m^2

8 minutes (Flashover)

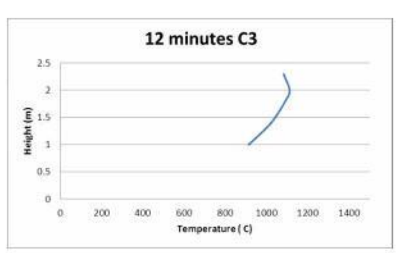


Heat release rate 3.5 MW

Maximum Temperature 950°C

Radiation intensity at 4 m, 2.7 kW/m^2

9 minutes (Post flashover)



Heat release rate 3.5 MW

Maximum Temperature 1131°C

Radiation intensity at 4 m, 4.7 kW/m^2

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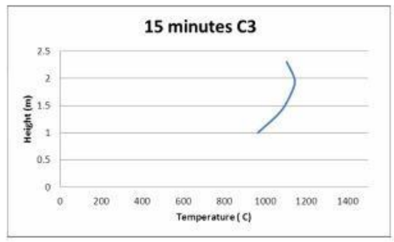
12 minutes

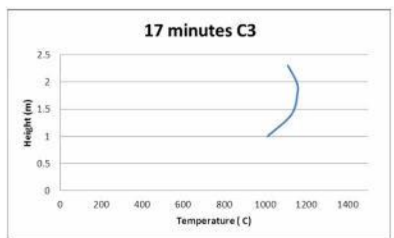


Heat release rate
No data

Maximum
Temperature 1162°C

Radiation intensity at
4 m, 5.6 kW/m^2

15 minutes

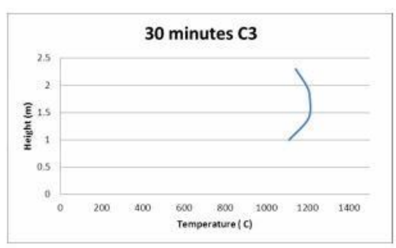


Heat release rate
No data

Maximum
Temperature 1158°C

Radiation intensity at
4 m, 6.3 kW/m^2

17 minutes (end of mass loss rate data)



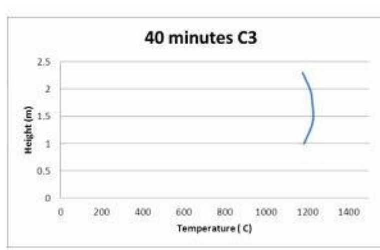
Heat release rate

No data

Maximum
Temperature 1230°C

Radiation intensity at
4 m, 8.6kW/m^2

30 minutes (prior to target at 2m falling away)



Heat release rate

No data

Maximum
Temperature 1231°C

Radiation intensity at
4 m, 9.4 kW/m^2

40 minutes (frame above sill falls away)

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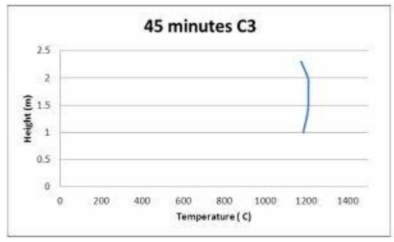


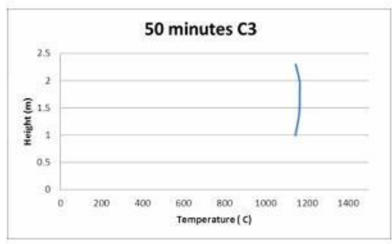
Heat release rate

No data

Maximum Temperature 1213°C

Radiation intensity at 4 m, 10.2 kW/m^2

45 minutes



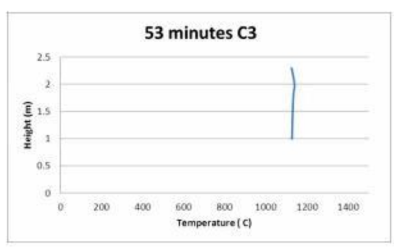
Heat release rate

No data

Maximum Temperature 1211°C

Radiation intensity at 4 m, 9.3 kW/m^2

50 minutes



Heat release rate

No data

Maximum Temperature 1172°C

Radiation intensity at 4 m, 7.7 kW/m^2

53 minutes (at termination)

Figure 14 - Time line for Experiment 1

An indicative column element with an intumescent coating was present in the rig under the ceiling near location C3. Figure 15 shows the temperature history at three points on the element.

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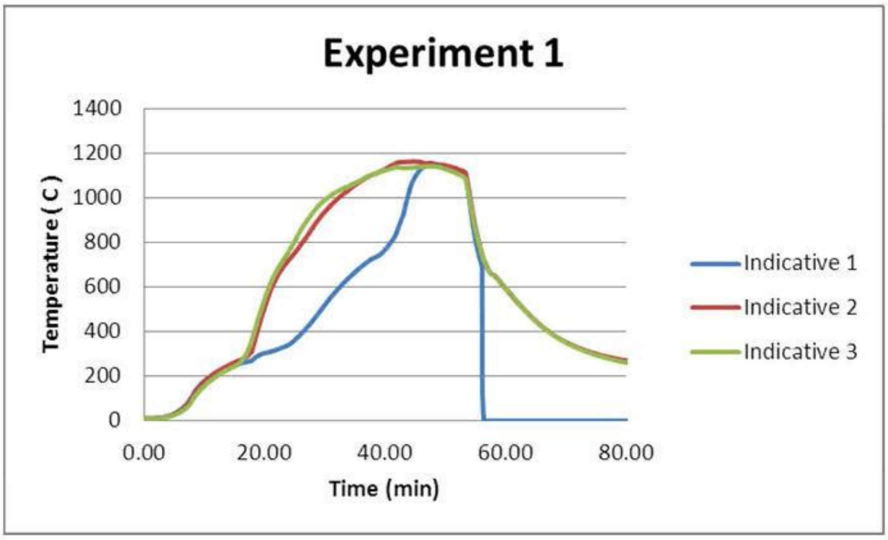

Figure 15 - Indicative column element temperatures for Experiment 1

The rise in temperature after ~18 minutes indicates failure of the protective coating on the indicative column.

After the test was terminated, during the period while the fire was being extinguished, the lintel above the 2 m opening failed explosively. There had already been some spalling of some of the roof beams at this time. It is not clear from video records whether the spalling was a consequence of the structure entering a cooling phase or if fire-fighting water had come into contact with the lintel.

Figure 16 shows some images of the roof beams after the fire had been extinguished.

Figure 16 - Roof beams after Experiment 1

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Experiment 2 - details and observations

Date and time: 11th December 2013 at 10:00

Ventilation: Wall opening 1.5 m wide, 1.0 m high, sill 0.9 m above floor.

Ventilation factor ($A\sqrt{H}$) = 1.5 $m^{3/2}$

Opening Factor ($A\sqrt{H}/A_T$) = 1.5/47.5 = 0.032 $m^{1/2}$

Insulation: High (see Table 15)

Thermal inertia, b = 520 $J/m^2s^{1/2}K$

Fire load: Six wood cribs, fire load = 570 MJ/m^2

Observations: Laboratory ambient temperature 7°C prior to ignition

Time (mins: secs)	Observation
-5:00	Ignition countdown started: data logging begins
0:00	Ignition started
1:30	Ignition established, lower section of opening in place
1:30 to 4:30	Grey smoke issuing, buoyant plume
9:48	Flames filling compartment
10:00	Flashover
11:00	Intumescent activated
20:40	Smoke coming from 2 m wood target
23:15	Smoke coming from 3 m wood target
30:30	Lintel spalls
35:00	Top third of opening 2 m wide (plasterboard at sides fails)
41:00	Opening 2 m wide over full height
42:40	2 m wood target falls from stand
	Fire left to burn out naturally
90:00	Data logging stopped

Table 19 - Experiment 2 observations

Experiment 2 – results

When clearing the debris from the fire, it was noted that much more of the fuel had been consumed at the front of the compartment when compared to the back.

Figure 17 shows the spatially-averaged temperature of the three thermocouples mounted 1 m below the ceiling (at approximately the centre height of the opening) on grid lines 2 and 3 and some of the key events during the experiment.

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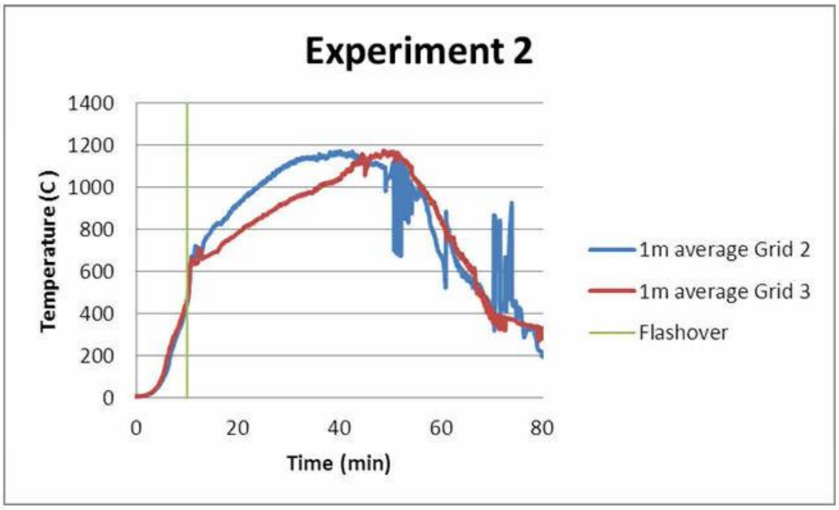

Figure 17 - Average temperature below ceiling and key events for Experiment 2

To illustrate the severity of the conditions in the compartment, Figure 18 shows a comparison between the average temperature 1 m below the ceiling and the standard "fire resistance" curves.

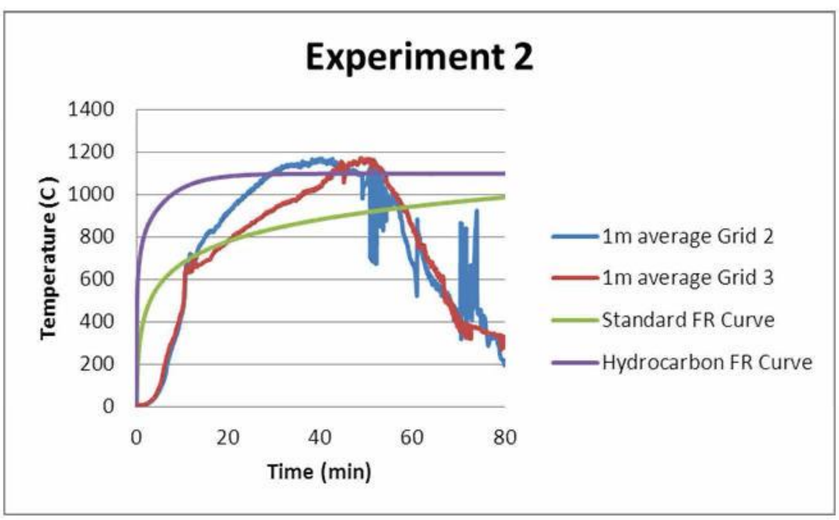

Figure 18 - Average temperature 1 m below ceiling and standard "fire resistance curves" for Experiment 2

Figure 19 summarises the development of the fire using a series of "snapshots" of the data at key times during the experiment. This shows an image of the fire, the vertical temperature profile at location C3 (above the back centre crib), a calculation of heat release rate based on the weighing platform data as described previously, maximum temperature recorded and the radiation intensity 4 m from the centre of the opening.

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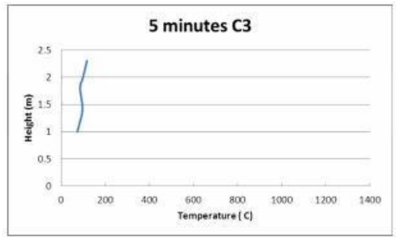
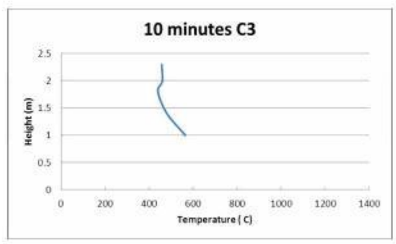


Heat release rate
1.3 MW

Maximum
Temperature 180°C

Radiation intensity at
4 m, 0.03 kW/m^2

5 minutes (Pre flashover)

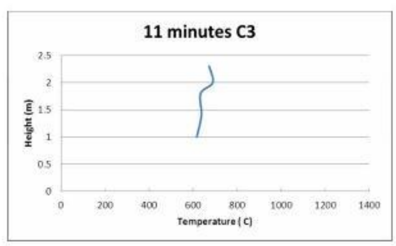


Heat release rate
1.3 MW

Maximum
Temperature 593°C

Radiation intensity at
4 m, 0.47 kW/m^2

10 minutes (Flashover)

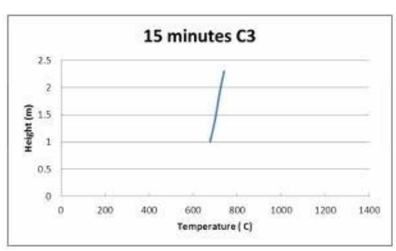


Heat release rate
1.3 MW

Maximum
Temperature 788°C

Radiation intensity at
4 m, 1.3 kW/m^2

11 minutes (Post flashover)

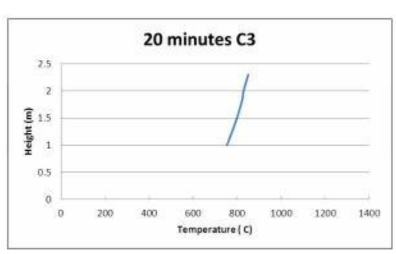


Heat release rate
No data

Maximum
Temperature 837°C

Radiation intensity at
4 m, 2.5 kW/m^2

15 minutes



Heat release rate
1.9 MW

Maximum
Temperature 966°C

Radiation intensity at
4 m, 4.0 kW/m^2

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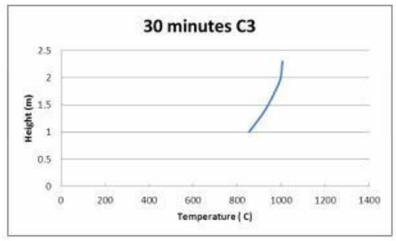
20 minutes

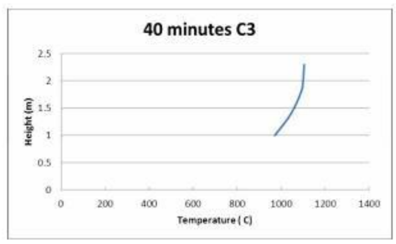


Heat release rate
2.3 MW

Maximum
Temperature
1127°C

Radiation intensity at
4 m, 8.0 kW/m^2

30 minutes

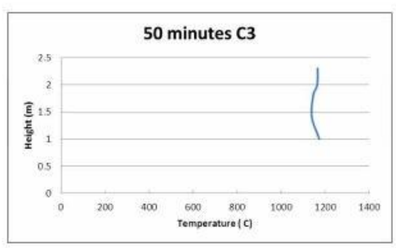


Heat release rate
2.7 MW

Maximum
Temperature
1190°C

Radiation intensity at
4 m, 10.6 kW/m^2

40 minutes



Heat release rate
No data

Maximum
Temperature
1195°C

Radiation intensity at
4 m, 9.6 kW/m^2

50 minutes

Figure 19 - Time line for Experiment 2

An indicative column element with an intumescent coating was present in the rig under the ceiling near location C3. Figure 20 shows the temperature history at three points on the element.

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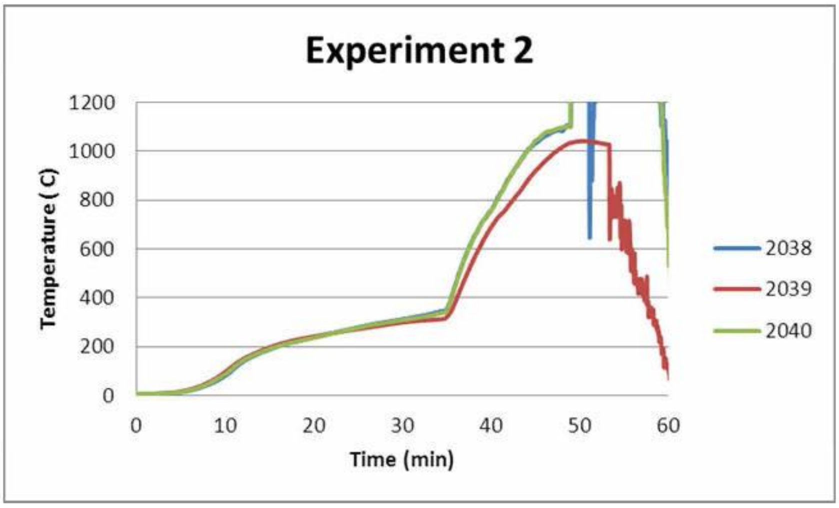

Figure 20 - Temperatures of indicative column element for Experiment 2

The rise in temperature after ~35 minutes indicates failure of the protective coating on the indicative column.

Experiment 3 – details and observations

Date and time: 17th December 2013 at 15:00

Ventilation: Wall opening 1.5 m wide, 1.0 m high, sill 0.9 m above floor.

Ventilation factor ($A\sqrt{H}$) = 1.5 $m^{3/2}$

Opening Factor ($A\sqrt{H}/A_T$) = 1.5/47.5 = 0.032 $m^{1/2}$

Insulation: Low (see Table 15)

Thermal inertia, b = 660 $J/m^2s^{1/2}K$

Fire load: Six wood cribs, fire load = 570 MJ/m^2

Observations: Laboratory ambient temperature 9°C prior to ignition

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Time (mins: secs)	Observation
-5:00	Ignition countdown started: data logging begins
0:00	Ignition started
1:30	Ignition established, lower section of opening in place
1:50	Buoyant smoke plume rising from compartment
8:28	Intumescent starts to activate
11:57	Flames just starts to come out of opening
12:50	Intermittent flames out of opening
14:28	Back of compartment visible
16:16	Back of compartment visible; appears as though one crib is out
23:00	Flashover
23:29	Fire "picking up"
28:25	Insulation went
32:35	Back of compartment visible
35:30	Test terminated due to development of severe cracks in structure of rig
90:00	Data logging stopped
Post test	Due to the damage to the experimental rig that occurred, it was decided not attempt another experiment with exposed blockwork until the end of the programme.

Table 20 - Experiment 3 observations

Experiment 3 – results

Figure 21 shows the spatially-averaged temperature of the six thermocouples mounted 1 m below the ceiling (at approximately the centre height of the opening) and some of the key events during the experiment.

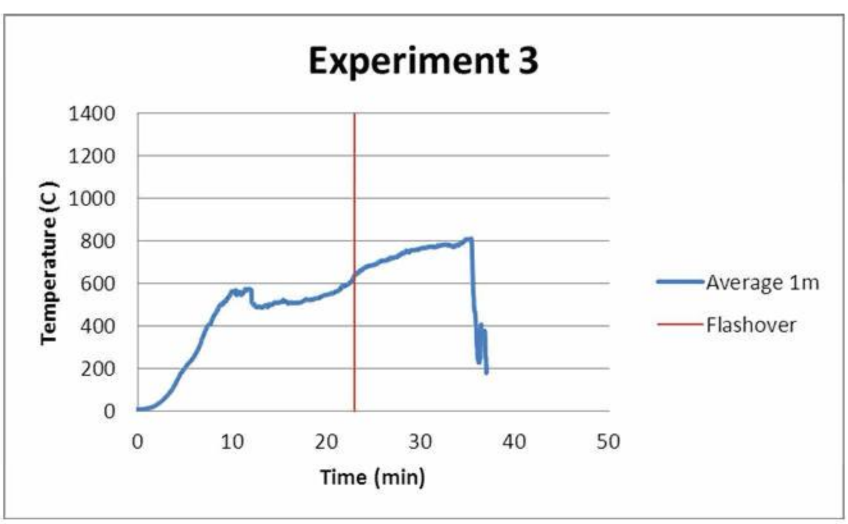

Figure 21 - Average temperature 1m below the ceiling and key events for Experiment 3

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To illustrate the severity of the conditions in the compartment, Figure 22 shows a comparison between the average temperature 1 m below the ceiling and the “fire resistance” curves.

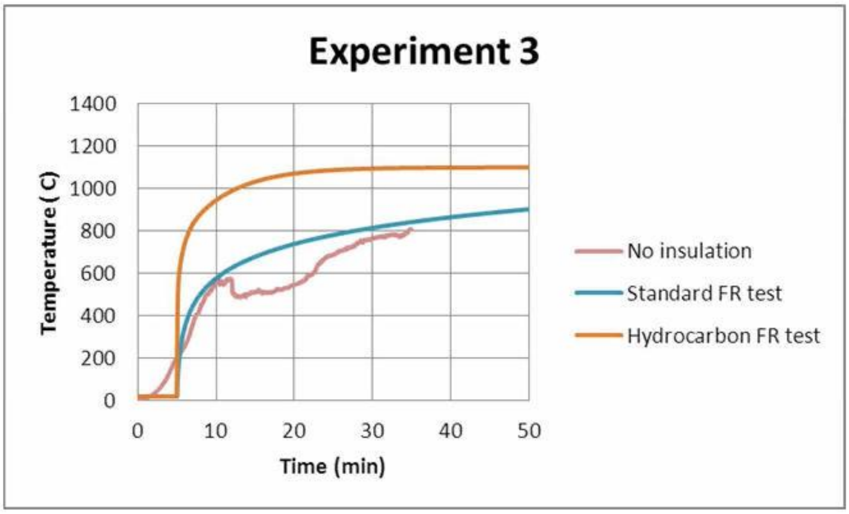

Figure 22 - Average temperature 1 m below the ceiling and “fire resistance curves” for Experiment 3

Figure 23 summarises the development of the fire using a series of “snapshots” of the data at key times during the experiment. This shows an image of the fire, the vertical temperature profile at location C3 (above the back centre crib), a calculation of heat release rate based on the weighing platform data as described previously, maximum temperature recorded and the radiation intensity 4 m from the centre of the opening.

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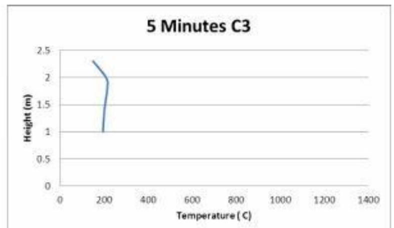
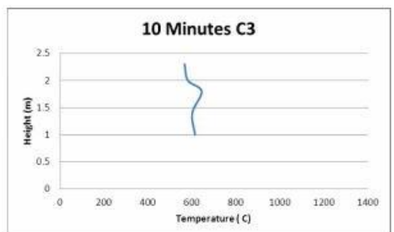


Heat release rate --
No data

Maximum Temperature
219°C

Radiation intensity at
4 m, 0.01 kW/m^2

5 minutes

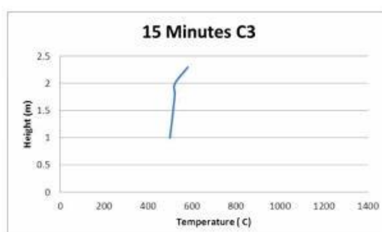


Heat release rate
No data

Maximum Temperature
647°C

Radiation intensity at
4 m, 0.43 kW/m^2

10 minutes

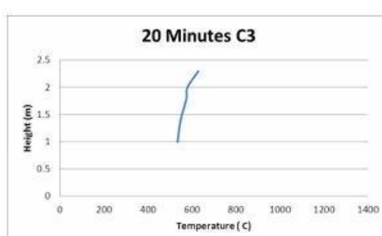


Heat release rate
1.8 MW

Maximum Temperature
728°C

Radiation intensity at
4 m, 1.1 kW/m^2

15 minutes



Heat release rate
1.8 MW

Maximum Temperature
731°C

Radiation intensity at
4 m, 1.34 kW/m^2

20 minutes

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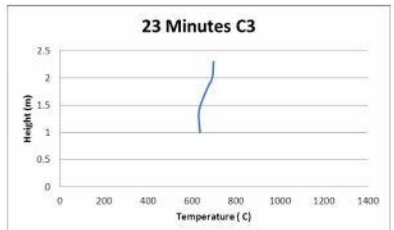
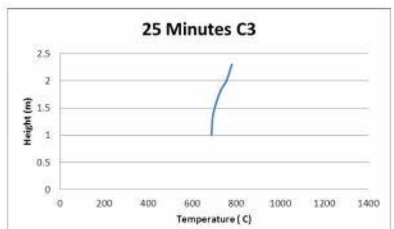


Heat release rate
1.8 MW

Maximum Temperature
797°C

Radiation intensity at
4 m, 1.7 kW/m^2

23 minutes (flashover)

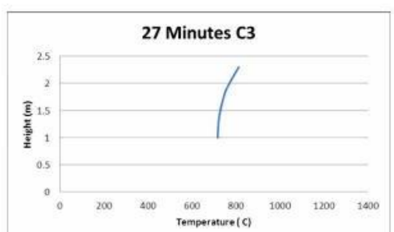


Heat release rate
1.8 MW

Maximum Temperature
884°C

Radiation intensity at
4 m, 2.4 kW/m^2

25minutes

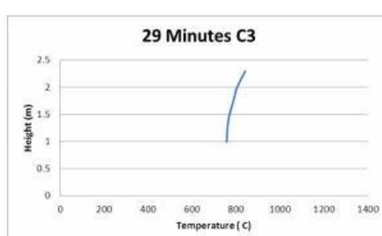


Heat release rate
1.8 MW

Maximum Temperature
910°C

Radiation intensity at
4 m, 2.7 kW/m^2

27 minutes (Left hand side panel moves)



Heat release rate
1.8 MW

Maximum Temperature
942°C

Radiation intensity at
4 m, 3.2 kW/m^2

29 minutes

Figure 23 – Timeline for Experiment 3

An indicative column element with an intumescent coating was present inside the rig under the ceiling near location C3. Figure 24 shows the temperature history at three points on the element.

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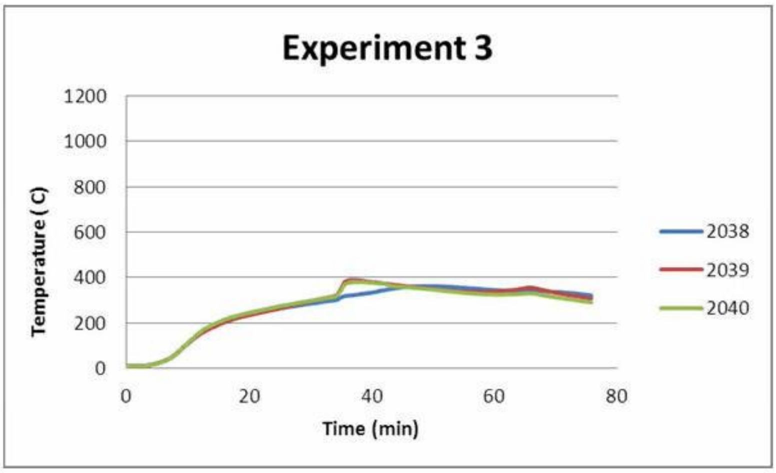

Figure 24 – Temperatures of indicative column element for Experiment 3

2.6 Analysis and Cost Benefit Analysis

The work conducted under this work stream has considered the background to the current guidance in relation to periods of fire resistance. New performance based methods for characterising fire severity and specifying fire resistance periods have been evaluated through a consideration of data from a large series of full scale fire experiments. In order to consider the impact of the levels of insulation typical of modern forms of construction on fire growth and development, a number of new fire experiments have been undertaken.

The anticipated fire severity in terms of peak temperature as calculated from the parametric approach is compared to the measured data from the three new fire experiments conducted as part of the current research project. The results are shown in Figure 25.

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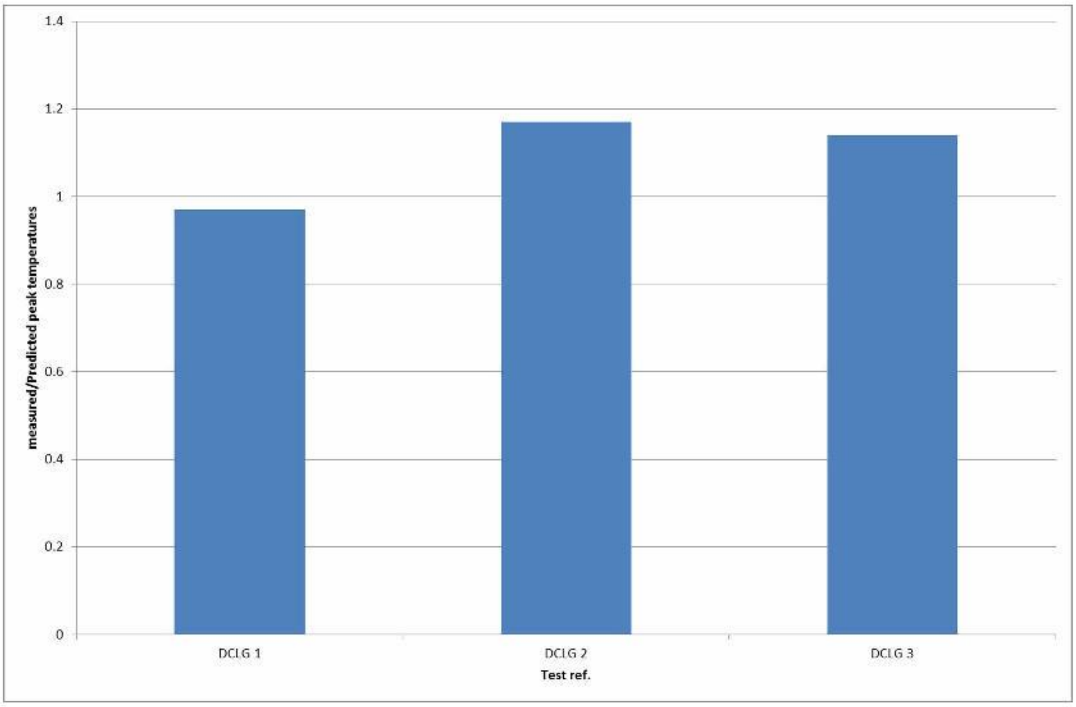

Figure 25 - Measured/predicted peak temperatures for the Work stream 1 experiments

The corresponding relationship for time to peak temperature is illustrated in Figure 26.

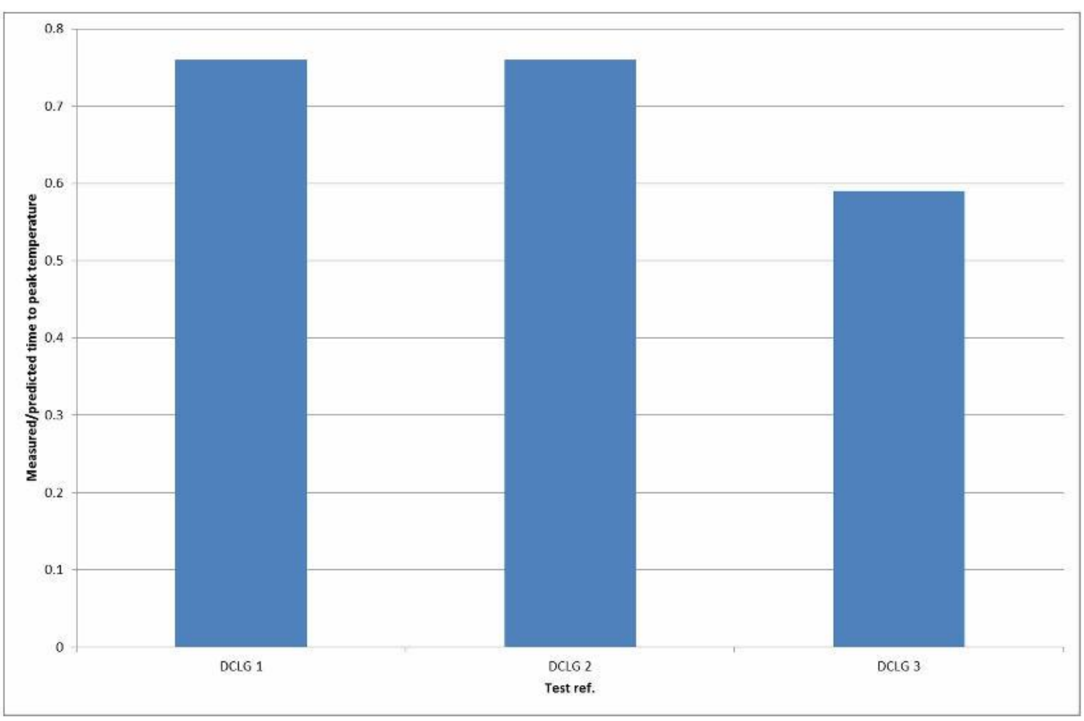

Figure 26 - Measured/predicted time to peak temperatures for Work stream 1 experiments

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The results show a good correlation between the predicted and measured values. The reason for the low values in Figure 25 was mainly due to the requirement to terminate the experiment to prevent more extensive damage to the fire compartment.

The work considered under this work stream has provided validation for design methods already in the public domain and already in widespread use. As a consequence, there are no specific changes proposed to either the guidance or the regulations therefore a Cost Benefit Analysis is not required for this work stream.

3 Discussion on structural fire engineering design

This report has considered the scope and applicability of performance based methods for characterising fire severity through a comparison with data from full scale fire experiments. Specifically, the parametric approach set out in BS EN 1991-1-2 and the time equivalent methodology underpinning the alternative approach to specifying fire resistance periods in BS 9999 have been considered.

In terms of specifying fire resistance for elements of structure, the BS 9999 approach allows the designer to choose from either a "prescriptive" specification (Table 25) that mirrors Table A2 of Approved Document B or an alternative approach (Table 26) that requires the designer to check if ventilation conditions permit the use of the table.

The values in Table 26 were developed by a Task Group under the auspices of the British Standards Institution. The tabulated values were derived from extensive fire engineering calculations based upon a time equivalent approach to specifying fire resistance periods which incorporated parametric fire calculations, heat transfer to protected structural steel elements and a Monte Carlo method to incorporate a large number of variable parameters used as input to the initial compartment fire calculations. The analysis procedure is as follows:

1. Calculate natural (parametric) fire curve for specific parameters (O, b, q_{td}) within a specified range.
2. Calculate the temperature of a structural member exposed to the natural fire curve using the fundamental principles of heat transfer – for steel beams, the protection thickness is specified such that the steel temperature does not exceed 550°C.
3. Calculate the temperature history for the same member when subject to the standard fire curve.
4. The time equivalent period (for this fire curve) is the time taken to reach 550°C under the standard fire curve.

This procedure is repeated many times using the Monte Carlo method to develop the cumulative frequency distribution.

While the fundamental calculations in relation to parametric fire exposure and time equivalence have been validated within the current project for the range of parameters considered in the experimental work, there are a number of issues within the derivation of the tabulated BS 9999 fire resistance periods that require further consideration. These include:

- Risk analysis. The outputs from the fire engineering analysis (cumulative plot of equivalent fire resistance periods) were quantified in terms of risk to life safety depending upon the height of the building. A decision was made to determine what risk is deemed to be acceptable by relating a specific height and occupancy type to a particular value from the cumulative plot. A time equivalent

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period of 60 minutes was chosen to apply to an office building of 18 m height. This corresponds to a fractile value of 80%. In this case, this corresponds to 80% of the cases considered in the Monte Carlo analysis for that specific occupancy having a time equivalent value less than 60 minutes. This provides a fixed point from which the risk associated with height (and occupant awareness and mobility) can be varied.

- Suppression. The influence of a sprinkler system is accounted for by multiplying the fire load density by 0.61 to provide a reduced cumulative plot of equivalent fire resistance periods for each occupancy type. This factor was derived as part of the Natural Fire Safety Concept[25] based on a semi-probabilistic approach to derive an acceptable target failure probability (p_t) of 7.23 x 10^{-5} per building life (1.3 x 10^{-6} per year).
- Occupant awareness and mobility. The tabulated values in BS 9999 incorporate the influence of occupant awareness and mobility with respect to evacuation characteristics. Specifically, the impact of sleeping risk is related to an increased fire resistance requirement by moving up a consequence rating. A similar approach is adopted in areas such as medical care facilities incorporating horizontal evacuation within a place of safety. In such cases, the consequence rating is increased by two categories.
- New height categories. Two new height categories have been introduced at 11 m and 60 m to provide a more rational approach to probability of fire occurrence and consequence of failure.

The current project has provided a justification for the basic analytical methodology underpinning the tabulated approach in BS 9999 with specific reference to the parametric time-temperature calculations and the concept of time equivalence. However, the cumulative distribution curves for the various occupancies have been derived based on a single "failure" temperature related to a time taken for a protected steel section to achieve a specific temperature. The question arises as to the relevance of this to other forms of construction. In some ways the outcome can be seen as material independent as it is really just a means of quantifying severity in a comparative manner. Certainly, the current prescriptive approach does not attempt to define different periods of fire resistance for different structural elements based on specific mechanisms of failure. It should be possible to derive similar curves based on a specific limiting temperature for a specific reinforced concrete beam, although the heat transfer calculations would be somewhat more complicated. Similarly, there is no reason in principle why similar calculations could not be undertaken on a protected timber floor joist with "failure" based on a specified charring rate. However, this approach would require a great deal of effort and the current state of knowledge with regard to the performance of such elements in fire is limited.

One potential approach is to derive similar values based on a time equivalent calculation approach. Although the original purpose of the time equivalent methodology was to enable fire severity to be evaluated in terms of an equivalent period of heating of a protected steel member in a standard furnace test, it has been used (within BS EN 1992-1-2) to derive fire resistance periods independent of the form of construction. Such an approach would still need to incorporate probabilistic methods to take into account issues such as height of the building, occupant awareness and mobility, etc.

The inclusion of a new table of fire resistance periods alongside the existing Table A2 in AD B is not a sensible approach as designers will undoubtedly "cherry pick" the lowest values from each table. Replacing the existing Table A2 (and Table A1) is one option. The new approach to specifying fire resistance periods set out by the BS 9999 Task Group is a serious attempt to produce a scientifically derived methodology that takes into account the principal parameters influencing fire growth and development. It could be argued that

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it incorporates factors (such as thermal properties of compartment linings) that are not taken account of in the current prescriptive approach. However, there are a number of areas that require further investigation. A third option would be to reference the design approach within BS 9999 and that of BS EN 1991-1-2 without providing any further technical or supporting guidance. This would simply be a means of legitimising the current situation with the possibility of including further information on the scope of applicability of the various methods and the degree of competence required to apply them.

To illustrate the importance of a variation in specific parameters, the time equivalent calculation methodology has been used to consider a limited variation in parameters for a compartment with a plan floor area of 12 m by 12 m, a floor to ceiling height of 3.6 m and lined with plasterboard to give a value for thermal diffusivity of 720 $J/m^2s^{½}K$. A variation in fire load density covering the average, 80%, 90% and 95% fractiles for fixed conditions of a single ventilation opening with a width of 7.2 m and a height of 3.4 m was considered. The fire load density was then fixed at the 80% fractile value and the width of the single ventilation opening varied and the final case considered the influence of a reduction in the height of the ventilation opening.

The cases considered are summarised in Table 21 and illustrated in Figure 27.

Case	Fire load density $q_{f,d}$ (MJ/m²)	Height of ventilation opening h_v (m)	Width of ventilation opening w_v (m)
1a	420	3.4	7.2
1b	570	3.4	7.2
1c	670	3.4	7.2
1d	760	3.4	7.2
2a	570	3.4	7.2
2b	570	3.4	5.0
2c	570	3.4	3.0
2d	570	3.4	2.0
3a	570	3.4	7.2
3b	570	2.5	7.2
3c	570	1.5	7.2
3d	570	1.0	7.2

Table 21 - Cases considered for study of influence of variation in fire load density and ventilation conditions using EN 1991-1-2 time equivalent calculation

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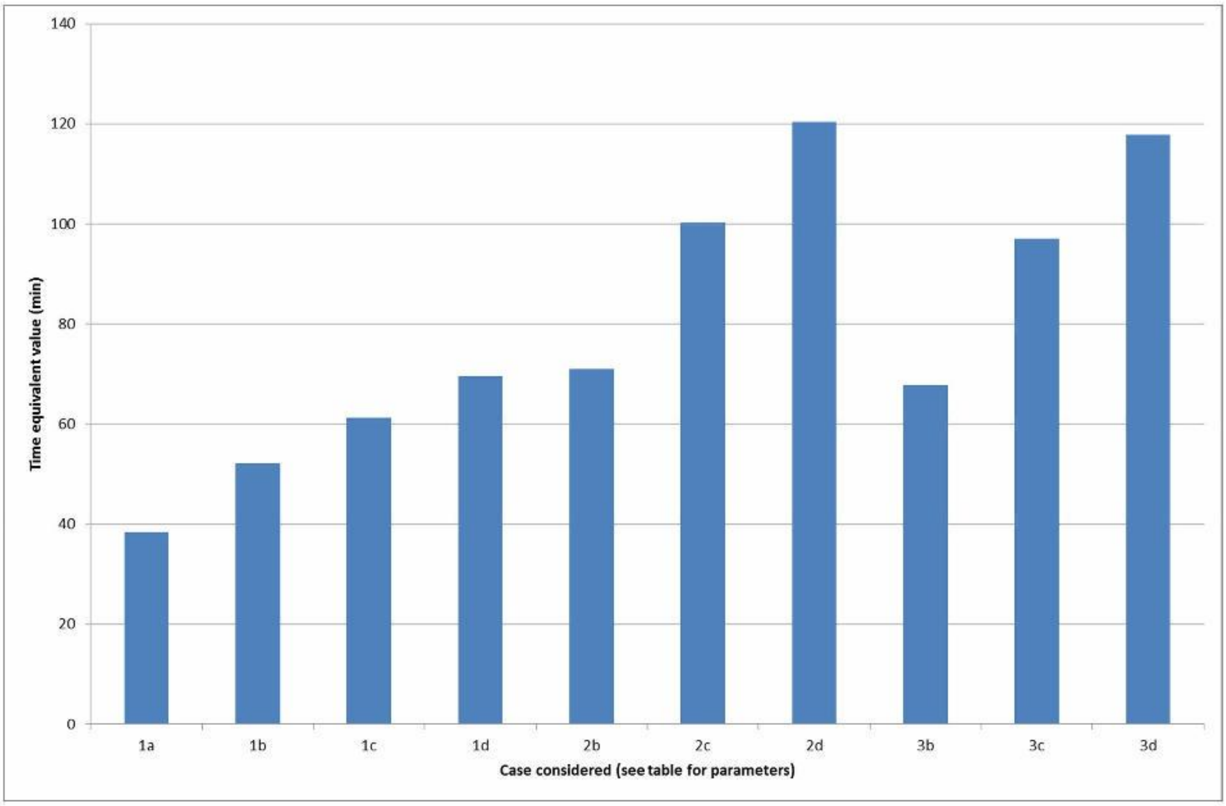

Figure 27 - Effect of variation in fire load density and ventilation conditions

In this simple study, Case 1b could be seen as the base case representing a fire load density corresponding to the 80% fractile usually adopted for fire engineering design calculations. Reductions to the area of the ventilation opening increase the equivalent severity of the fire relative to this base case. Using this method, it is possible to construct a cumulative distribution as shown in Figure 28 without recourse to either parametric fire calculations or heat transfer to protected structural steel elements.

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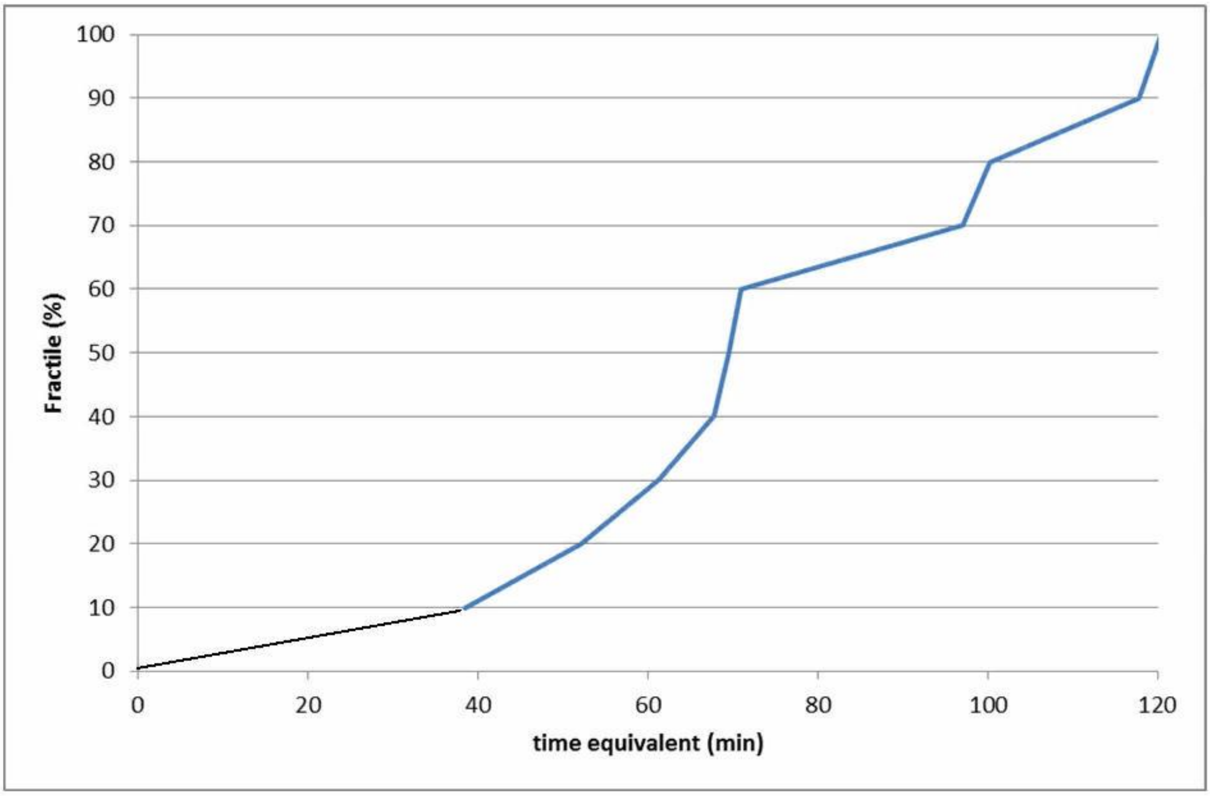

Figure 28 - Cumulative distribution for limited case study using Eurocode time equivalent calculation

The use of a Monte Carlo technique to account for the influence of design variables has a number of advantages. It can be used to determine which variables have the greatest influence on the severity of the fire and which are relatively unimportant. It is clear from the simple study above that ventilation has a significant impact on calculated severity where a reduction in either the height or the width of the opening can result in a calculated equivalent severity of more than twice the base value.

The attempt to produce a simplified table for use by those without any specialist fire engineering knowledge is a worthy aim. However, compartment fire behaviour is difficult to predict and even small changes to specific parameters can have a marked effect on fire severity. In terms of fire resistance, requirements should be related to either a known and accepted standard of reliability, as represented by the guidance in AD B, or by an alternative procedure, supported by an understanding of the principles of fire dynamics and a knowledge of structural fire engineering.

The existing tabulated guidance in AD B is by no means perfect and it is entirely possible that the changes proposed in the Table 26 approach in BS 9999 are a more accurate representation of the risk in relation to life safety. However, if they are to be used alongside AD B guidance, then designers will simply cherry pick the lowest value for their particular circumstance. If the Table 26 values were to replace the existing guidance then this would have a profound effect on the nature of the UK construction market and the relative competitiveness of specific sectors of the industry.

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4 Conclusions

The principal objective of this work stream was to produce robust evidence and data to explore the potential to adopt a more flexible approach to the specification of fire resistance periods in Approved Document B. Alternative methodologies for determining compartment fire severity and specifying fire resistance periods have been evaluated and validated within specific limitations as part of this work stream.

The fire tests undertaken in support of this work stream have demonstrated that enhanced levels of thermal insulation result in higher peak temperatures within the compartment and higher levels of thermal radiation from the compartment to adjacent buildings. It is important that this issue is considered in any future revision of regulatory guidance for fire safety.

The calculation methods set out in BS EN 1991-1-2 and used to develop the alternative tables in BS 9999 provide an accurate prediction of compartment peak temperature and overall fire duration for a range of different parameters and are capable of taking into account the impact of high levels of thermal insulation on fire growth and development as represented by the thermal diffusivity present in modern buildings which typically range from 300 to 1500 $J/m^2s^{1/2}K$. The conclusion is based on comparison with experimental results covering a number of different compartment sizes, geometries, ventilation conditions and fuel loads. However, the scope of validation only covers fire compartments with a floor area up to 378 m^2. Beyond this value, the parametric fire calculations may still be used but will tend to yield unduly conservative results. This is because the parametric approach assumes a single zone temperature distribution with the maximum value present throughout the compartment when, in reality, there will be significant spatial temperature variations throughout any large fire compartment.

The calculation methods in BS EN 1991-1-2 and BS 9999 are currently in the public domain and are widely used as an alternative approach to the guidance set out in Table A2 of AD B. Consideration could be given to making a specific reference to these approaches as part of an overall fire engineering strategy within any subsequent revision of AD B.

5 Acknowledgements

The authors, Tom Lennon and Richard Chitty, would particularly like to acknowledge the valuable contribution provided by the following:

- Satellite Steering Group A and the overall Project Steering Group.
- BRE colleague: Corinne Williams.
- BRE project team members: Luke Bisby, University of Edinburgh and Neal Butterworth, Arup Fire.
- BRE experimental team for Experiments 1 to 6: Tom Lennon, Phil Clark, Simon Barrow, Harry Granados.
- Steering Group member companies who contributed materials for construction, rig linings and indicative test specimens for BRE Experiments 1 to 6: The Concrete Centre - beam and block floor and blocks for walls, ASFP- plasterboard for linings, insulation blanket, and protected steel indicative specimens.
- Steering Group members who provided specialist advice in relation to the construction of the experimental rig.

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Appendix A – Summary of the Research

Building Regulations and Standards Division, Department for Communities and Local Government (DCLG) commissioned BRE to carry out a project titled "Compartment sizes, resistance to fire and fire safety". The main aim of this project was to produce robust evidence and data based on research, experimental fire testing, computer modelling and laboratory testing, where necessary, on a number of linked work streams in relation to fire safety and associated provisions in Schedule 1 of Part B of the Building Regulations 2010.

This Final work stream report describes the findings of the research for Work stream 1 – Periods of fire resistance. The aim of this work stream was to produce robust evidence and data to explore the potential to adopt a more flexible approach to the specification of fire resistance periods in Approved Document B.

The work conducted under this work stream has considered the background to the current guidance in relation to periods of fire resistance. New performance based methods for characterising fire severity and specifying fire resistance periods have been evaluated through a consideration of data from a large series of full scale fire experiments. In order to consider the impact of the levels of insulation typical of modern forms of construction on fire growth and development a number of new fire experiments have been undertaken. Alternative methodologies for determining compartment fire severity and specifying fire resistance periods have been evaluated and validated as part of this work stream.

The fire tests undertaken in support of this work stream have demonstrated that enhanced levels of thermal insulation result in higher peak temperatures within the compartment and higher levels of thermal radiation from the compartment to adjacent buildings. It is important that this issue is considered in any future revision of regulatory guidance for fire safety.

The calculation methods set out in BS EN 1991-1-2 and used to develop the alternative tables in BS 9999 provide an accurate prediction of compartment peak temperature and overall fire duration for a range of different parameters and are capable of taking into account the impact of high levels of thermal insulation on fire growth and development as represented by the thermal diffusivity present in modern buildings which typically range from 300 to 1500 $J/m^2s^{1/2}K$. The conclusion is based on comparison with experimental results covering a number of different compartment sizes, geometries, ventilation conditions and fuel loads. However, the scope of validation only covers fire compartments with a floor area up to 378 m^2. Beyond this value, the parametric fire calculations may still be used but will tend to yield unduly conservative results. This is because the parametric approach assumes a single zone temperature distribution with the maximum value present throughout the compartment when, in reality, there will be significant spatial temperature variations throughout any large fire compartment.

The calculation methods in BS EN 1991-1-2 and BS 9999 are currently in the public domain and are widely used as an alternative approach to the guidance set out in Table A2 of AD B. Consideration could be given to making a specific reference to these approaches as part of an overall fire engineering strategy within any subsequent revision of AD B.

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