DTLR Closing Report :

External fire spread via windows - Closing report

Project report number 203141

Prepared for :

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Safety and Health Theme

External Fire Spread via Windows

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Executive Summary

This Closing Report is a compilation of the previous three reports produced on this project. They are;

Report 1(Task 1); A survey of available information on incidents of flame spread through windows, Project report number 203130

Report 2 (Task 3); A review of codes and standards relating to fire spread through windows, Project report number 203132

Report 3 (Task 2); External fire spread via windows - Analysis of the findings, Project report number 203131.

The object of the project was to examine the issues surrounding the phenomenon of external fire spread via windows, in order to provide comprehensive and up-to-date advice on the scale of the problem and cost-effective ways of minimising the risks.

The objectives set out were:

- to collate and evaluate existing knowledge and research from the UK and around the world on methods of preventing vertical flame spread through windows
- to produce design guidance on preventing external fire spread through windows.

It was concluded that fire spread up the outside of buildings via the windows is not a significant threat to life compared with the other risks from fire in tall buildings. The UK guidance given in Approved Document B Fire Safety, deals with the issue of life safety for different occupancies by application of building construction and limits on performance of material.

The evidence acquired for this project leads to the conclusion that the measures currently called upon through Approved Document B are still commensurate with the risk.

Following from the above it was decided not to proceed with Task 4, 5 and 6 and as such the second objective has not been fulfilled.

Contents

1 Introduction

1.1 General

This Closing Report is a compilation of the previous three reports produced on this project. They are;

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The objective of the project was to examine the issues surrounding the phenomenon of external fire spread via windows, in order to provide comprehensive and up-to-date advice on the scale of the problem, and cost-effective ways of minimising the risks. No matter how effective the internal compartmentation of a building is, this can be negated if a fire breaks out of a compartment through the windows and re-enters on upper floors via the windows that are there. This phenomenon is also sometimes known as 'autoexposure'.

Task 1 of the project was to review the information that is available on all aspects of the problem. It outlined the findings from a comprehensive survey, covering a wide variety of sources.

Task 3 reviewed the regulations and codes that are related to the external spread of fire via windows in buildings. Surveys were carried out on regulatory aspects of the phenomenon in the UK and overseas.

Task 2 analysed and assessed the survey findings of Task 1 and the current Codes and Guidance as highlighted in Task 3 reports. Assessment of the risks posed were assessed and guidance offered.

1.2 Achievements against original objectives

The object of the project was to examine the issues surrounding the phenomenon of external fire spread via windows, in order to provide comprehensive and up-to-date advice on the scale of the problem and cost-effective ways of minimising the risks.

Specifically, the objectives were:

1. to collate and evaluate existing knowledge and research from the UK and around the world on methods of preventing vertical flame spread through windows

2. to produce design guidance on preventing external fire spread through windows.

The proposed approach was to carry out a detailed literature survey and analysis of existing information. The survey included, amongst other:

- Real fire incidents and real loss incidents
- The Home Office statistics
- Research findings, research in progress
- Experimental data, for example, the Timber Frame 2000 programme, the Cardington Steel Building programme, the ABI/LPC programme)
- The DETR Facades programme

Specified tasks were allocated to report on the individual findings, broken down into the following:

Task 1. A survey of available information on incidents of flame spread through windows and other information

An extensive literature survey was to be carried out on and around all aspects of the subject of external flame spread via windows.

Task 2. Analysis of the findings

Potential protective or mitigatory measures were to be identified. The risks to life from this fire spread mechanism were to be assessed and a risk analysis carried out. The lives lost (currently) and the potential savings of life (for the various measures) were to be estimated.

Task 3: Review codes and standards relating to flame spread through windows.

A review was to be carried out to identify current and proposed Code, regulatory, Standard or recommendatory guidance to prevent or limit the external spread of fire.

Task 4: Design advice document summarising and evaluating the available information and commenting on its suitability for UK construction.

This document was to summarise and evaluate the available information and comment on its suitability for UK construction. It was to include the risk assessment and indicate the cost-benefit of alternative measures.

Task 5: Draft design guidance on methods to limit or prevent external fire spread via windows

Alternative measures were to be presented as appropriate.

Task 6: An examination of some options using modelling techniques.

Within the limits of the available funding, computer modelling techniques (possibly including CFD) were to be used to assess one or more of the various methods to prevent or reduce external fire spread via windows.

The findings from these analyses were subject to a careful review to decide whether any useful, effective and cost-effective guidance was to prove plausible.

Tasks 1, 2 and 3 were completed and reports issued to the DTLR.

Task 1 carried out an extensive survey in order to gather information regarding all aspects of this phenomenon. This encompassed literature searches from journals and publications, statistical databases, on-line news agencies and discussion groups, and professional contacts and colleagues. It also included material to allow an assessment of the likely hazards and risks.

A large volume of information was gathered, covering case studies of incidents in which external spread via windows was reported, experimental and theoretical research into many aspects of the problem, and approaches to modelling the phenomena involved. It proved difficult to obtain information on the rate of occurrence of fire spread via windows in cases that have not been widely reported.

Task 3 was a review of codes and regulations related to the external spread of fire via windows. It again proved difficult to find information directly related to this phenomenon. Many countries codes address general problems in external spread but few dealt directly with floor-to-floor spread via the windows.

It was found that most locales have codes that control the external spread of fire, primarily to protect the structure itself and to prevent the spread of fire to adjacent buildings, but few addressed the problem of re-entry of fire on upper floors directly. Those codes which were obtained, that directly addressed the problems of vertical spread via the windows, tended to emphasise the conflict between the effective hindrance of external vertical fire spread, and the aesthetic or practical issues of façade construction. Other protective measures, such as automatic sprinklers or fire-resistant glazing were proposed in these cases, as alternatives to excessive window separations or horizontal projections.

There were indications that many regulatory and guidance codes tended to focus more on internal spread of fire (or smoke) through the building, rather than the potential for external spread (other than that which is confined to the outer surfaces).

The aim of the Task 2 report was to analyse and assess the survey findings of Task 1 and the current Codes and Guidance highlighted in Task 3.

There were relatively few documented cases found of extensive external vertical fire spread involving combustible claddings or glazed facades, and there were even fewer cases where such spread significantly compromised life safety.

It was clear from the Task 1 and 3 reports and from that found within Task 2, that there is insufficient guidance provided by national regulation within England and Wales, or codes of practice to effectively address the particular problems of fire spread via windows.

Where requirements for vertical separation of openings are given, consideration should be given to the removal of the requirement for 900mm high spandrels in favour of horizontal projections or sprinkler protection.

However, it is very likely that this change would be unacceptable to most building developers and architects due to the aesthetic implications, or potentially large expense of a building wide sprinkler installation.

International research showed spandrel walls need to be of impractical height to be effective for controlling vertical fire spread. It was also shown that horizontal projections are far more effective than spandrel walls.

Curtain wall constructions have particular problems of fire spread via the void junctions between the floor slab edge and the façade itself. Distortion of the wall panels can lead to collapse of the passive protection at the floor slab.

Horizontal applications would be incompatible with curtain wall constructions. Here, the only real means of limiting or preventing the risk of vertical fire spread would be the use of sprinkler systems or fire resistant glazing.

A number of mitigatory or protective measures were identified including:

- *Spandrel panels* – although not always an appropriate solution, they still perform an important task and could be critical in some buildings and occupancies. Buildings of particular concern are the high-rise buildings with slow evacuation times such as apartment blocks, hospitals, or where phased evacuation is undertaken.
- *Horizontal projections* – more effective than spandrel panel system in reducing the heat exposure to the upper floor level. Does have an aesthetic implication for building design. Impractical for large glazed areas.
- *Window orientation and size* – the heat exposure can be influenced and to a point controlled by the use of tall and thin window dimension, low and wide orientation results in a much higher heat intensity on the above façade.
- *Sprinklers* – the most effective and accessible control method. Reduces the gas temperature to levels that are not threatening to the non-fire resisting façade. Especially useful with curtain walling systems. Favoured by the international community over the use of spandrel and/or apron projection.
- *Limited combustibility of claddings* – submit all cladding materials to appropriate test methods available. Additional full size testing should be carried out for applications of glazed façades.
- *Fire resistant glazing and facades* – windows or openings introduce a weakness to the façade. Use of fire resistant materials provides improved integrity of glazed systems. Full scale tests allow for assessment of the whole system performance.
- *Sterile zones* – for combustible products so use non-combustible curtains, blinds etc. Limits fire load adjacent to window openings and hence the risk of exposure from external flaming.
- *Staggering the window layouts* – to increase spandrel height in a façade.

Following from the above findings it was decided not to proceed with Task 4, 5 and 6 and as such Objective No.2 has not been fulfilled.

2 Findings

2.1 Review of information

A wide range of information sources, both formal and informal, was trawled during the early stages of this project. The objective was to obtain observational, empirical and theoretical data covering all the main aspects involved external fire spread via windows. This included the following broad categories:

- Well-documented case histories for incidents in which fire has spread externally via the windows
- The rate of incidence of this phenomenon in the UK, and approximation of the risk factors based on statistical data for fire incidents and the UK building stock
- Experimental investigations into the projection of flames or hot gases from compartment fires through the windows
- Experimental studies on the effects of flames or thermal plumes on windows and facades
- The development of theoretical descriptions of the phenomena involved, and associated calculation methods
- The use of computer modelling techniques to assess the effects of various parameters, such as geometry of the building, wind effects, glazing performance etc.

A number of primary sources were exploited in obtaining this data. The main sources used include:

- BRE library databases, incorporating FLAIR and BRIX
- Fire Protection Association databases, covering publications, research, legislation and guidance
- Various on-line publication databases accessible to BRE, including those at the University of Greenwich, NIST (National Institute of Standards and Technology, USA), VTT (Netherlands), NRC (National Research Council, Canada), and various UK and overseas governmental websites
- The Home Office (now DTLR) fire statistics database
- Domestic and non-domestic databases at BRE, covering the UK building stock
- Contacts within the Fire Brigade and other fire-related organisations

- Colleagues within BRE and LPC
- On-line news agency databases
- On-line discussion groups and bulletin boards.

Findings

There was considerable variation in the volume and detail of information gathered, depending on the topic and source. Some difficulty was experienced in obtaining certain kinds of information, and some of the more obscure publications proved hard to obtain.

An overview of the results of the information-gathering exercise is presented in the following sections. This has been categorised according to the broad themes investigated. Brief descriptions of the findings are presented – this is to provide a general assessment of the subject matter.

References from this Review of Information are presented in Appendix 2. This list is not exhaustive, but is intended to provide a representative sample of the available (and most relevant) information that was gathered.

Real fire incidents in the UK and abroad

Searches were made on various library and news databases, as well as on-line discussion groups, and informal contacts were approached for further information. It quickly became apparent that cases which had involved fatal casualties or major losses would be well-documented and readily accessible, while those that did not would prove almost impossible to trace systematically. As a consequence, detailed case studies were collected on a number of serious or noteworthy incidents involving external vertical fire spread, while only indicative data was acquired regarding incidents which may have involved this phenomenon but were not widely reported.

Documented case studies

Case studies were acquired for 18 fires in which external vertical fire spread was identified as a significant factor. Some incidents were reported in more than one reference, and some discrepancies were found between reports of these cases. A summary of the reported incidents for which documentation has been obtained is shown in **Table 1**.

Table 1. Summary of reported incidents

Building	Date	No. storeys in building	Storeys involved	No. fatalities
Los Angeles County Health Building	15/2/1992	14	7 – 13	-
One Meridian Plaza, Philadelphia	23/2/1991	38	21 – 29	3
First Interstate Bank, Los Angeles	4/5/1988	62	11 – 14	-
Andraus Building, Sao Paulo, Brazil	24/2/1972	31	3 - 30	16/20
Hotel Tae Yon Kak, South Korea	1972	21	1 - ?	163
Joelma Building, Sao Paulo, Brazil	1/2/1974	25	11 - 24	179
Avianca Building, Bogota, Columbia	23/7/1973	36	12 - 35	4
Las Vegas Hilton	10/2/1981	30	7 - 29	8
Villiers House, London	18/1/1979	8 - 11	3 - 8	-
Mercantile Credit HQ, Basingstoke, Hampshire	16/4/1991	14	8 - 10	-
South African Agricultural Union Bld., Pretoria	15/6/1994	30	18 - 29	-
President Hotel, Bangkok, Thailand	23/2/1997	37	6 - 9	-
Knowsley Heights, Huyton, Merseyside	5/4/1991	10	G - 9	-
Westchase Hilton Hotel, Houston, Texas	6/3/1982	13	3 - 4	12
Glasgow House, Maida Vale, London	15/3/1996	17	6 - 7	-
Garnock Court, Irvine, Scotland	11/6/1999	14	5 - 13	1
Banker's Trust Building, New York	31/1/1993	30 - 42	5 - 6	-
One New York Plaza, New York	5/8/1970	50	32 - 33	-

Notes "No. storeys in building" includes ground floor

"Storeys involved" includes fire/heat damage, and is given using UK convention, such that top floor is *n*-1 where *n* is no. storeys in building

The cases found represent a mixture of types of building and occupancy, the most common ones being offices and residential tower blocks, although some of the incidents occurred in buildings of multiple use. For example, the President Hotel building comprised offices, retail premises hotel rooms and a bakery. Some of the incidents involved buildings under construction, or undergoing major works. The most severe fires occurred in buildings which contained large fire-loads and/or combustible ceiling or wall coverings. For example, in both of the Sao Paulo fires and the Bogota fire the presence of flammable ceiling and wall linings contributed significantly to the development of the initial compartment fire, which resulted in significant exposure to the external facades.

Many incidents were exacerbated by lack of effective automatic detection and warning systems. In some cases where there was significant loss of life, the means of escape provision appear to have been woefully inadequate. None of the cases cited had functional automatic sprinkler systems which operated at the time of the fire. Some of the buildings had only partial sprinkler provision, some were in the process of having sprinklers installed. In the Meridian Plaza fire, the fire was halted on the 29th floor by a sprinkler system which was fed by the brigade water supply.

There were several common problems encountered by virtue of the height of the buildings involved. These included hindered evacuation, internal access by fire-fighters (absence or failure of suitable lifts, contamination or obstruction of stairs), external access (limits on reach of aerial platforms and jets), problems with water supply pressure, falling debris and hot materials, and constraints on fighting fires on several floors simultaneously.

Some reports comment on the effects of the wind, which could have beneficial or detrimental effects on the egress of occupants and fire-fighting activities, depending on the wind direction and speed, and the state of the structure. For example, where an entire floor was involved and windows had failed on two or more sides, there were claims that the wind increased the intensity of the fire and the external projection of flames.

External cladding systems which contributed to the spread of flame featured in only a small number of the incidents. However, of the five UK incidents reported, two appeared to involve significant contributions from the cladding.

The problems associated with curtain wall systems, highlighted in many of the reports, may include spread via the mechanism of concern, but may also involve spread which is, strictly, within the building, due to inadequate, damaged or absent fire-stopping between the floor slabs and the curtain wall.

It is important to note that, although these cases have been selected because there was at least some external spread via the windows, in many cases there were other mechanisms of vertical spread, such as through voids and shafts within the building. From the information available in some cases, it was difficult to ascertain the real significance of the external spread, because the exact nature of the internal compartmentation was not clear.

Other UK cases

The primary source for data on fire incidents in the UK is the Home Office (now DTLR) fire statistics database, which contains a representative sample of all incidents attended by brigades. BRE has access to the full computerised dataset, as supplied by the Home Office (now DTLR), and a preliminary investigation of the suitability of the data for cataloguing cases of external fire spread via windows was carried out.

The information recorded on the database, which is taken from brigade FDR1 report forms, is fairly comprehensive, and includes characteristics of the building such as the number of storeys present and the number damaged. Unfortunately, the level of detail is not quite sufficient to allow the mechanism of vertical fire spread to be ascertained with any confidence. Consequently, it became apparent that it was not - possible to estimate the number of incidents which involved this mechanism in the UK, where they were not widely reported.

Searches were also made using the Fire Protection Association (FPA) database. This was found to use a system of categorisation that was less sophisticated than the Home Office one, which made searching for the required cases difficult. Moreover, the cases in the FPA database tend to represent more serious fires, in which there was significant loss.

A request was lodged with Chief and Assistant Chief Fire Officers' Association (CACFOA), to interrogate the FINDS (Fire Inter-Networking Database Service) database. Other brigade contacts were also approached.

Existing data was used to assess the risk factors involved in fire spread to other floors (by whatever means). The data from the Home Office (DTLR) statistics was compiled, and data on the UK building stock, in terms of number of buildings categorised by number of storeys and purpose group, was also collected from internal BRE databases. This allowed a risk analysis to be carried out that pertained to vertical fire spread in general, though this was not be restricted to external fire spread via windows.

Experimental and theoretical evidence

Several areas of fire research through the years have some bearing on the external spread of fire via windows, even where the objective of the research was concerned with another specific application. There have also been a small number of experimental studies, and theoretical approaches, which have been aimed directly at improving the understanding of this phenomenon. A few of the major research areas which emerged during the information gathering are as follows:

- Vertical spread of fire – vertical separation of windows, effects of projections
- Venting of hot gases or flames from openings in compartments, effects of fire load, opening geometry, wind
- Effects of exposure to radiation from compartment fires, and the effect on safe building separation
- Performance of glazing systems exposed to internal or external fires
- Cladding – its role in vertical fire spread, and radiation effects on the building facade
- Curtain walls – exposure to compartment fires and role in vertical spread
- Movement of smoke and thermal plumes, balcony and spill plumes

The applicability of these research areas to the phenomenon in question were varied, but taken together they represented a reasonably well-developed body of work with which to address the problem. The following sections introduce the information available on each of the major aspects that have been identified. It should be noted that there is some overlap between the categories in many cases.

Experimental work on window-to-window spread

Observations from some of the experiments carried out by BRE on the Timber Frame building at Cardington provided some of the impetus from this project. During some tests [B1] on this six-storey building, there was concern that the compartment above the fire room should not be damaged. To this end, the windows were boarded up, and a heat flux meter was placed at this location to measure the levels of incident radiation. The heat flux peaked at around 30kW/m^2, which, it was stated, would have been sufficient to ignite the wooden frame or any curtains that may have been present.

The Fire Research Station (FRS) conducted a series of experiments [B4] in 1960, using scale models and a full-scale four-storey building. Various glazing geometries were investigated, including the effect of vertical separation. The authors noted that the weather could influence the flame height in a complex way.

The Building Research Institute of Japan produced a very detailed report [B13] on vertical fire spread, which involved small- and large-scale tests, and investigated the temperature distributions and trajectories of plumes, and the effects of spandrel widths & projections.

Flame height and radiation from fires

Several reports have been published which address flame heights from compartment fires, and the effects of geometry and ventilation.

New Eurocode guides, which are currently in development, describe methods for calculating the exposure to steel structures from compartment fires, including flames and radiation. Some of the material may be readily applicable in assessing the hazards and risks of spread via windows.

A number of reports describe the heat transfer to facades from compartment fires, and much of this could be applied to glazing systems. The effects of spandrel height and vertical or horizontal projections was also investigated.

The performance of glazing systems

Several experimental studies on glazing systems have been reported. Many of these have focussed on the temperature and/or heat flux at which glazing has cracked and/or fallen out of the frame. Some researchers have commented on the importance of the distinctions between cracking and falling out, as this will clearly affect the ventilation to the compartment fire and the emission of flames or gases from the opening. Another crucial parameter is the material of construction, and some work has been reported which investigated wood, uPVC and aluminium frames. Single and double glazed systems have been examined, and the improved performance of fire-resistant glass has also been investigated. Calculation methods for predicting the failure of glazing systems have been reported (see Modelling Approaches below).

Another crucial aspect of the hazard regarding glazing that is difficult to quantify, but may have a significant effect on the risk of fire re-entry on upper floors, is where the windows are in the open position at the time of the fire. Various methods of opening are in use, including bottom-, top- and centre-hung, and hinging in the vertical or horizontal plane. The facility for opening of windows in high-rise buildings will depend mainly on the heating, ventilation and air-conditioning systems that are installed. There do not appear to be any UK guidelines on the nature of window openings, other than those that are intended to reduce the risk of falls from height. Clearly the risk of flames or hot gases entering the upper storeys of a building when the windows are open will depend on how they are hinged (e.g. top-hung windows opening outwards may act as a scoop), and the presence of combustibles in the vicinity.

Cladding systems

There has been significant interest in the hazards associated with cladding systems in recent years, and much of the experimental and theoretical work which has been carried out may be applicable to the problem of spread via windows. A significant volume of material came to light on this topic, and it is an area in which BRE has considerable expertise. Some of the studies which have described flame projection or radiation from openings have been prompted by concerns about the ignition of cladding. Furthermore, research on the performance of glazing systems has sometimes assumed that a cladding fire may be the source of the exposure.

This issue had already attracted a great deal of interest, and was the subject of a Select Committee review. However, although there was a wealth of information available, the majority of this work focussed on the contribution made by the cladding in any external spread of flame, rather than the wider issues involved in vertical spread, in terms of fire re-entering the building at higher levels. Data on the relative costs of various systems was also available.

Curtain walls

The Loss Prevention Council (LPC) carried out a major series of studies on the problems of vertical spread in building with glazed and non-glazed curtain wall systems. This included large-scale tests on multi-storey assemblies.

The major concerns surrounding curtain walls appear to revolve around the absence or inadequacy of fire-stopping between the floor slab and the façade itself, and also the nature of the supporting system to which the curtain wall panels are anchored (which are often made of aluminium). Considerable research has been undertaken into these and other issues. Data on the relative costs of various systems is also available, and this may be used to formulate impact assessments for any new guidance.

Further work ongoing by LPC Centre for Risk Sciences, now part of BRE, examined the issue of separation between glazed-panels, where non-glazed spandrel panels are used, in order to minimise vertical spread in buildings that employ curtain walling. Through this work, a significant volume of information has become available to BRE.

Modelling approaches

Various methods of modelling fire and its effects have emerged as having some useful application to the problem of vertical fire spread via windows. This has included modelling of:

- compartment fires, with regard to ventilation effects with different fuel loads and opening geometries
- the thermal plumes that emerge from openings in fire compartments
- the projection of flames from compartments
- the effect of balconies, downstands, or other horizontal or vertical projections
- the exposure resulting from flames or thermal plumes
- the performance of glazing systems under fire conditions.

Much of the work referred to here revolved around the development of zone modelling methods over a long period of time. From the experimental work that has been outlined above, and from theoretical or fundamental analyses, these methods have become widely used in fire engineering. There has also been considerable development in the modelling of smoke movement through large spaces, atria and malls, and some of this may be applicable to the modelling of window or balcony spill plumes. More recently, there have been a few reported applications of Computational Fluid Dynamics (CFD) simulations to the problem of external fire spread, and these have tended to focus on the same issues as the experimental studies outlined above, namely window geometry and façade protrusions.

Attention was also given to the modelling of glass and glazing systems, although the variability in design, construction and workmanship of the glazing system in its entirety tended to make accurate prediction very difficult. Furthermore, it seemed that the modelling of cracking of the glazing had been addressed in a few reports, but prediction of break-out of the glazing, i.e. when the glass starts to fall away from the frame, was much more unpredictable. Another aspect of the role of glazing in this phenomenon that does not appear to have received so much attention is that of the rate of transmission of radiation through an intact window. This affects the risk of ignition of room contents close to the window. It is generally believed that glass blocks a significant proportion of the incident radiation, and Malhotra [D8] stated that external flames would need to be very hot to ignite such items, but this may require further investigation. Law [B14] also cited experiments that examined the transmission of radiation through glass, and ignition of room contents. This leaves the questions of failure and break-out of the glazing, and how long this will take, for which there is considerable data, and the re-radiation to the contents of a room as the glazing temperature rises. Little data referring directly to the latter was found, and although it is considered a relatively simple physical process, it is also subject to large uncertainties in terms of the type and properties of glazing in use.

There are numerous techniques available which would allow a reasonably thorough numerical investigation of the mechanisms involved in vertical spread via windows to be carried out. Initial calculations using 'traditional' fire engineering calculation methods could be usefully supplemented by CFD simulations. A project carried out by BRE [C3] investigated the risk of external fire spread in a new building fitted with external louvres to control solar shading. There was concern that, if a fire were to occur while the louvres were closed, the cavity between the façade and the louvres may act as a flue. This was examined using JASMINE, a special-purpose CFD simulation tool to model the heat and mass transfer processes involved in the dispersion of combustion products from a fire, developed over many years by FRS/BRE. The influence of the wind was also investigated to some extent, whereby a few different wind conditions were simulated. The temperature and velocity data resulting from the JASMINE simulations were fed into the BREAK1 model [D9], to give an indicative prediction of the time to failure of the glass. The potential application for such an approach to the problem of vertical spread via windows is worthy of further consideration.

2.2 Review of codes and standards

Although information relating to the phenomenon in question has been found, very few cases of explicit reference to external spread from floor to floor via the windows has been found. Most of the codes reviewed addressed the problems of external spread in a wider context, that is, controlling the nature of the external surfaces and roofs of the building (materials, cavities etc.), and the spread of fire beyond the site boundary.

United Kingdom

Current regulations

The UK Building Regulations are the main codes that control fire spread in and around buildings. Approved Document B (AD B) (1) provides practical guidance on meeting the requirements of the Building Regulations, 1991. Paragraph B4(1) of schedule 1 to the 1991 Building Regulations states:

> External fire spread
>
> B4.-(1) The external walls of the building shall adequately resist the spread of fire over the walls and from one building to another, having regard to the height, use and position of the building.

Provisions are made in Section 13 AD B to limit the risk of ignition and fire spread in the external walls. The provisions depend on the height of the building and the distance to the notional boundary.

Section 14 of AD B presents provisions for the unprotected areas in the sides of buildings, which includes openings or areas with a combustible surface. These provisions are designed to limit the risk of fire spread by radiation from one building to another, although they are also related to the risk of external spread via the windows upon a single building.

Two methods are given in AD B for calculating the maximum acceptable unprotected area. Method 1 can be applied to small residential buildings (excluding institutional premises), and method 2 may be applied to all other building or compartment types. Both methods provide tables of boundary distances and maximum total area of unprotected surface. Method 2 is applicable only for buildings or compartments which are 10m or less in height.

Where a more precise calculation is required, or for buildings which are not small residential and which are greater than 10m in height, AD B Section B4 paragraph 14.15 refers to an alternative method, described in BRE Report BR187 (2). This report provides methods for calculating the level of radiation from compartment fires and fires on a building façade. It also outlines the factors involved in the ignition of the contents of a compartment due to radiation through the opening or glazing. The methods for calculating building separations may involve a 'geometric' method or a 'protractor' method. The objective of the methods is to ensure that the boundary distance of the building is sufficient to limit the thermal radiation at all the unprotected areas.

AD B Section B4 paragraph, 14.17 states that where a sprinkler conforming to BS 5306: Part 2 (3) is fitted, the boundary distance may be half of that given by the AD B methods or BR187 (subject to a minimum of 1m), *or* the total unprotected area may be doubled.

The LPC Design guide for the fire protection of buildings (4) refers to the problem of spread via windows. Section 3 covers compartmentation, and paragraph 3.3.1.3 states:

> Without substantially affecting the nature or aesthetics of the building it is generally difficult to build in measures that will prevent vertical spread as a result of fire by-passing the compartment floor by egressing from the windows below and re-entering via the windows above. However, where each floor is sprinklered the risk of fire spread is smaller.
>
> It is important to asses the risk in order to identify whether additional protection is necessary to overcome or reduce the potential threat to floors containing operations that are vital to the business.
>
> Where the building is not sprinkler protected the following measures are recommended for consideration:

(a) The external walls to the ground floor should have at least 30min fire resistance in terms of integrity and 15min insulation. Windows should be fire-resisting glazed assemblies and have fire resistance in terms of integrity of 30min. Secondary glazed with fire-resisting glass in fire-resisting frames that meets that standard may also be used. Glazed systems should be approved by LPCB in accordance with LPS 1158, issue 2. If part of the wall is less than 1.0m from the relevant boundary as defined in the supporting documents to the building regulations, higher levels of performance will be required. In addition, consideration should be given to the protecting the external walls and windows to upper floors to the same standard where appropriate;

(b) Where floors contain high values or equipment which is vital to the business, the external walls to such floors should comply with (a) above.

Note: Balconies, deflectors or upstands and downstands may not be completely effective but should be considered.

LPC also publisheed several reports relating to the specific problems associated with curtain walls (5, 6, 7). These tended to focus on the most common route of fire spread with such panels, which is between the floor slab and the façade itself, due to absent or inadequate fire-stopping.

No significantly different approaches to the problem were identified under Scottish, Welsh or Northern Ireland regulations and codes.

Previous regulations

According to Ashton and Malhotra (8), the issue of external fire spread in buildings first appeared in the regulations in 1952, as a result of the Fire Grading of Buildings Committee (9). The byelaws recommended that a reasonable level of protection could be obtained by having a window separation of 3ft (0·91m), at least 2ft (0·61m) should be above floor level. The Department of Health for Scotland adopted this recommendation, and added an alternative approach of using a horizontal projection of 2ft (0·61m) or more. London County Council byelaws (10) limited the total area of openings above the soffit of the first floor to one half of the total elevational area, and specified a minimum height above the floor of 2ft 6in (0·76m) for openings on each storey. The authors noted that similar provisions were found in other countries and cities abroad.

The report (8) concluded that vertical separations of 3ft (0·91m) or horizontal projections of 2ft (0·61m) are insufficient to prevent the re-entry of flames from a lower floor unless fire resistant glazing is used.

Hong Kong

The Hong Kong regulations relating to external fire spread Building Authority of Hong Kong Code of Practice for Fire Resisting Construction 1996 (11). The provisions for building separation is given in paragraph 7. Paragraph 12 provides details of the provisions for limiting external spread of fire. Paragraph 12.2 states:

> 12.2 A curtain wall or other similar construction, which protects the building against the elements and which extends beyond one storey in height, should be constructed entirely of non-combustible materials. Any void formed between the curtain wall and the perimeter of the building onto which the curtain wall is fixed should be solidly infilled at each floor level by non-combustible materials having an FRP [fire resistance period] of not less than that required by the floor.

Paragraph 12.3 gives explicit instructions on spandrel heights:

> 12.3 Subject to paragraph 7, the external wall of a building at any floor should be separated from the external wall at the floor next below by a spandrel which :
>
> (a) is not less than 900 mm in height; and
>
> (b) is of non-combustible materials having an FRP of not less that that of the intervening floor.

The fire resistance periods referred to in these clauses are determined both by the purpose group and compartment volume.

Australia

Fire Engineering Guidelines [(12)] provides guidance on meeting the provisions of the Building Code of Australia. Section 5 presents design guidance on various aspect of fire safety, and paragraph 5.5.5 describes the management of vertical fire spread. Paragraph 5.5.5.2 deals specifically with external vertical spread, and states:

> 12.3 Subject to paragraph 7, the external wall of a building at any floor should be separated from the external wall at the floor next below by a spandrel which :
>
> (a) is not less than 900 mm in height; and
>
> (b) is of non-combustible materials having an FRP of not less that that of the intervening floor.

5.5.5.2 External vertical spread route

Fire may spread to the next floor via flames which project through external openings and radiate back to the windows above. In the Building Code of Australia, if the building is unsprinklered, spandrels are required to be constructed to limit this type of vertical flame spread. Spandrels which project vertically have been shown to be less effective than horizontal projections whilst the latter lacks architectural appeal. Calculation of the radiation level on the window above, based on an empirically derived flame shape is available (Drysdale 1988). However, flame projections from windows are highly variable and such calculations should be used with caution.

Automatic sprinklers (see 5.6) are highly effective in controlling fire spread via an external route. Drencher systems are also effective if they are designed to prevent glazing from breaking out but may not sufficiently reduce the intensity of the fire.

The guidelines present a brief overview of the issues involved, but no quantitative guidance.

Further information was found directly from the Building Code of Australia [13], which supplements that stated above. The Deemed to Satisfy Provision C2 - Compartmentation and Separation, sets out specific guidance directly relevant to vertical fire spread:

C2.6 Vertical separation of openings in external walls

(a) If in a building of Type A construction, any part of a window or other opening in an external wall is above another opening in the storey below and its vertical projection falls no further than 450mm outside the lower opening (measured horizontally), the openings must be separated by -

i) a spandrel which -

A) is not less than 900mm in height; and

B) extends not less than 600mm above the upper surface of the intervening floor; and

C) is of non-combustible material having an FRL of not less than 60/60/60;

OR

ii) part of a curtain wall or panel wall that complies with (i); or

iii) construction that complies with (i) behind a curtain wall or panel wall and has any gaps packed with a non-combustible material that will withstand thermal expansion and structural movement of the walling without the loss of seal against fire and smoke; or

iv) a slab or other horizontal construction that -

A) projects outwards from the external face of the wall not less than 1100mm; and

B) extends along the wall not less than 450mm beyond the openings concerned; and

C) is non-combustible and has an FRL of not less than 60/60/60.

(b) The requirements of (a) do not apply to - ……….

iii) a building which has a sprinkler system complying with Specification E1.5 installed throughout

Subject to the type of construction, the above requirements would apply to buildings typically between three and eight storeys in height. Below this, provision for vertical separation is not required and above which buildings are required to be sprinklered.

New Zealand

The New Zealand Building code is accompanied by the Fire Engineering Design Guide [14], which is a comprehensive introduction to fire safety & design. The approach is similar to that adopted in Australia. Section 8.4 deals with fire spread to other storeys, the paragraph on exterior spread states:

Exterior windows

Spread of fire via exterior windows is a major hazard in multi-storey building, as shown in figure 8.4 (b).

Building codes have traditionally specified vertical spandrels or horizontal apron projections to limit vertical flame spread. Vertical spandrels are not much use unless they are so high as to severely restrict window openings. Horizontal apron projections are much more effective (Oleszkiewicz, 1991), although they are often less acceptable for architectural purposes.

A suggested design procedure is to calculate the size and shape of the expected flame from a window and then calculate radiation back to the building via the window above. Approximate flame size calculations are given below (Drysdale, 1988). Flame sizes from windows are extremely variable, depending on room geometry, fuel orientation and especially wind conditions, so these calculations should be used with caution.

Again, the guide recommends sprinklers as an effective method of controlling the fire, or window drenchers to reduce the risk of window failure.

The New Zealand Building Code (NZBC 1992) [15] deals with the fire performance of external walls through Clause 3.3.5, which states:

External walls and roofs shall have resistance to the spread of fire, appropriate to the fire load within the building and to the proximity of other household units and other property.

The Acceptable Solution C3/AS1 of the New Zealand Building Industry Authority (BIA 1992) Approved Documents, provides one approved means of complying with this clause. C3/AS1 seeks to reduce the likelihood of fire propagating vertically up a combustible façade either as a result of direct flame impingement from an adjacent building on fire, or as a result of flames projecting through openings at a lower level in the same building and igniting the façade in the vicinity of the opening. The requirements seek to control either the ignitability or the contribution of the cladding to fire development and thereby indirectly influence the rate of vertical flame spread, by use of standard test methods.

For external walls, the acceptable properties of exterior surface finishes depend on the purpose groups exposed to the fire hazard, the building height and distance from the relevant boundary.

New Zealand currently has requirements for aprons of 0.6m wide or spandrels of 2.5m high to be provided in unsprinklered buildings containing sleeping accommodation on upper floors. However, the minimum spandrel height is likely to be reduced to 1.5m. There are no requirements for aprons or spandrels in office buildings (sprinklers are required when the building height is above 25m).

Singapore

Guidelines are presented in the Code of Practice for Fire Precautions in Buildings (16). Section 3.5 deals with external walls, and specifies boundary separations, limits on unprotected areas in the sides of buildings, and external spread due to fires on roofs affecting the sides of a building. There is no explicit reference to spread via windows.

Canada

The National Building Code of Canada (17), provides prescriptive guidance on the use of combustible components for exterior walls with or without sprinklers, however it does offer additional guidance on exposure protection of openings. Section 3.2.3.16 deals with canopy protection from vertically separated openings:

1. If a storey is required to be separated from the storey above by a fire separation,

(a) every opening in the exterior wall of the lower storey that is located vertically below an opening in the storey above shall be separated from the storey above by a canopy projecting not less than 1m from the face of the building at the intervening floor level, and

(b) the canopy required by Clause (a) shall have a fire-resistance not less than that required for the floor assembly but need not be more than 1 hour.

2. Except as permitted by Sentence (3), the canopy required by Sentence (1) is permitted to be omitted if the exterior wall of the upper storey is recessed not less than 1m behind the exterior wall containing the opening in the lower storey.

3. The requirements of Sentences (1) and (2) are permitted to be waived if the building is sprinklered throughout.

However, the above guidance relates only to Group E or F occupancies. Group E is 'Mercantile Occupancies' used for the displaying or selling of retail goods, wares or merchandise, ie. department stores and for use in unsprinklered occupancies only. Group F is for high and medium hazard occupancies such as industrial occupancies or factories. There is no specific guidance for Group C Residential, or Group D Business Occupancies.

Part 9 of the Code deals with Housing and Small Buildings. Small buildings are classed as those of 3 storeys or less in building height and having a building area not exceeding 600m^2. Section 9.10.12 Prevention of Fire Spread at Exterior Walls and Between Storeys states for separation of exterior openings:

1. In buildings or mercantile or medium hazard industrial occupancy, exterior openings in one storey shall be separated from exterior openings in an adjacent storey by

(a) a wall not less than 1m in vertical dimension, or

(b) a canopy or balcony not less than 1m in width.

Again the canopy, wall or balcony must have a fire resistance rating comparable to that of the floor, but not greater than 1hour.

Elsewhere, the guidance relates only to the limits on distance between building facades.

Sprinklers are required in all buildings greater than three storeys in building height, subject to constraints on building area.

USA

The Uniform Building Code [18] refers to office buildings as Group B and residential occupancies as Group R.

Section 403 states that all occupancies of Group B and R type shall be sprinkler protected throughout, where the building height exceeds 75 feet (22.86m) above the lowest level of fire department access.

Guidance in Section 709 for Walls and Partitions addresses the problem of vertical fire spread at external walls:

709.3.2.3 Exterior

When openings in an exterior wall are above and within 5 feet (1524mm) laterally of an opening in the storey below, such openings shall be separated by an approved flame barrier extending 30 inches (762mm) beyond the exterior wall in the plane of the floor, or by approved vertical flame barriers not less than 3 feet (914mm) high measured

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vertically above the top of the lower opening. Flame barriers shall have a fire resistance of not less than 3/4 hour.

Exceptions:

1. Flame barriers are not required in buildings equipped with an approved sprinkler system throughout.
2. This section shall not apply to buildings of three storeys or less in height.

Further passive fire protection is required at any gap between the edge of the floor assembly and an external wall.

Sweden

There are two documents available relating to building construction and fire spread.

The Swedish Building Code SBN 1980, Chapter 37, Fire Protection deals with external walls in Section 423. However, this is limited to specifying that external walls in fire resistant buildings shall be constructed in such a way that the risk of fire spread along or through the walls is limited and constructed of incombustible materials. There is no specific guidance to fire spread via windows here.

An alternative document is the Swedish Regulations for New Construction (19), which makes reference to the problems of external fire, spread via windows. Section 8.43 states that for external walls and windows, the materials used in the façade cladding shall have a very high ignition temperature. The external walls themselves shall be constructed so that 'the risk of fire spread via windows is limited' but does not quantify that statement.

However, it does venture further to state ' between windows in different fire compartments, the vertical distance should not be less than 1.2m unless the windows inside this distance are constructed to not less than Class F15'.

Malaysia

Guidance presented in the Uniform Building By-Laws (20) is minimal, however Section 149 of the document makes specific reference to protection of openings in an external wall:

Horizontal and vertical barriers of the external wall:

Openings in external walls located vertically above one another shall be protected by approved flame barriers either extending 750mm beyond the exterior wall in the plane of the floor or by vertical panels not less than 90mm in height.

(It should be noted here that it is the author's belief that the 90mm-height requirement stated above should read 900mm, and is a translation error in the original text.)

Section 142 Part 3 requires the external wall of a building, which exceeds 15m in height to be constructed wholly of non-combustible material. The test methods stated for evaluation are generally not deemed adequate for evaluation of the end-use performance of exterior cladding materials and systems.

Countries such as Malaysia tend to look towards USA and Europe and readily adopt controls and test methods developed and tested there.

2.3 Analysis of findings

There have been a relatively low number, yet high profile fires in high-rise buildings over the recent years involving domestic apartment/residential buildings and commercial office buildings. There are approximately 3500 residential tower blocks of greater than ten storeys in height in the UK with approximately 500 of these fitted with external cladding [(21)].

The fire mechanisms by which exterior cladding systems may ignite and contribute to vertical fire spread include:

- Flames projecting from broken windows in the room of origin, exposing the façade and any windows above, thus allowing for the upper windows to fail and allow flames & hot gases to enter the floor above
- Inadequate fire stopping of the gap between the edge of the floor slab and the exterior wall allowing for flames and hot gases to pass directly to the floor above. This is especially notable with curtain wall construction.
- Heat induced distortion of supporting frameworks causing the fire-stopping to become inadequate or collapse
- Direct contribution of the external cladding material to vertical fire spread. Ignition may occur following exposure to flames projecting from window openings.

Some of the more notable and international fire incidents include:

- a 31-storey department store and office building – Andraus Building, Sao Paulo, Brazil 1972 – *no fatalities*
- a 25-storey office building – Joelma Building, Sao Paulo, Brazil 1974 – *179 deaths*
- a 30-storey hotel – Las Vegas Hilton Hotel, 1981 – *eight deaths in various locations*
- 62-stoery tower – First Interstate Bank Building, Los Angeles, California 1988 – *no fatalities*
- a 12-storey office block – Mercantile Credit Building, Basingstoke 1991 – *no fatalities*
- a 38-storey bank building – One Meridian Plaza Building, Philadelphia 1991 – *no fatalities*
- a 11-storey residential tower block, Knowsley Heights, Liverpool, 1991 – *no fatalities*

- a 37-storey retail, commercial office and hotel development - President Tower, Bangkok 1997 – *no fatalities* , and
- 13-storey residential tower block, Irvine, Scotland, 1999 – *one death in the flat of fire origin*

All those incidents mentioned above directly involved exterior fire spread via the curtain walling façade or non-combustible spandrel material. None of the buildings had sprinklers installed and/or available and they were difficult to extinguish. Fire fighters were forced to tackle the fires on the upper floor levels from outside the building, as it was unsafe for them to enter floors above the fire zone.

There is no information held by BRE's historical records of fire incidents, which indicate the number of deaths in the room of origin.

It is clear that the guidance provided by national regulation within England and Wales, or codes of practice does not effectively address the particular problems of fire spread via windows.

Out of the nine international countries reviewed here over half (Canada, USA, Australia, New Zealand and Malaysia), offer guidance on use of both spandrel or apron applications, although the restrictions to building occupancy type and height do vary across the board. Hong Kong makes reference to spandrel height only. Only three countries, Canada, USA and Australia, state that requirements for spandrel height and/or apron projections can be waived if the building is sprinklered throughout. The UK regulations notably lack guidance on either, however it does have a requirement for sprinkler protection in buildings over 30m in height, however this would not apply to any Purpose Group 1(a) (flats) part of a mixed use building.

International research has shown that the requirements for setting minimal spandrel heights (set out by those countries that attempt to address this problem), is an option that remains largely ineffective. Research, particularly that carried out by the National Research Council of Canada, has shown that spandrel walls need to be of an impractical height (>2.5m) to be effective for controlling vertical fire spread. The Canadian results show that by using an 1100mm wide apron, the exposure to the wall face was reduced to approximately 10% of that experienced by the 900mm spandrel height.

In order to overcome the problem of excessive spandrel height, consideration could be offered to the use of staggered window positions within a façade. This would serve to increase the spandrel height without having an implication on the slab to slab distances per storey. Careful planning of residential tower blocks could position window openings to accommodate the suggested 2.5m separation distance.

Igor Oleszkiewicz from the National Fire Laboratory, National Research Council, Canada carried out a substantial amount of research work into this area including vertical separation distances of spandrel panels and horizontal projections and the effects of flame spread on combustible cladding.

His research [22] suggested that the equal weighting usually given by building regulations and codes with respect to spandrel height and apron width needed to be re-examined. A series of tests were carried out on a three storey high enclosure with a 2.6m (width) x 1.37m (height) window opening. Two different heat release rates were used which were typical for the size of compartment, window dimension and fire load. Horizontal projections were located immediately above the window and were 1.0m, 0.6m and 0.3m in depth. The experiments combined the use of each heat release rate with and without a projection. It was found that without the use of the projection, the maximum flame heights above the top of the opening were approximately 2m and 3m for the low and high heat release rates, respectively.

The experimental data showed that the level of protection afforded to the wall increased with the depth of projection. The 0.6m projection reduced the exposure by approximately 60%. At 1m above the opening, the 1m projection reduced the exposure by 85% when compared to readings without any projection.

In the same experiments it was found that in order to achieve a 50% reduction in exposure to the wall above the window opening, a 2.5m high spandrel would be required. It is interesting to note that the same level of protection offered by the 2.5m spandrel was afforded by the 0.3m deep projection at 1m above the opening and less than 0.5m above the opening when using the 0.6m projection.

Further work was undertaken by Oleszkiewicz, which included the effects of window orientation and dimension [23]. A similar test apparatus as discussed above was used. Four levels of fire load were assumed ranging from a room furnished with traditional wood furniture (low range of fire intensity) up to a fire involving a large quantity of thermoplastics or thin combustible panelling, representing the higher fire intensities. Three windows of different dimension were used, 2.6m (width) x 2.7m(height), 0.94m (width) x 2.70m (height) and 2.6m (width) x 1.37m (height). Measurements of heat intensity were taken at 0.5m above the top of the window opening.

The data showed that the fire exposure to the exterior wall depends greatly upon both the window dimensions and heat release rate from the room. The wide and shallow window opening (2.6m x 1.37m) provided the highest thermal exposure on the façade. This is due to the velocity of the gases exiting the compartment. Gases are driven by buoyancy, which increases with the height of the window opening. The velocity is kept lower with this window dimension; the flames remain better attached to the wall above the window and so transfer more heat to the wall than did the flames issuing from the taller windows. Tall windows tend to project the flame plume away from the wall decreasing the thermal coupling of flames with the wall and cause relatively lower thermal exposure. The lowest heat release rates measured were from the more square shaped window, 2.6m x 2.7m.

Another factor found to influence the window fire plume, is the shape of the façade. Features such as 'sun shades' and deep mullions can either protect the façade from the plume, or cause greater fire exposure.

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A test carried out using vertical projections channelled the flame plume up and caused a 50% increase in the heat intensity measured above the window opening. This means that locating windows in a vertical recess or providing vertical shades or privacy screens would increase the fire exposure to the wall above the venting window as well as to the window in the storey above.

Certain combustible claddings can support unlimited vertical flame spread. However, some do not, if the combustibility of the cladding is not significant. Factors such as the amount of combustibles per unit area, their heat of combustion, the ignition temperature of the combustible components, composition of the cladding and preservation of integrity when exposed to fire determine the propensity for vertical flame spread and hence its contribution to the window flame plume.

It is very difficult to identify whether a façade fire directly influences the occurrence of casualties during the incident. Information from various databases is limitedand the ability to decipher the recorded statistics is somewhat masked by the method of reporting on the UK FDR1 fire reports. Information has been taken from the FDR1 statistics for the year 1998 and is shown below in **Table 2** to **Table 6**. The data below refers to the number of fires in buildings by total number of floors in the building, number and type of casualty. The data also only relates to the classification of 'Other Buildings' and hence does not include for domestic fires in homes. Although generally based on a weighted sample of 20% of UK incidents, all fires are recorded where a fatality has occurred. The number of casualties also includes the Brigade personnel. In 1998, there were 681 non-fatal Brigade casualties, but no fatalities.

Table 2 to **Table 5** look at the casualties over a range of building heights. This data does not identify which floor is the floor of 'fire origin', merely the total number of floors in any particular building. It does, however, highlight the location of the casualty with respect to the fire location. It can be seen that the majority of casualties are found in the room of fire origin and as such, cannot be directly attributed to the effects of external fire spread.

Table 2 Fatal casualties injured by burns an/or scalds and location of casualty relative to fire

Total number of floors in building	Number of Fatalities – Burns and/or Scalds					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor - 1	≥ Floor - 2
1	18	1				
2	52	5	1			
3	16	1	1			
4	2					
5	2					

Table 2 Continued

Total number of floors in building	Number of Fatalities – Burns and/or Scalds					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor - 1	≥ Floor - 2
6-10	3					
11-15						
16-20	1	1				
21+	1					

Table 3 Non-fatal casualties injured by burns an/or scalds and location of casualty relative to fire

Total number of floors in building	Number of Non-Fatal Injuries – Burns and/or Scalds					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor - 1	≥ Floor - 2
1	241	20			1	
2	844	114	32		17	
3	228	34	10	1	5	1
4	62	9	1	1		
5	15	3		3		
6-10	22	1			1	
11-15	19	9	1			
16-20	6	2				
21+	1					

Comparing the range of injury type, it is clear that there are a greater number of injuries caused by inhalation of smoke and toxic fumes than actual burns or scalds. As the spread is also wider for the non-fatal injury (**Table 5**), this can be attributed to smoke spread through the building compartments and floors. Surprisingly, we also see a number exposed to smoke spread on floors below the floor of fire origin.

Table 4 Fatal casualties injured by smoke and/or gas inhalation and location of casualty relative to fire

Total number of floors in building	Number of Fatalities – Smoke and/or gas					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor - 1	≥ Floor - 2
1	15	12	1			
2	75	48	45		4	
3	20	21	13	1		
4	5	2	4			
5		4				
6-10	3	4				
11-15	2		2			
16-20		1				
21+		2				

Table 5 Non-fatal casualties injured by smoke and/or gas inhalation and location of casualty relative to fire

Total number of floors in building	Number of Non-Fatal Injuries – Smoke and/or Gas					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor - 1	≥ Floor - 2
1	235	189	8	1		
2	1277	1246	699	6	122	2
3	379	484	182	71	31	6
4	147	213	66	43	8	1
5	38	45	21	28		
6-10	34	61	15	1		4
11-15	37	75	3	7	4	3

Table 5 Continued

Total number of floors in building	Number of Non-Fatal Injuries – Smoke and/or Gas					
	Room of origin	Floor of origin	Floor +1	≥ Floor + 2	Floor – 1	≥ Floor – 2
16-20	16	39	1	6		
21+	4	18	1			1

From **Table 2** to **Table 5**, we see that the majority of injuries and fatalities occur within relatively low rise buildings which can be easily accessible by the Brigade. Within the lower rise buildings, the spread of smoke and toxic gases appears to enter the majority of floors within the building. This would most likely be due to occupants or Brigade personnel opening doors for means of escape and to gain access.

Table 6 below looks at two specific building heights, 12 and 10-storeys. Clearly, the majority of fires occur on the ground floor level, with a relatively even distribution over the remainder of the floors. This would tend to imply deliberately set fires, possibly through the setting of rubbish fires.

Table 6 Number of fires in buildings by floor of origin for a 12 and 10-storey building

12-Storey Building			10-Storey Building		
Floor Number	Number of Fires	Percentage Number of Fires	Floor Number	Number of Fires	Percentage Number of Fires
	16.3	30.			
-1	7.3	1.3	-1	5.8	1.2
0 (GROUND)	132.3	24.3	0 (GROUND)	150.9	32.0
1	46.6	8.6	1	42.0	8.9
2	32.8	6.0	2	36.5	7.7
3	32.3	5.9	3	42.7	9.1
4	32.9	6.0	4	37.1	7.9
5	37.6	6.9	5	26.2	5.6
6	46.5	8.5	6	34.0	7.2

Table 6 Continued

12-Storey Building			10-Storey Building		
Floor Number	Number of Fires	Percentage Number of Fires	Floor Number	Number of Fires	Percentage Number of Fires
7	37.8	6.9	7	26.6	5.7
8	37.8	6.9	8	31.4	6.7
9	19.9	3.6	9	38.3	8.1
10	16.3	3.0			
11	48.6	8.9			
Total	545	100 %	Total	433.1	100 %

Assessment of risk

There are relatively few documented cases of extensive external vertical fire spread involving combustible claddings or glazed facades, and there are even fewer cases where such spread has significantly compromised life safety.

Façade fires do not generally threaten building occupants, but the concern is that fire spread through the openings into upper levels may result in secondary fires, which can threaten occupants. It has been suggested that 'sterile zones' could be employed in regions close to windows, with managed policies of no combustibles near windows. This however is difficult to enforce in a domestic (or indeed many other) installations.

The UK guidance given in Approved Document B Fire Safety, deals with the issue of life safety for different occupancies by application of building construction and limits on performance of material. It is the Insurance Industry which is leading the risk assessment of buildings with fully or partially glazed installations, however this is with a view to effects of business interruption and replacement costs.

Building fires result in damage to the fabric and contents of the building and often extensive business interruption. The impact of fire, flame smoke and extinguishing water on a building is dependent upon the fire severity. In 90% of fires, damage is limited to a single compartment or room. However, this means that in 10% of fires, they continue to spread and hence fire damage goes beyond the original enclosure. As a result of experimental work carried out by the Loss Prevention Council, the Association of British Insurers (ABI) published guidance for their members, concerning the estimated maximum loss (EML) in high-rise and multi-storey buildings. Here a fire risk assessment was made of the façade (6) to determine the

- associated fire hazards (occupancy, building design and construction)

- fire protection (management, sprinklers, fire brigade operations)
- type of façade employed (design, key features and construction materials)

The Fire Risk Assessment Form [6] looks at the construction of the façade including types of structure, fixings, window, cavity etc. Information is given as to the design and material performance with an assessment as to the relative fire performance on a scale of 0 to 2. An example of such for cladding panels would be:

- 0 non-combustible and fire resistant or adequately protected eg. By an approved

drencher system;

- 1 limited combustibility (Class O and full-scale testing), some inherent strength

and/or obstruction preventing direct flame impingement on susceptible parts;

- 2 combustible, poor fire resistance and exposed to direct flame impingement

Finally recommendations are made as to the provision of additional protection requirement or further testing.

A figure for the total fire performance of the system is calculated from the sum of the individual components. This figure is input into an assessment of the extent of damage for a particular façade.

The extent of damage incurred will depend on the characteristics of the fire, enclosure and façade. Extent of damage can be divided up into two components, enclosures (number of floors above the fire enclosure that could be damaged due to fire spread) and façade (extent of damage over the façade in terms of number of floors above the fire enclosure). The estimated number of damaged storeys is always assumed to be the minimum, with indication made as to where the fire could involve more than one floor or multiple floors.

More floors are likely to be damaged when:

- the façade is constructed from materials that have a weak performance in fire ie. glass;
- combustible products form part of the façade;
- a combustible cavity exists (between structural elements and the façade)

Damage to multiple storeys is more likely to occur with façades that have a continuous cavity between the backing wall and façade or containing combustibles. However, this does also depend upon the fire severity and fire-fighting availability.

The ABI's EML definitions for extent of damage are:

- an enclosure rating 2+ (façade fire performance rating >7) to be equivalent to a 4-floor fire zone and 20% damage on other floors;
- an enclosure rating of 1-1+ (façade fire performance <7) to be equivalent to a 2-floor fire zone and 10% damage on other floors

The size of the floor area and fire load will determine the extent of damage per floor and the length of the façade within the enclosure area will determine the extent of damage per façade width.

The possible extent of damage will then lead on to consideration of cost of replacement. Damage due to fire will require the replacement of sections of the façade or individual panels. Where the construction of a particular type of façade does not enable the replacement of sections of the system, the building owners and/or insurers may incur excessive costs for replacing the whole system. A number of factors will influence the cost of replacement. The factors include: type and design of the façade system, type and colour of the original cladding panels, weathering, age, cost of original system and access to the façade.

The cost of the original system per unit area will give some guidance as to the cost of replacing a damaged façade. However, the cost of replacement of small sections will undoubtedly incur greater costs due to lack of bulk purchasing capacity and installation practicalities. Indicative costs for new systems are shown below:

Façade Type	Cost £/m^2
Facings	35-640
Concrete Panels	275-750
Rainscreen – flat wall	85-400
Rainscreen type – composite wall panels	30-300
Curtain walling	250-1000+

In addition to the above, where the performance of a component of a façade system is not well established, the building owner is advised to seek test reports from appropriate standard tests. Similarly, where a complete wall façade system performance is not well established, tests on full scale system should be carried out following standards such as BRE Fire Note 9 [25] or LPR 11[5], as appropriate.

3 List of outputs

BRE Output / Milestone Reference	Title	Date submitted
203137	Quarterly progress report	June 2001
203130	Task 1 – A survey of available information on incidents of flame spread through windows	August 2001
203132	Task 3 – A review of codes and standards relating to fire spread through windows	August 2001
203138	Quarterly progress report	September 2001
203131	Task 2 – Analysis of the findings	November 2001
203139	Quarterly progress report	December 2001

4 Discussion

This Closing Report is a compilation of the previous three reports produced on this project. They are;

Report 1(Task 1); A survey of available information on incidents of flame spread through windows, Project report number 203130

Report 2 (Task 3); A review of codes and standards relating to fire spread through windows, Project report number 203132

Report 3 (Task 2); External fire spread via windows - Analysis of the findings, Project report number 203131

Review of information

A survey of the information available on external fire spread via windows was undertaken, from a wide variety of sources. This was to include any material that may inform an assessment of the likely hazards and risks.

A large volume of information was collated, which included case studies of relevant fire incidents, experimental research and data, theoretical approaches to the phenomena involved, and modelling techniques that have (or may be) applied to the problem. An assessment of the information gathered was carried out.

There remain some areas, however, for which little if any data has been found. This has been mainly in the area of fire incidents which were not widely reported (presumably because there was no major loss involved), yet which may nevertheless have involved some vertical spread via the windows.

Review of codes and standards

Regulatory guidance and codes that relate specifically to the external spread of fire via windows proved hard to obtain. Codes from most locales contain guidance on external spread due to flammable materials, or the spread of fire between adjacent buildings, yet few address the problem or re-entry of fire on upper floors directly. Of those that do which have been obtained in this survey, only one gives any quantified requirements (Hong Kong specifies 900mm spandrel widths). Others that do refer to the problem explicitly have tended to point the designer in the direction of various calculation methods, suggesting a more performance-based approach.

Many of the codes that have been identified stress the conflict between the effective hindrance of external vertical fire spread, and the aesthetic or practical issues of façade construction. For this reason, a number of other protective measures have been frequently proposed, particularly automatic sprinklers and fire resistant glazing.

There are indications that many regulatory and guidance codes tend to focus more on internal spread of fire (or smoke) through the building, rather than the potential for external spread (other than that which is confined to the outer surfaces). It may be that this reflects a genuine difference between the risks from internal and external spread. However, if it is to be assumed that the levels of internal compartmentation in modern UK buildings is now of a generally high standard, due to improved design and construction, it may be that the relative balance has shifted somewhat, and the potential risk of external floor-to-floor spread should not be neglected.

Analysis of findings

For fire to spread up a building, the fire must break out of a window from a fully involved compartment (i.e. a flashed over fire). Fires on stairways and other escape routes are unlikely (thought not impossibly) to contain sufficient fuel to allow for a fully developed fire.

In general, although not invariably, the layout of a building will result in a stairway window being above another stairway window (usually the same shaft). Similarly, a room (compartment) window will usually be above another compartment window. It follows that a fire from a stairway window would most probably spread to another stairway window, and a fire from a compartment window would most probably spread to another compartment window. Escape routes (except for stairways and stairway lobbies) are usually on the interior of the building. If an exterior fire attacks a compartment (as a result of fire spread up the outside of the building) this will not compromise escape.

Compartment fires do not instantly go to flash-over; there will nearly always be a time delay. It is quite unlikely then that a fire in a large building can reach flashover without the occupants being aware that an incident is in progress.

For these reasons it might be expected that the numbers of people killed or injured as a result of this particular mechanism for fire spread would be quite low.

There are relatively few documented cases of extensive external vertical fire spread involving combustible claddings or glazed facades, and there are even fewer cases where such spread has significantly compromised life safety.

However, there have been incidents where fire has spread up the outside of a building and where there has been a fire fatality from the same incident (Irving, 1999). It is notable that this fatality was not as a result of the fire spread.

Where requirements for vertical separation of openings are given, consideration should be given to the removal of the requirement for 900mm high spandrels in favour of horizontal projections or sprinkler protection.

However, it is very likely that this change would be unacceptable to most building developers and architects due to the aesthetic implications, or potentially large expense of a building wide sprinkler installation.

International research (particularly that carried out by the National Research Council of Canada) has shown that spandrel walls need to be of impractical height to be effective for controlling vertical fire spread. It was shown that horizontal projections are far more effective than spandrel walls.

Curtain wall constructions have particular problems of fire spread via the void junctions between the floor slab edge and the façade itself. Distortion of the wall panels can lead to collapse of the passive protection at the floor slab.

Horizontal applications would be incompatible with curtain wall constructions. Here, the only real means of limiting or preventing the risk of vertical fire spread would be the use of sprinkler systems or fire resistant glazing. Work undertaken by the LPC has shown that a fire resisting façade was able to survive elevated temperatures during a fire and prevent breakout and subsequent spread up the system.

A number of mitigatory or protective measures have been identified within the body of this report and include:

- *Spandrel panels* – although not always an appropriate solution, they still perform an important task and could be critical in some buildings and occupancies. Buildings of particular concern are the high-rise buildings with slow evacuation times such as apartment blocks, hospitals, or where phased evacuation is undertaken.
- *Horizontal projections* – more effective than spandrel panel system in reducing the heat exposure to the upper floor level. Does have an aesthetic implication for building design. Impractical for large glazed areas.
- *Window orientation and size* – the heat exposure can be influenced and to a point controlled by the use of tall and thin window dimension, low and wide orientation results in a much higher heat intensity on the above façade.
- *Sprinklers* – the most effective and accessible control method. Reduces the gas temperature to levels that are not threatening to the non-fire resisting façade. Especially useful with curtain walling systems. Favoured by the international community over the use of spandrel and/or apron projection.
- *Limited combustibility of claddings* – submit all cladding materials to appropriate test methods available. BRE cladding test – Fire Note 9 outlines such a test. Additional full size testing should be carried out for applications of glazed façades.
- *Fire resistant glazing and facades* – windows or openings introduce a weakness to the façade. Use of fire resistant materials provides improved integrity of glazed systems. Full scale tests allow for assessment of the whole system performance.
- *Sterile zones* – for combustible products so use non-combustible curtains, blinds etc. Limits fire load adjacent to window openings and hence the risk of exposure from external flaming.
- *Staggering the window layouts* – to increase spandrel height in a façade.

The relatively low number of deaths or injuries is supported by the Brigade statistics identified here. It has not been possible to identify any incidents in the UK where death or injury has resulted from fire spread up the outside of a building where the fire has broken out of one window and re-entered at another. Indeed, very few people are killed or injured from fire who are elsewhere than on the fire floor. Most deaths or injuries on floors other than the fire floor are as a result of smoke.

It therefore may be concluded that fire spread up the outside of buildings via the windows is not a significant threat to life compared with the other risks from fire in tall buildings. The UK guidance given in Approved Document B Fire Safety, deals with the issue of life safety for different occupancies by application of building construction and limits on performance of material. It is the insurance industry which is leading the risk assessment of buildings with fully or partially glazed installations, however this is with a view to effects of business interruption and replacement costs. For buildings that are seen as being at particular risk from this process (for example, for property or contents) then the various methods given above could be applied.

Those that are most effective are the ones that have the greatest impact on the design of the building. The optimum response to this particular risk is sprinkler protection, to limit the probability of a large fire and to limit its spread. Sprinklers are already a requirement for buildings over 30m in England and Wales, except for residential.

The evidence acquired for this project therefore leads to the conclusion that the measures currently called upon in England and Wales through AD B are still commensurate with the risk. An assessment needs to be made, on an individual basis, as to the incorporation of additional measures that may be required. Buildings with potentially high risk occupancies ie. intensive care wards in a multi-storey structure, would be one such example.

Only in exceptional circumstances should special measures be applied.

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5 Conclusions and recommendations

The relatively low number of deaths or injuries is supported by Fire Brigade statistics. It has not been possible to identify any incidents in the UK where death or injury has resulted from fire spread up the outside of a building where the fire has broken out of one window and re-entered at another. Indeed, very few people are killed or injured from fire who are elsewhere than on the fire floor. Most deaths or injuries on floors other than the fire floor are as a result of smoke.

Fire spread up the outside of buildings via the windows is not a significant threat to life compared with the other risks from fire in tall buildings. The UK guidance given in Approved Document B Fire Safety, deals with the issue of life safety for different occupancies by application of building construction and limits on performance of material. It is the Insurance Industry which is leading the risk assessment of buildings with fully or partially glazed installations, however this is with a view to effects of business interruption and replacement costs.

Those mitigatory measures that are most effective are the ones that have the greatest impact on the design of the building.

The evidence acquired for this project leads to the conclusion that the measures currently called upon in England and Wales through Approved Document B are still commensurate with the risk.

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6 Recommendations for further work

Fire spread up the outside of buildings via the windows is not a significant threat to life at this time, compared with the other risks from fire in tall buildings.

However, monitoring of fire incidents in tall buildings will continue as part of the FRS fire investigation programme for DTLR and shall be reported as necessary.

As the insurance industry is tending towards a more risk-based approach of assessment with respect to the construction and building design of multi-storey buildings, it would be useful to liase with contacts in that industry to ascertain the effectiveness of constraints placed on a 'business interruption' basis.

It would also be useful, although very time-consuming, to follow up individual cases highlighted by the Home Office (DTLR) database search, to ascertain whether external spread via windows was a significant factor. This would involve obtaining original FDR1 reports, selected according to specified criteria relating to number of stories damaged, for example. It is by no means certain that this would reveal the extent of the problem with any degree of confidence, as the assessment would depend on the supplementary comments (if any) made by the reporting officer.

7 References

Task 1 – A survey of available information on incidents of flame spread through windows, BRE Report No. 203130

Task 2 – External fire spread via windows – Analysis of the findings

Task 3 – A review of codes and standards relating to fire spread through windows, BRE Report No. 203132

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Appendix 1 – Historical fires involving claddings and façades

Andraus Building, Sao Paulo, Brazil 1972 (15)

This was a 31-storey department store and office building. The fire developed on four floors of the department store and then spread externally up the side of the building, involving another 24 floors. Wind velocity and combustible interior finishes and contents were contributing factors to the fire spread. The building construction was reinforced concrete. The building façade had extensive floor to ceiling glazed areas, with a spandrel of only 350mm in height and projecting 305mm from the face of the building. After the fire broke through windows they formed a front exposing the three to four floors above the department tore. Radiant heat then ignited combustible ceiling tiles and wood partitions on each floor. The flame front then increased in height as more floors became involved. At its peak the mass of flame over the external façade was 40m-wide and 100m-high and projecting at least 15m into the street.

Joelma Building, Sao Paulo, Brazil 1974 (15)

This was a 25-storey office building of reinforced concrete structure (beams, columns, floor slab) and an exterior curtain wall with hollow tiles rendered with cement plaster on both sides and windows with aluminium framing. The floor slabs were poured in situ and provided a 900mm projection on the north wall and a 600mm projection on the south wall. Fire started on the 12th floor near a window. The fire spread externally up two of the façades to the top of the building, readily igniting combustible finishes inside the windows of the floors above which allowed vertical spread to continue.

There were 179 deaths.

Las Vegas Hilton Hotel, 1981 (15)

This was a 30-storey hotel of reinforced concrete construction. Glass windows between floors were separated vertically by a 1m spandrel prefabricated of masonry, plaster and plasterboard on steel studs.

Fire occurred on the eighth floor of the East tower lift lobby, where the fire involved curtains, carpeting on the walls, ceiling and floor and furniture. The plate glass window to the exterior shattered allowing a flame front to extend upwards on the exterior of the building. It apparently took 20-25 minutes for exterior fire spread from the eighth floor to the top of the building (about 20 floors). Two mechanisms were identified for the vertical fire spread:

Flames outside the upper windows radiated heat through the windows and ignited curtains, timber benches with polyurethane foam padding, which then ignited carpeting on room surfaces.

Flames contacted the plate glass windows. It is believed that the triangular shape of the spandrels and recessed plate glass caused additional turbulence, which rolled the flames onto the windows resulting in early failure.

There were eighth deaths in this fire. Three were in the eighth floor lift lobby, one by jumping/falling from the 12t^{h} floor and four in hotel rooms in the East tower. The doors to the hotel rooms where the deaths occurred were open or had been opened during the fire. There were no fatalities in rooms where the door had been kept closed. This suggests that internal rather than external fire spread was the main reason for the deaths.

First Interstate Bank Building, Los Angeles, California 1988 (15)

The bank was a 62-storey tower with sprinkler protection only in the basement, garage and underground pedestrian tunnel. An automatic sprinkler system was being installed in the building at the time of the fire. The building had a structural steel frame with spray-on fire proofing with steel floor pans and lightweight concrete decking. The exterior curtain walls were glass and aluminium with a 100mm gap between the curtain wall and the floor slab, where the fire stopping, comprised 15mm gypsum board and fibreglass caulking. The fire started on the 12th floor and extended to the floors above primarily via the outer walls of the building. Flames also penetrated behind the spandrel panels around the ends of the floor slab where there was sufficient deformation of the aluminium mullions to weaken the fire stopping, allowing the flames to pass through even before the windows and mullions had failed. Flames were estimated to be lapping 9m up the face of the building. The curtain walls including windows, spandrel panels and mullions were almost completely destroyed by the fire. The upward extension stopped at the 26th floor level.

Mercantile Credit Building, Basingstoke 1991 (15)

This was a 12-storey office block. Fire on the eighth floor spread up the building and broke out on the eight floor. Flame spread externally behind glass curtain walling to the tenth floor, fanned by strong winds.

One Meridian Plaza Building, Philadelphia 1991 (15)

This fire occurred on the 22nd floor of a 38-storey bank building. The building frame was structural steel with concrete floors poured over metal decks and protected with spray-on fireproofing materials. The exterior of the building was covered by granite curtain wall panels with glass windows attached to perimeter floor girders and spandrels. At the time of construction only the blow ground service floors were fitted with sprinklers and since then they had been added to the 30th, 31st, 34th and 35th floors and parts of floors 11 to 15. Fire broke through windows on the 22nd floor and heat exposure from the window plumes ignited items on the floor above. The fire was stopped when it reached the 30th floor which was sprinklered.

Knowsley Heights, Liverpool, 1991 (15)

This was an 11-storey residential tower block. The fire was started deliberately in the rubbish compound outside the building. Fire spread up through a 90mm gap between the building's rubberised paint-covered concrete outer wall and a recently installed rain screen cladding. The rapid spread of fire was thought to have been caused by the lack of fire barriers in the cavity gap passing all eleven floors and providing a flue for hot gases to rise. The fire destroyed the rubbish compound and severely damaged the ground floor lobby, outer walls and windows of all the upper floors. No smoke or fire penetrated into the flats and the building was reoccupied by tenants later the same day. The rain screen cladding material was a Class 0 rated product. Building Regulations were changed as a result of this fire.

President Tower, Bangkok 1997 (15)

This was a 37-storey retail, commercial office and hotel development. A sprinkler system was not yet operational as the interior fir out was not fully completed. An explosion and fire started on level seven causing the destruction of the aluminium framed curtain walling system. The effectiveness of fire stopping at the floor edge was compromised by floor to floor cabling. Window and spandrel glass shattered and collapsed before structural silicone sealant bonds between the glass and aluminium were destroyed. Many heat strengthened glass panels sustained elevated temperatures but fractured and collapsed as they cooled. The vertical fire spread extended up to level ten.

Residential tower block, Irvine, Scotland, 1999 (15)

The fire, which started in a flat on the fifth floor of a 13-storey block of flats, broke out through the window and quickly spread vertically up the exterior face of the building, engulfing the upper nine floors within minutes. The building was of concrete construction but had full height composite window units comprising a GRP panel below the window and u-PVC window frames. The fire ignited the GRP panels and spread vertically.

There was one death in the incident and that was in the flat of fire origin. Therefore the combustible window components were unlikely to have contributed to the death.

Appendix 2 – Summary of major references

This section provides brief details and references for the major reports and sources used in the report. Notes

Note : US & Australian publications, indicated with *, give storey numbers starting at 1 for the ground floor (i.e. UK=US-1). Notes here are shown as published.

Fire incidents

Topic	Ref ID	Reference	Notes
Los Angeles County Health Building 15/2/1992	A1*	Klem, T.J. Three major high-rise fires reveal protection needs. NFPA Journal, September/October 1992, pp 56-62	14 storeys, offices. Concrete & glass façade. Fire on 7th, discovered by staff. 20-foot flames from window. Smoke & heat damage to upper floors. 80 minutes to control from call. No sprinklers. Detectors in elevator lobbies. Saturday, so few people present
One Meridian Plaza, Philadelphia 23/2/1991	A1*		38 storeys, offices. Granite & glass façade. Fire on 22nd, spread up to 30th (via internal shafts?) where halted by sprinklers, fed by fire dept (none on fire origin floor).18.5 hours to control. Detector alerted staff. Power failure. 3 fire-fighters died. Saturday, few present.
	A2*	Klem, T.J. High rise fire claims three Philadelphia fire fighters. NFPA Journal, September/October 1992, pp 64-89	Fire & smoke also spread down to 21st via open stairway. Heat transfer via broken windows, and void between floor slab & façade. Inadequate water pressure.
	A3*	Eisner, H. and Manning, B. One Meridian Plaza fire. Fire Engineering, August 1991, pp 51-70	Describes curtain wall construction. Falling glass cut hose lines. Means of spread was mainly "autoexposure" through curtain wall, and conduction through floor. Some minor spread via shafts etc.
	A4	FPA. High-rise offices, Philadelphia. Fire Prevention, vol. 248, April 1992, pp 36-38	
First Interstate Bank, Los Angeles 4/5/1988	A1*		62 storeys, offices, fire on 12th. Flames from windows. Spread to 15th. Sprinklers being installed, not functional. Detectors operated but were repeatedly reset by staff. One maintenance worker died. Inadequate water supply. About 40 people present, working late.
	A5	FPA. The First Interstate Bank Fire – what went	Started on 12th (?), stopped at 16th (?) curtain wall construction, flames broke windows and re-entered on upper floors. Also spread through gap between

		wrong? Fire Prevention, vol. 226, January/February 1990, pp 20-26	floor slab and curtain wall, as deformation caused failure of fire-stopping. Plastic-coated windows fell out intact, posing great hazard to people below. Estimated loss - £235m.
Andraus Building, Sao Paulo, Brazil 24/2/1972	A6*	Willey, A. E. High-rise building fire. Fire Journal, July 1972, pp 7-?	31 storeys (department store on 1-7, 8-27 offices, remainder vacant). 16 killed, 375+ injured. Extensive full-height glazing, 14 inch reinforced concrete spandrels. No sprinklers, detectors or alarm. Temperature was 73F and some windows were open. Fire observed coming from light/ventilation well on 4th. Spread across 5th & 4th, via combustible ceiling tiles. Spread to 6th & 7th via open stairs, then broke through windows on all 4 floors. External flames ignited combustible ceiling tiles & wood partitions on successive floors (another 24). When brigade arrived, external flames were 330ft high & projected over 50ft into street. Radiation damaged building opposite, 98ft away. External spread was on north & west facades. Wind (17mph) exacerbated fire, by ventilating through building and projecting flames, but also helped those on office stairway & heliport. Hundreds rescued, including some from roof heliport.
	A7	Whitaker, E. H. Are British standards based on the correct criteria? Fire, May 1972, pp 565-567	Refers to JFRO Note No. 8. States that 20 died, fire started on 3rd. Estimated 1200 occupants.
Hotel Tae Yon Kak, Seoul, South Korea 1972	A7		No details
	A8*	Smith, D.E. Lesson from fires. Fire Journal (Australia), vol. 4 no.1, March 1980, pp 37-40	21 storeys, 18 month old building. Part office and part hotel, vertically divided. LP gas leakage on 2nd floor started fire, which quickly spread via un-enclosed staircase. Vertical ducts and combustible linings spread fire, but there was some external spread via windows at lower levels. 163 people lost their lives.
Joelma Building, Sao Paulo, Brazil 1/2/1974	A9*	Sharry, John, A. South America burning. Fire Journal, July 194, pp 23-33	25 storeys, fire started on 12th in A/C unit. Curtain wall facade. 1st floor storage, 2nd-10th open-air parking, 11-25 offices. No sprinklers, detectors or alarms. Around 756 occupants. Only one staircase, not enclosed. Combustible ceiling tiles, wooden partitions consumed. Rapid external spread on north & south walls. Approx 50 mins after ignition, top 14 floors involved. Importance of

			internal load demonstrated at 13th floor (unoccupied and small fire load, hardly involved while 14th rapidly fully involved and burst out at opposite side). Wind not a factor, unlike Andraus, thus fire spread up two facades ("not one as in Andraus"?). All contents consumed on 12-25th. 179 died, many of whom went to roof expecting rescue.
Avianca Building, Bogota, Colombia 23/7/1973	A9*		36 storeys, offices, exterior: glass & metal panels set between concrete mullions, gap between floor slab & skin enclosed with plywood. Much interior wall lining was flammable. No sprinklers, no detection, no alarm. Fire on 13th in storage area. Early morning, ~300 occupants. Slower vertical spread than Joelma, internal & external. Mostly via floor-skin gaps, but some window to window spread on floors with sufficient fire load. Top 24 storeys eventually involved. Falling glass cut hose. Water supply problems. Four fatalities. Light wind may have helped keep stair on windward side tenable on some levels.
Las Vegas Hilton 10/2/1981	A10*	FPA. Eight die in Las Vegas Hilton Hotel fire. Fire Prevention, vol. 150, pp 33-36	30 storeys, hotel plus entertainment & gambling, 2800 rooms, ~4000 occupants present. 3 portions built at different times. Reinforced concrete, with 6mm glazing 3m x 2m high, with 1m spandrel of masonry, plaster & plasterboard. Various detectors depending on location. Sprinklers only in parts of 1st & 2nd floors. Fire started on 8th, deliberately, & reported. Furniture, & Carpeting on walls, floors & ceiling rapidly involved, glazing failed & flames ejected. Approx 20-25 mins to spread externally to top of building, but no vertical spread by internal routes. Radiation at window ignited curtains & PU padding on benches present at each floor lobby. Arrangement of triangular spandrel projection & recessed glazing believed to invoke turbulence which caused flames to hug window, accelerating failure. Balcony overhanging 3m at 29th floor deflected more heat into corridor on 29th floor. Diagram suggests that external spread halted here, but not clear in text. Sounders triggered manually but many occupants claimed they didn't hear them. 8 fatalities.
Villiers House, London 18/1/1979	A11	FPA. Fire in office block. Fire Prevention, Vol. 135, 1980, p 51	8-11 storeys, offices. Fire started on 3rd floor kitchen, discovered by caretaker. Brick in-fill walls, 0.9m separation of windows & back-up brick walls. Flames from window on 3rd soon attacking those on 4th. Strong NE wind blowing into windows on one face, projecting flames out from SW face. At least half contents on of 4th-8th damaged by fire, heat, smoke & water. All other stories [above?] damaged by heat & smoke. Office contents ignited on each fire floor. Estimated damage: £4.4m

Mercantile Credit HQ (Churchill Plaza), Basingstoke, Hampshire 16/4/1991	A12	Rosato, C. Offices, Basingstoke, Hampshire. FPA, Fire Prevention, No. 242, September 1992, pp 30-31	14 storeys, offices. Steel frame structure, with aluminium frame glazed curtain wall. Detection & alarm fitted, no sprinklers. Large fire load in plastic furniture/equipment. Fire on 8th, brigade arrived 4 minutes after call and flames already projecting externally. More windows on west face failed, flames fanned by strong wind. 71 mins after call fire spread to 9th. Wind accelerated spread through building. External spread on south & west faces, penetrated 10th 2h28min after call. Controlled at 4h34min after call. Some mineral wool slabs between floor slab & curtain wall displaced, allowing some smoke & fire spread. Estimated loss: £15.6m
South African Agricultural Union Building, Pretoria, South Africa 15/6/1994	A13* ?	FPASA, High-fire, the day Pretoria burned. Fire Protection, Vol. 21 (3), September 1994, pp 14-18	30 storeys, offices, brick construction with reinforced concrete pillars. Detection & alarm fitted, but no sprinklers (except for basement & 2 parking levels). Open-plan design, with chip-board wall partitions, large fire load. Fire started in unoccupied office on 19th. Flames penetrated west face, glass & concrete falling. Helicopter rotors believed to accelerate spread during rescues. Problems with water supply, & lines cut by glass. ~3.5 hrs after call fire had reached top of building. Some fire escape doors locked, & staircase contaminated. Spread internal (via A/C & service shafts) and external. Several rescues from ledges & roof. Estimated damage: R32m
President Hotel, Bangkok, Thailand 23/2/1997	A14* ?	Hartog, P. Performance of the lightweight curtain wall in the President Hotel fire. Conference proceedings, Interflam '99, Interscience Communications, pp 93-112.	37 storeys, offices, retail & hotel, under construction & partly occupied (shops, restaurant & bakery). Sprinkler present, did not operate. Building materials, files, etc were in various parts, & doors & ducts were propped open for delivery/installation. Fire started on 7th – vapour explosion propelled ~13 panels up to 15m, from 7th & 8th, others damaged. Internal spread via open lift & service shafts. Spread to 10th
Knowsley Heights, Huyton, Merseyside 5/4/1991	A15	FPA. Fire in high-rise flats. Fire Prevention, No, 252, September 1991, p 56	Residential flats, 10 storeys. Deliberate fire started in rubbish stacked at base of building. Rainshield cladding had 90mm continuous gap to top of building, which acted as flue. Windows at every level severely damaged. Living spaces not damaged. Wind may have contributed to spread.
	A16	Morgan, P. Fire at Knowsley House. BRE FSIS Advance report,	Smoke penetrated each floor in access area behind each damaged window, and into lift lobby on 1st & ground. Fire damage on most floors limited to paint delamination & cracking of Georgian wired glass in access areas. On ground

		1991	floor, fire spread from access area into adjacent section. Recommendations include concrete panels at ground & 1st, barriers to prevent dumping at base of building, improved management of these areas.
Westchase Hilton Hotel, Houston, Texas 6/3/1982	A17*	NFPA. Twelve die in fire at Westchase Hilton Hotel. Fire Journal, January 1983, pp 10-15, 20-23, 54-56	13 storeys, hotel, fire on 4th started by cigarette on upholstered chair. About 200 occupants. Exterior was tempered glass in aluminium floor-to-ceiling frames. Aluminium plates filled gap between floor slabs & façade, with mineral fibre insulation in voids. Detection fitted, but battery operated in rooms, not linked. Sprinklers fitted in parts of building. Other furniture in room ignited, smoke & heat entered corridor through door, which did not close properly (possibly due to carpeting). Smoke spread to upper floors via lift shafts & HVAC system. Fire broke window in room of origin, flames causing minor damage to rooms on 5th. 12 dead.
Glasgow House, Maida Vale, London 15/3/1996	A18	LFCDA. Notifiable fire report, Glasgow House. London Fire Brigade, incident No. 96/49072. Also Fire Investigation Statistical Report.	17 storey residential block. Fire in living room on 6th. Front door to flat was forced open prior to brigade arrival, which ventilated fire. Plastic-framed full-height picture window failed & was partially consumed. Falling debris hazard. Flames penetrated flat above through that picture window
Garnock Court, Irvine, Scotland 11/6/1999	A19	Morgan, P., Martin, B. and Morris, T. Fire at Garnock Court, Irvine on the 11th June 1999. BRE Client Report 79902, August 1999.	14 storey residential block, concrete. Refurbishment in 1989 – uPVC windows & GRP cladding to address problem of water penetration. Fire started in living room on 5th, rapidly spread external on GRP panels. Still conditions (2.5km/h), likely that many windows were open, or opened by tenants on hearing alarm. Discarded furniture left in staircases impeded brigade access. Hot smoke & gases entered all 8 flats on upper floors via windows. Falling debris ignited tyre on brigade appliance. One fatality in fire room. Suggest that ageing of GRP may have compromised fire characteristics of panels.
	A20	Morgan, P. Fire at Greenock Court, Irvine Phase 2 – Fire tests on GRP cladding	Tests carried out on panel samples. Material probably never was Class O. design of window pods & spandrel panels contributed to spread by presenting a cut edge to flames & gases.
Banker's Trust Building, New York, New York 31/1/1993	A21*	Routley, J. G. New York City bank building fire: Compartmentation vs. sprinklers. United States	H-Shaped offices building, 2 towers (42 storey & 30 stories) linked by 17 storey section. Steel structure, curtain walls with large windows & metal spandrel panels. No sprinklers. Fire started in overheated cables in ceiling plenum space, on 6th floor. Sunday night – security & maintenance staff only. Open

		Fire Administration, National Fire Data Center, 1993.	plan offices, large fire load. Smoke detector triggered. Flames seen emanating from row of windows on 6th some time later, then across full width of south face. Windows on 7th starting to break, also cracks in floor slab transmitting flames. Brigade crew ordered out of building, to focus on external attack. Height was close to limit of equipment. 7th involved. Wind pushed air into 6th, containing smoke, until fire-fighters opened doors to gain access, when smoke was pushed into the stair shafts. Estimated loss: $10m, excluding business interruption.
One New York Plaza, New York 5/8/1970	A22*	Powers, W. R. New York office building fire. Fire Journal, January 1971, pp 18-23, 87	50 stories, offices. Reinforced concrete, with aluminium panel window sections & concrete block curtain wall.16 inch gap in stopped with aluminium flashing at each level to collect condensation & carry it to external weep hole. Polystyrene foam board insulation. Fire started on 33rd, in office or plenum above it. Spread through plenum, towards walls, igniting foam & dripping onto furniture beneath, igniting foamed polyurethane. 30 mins after discovery, entire south section of 33rd, spreading to 34th through openings, and via insulation in outer wall. [Not clear that 'autoexposure' occurred here.]

Experimental & theoretical evidence

Topic	Ref ID	Reference	Notes
BRE Timber frame building tests	B1	Lennon, T. & Bullock, M. J. The fire resistance of timber frame buildings (closing report, results & observations). BRE Report No. 79485-1, BRE 2000.	Details test carried out on full-scale 6 storey timber frame experimental building at the BRE Cardington Laboratory, on 15/9/1999. Fire started in living area of flat on 2nd floor. As a precaution against vertical spread, windows above the fire compartment were sealed off. Flashover occurred ~24mins, at which time heat flux at the 'windows' to the floor above was around 30kW/m^2 (enough to ignite wooden frame or curtains, it is stated).
Window size & shape	B2*	Sultan, M. A. reducing fire hazards in small buildings. Building Science Insight '90, National Research Council of Canada, 1990.	Reproduces table from Oleszkiewicz ("Heat transfer from a window fire plume to a building façade"), which is not in library. Table shows effect of window shape (5 conditions) on heat flux at 4 different heights above opening, for two fire sizes. Large windows allow more burning inside compartment, decreasing external plume temperature. Tall windows project flames away from window. Horizontal projections offer protection to façade immediately above (graph). Vertical projections increase heat flux, restricting air supply to sides of plume, thereby extending combustion zone vertically.
	B3*	Oleszkiewicz, I. Fire and combustible cladding. NRC (originally published in Construction Canada, vol. 32 (4), July/August, pp 16-18, 20-21.	Graph shows similar (same?) heat flux data as above, but for 3 window shapes & 4 fire sizes. Low velocity fire plumes (from low window height) were better adhered to façade, transferring more heat. Describes results of projections: 90% drop in flux with horizontal projection, 50% increase with vertical projections. Maximum flame spread & heat flux 0.5m above opening are shown for various cladding systems, from full-scale tests.
	B4	Ashton, L. A. and Malhotra, H. L. External walls of building Part 1. The protection of openings against spread of fire from storey to storey. FR Note, No. 436. Fire Research	Large scale experiments on 4 storey building. Fire size, window size, cladding material investigated. Brief outline of bye-laws on separation (UK, New York, Canada). Model experiments had shown that for large windows flame height depended on fuel burning rate, which depends on surface area. For small windows, flame height depended on air flow factor (window area × height), but weather complicated this. Windows (wooden frame, presume single glazed) in storey above broke in all tests but one, igniting curtains/pelmets. Sometimes 2nd storey windows were broken. Full-height glazing lead to highest 1st floor

		Station, July 1960	temperature, but did not ignite it. Concludes: internal spread more likely & hazardous; flaming for up to 15mins may not necessarily ignite 1st floor, but bye-law separations would not prevent ignition of combustibles close to window; fire resisting separation reduces radiation to 1st floor, but will not protect items at higher level from ignition; nor would vertical downstand in fire room have much effect on flame height; horizontal projections would need to be much greater than 2ft (0·61m) to be effective; vertical separations investigated were insufficient to prevent spread; reduction in fire resistance of spandrel may not reduce level of safety (solid timber was acceptable – other combustibles would need further tests). Problem in test comparisons due to varying wind.
	B12	Thomas, P. H., and Law, M. The projection of flames from buildings on fire. Fire Prevention Science and Technology, No. 10, pp 19-16.	Examines earlier work on flame projection in the context of the siting of external structural steel members. Reviews work of Yokoi (widest range of window geometries; projections; plumes not flames), Webster (flame lengths), Seigel (flame temperature). In Webster & Yokoi methods buoyancy is dominant, while Seigel's treats flames as forced horizontal jets. This affects adhesion of plume. Describes correlations between methods. Seigal's assumption of 'normal burning', whereby additional air was forced into room if openings were too small for maximum burning rate. Longer flames can be produced where there is wind across building (see St. Lawrence Burns), flammable linings were used, or where another fire on *lower* floors creates chimney effect.
	B13	Yokoi, S. Study on the prevention of fire spread caused by hot upward current. Building Research Institute (Japan), Report No. 34, November 1960.	Very detailed treatment of small- and large-scale tests, and theory. Temperature distributions & trajectories of plumes, effects of spandrel width & projections.
Separation of windows, & projections	B5	Oleszkiewicz, I. vertical separation of windows using spandrel walls and horizontal projections. Fire Technology,	Describes full-scale 3 storey tests to examine effectiveness of horizontal projections, and spandrel heights that would be required to give equivalent protection. Projection 1m deep reduced flux at 1m above opening by 85%. To achieve a reduction of 50% would require a spandrel 2·5m high – impractical.

		November 1991, pp 334-340.	
Cladding	B6	Oleszkiewicz, I. Fire exposure to exterior walls and flame spread on combustible cladding. Fire Technology, November 1990, pp 357-375.	Full-scale experiments, assessment tests for cladding, correlations with standard flame spread tests (Steiner tunnel, radiant panel, roof deck). Effect of fire size & window dimensions on flux. Horizontal projections decreased flux, vertical increased it. Vertical spread & flux for 13 wall assemblies tested. Concludes that full scale tests are best assessment method.
	B7	Colwell, S., Foster, J. and Martin, B. Fire spread in external cladding – A literature review. BRE Report No. 80415, July 2000.	Describes types of cladding systems, building regulations (spread, insulation, subdivision of cavities). Historical tests on external cladding (materials, cavity effects, fire stopping).
	B8	Connolly, R. J. Investigation of the behaviour of external cladding systems in fire – report on 10 full-scale fire tests. BRE Client Report CR 143/94, April 1994.	Highlights problem in UK – around 3000 tower blocks, many due for refurbishment. Hazards: surface flame spread, spread to upper compartments via windows, spread within cladding assembly, collapse of assemblies. Must be balanced with need for ventilation. Describes 10 full-scale BRE tests. Cites Swedish research that suggests limit of 80kW/m^2 for breakage of upper windows & ignition of contents. Test 1 found 50, 23 & 13 kW/m^2 at 1st, 2nd & 3rd floor windows respectively. Concludes that full-scale tests are essential, as only then can the interaction of all components of the system be assessed. Emphasises importance of fire stopping.
Curtain walls	B9	Jackman, L. and Finnegan, M. Non-glazed curtain walling: Furnace test results and recommendations. LPC report LPR19:2001, Loss Prevention Council/BRE, 2001.	Points to previous LPC work which suggested that vertical fire spread via fully glazed systems is possible (and indeed likely in non-sprinklered buildings). Reports tests on non-glazed panels, which were found to perform better than glazed ones. Highlights need for effective fire stopping, and dangers of 'hidden' fire spread.
	B10	LPC. Fire spread in multi-storey buildings	Examines ability of fully glazed systems to inhibit spread to upper storeys. Describes typical curtain wall system. spandrel panels can be exposed to

		with glazed curtain wall facades. LPC Report LPR11:1999, LPC/BRE, 1999.	buoyancy-induced high temperatures at ceiling of fire compartment, and aluminium is commonly used in frames (weakens at 200ºC, melts 550-650ºC). displacement of fire stopping at junction of floor slab & façade.
Fire spread in facades	B11	Raes, H. The role that facades play in fire spread –1, and Bechtold, R. The role that facades play in fire spread –2. Fire International, No. 59, pp 18-40.	Part 1 gives review of some experimental work and theoretical considerations, covering window dimensions, façade type, etc. Part 2 describes German tests on full-size facades, with isothermal diagrams for various wind conditions. Describes relationship between internal & external temperatures. Temperature rise of steel & reinforced concrete columns placed around the opening are shown. A PVC curtain wall was found not to contribute to vertical spread.
Radiation from fires, flame height	B14	Law, M. Heat radiation from fires and building separation, in External fire spread: Building separation and boundary distances, ed. Read, R. E. H. BR 187 BRE, 1991.	Discusses intensity of radiation from compartment fires, both fully-ventilated and ventilation-restricted, also calculation of radiation from facades. Used in developing guidance on building separation. May not be directly applicable.
	B15	Seigel, L. G. The projection of flames from burning buildings. Fire Technology, Vol. 5 No. 1, 1969, pp 43-51	Looks at gas velocities, flame heights etc from compartment. Notes importance of wind, but no guidance.
	B16	Webster, C. T. and Raftery, M. M. The burning of fires in rooms, part 2.Fire Research Note, FR 401/1959, JFRO	Flame heights and radiation level investigated – effects of scale & fire load.
	B17	Webster, C. T., Raftery, M. M. and Smith, P. G. The burning of fires in	As above, effects of wood crib used (stick size).

		rooms, part 3.Fire Research Note, FR 474/1961, JFRO	
	B18	Webster, C. T. and Smith, P. G. The burning of well ventilated compartment fires, part 4.Fire Research Note, FR 578/1964, JFRO	As above, in brick compartment
	B19	BSI. Eurocode 3: Design of steel structures, Part 1.2 – Structural fire design. (Draft for Development). DD ENV 1993-1-1:2001.	Methods for calculating fire insult on steel beams, including radiation flames from openings etc.

Modelling

Topic	Ref ID	Reference	Notes
Emerging plumes and window to window spread	C1	Satoh, K. and Kuwahara, K. A numerical study of window-to-window propagation in high-rise building fires. Fire Safety Science, Proceedings of the 3rd International Symposium, pp 355-364.	Two-dimensional finite-difference code used to examine 9 cases, varying balcony projection, soffit height, window height, and upper window condition (open/closed). Found similar flow patterns for different soffit & balcony configurations. Adhesion of plume to wall observed, large-scale vortices induce time-dependent motion up façade and into upper room (when window open). Isotherm diagrams and temperature/height profiles presented.
	C2	Galea, E. R., Berhane, D. and Hoffman, N. A. CFD Analysis of fire plumes emerging from windows with external protrusions in high-rise buildings. Proceedings, Interflam '96, pp 835-839.	Trajectory & temperature profile of plumes, and effects of horizontal projections. From Yokoi, window aspect ratio n=2W/H, for n<2.5 plume is not adhered to façade, n>6 plume is strongly deflected towards wall. Claimed confirmation in 3D fire field models by authors (in previous reports). 1 MW heat source, wide windows with no protrusion, 0·5m or 1·0m. Isothermal diagrams presented. With protrusions plume still adheres partially, but hot core of plume is deflected away from façade. Temperature at 3m above opening ~200ºC with 0·5m and ~100ºC with 1·0m protrusion. Gas exit velocity: overall velocity is higher with protrusions, but peak velocity is higher without protrusion.
	C3	Chitty, R. Application of JASMINE to the CFD modelling of smoke movement in the "Berlaymont 2000" Building. BRE TCR 25/98.	Describes CFD modelling on building with glass louvres on external face which move in response to changing incident light levels. Client was concerned about possible chimney action of louvres when in closed position. Three scenarios: closed louvres, wind perpendicular to building at 5m/s; open louvres, perpendicular wind 0, 5 & 10m/s; open louvres, wind parallel at 5m/s. Fire 3·6MW. Conditions very sensitive to wind, due to low exit velocities. Temperature & velocity output was fed into Berkley BREAK algorithm to give indication of glazing temperature & failure (generic glass parameters only used). Closed louvres, 5m/s perpendicular: >119ºC after 300s, breakage at 290s (breakage up to floor +4, which occurs at 767s). Open louvres, 5m/s

			perpendicular: 99ºC after 300s, breakage at 403s. Open louvres, 5m/s parallel: 26ºC after 300s, no breakage, plume leans over. [Need more info on dimensions of façade.]
Plume modelling	C4	NFPA. Guide for smoke management systems in malls, atria and large areas (2000 Edition). NFPA 92B, 2000.	Guidance for designers, code authorities and fire departments etc., on smoke movement. Section 3.8describes calculation methods for estimating mass flow rates in balcony and window plumes, plume width and temperature (for strongly buoyant plumes).
	C5	Morgan, H. P., Ghosh, B. K., Garrad, G., Pamlitschka, R., De Smedt, J. C. and Schoonbaert, L. R. Design methodologies for smoke and heat exhaust ventilation. BR 368, BRE, 1999.	Annexes D and E describe spill plume calculation methods (BRE, Thomas et al, Poreh et al), that may be used to derive estimates of plume temperature at various heights above opening. Adhered plumes calculations are addressed.
	C6	Drysdale, D. An introduction to fire dynamics. John Wiley & Sons, Chichester, 1985.	Sections 10.6 & 10.7 (pp 346-350) describe calculation methods for estimating flame height, horizontal projection and burning rate. Highlights reliance on empirical data (Thomas & Law, Yokoi, Seigel) – theory (Bullen & Thomas, 1979) not fully verified. Notes large scatter in the data nevertheless. Correlations not valid under some circumstances, including when there is wind (deflection & shortening of flame), if there is a fire on another lower floor (oxygen depletion caused by rising lower plume lengthens flame. Notes that flames can merge from several floors, as in Sao Paulo 1972 & 1974 fires.) States that relatively small horizontal projections can be effective if the shape factor (2B/H) is small, but not for wide windows (Yokoi, 1960), generally confirmed in large scale tests (Ashton & Malhotra, 1960; Moulen, 1971; Harmathy, 1979).

Performance of glazing systems

Topic	Ref ID	Reference	Notes
Cracking, break-out, radiation transmission	D1	Cuzzillo, B. R. and Pagni, P. J. Thermal breakage of double-pane glazing by fire. Journal of Fire Protection Engineering, Vol. 9 (1), 1998, pp 1-11.	Development of BREAK1 model, to encompass double-glazing, (heat transfer and cracking). Applicable to compartment fires and urban/wildland fires. Radiation is shown to dominate inter-pane gap transport (unless low emissivity interior glass is used). Notes shortcoming that cracking is predicted, but not time at which pane falls out. Suggests that energy-efficient films, if attached to both interior surfaces, then outer pane may be held in place longer, thereby protecting inner pane (in context of wildland fires).
	D2	Silcock, G. W. and Shields, T. J. An experimental evaluation of glazing in compartment fires. Proceedings, Interflam '93.	Describes 50 experiments in half-scale compartment with large picture window & partly-open door. Found that glass cracked but remained in place for over 15mins. Calls into question assumption of 'unique temperature difference criteria' of existing models, and that models need modification to cover slowly developing fires. Refers to early work which predicts breakage when ΔT (temperature difference between shaded & unshaded part of glass) reached about 80º - called into question.
	D3	Shields, T. J., Hassani, S. K. S. and Silcock, G. W. H. Behaviour of glazing systems in real fires. In Fire, static and dynamic tests of building structures, Proceedings of the 2nd Cardington Conference, March 1996. Ed. Armer, G. S. T. and O'Dell, T., E & FN Spon.	Draws attention to need for betting understanding of actual failure of glazing systems, as this has major effect on venting of fire. Some more background on tests cited above.
	D4	Hassani, S. K. S., Shields, J. and Silcock, G. W. An experimental	More detailed account of experiments in half-scale room. Performance of various glazing types.

		investigation into the behaviour of glazing in enclosure fire. Journal of Applied Fire Science, 1995, Vol. 4 No. 4, pp 303-323.	
	D5	Babrauskas, V. Glass breakage in fires. Fire Science and Technology Inc., Washington. http://doctorfire.com/glass.html (26/4/2001)	Review of research. Mowrer (1998) exposed glazing to simulated wildland fire. Maximum heat flux (16kW/m^2) caused cracking but not breaking out. Cracking of single-strength glass at 4-5kW/m^2. Found 33% of radiation on single-strength pane was transmitted through. Reviews shields et al. Cites BRI Japan report which presents probability of break-out with temperature. Cohen & Wilson (1994) found small panes did not fall out at 17.7 kW/m^2, larger ones 1 out of 3 fell out at 16-50 kW/m^2, large double-glazed required 20-30 kW/m^2 to cause both panes to fall out. Frame effects: Mowrer found vinyl frames failed before the glazing in them, 8-16 kW/m^2; McArthur (1991) found aluminium framed systems performed better than wood.
	D6	Ondrus, J. and Pettersson, O. Fire hazards of window frames of plastics, aluminium and wood. Lund University Report LUTVDG (TVBB-3037), 1987. (In Swedish, with English summary & contents.)	Full scale multi-storey study, looked at PVC, PUR, aluminium alloy and wood (inward opening or 'standing'). Found that PVC & PUR frames did not pose greater hazard than standard wooden frames. Also investigated effect of cladding type (alludes to later report). There was no significant difference in hazard from falling glass between the fame types. Aluminium systems cracked earlier due to greater thermal strain. States that risk of flame spread due to plastic materials in frames is negligible.
	D7	Shields, T. J., Silcock, G. W. H. and Hassani, S. K. S. behaviour of glazing in a large simulated office block in a multi-storey building. Journal of Applied Fire Science, Vol. 7, No. 4,	Describes tests in LBTF at BRE Cardington, using double-glazed facades. Concludes that existing calculation methods concerning flashover prediction (incorporating $A\sqrt{H}$) may not be applicable for double-glazed compartments. Observations support previous findings on glazing performance.

		1997/8, pp 333-352.	
	D8	Malhotra, H. L. Fire safety in buildings. BRE Report 987, December 1986.	States that transmission of radiation to upper room would often be insufficient, as 30 kW/m^2 required for ignition of contents, and glazing may block 50% of radiation from flames – they would need to be very hot & only contents in vicinity of window would be affected. Proposals include 1m vertical separation & 0·6m horizontal separation of windows.
	D9	Joshi, A. A. and Pagni, P. J. User guide to BREAK1, the 'Berkely Algorithm of Breaking Glass in a Compartment Fire', NIST-GCR-91-956. National Institute of Standards and Technology, 1991.	User guide for the model.