DTLR Building Regulations Division Project Report :

A survey of available information on incidents of flame spread through windows

Project report number 203130

Prepared for :

Anthony Burd
DTLR

15 August 2001

Safety and Health in Buildings Theme

External fire spread via windows

Contract Ref 36/8/132

Task 1 Report

Prepared for	Anthony Burd
Prepared by	Mark Bensilum Fire Safety Engineering Centre
BRE output/ milestone no.	203130

Approved on behalf of BRE	
Signature	
Name	Nigel Smithies
Position	Director of Fire Safety Engineering Centre
Date	15 August 2001

BRE
Fire and Risk Sciences Division
Bucknalls Lane
Garston
Watford
WD25 9XX

Tel [redacted]
Fax

Email : frsenquiries@bre.co.uk
Website : www.bre.co.uk

Executive Summary

As part of a project to investigate the problem of external fire spread via windows, an extensive survey has been carried out to gather information regarding all aspects of this phenomenon. This has encompassed traditional literature searches (i.e. library searches on journals and publications), and various other sources, such as statistical databases, on-line news agencies and discussion groups, and professional contacts and colleagues.

A large volume of information has been 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.

Although it is believed that the body of work which exists permits a good theoretical and practical understanding of the issues involved, it has proved very difficult to obtain information on the rate of occurrence of fire spread via windows in cases which have not been widely reported. There are also certain aspects of the problem which, although described in previous research, remain difficult to predict in practice due to wide variability in, for example, materials and workmanship.

Some of the lines of enquiry are still ongoing, and it is hoped that further information will come to light during the next stages of the project, which will be incorporated into the detailed analysis of the findings.

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1 Introduction

The objective of the project, of which this report is a part, is 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'.

The aim of this report is to outline the information that is available on all aspects of the problem. It outlines the findings from a comprehensive survey, covering a wide variety of sources. These findings are presented in outline only – the detailed analyses will be given in subsequent reports.

Note: different countries use different conventions in describing building storey number. The UK convention has been adopted in the body of this report, and where applicable, references to storey numbers cited in overseas publications have been amended.

2 Sources of information

A wide range of information sources, both formal and informal, has been 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.

Another major area of interest was the nature and extent of regulations and codes relating to external fire spread, both in the UK and abroad. This has been dealt with in a separate report (BRE Report Number 203132), and is not covered here.

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 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.

3 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 have proved hard to obtain. A number of lines of enquiry have been initiated which may yield further information at a later stage in the project. In this respect, the process of data gathering is on-going, and it is hoped that new information which comes to light can be incorporated into subsequent reports (particularly the Task 2 report, which will present a detailed analysis of the findings).

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 preliminary assessment of the subject matter. The detailed analysis, which will be contained in the Task 2 report, will provide a more comprehensive assessment of the relevance, importance and outcomes from the research, and the final conclusions therein may well differ from any that are expressed here.

A table summarising the major references used so far is presented in Annex 2. This list is not exhaustive, but is intended to provide a representative sample of the available information that has been gathered to date.

3.1 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 have been collected on a number of serious or noteworthy incidents involving external vertical fire spread, while only indicative data could be acquired regarding incidents which may have involved this phenomenon but were not widely reported.

3.1.1 Documented case studies

Case studies have been acquired for 18 fires in which external vertical fire spread was identified as a significant factor. Some incidents have been 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.

3.1.2 Other UK cases

The primary source for data on fire incidents in the UK is the Home Office 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, and a preliminary investigation of the suitability of the data for cataloguing cases of external fire spread via windows has been 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 appears that it may not be possible to estimate the number of incidents which involve this mechanism in the UK, where they are 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.

Other lines of inquiry are being investigated, which, it is hoped, may yield further data. A request has been lodged with Chief and Assistant Chief Fire Officers' Association (CACFOA), to interrogate the FINDS (Fire Inter-Networking Database Service) database. Other brigade contacts have also been approached. It is generally agreed, however, that data of the desired detail may be impossible to obtain.

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

It would also be possible, although very time-consuming, to follow up individual cases highlighted by the Home Office 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.

3.2 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 have 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 varies, but taken together they would appear to represent 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.

3.2.1 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 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.

3.2.2 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 has been investigated

3.2.3 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 Section 3.3).

There is 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, and that 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 and ventilation 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.

3.2.4 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 has come 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.

Clearly this issue has already attracted a great deal of interest, and has been the subject of a Select Committee review. However, although there is a wealth of information available, the majority of this work has 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 is also available, and this may be used to formulate impact assessments for any new guidance.

3.2.5 Curtain walls

The Loss Prevention Council (LPC) has carried out a major series of studies on the problems of vertical spread in building with glazed and non-glazed curtain wall systems. This has 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 is ongoing at LPC, examining 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.

3.3 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 revolves 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 has also been given to the modelling of glass and glazing systems, although the variability in design, construction and workmanship of the glazing system in its entirety tends to make accurate prediction very difficult. Furthermore, it seems that the modelling of cracking of the glazing has 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, is 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 has been 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.

It seems that 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 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 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.

4 Conclusions

The objective of Task 1 of this project was to undertake a survey of the information available on external fire spread via windows, 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 has been collated, which includes 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. A preliminary assessment of the information gathered has been carried out, and although it is felt that a sufficient amount of information has been compiled to allow a comprehensive review and recommendations to be made, it is still anticipated that further useful information will become available during Task 2, as the information is analysed in depth.

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.

Annexes

Annex 1 – List of previous reports, with references, for this project

BRE output/ milestone reference	**Title**	**Date submitted**
203137	Quarterly progress report	June 2001

Annex 2 – Summary of major references

This section provides brief details and references for the major reports and sources used in the report. The list is not exhaustive, and there are continuing lines of enquiry that are being pursued which are not reflected here.

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Notes

- 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 wrong? Fire Prevention, vol. 226, January/February 1990, pp 20-26	Started on 12th (?), stopped at 16th (?) curtain wall construction, flames broke windows and re-entered on upper floors. Also spread through gap between 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	A6*	Willey, A. E. High-rise building fire. Fire Journal,	31 storeys (department store on 1-7, 8-27 offices, remainder

24/2/1972		July 1972, pp 7-?	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, 1991	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 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	A19	Morgan, P., Martin, B. and Morris, T. Fire at	14 storey residential block, concrete. Refurbishment in 1989

11/6/1999		Garnock Court, Irvine on the 11th June 1999. BRE Client Report 79902, August 1999.	– 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 Fire Administration, National Fire Data Center, 1993.	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 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,

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			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 Station, July 1960	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 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,	Very detailed treatment of small- and large-scale tests, and theory. Temperature distributions & trajectories of plumes, effects of spandrel width & projections.

		November 1960.	
Separation of windows, & projections	B5	Oleszkiewicz, I. vertical separation of windows using spandrel walls and horizontal projections. Fire Technology, November 1991, pp 334-340.	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.
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 with glazed curtain wall facades. LPC Report LPR11:1999, LPC/BRE, 1999.	Examines ability of fully glazed systems to inhibit spread to upper storeys. Describes typical curtain wall system. spandrel panels can be exposed to 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 rooms, part 3.Fire Research Note, FR 474/1961, JFRO	As above, effects of wood crib used (stick size).
	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.

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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 investigation into the behaviour of glazing in enclosure fire. Journal of Applied Fire Science, 1995, Vol. 4 No. 4, pp 303-323.	More detailed account of experiments in half-scale room. Performance of various glazing types.
	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, 1997/8, pp 333-352.	Describes tests in LBTF at BRE Cardington, using double-glazed facades. Concludes that existing calculation methods concerning flashover prediction (incorporating A√H) may not be applicable for double-glazed compartments. Observations support previous findings on glazing performance.
	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.

31 A survey of available information on incidents of flame spread through windows