STUDY REPORT

No. 136 (2005)

Design Fires for Apartment Buildings – Literature Review

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Preface

This is a report comprising a literature review relating to design fires in apartment buildings.

Acknowledgements

This work was jointly funded by Building Research from the Building Research Levy (New Zealand) and by CSIRO (Australia).

Note

This report is intended for fire engineers and regulatory authorities.

DESIGN FIRES FOR APARTMENT BUILDINGS – LITERATURE REVIEW

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KEYWORDS

Apartment buildings, fire, design, fire scenario, fire incident statistics, fire safety, heat release rate, furniture

ABSTRACT

The objective of this project is to develop a credible set of design fires for apartment buildings that will be acceptable for use by fire engineers and approving authorities, and lead to greater consistency in the safety levels applied in the fire design of apartment buildings. A design fire is a quantitative description of a fire that is representative of a particular scenario or sequence of events. The description is given in terms of the heat release rate history, production rates of various products, and combustion parameters as well as the probability of the event/scenario. Typically this would form the basic input to a fire model describing a scenario, with the fire engineer deciding on the appropriate design variables and parameters to be used on any particular project.

This report covers Phase 1 of the project comprising a review and discussion of previous relevant research, and other data from the literature applicable to this project.

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1. INTRODUCTION

The objective of this project is to develop a credible set of design fires for apartment buildings that will be acceptable for use by both fire engineers and approving authorities, leading to greater consistency in the safety levels applied in the fire design of apartment buildings. A design fire is a quantitative description of a fire that is representative of a particular scenario or sequence of events. The description is given in terms of the heat release rate history, production rates of various products, and the various combustion parameters, as well as the probability of the event or scenario. Typically this would form the basic input to a fire model describing a fire scenario, with the fire engineer deciding on the appropriate design variables and parameters to be used on any particular project.

This report covers Phase 1 of the project comprising a review and discussion of previous relevant research, and other data from the literature applicable to this project.

2. BACKGROUND

2.1 Design fires – general

For consistency, the definition of design fire, design fire scenario and fire scenario as proposed by ISO TC92 SC4 (ISO/CD 16733 2004) will be applied in this project. They are:

> **Design fire** – "a quantitative description of assumed fire characteristics within a Design Fire Scenario. Typically, an idealised description of the variation with time of important fire variables such as heat release rate and toxic species yields, along with other important input data for modelling such as the fire load density."
>
> **Design fire scenario** – "a specific fire scenario on which a deterministic fire safety engineering analysis will be conducted. As the number of possible fire scenarios can be very large, it is necessary to select the most important scenarios (the design fire scenarios) for analysis. The selection of design fire scenarios is tailored to the fire safety design objectives, and accounts for the likelihood and consequences of potential scenarios."
>
> **Fire scenario** – "a qualitative description of the course of a fire with time identifying key events that characterise the fire and differentiate it from other possible fires. It typically defines the ignition and fire growth process, the fully developed stage, and decay stage as well as systems that impact on the course of the fire and the nature of the local environment. Identification of potential fire scenarios is an important step whether a deterministic analysis or a risk assessment is envisioned."

Yung and Bénichou (Yung & Bénichou 2000) described how design fires can help analyse the fire hazards to the occupants of a building, and how such design fires can help standardise the fires that are used in fire safety evaluation. They favoured an approach where only three generic types of fire are considered: smouldering fires, where only smoke is generated; non-flashover flaming fires, where a small amount of heat and smoke is generated; and flashover fires, where a significant amount of heat and smoke are generated. They also presented the probability of these fire types, after ignition, for apartment buildings in three countries, as shown in Table 1. These fire types can be combined with other random variables such as the compartment entry door being open or closed to arrive at a larger number of design fire scenarios.

Table 1: Probabilities of fire types for apartment buildings*

	Australia	USA	Canada
Smouldering fire	24.5%	18.7%	19.1%
Non-flashover fire	60.0%	63.0%	62.6%
Flashover fire	15.5%	18.3%	18.3%

* Extract from (Yung & Bénichou 2000).

Narayanan and Whiting (Narayanan & Whiting 1996) analysed New Zealand fire incident data for the period 1986 to 1993 and derived similar fire type groupings for apartment buildings, as shown in Table 2. The analysis was based on the extent of flame damage recorded in the FIRS database. Smouldering fires were defined as those where either the fire was confined to the object of origin or where no damage was recorded. Flashover fires were defined as those spreading beyond the room of origin. All other fires were considered to be non-flashover fires. There is likely to be greater uncertainty for this data compared to that in Table 1 due to the small sample size.

Table 2: Probabilities of fire types for apartment buildings in New Zealand*

	No. of fires	% of fires	No. of deaths
Smouldering fire	417	26.0%	2
Non-flashover fire	770	48.0%	4
Flashover fire	358	22.3%	13
Unknown	59	3.7%	2
Total	1604	100%	21

*Adapted from (Narayanan & Whiting 1996)

Bwalya, Sultan and Bénichou (Bwalya, Bénichou & Sultan 2003; Bwalya, Sultan & Bénichou 2003) carried out a literature review on design fires in order to establish the state-of-the-art and to identify future research requirements. This was in support of a research project on the fire performance of Canadian houses. Their literature review revealed an absence of fire load data for residential and commercial buildings in Canada. They identified the main parameters affecting fire development in small rooms and the commonly-employed methods for characterising design fires for pre-flashover and post-flashover fires. The majority of methods employed in characterising post-flashover fires were found to be based on parametric/empirical equations, whereas t-squared fires are the most widely used design fires for the pre-flashover stage.

Of particular relevance to this study are the activities of ISO TC92. In particular, ISO/TR 13387 Part 1 (ISO 1999a) is concerned with the application of fire performance concepts to design objectives, while Part 2 (ISO 1999b, 2003) covers design fire scenarios and design fires. ISO/TR 13387 can be considered a guidance document outlining matters to be considered when developing design fires. It does not go as far as specifying recommended design fires for any particular occupancy or scenario.

ISO/CD 16733 (ISO/CD 16733 2004) proposes a ten step process for identifying design fire scenarios. These are:

Step 1 – Location of fire: characterise the space and location in which the fire begins.

Step 2 – Type of fire: identify the items involved and the initial intensity and rate of fire growth.

Step 3 – Potential fire hazards: identify other critical high consequence scenarios.

Step 4 – Systems and features impacting on fire: identify fire safety systems or features that are likely to significantly impact on the development of the fire or untenable conditions.

Step 5 – People response: consider the effect of actions by people on the development of the fire or the movement of smoke.

Step 6 – Event tree: construct an event tree that describes the event sequences of alternative fire scenarios.

Step 7 – Consideration of probability: estimate the probability of each event using available data and engineering judgement.

Step 8 – Consideration of consequence: estimate the consequence of each scenario using available loss data and/or engineering judgement.

Step 9 – Risk ranking: rank the scenarios in order of relative risk.

Step 10 – Final selection and documentation: select the highest ranked fire scenarios for quantitative analysis.

In other work, Wu (Wu 2001) discussed issues concerning apartment buildings and provided a guidance matrix for their design. Minimum fire safety measures were recommended based on building height, sprinkler protection and building emergency plan.

Custer and Meacham (Custer & Meacham 1997) discussed the design process, identifying fire scenarios and developing design fires within the context of performance-based fire safety design.

3. FIRE INCIDENT STATISTICS

A summary of the reported fire incident statistics associated with apartments for Australia, Canada, New Zealand, the UK and the USA is presented.

3.1 Australia

Dowling and Ramsey (Dowling & Ramsey 1997) analysed fire incident statistics from AFIRS covering the period 1983 to 1993. The total number of residential structure fires over the period considered was 35,176, including 5,606 (15.9%) apartments. Apartment fires accounted for 38 (15.5%) of the total number (244) of deaths in residential buildings. Apartment fires accounted for 464 (21.4%) of the total number (2,165) of fire injuries in residential buildings. In general, cooking fires were the most common but not the most hazardous. It was reported that fires involving bedding were three times more likely to cause death than fires involving cooking materials. In addition, the number of deaths from fires involving soft furniture was over four times that associated with fires involving cooking materials.

Dowling and Ramsey (Dowling & Ramsey 1996) also analysed fire incident statistics from AFIRS covering the period 1989 to 1993. Of the total (48,802) reported fires for this four year period, it was reported that ceiling linings were involved in less than 10% of all fires (i.e. 4,098 of the total, 48,802). The number of fires, involving ceiling linings, that occurred in apartments was 234. Wall linings were involved in 6,879, of these, 498 occurred in apartments. Fires involving floor linings accounted for 6048, 592 of which occurred in apartments. Insulation was involved in 490 of the reported fires, eight of these occurred in apartments. External facings were involved in 1,959 fires, 108 of these occurred in apartments. The number of fires involving external facings was 3,003, and 75 of these occurred in apartments.

King (King 1995, 1997) analysed Australia-wide fire incident statistics for the 1992–93 year for fires attended by fire services. Fire in residential properties accounted for 62.4% of all structure fires, with apartments and flats accounting for 14.2% of all residential structure fires.

Thomas and Verghese (Thomas, I. R. & Verghese 2001) analysed apartment fire incident data for the years 1989 to 1993. On average, approximately 1.7 fires occurred in apartments per 1,000 apartments per year and 6.8 fatalities occurred per 1,000 apartment fires. Of the 254 fatalities that occurred in apartment fires that were examined by the Melbourne or London coroners, 10% were attributed to suicide, 4% were attributed to arson, 37% were attributed to fires where the cause of ignition was smoking materials, and 10% were attributed to cooking or open flames (e.g. lighting fires). Furthermore, the room of fire origin was reported as the bedroom for 31% of apartment fire fatalities, the lounge for 29%, and the kitchen for 18%. Of the known locations at ignition, 73% of civilian apartment fire fatalities were in the room of fire origin.

The Queensland Department of Emergency Services (QLD Dept of ES 1998) summarised statistical data associated with fire incidents that occurred in the period from 1 July 1993 to 30 June 1996 in the States and Territories of Australia. The cause of death, as shown in Figure 1, was primarily attributed to smoke inhalation, accounting for approximately three-quarters of fire-related deaths for all States and Territories, except for Queensland (where approximately 50% of deaths were attributed to burns or incineration, and the elderly and children were over-represented in these fatalities).

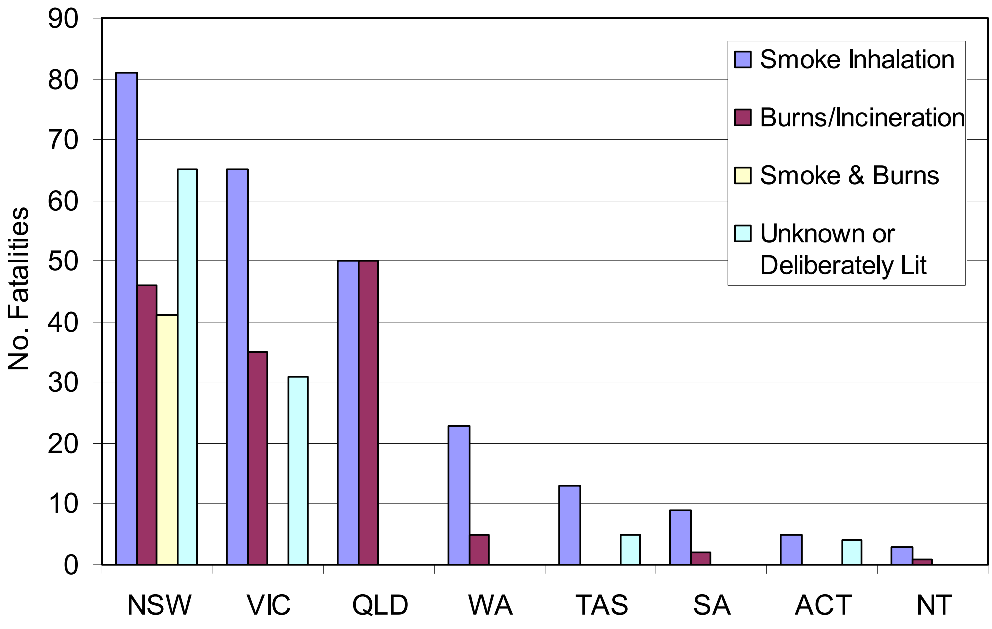


Figure 1: Cause of death for fire victims in Australia (1 July 1993 – 30 June 1996). Adapted from (QLD Dept of ES 1998).

From the available data (QLD Dept of ES 1998), the majority of structural fires resulting in death were located in residential properties. However there were significant portions of missing data, due to difference and discrepancies between the various State and Territory reporting procedures. Data was presented for owner-occupier and tenanted properties, but not broken down further in terms of building types.

Of the 541 fatal fire events that occurred in Australia between 1993 and 1996, a fire cause was not reported for 254 of the cases (QLD Dept of ES 1998). For 147 of these fires, it was not possible to determine the cause. The major cause of fatal fires, for the remaining 149 cases, was accidents involving discarded smoking materials, lighters or matches. A large number of the fires caused by smoking material, lighters or matches occurred because either the victim had unknowingly discarded the material because they were asleep or intoxicated with alcohol or a child was playing with the materials.

In Queensland, for 57 of the total fire fatalities (100), the cause of the fire was not determined. However, of the remaining cases, 14 of the victims died as a result of fires caused by heat from smoking materials (such as a discarded match or a smouldering cigarette). Eight of the fire fatalities resulted from cooking incidents in the kitchen, such as unattended food items being left on the stove or ignition of a victim's clothing. Portable heaters were identified as the cause of nine deaths. Problems associated with electrical equipment (either electrical faults or overloading of power outlets) accounted for six of the victims. Open flames (such as candles or mosquito coils) and deliberately lit fires using accelerants were listed as the cause of fires in the remaining six cases.

In New South Wales, the cause of fire for 75 of the deaths (of a total number of fatalities of 168) was not determined. However 45 of the fires were deliberately lit, 46 fires were caused by discarded smoking materials and accidents involving lighters and matches, 22 were caused by portable heaters, and 22 were caused by problems associated with electrical equipment. The cause of the remaining 24 fires was attributed to bushfires, direct flame, cooking accidents, candles, gas, explosions, accelerants or air conditioning.

In Victoria, the cause of the fire for 110 fatalities, of the total (100), was unknown. Five fatalities were caused by deliberately lit fires. Discarded smoking materials were attributed to 84 deaths. Fires involving heating equipment accounted for 29 deaths (typically where combustibles had been put too close to the heating unit). Electrical faults accounted for 15 fatalities and fires resulting from heat from open flames such as lighters and candles accounted for 12 deaths.

In the Australian Capital Territory, (of the total nine fatalities) four deaths were caused by deliberately lit fires. Four deaths were attributed to malfunctioning heating equipment and one death was attributed to discarded smoking materials.

Detailed statistics for each cause of fire were not provided for fires in Western Australia, South Australia or the Northern Territory during this period. However the general list of fire causes included heat from open flames (candles, matches and lighters), discarded cigarettes, portable heaters, accidents involving heat from properly operating equipment, misuse of heating equipment, unattended food items in the kitchen and child fire-play. For South Australia the major cause of accidental or preventable fires was listed as discarded smoking materials (i.e. smoking in bed or falling asleep while smoking).

The New South Wales Fire Brigades (NSWFB 2003) reported statistical information on fires, including statistics for fires involving apartments, units and flats, in their 2001/02 Annual Report. Unattended heat sources, such as cooking left on stove, were the main form of heat ignition for apartments (32%) compared to 22.8% for residential properties in total. The most commonly reported causes of ignition for apartments, units and flats were cooking (24%), an open flame or spark (11%, which included matches, lighters and candles) and smoking materials (7%, which included cigarettes, cigars, etc), as shown in Figure 2. The most commonly reported causes of ignition for all residential fires were cooking (11%), an open flame or spark (7%) and appliances (5%), as shown in Figure 3. The most common room of fire origin reported for apartments, units or flats was the kitchen (58%), followed by bedrooms (9%), storage areas (9%) and lounge (8%), as shown in Figure 4. The most common room of fire origin for all residential fires was also the kitchen (43%), followed by bedrooms (13%) and lounge (10%), as shown in Figure 5. For apartments, units and flats, of the reported material first lit, the most common were cooking materials (39.7%), power transfer equipment (5.5%), rubbish (5.5%) and mattresses, pillows or bedding (5.2%), as shown in Figure 6. For all residential fires, the most common materials first lit were cooking materials (27.0%), power transfer equipment (8.9%), structural (6.9%) and mattresses, pillows or bedding (5.5%), as shown in Figure 7.

From the statistics reported for fires that occurred in NSW during the financial calendar of 2000–2001 (NSWFB 2003), the number of fire-related fatalities was four and 20, for apartments, units and flats and all residential property respectively. The number of fire-related injuries was 134 and 464, for apartments, units and flats and all residential property respectively. Of the ignition factors reported for all fires, where an injury or fatality occurred, the most common was the "misuse of heat of ignition", which included situations where an occupant had abandoned or discarded material, had fallen asleep or was unconscious, had a mental or physical impairment, or was intoxicated, or where a child's play resulted in the fire.

Over the five year period, from 1995/96 to 1998/99 (NSWFB 2003), there was an average of seven fire-related deaths per annum in apartments, living units or flats compared to an average of 35 in all residential property. For the same period, there was an average of 105 fire-related injuries per annum in apartments, living units or flats compared to 426 in all residential property.

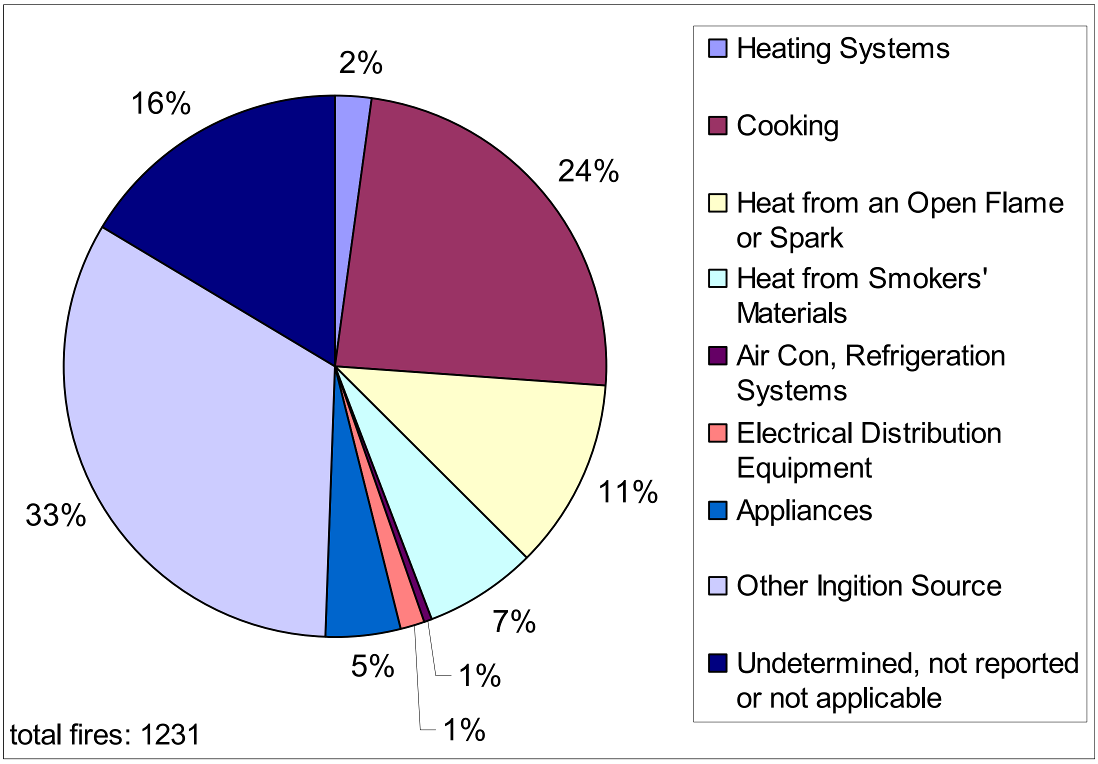


Figure 2: Proportion of cause of ignition for NSW apartments, units or flats, for 2000/2001. Extracted from (NSWFB 2003).

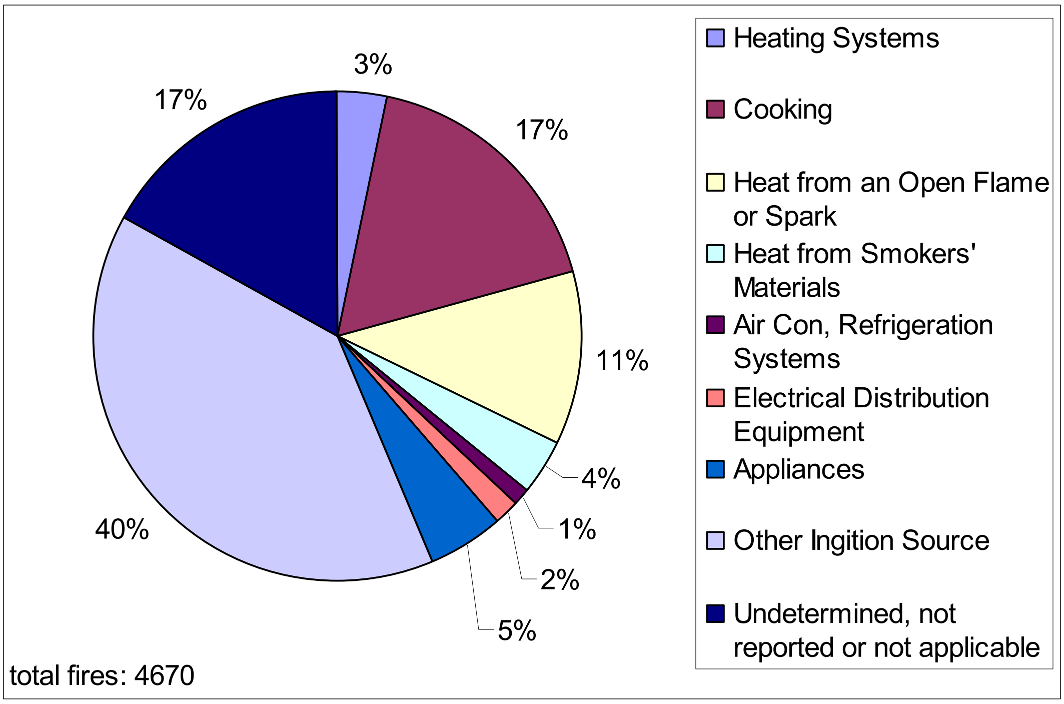


Figure 3: Proportion of cause of ignition for all NSW residential property, for 2000/2001. Extracted from (NSWFB 2003).

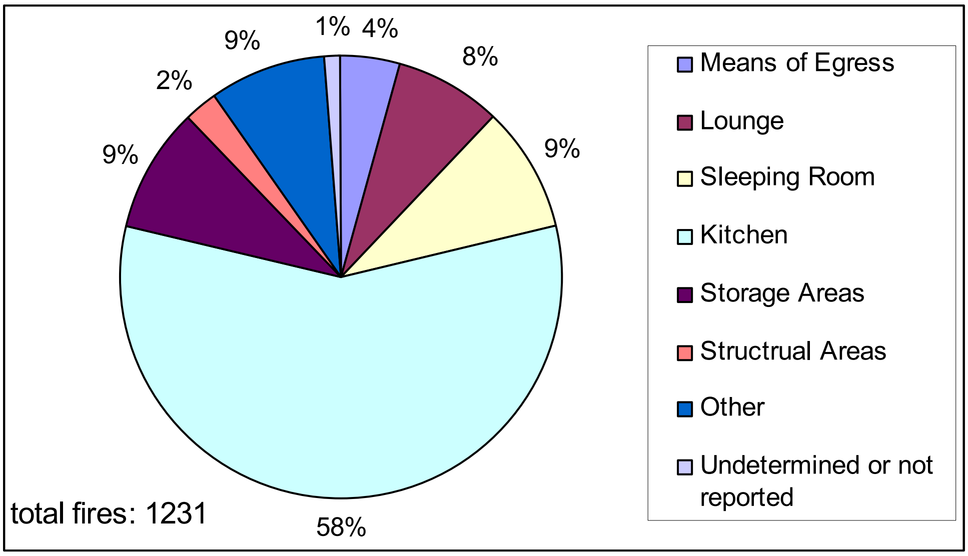


Figure 4: Proportion of location of fire origin for NSW apartments, units or flats, for 2000/2001. Extracted from (NSWFB 2003).

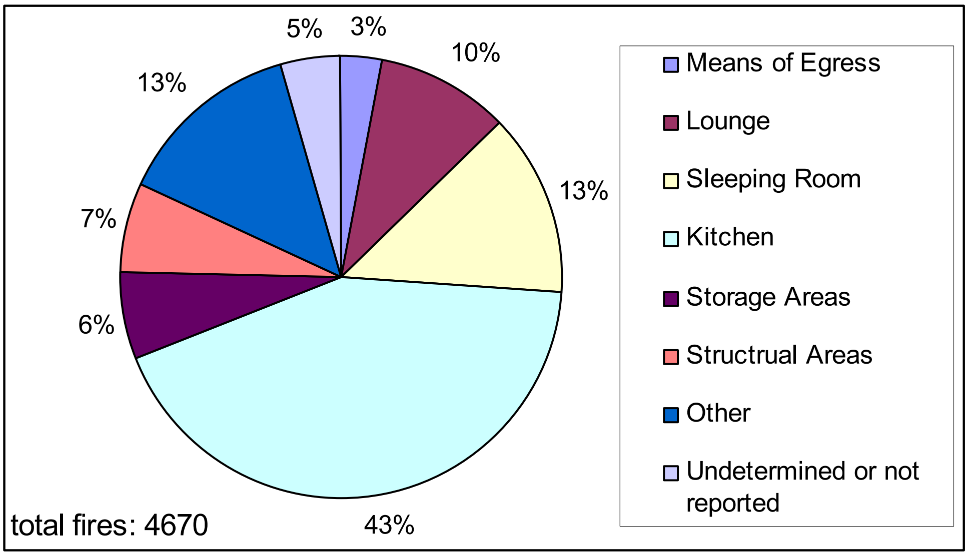


Figure 5: Proportion of location of fire origin for all NSW residential property, for 2000/2001. Extracted from (NSWFB 2003).

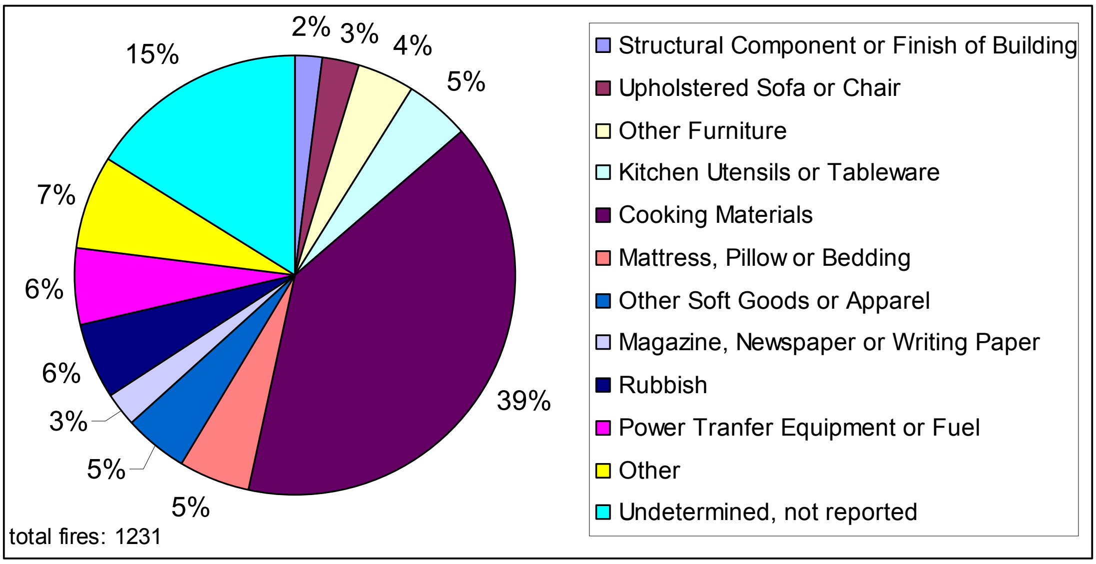


Figure 6: Proportion of first material ignited for NSW apartments, units or flats, for 2000/2001. Extracted from (NSWFB 2003).

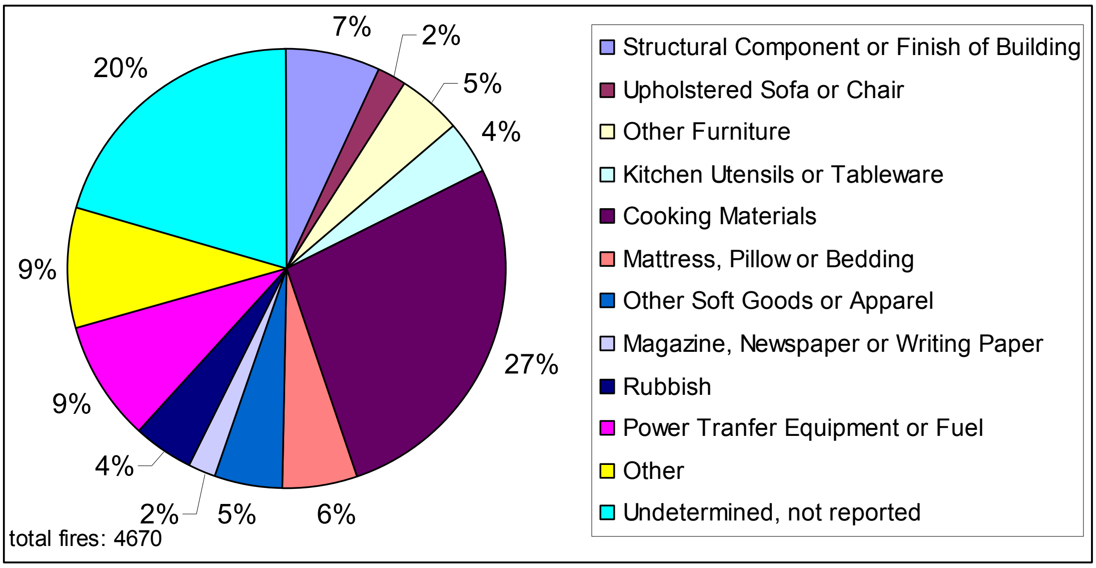


Figure 7: Proportion of first material ignited for all NSW residential property, for 2000/2001. Extracted from (NSWFB 2003).

3.2 Canada

In Canada, 85% of fire deaths occur in residential buildings (Canadian Wood Council 2000). Table 3 and Table 4 confirm that upholstered furniture, mattresses and bedding pose the greatest threat in fatal fires for both single-family dwellings and in apartments.

Table 3: Annual fire loss record for single-family dwellings – items first ignited*

Item first ignited (list not complete)	**Deaths per 100 fires†**	**Injuries per 100 fires**
Upholstered furniture	5.11	9.24
Mattress or bedding	1.94	7.48
Multiple forms	1.94	4.47
Gas or liquid	1.47	8.61
Floor covering	1.32	3.88
Structural members	0.75	1.78

* Extracted from (Canadian Wood Council 2000).
† Total number of fires in one and two family dwellings was 51,423 (1993–1995).

Table 4: Annual fire loss record for apartment buildings one–four storeys – items first ignited*

Item first ignited (list not complete)	Deaths per 100 fires†	Injuries per 100 fires
Upholstered furniture	4.16	15.73
Mattress or bedding	2.16	12.21
Multiple forms	1.91	10.00
Gas or liquid	1.65	6.53
Floor covering	1.56	10.94
Structural members	1.38	4.94

* Extracted from (Canadian Wood Council 2000).
† Total number of fires in apartment buildings was 17,677 (1993–1995).

Yung and Lougheed (Yung & Lougheed 2001) analysed Ontario fire statistics for houses (detached, semi-detached and attached) for the period from 1995 to 1998, from the Office of the Fire Marshal. For this period, there was an average of 5,429 house fires per year, 67 deaths per year, with an average dollar loss of CDN $21,800. As the room of fire origin, living areas constituted 11.3% of all house fires, but were associated with 32.3% of deaths. In addition, sleeping areas constituted 8.5% of all fires, but 15.4% of deaths. Furthermore, cooking areas constituted 25.6% of fires, but only 20.4% of deaths. Fires in these three areas accounted for 68.1% of all deaths. Similarly, Bounagui et al (Bounagui, Bénichou & Ederne 2004) analysed Canadian fire statistics available for the period 1986–2000. Residential properties accounted for 42% of fires and approximately 80% of all fire-related deaths. The annual average number of fires was 63,622 over the last 15 years.

Figure 8 shows the distribution of ignition sources from Canadian fire statistics for 1999 (HRDC 1999), with smokers' materials forming the largest group at 20%.

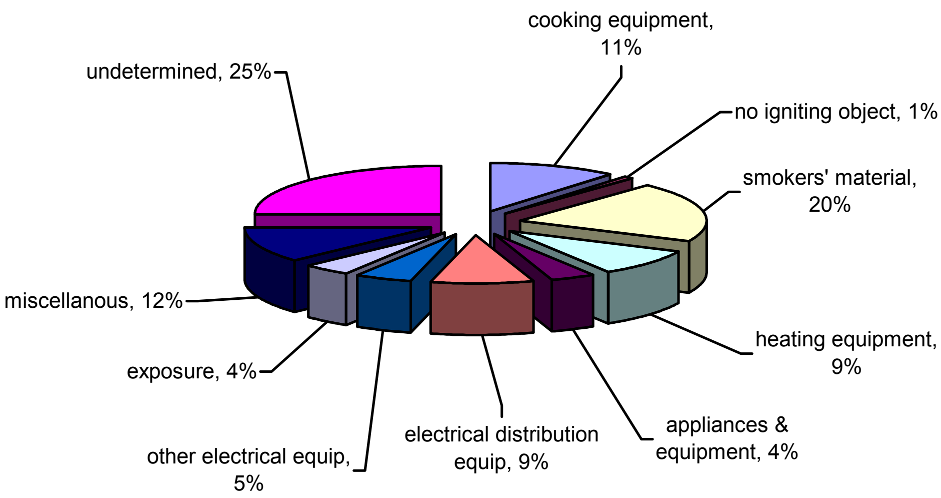


Figure 8: Summary of ignition sources for fires recorded in 1999. Extract from (Bwalya, Sultan & Bénichou 2003).

The number of fire-related deaths and injuries for various types of residential properties were presented by the Council of Canadian Fire Marshals and Fire Commissioners (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002). The general trend of the fire-related deaths associated with residential properties has decreased over the period from 1987 to 2001, as shown in Figure 9. Over this period 62% of fire-related deaths occurred in one or two-family dwellings (including both rural and urban situations) and 20% of deaths associated with residential property occurred in apartments, flats or tenements, as shown in Figure 10. However 53% of fire-related injuries occurred in one or two-family dwellings and 34% occurred in apartments or flats, as shown in Figure 11. The ratio of the total number of fire-related deaths to the total number of fires that occurred over the period considered was approximately the same (0.12) for both one and two-family dwellings, and apartments and flats, as shown in Figure 12. However the ratio of the total number of fire-related injuries to the total number of fires that occurred over this period was twice the value for apartments and flats (0.14) than for one and two-family dwellings (0.7), as shown in Figure 13. For both injuries and deaths, boarding and lodging houses had the highest number of casualties per fire (Figure 12 and Figure 13).

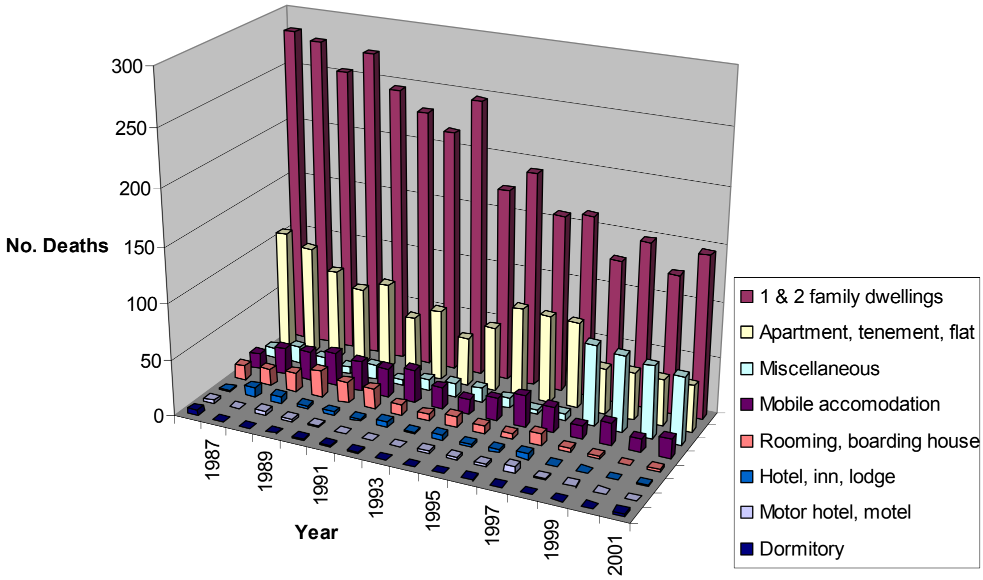


Figure 9: Number of fire-related deaths in Canada that occurred between 1986 and 2001. Adapted from (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

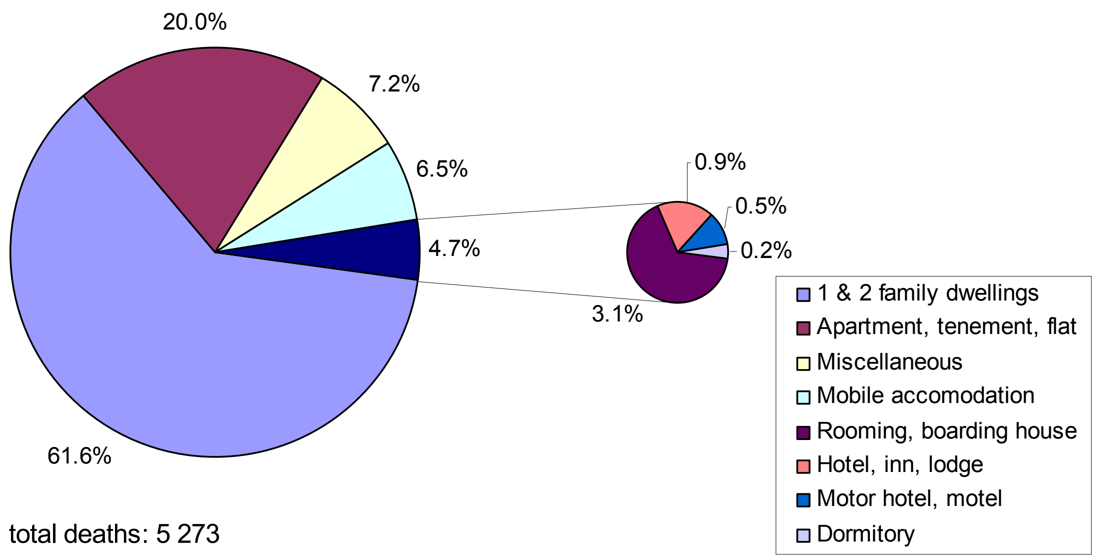


Figure 10: Proportions of Canadian fire-related deaths that occurred in residential properties from 1986–2001. Adapted from (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

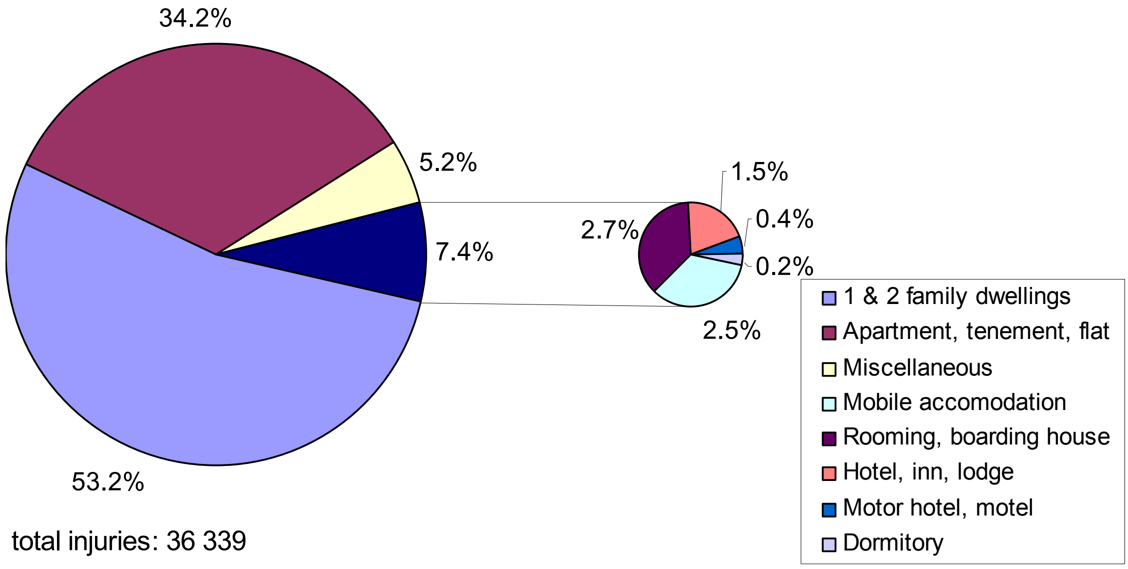


Figure 11: Proportions of Canadian fire-related injuries that occurred in residential properties from 1986–2001. Adapted from (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

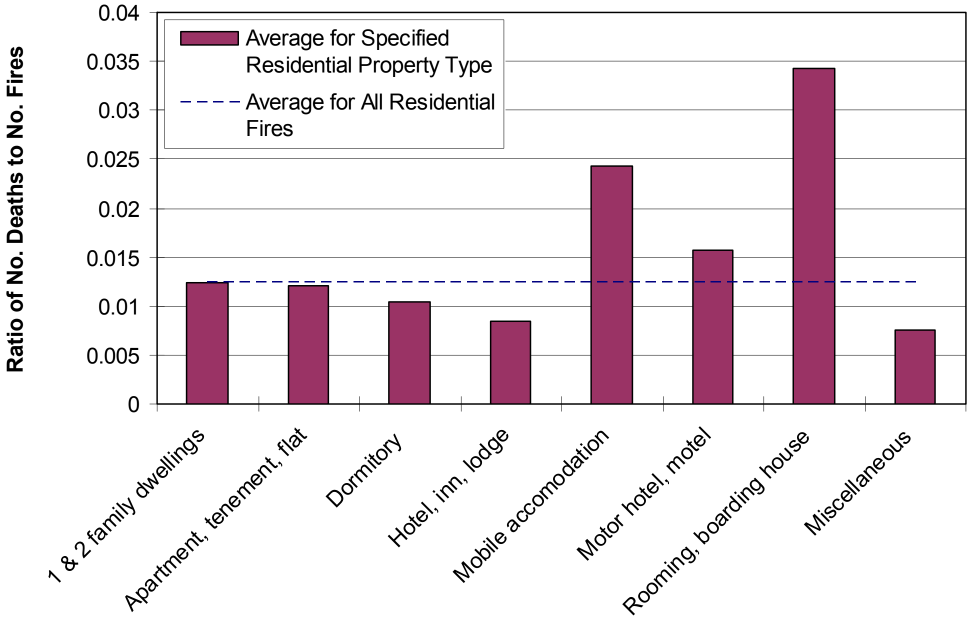


Figure 12: Ratios of the number of deaths to the number of fires that occurred in residential properties in Canada between 1986 and 2001. Adapted from (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

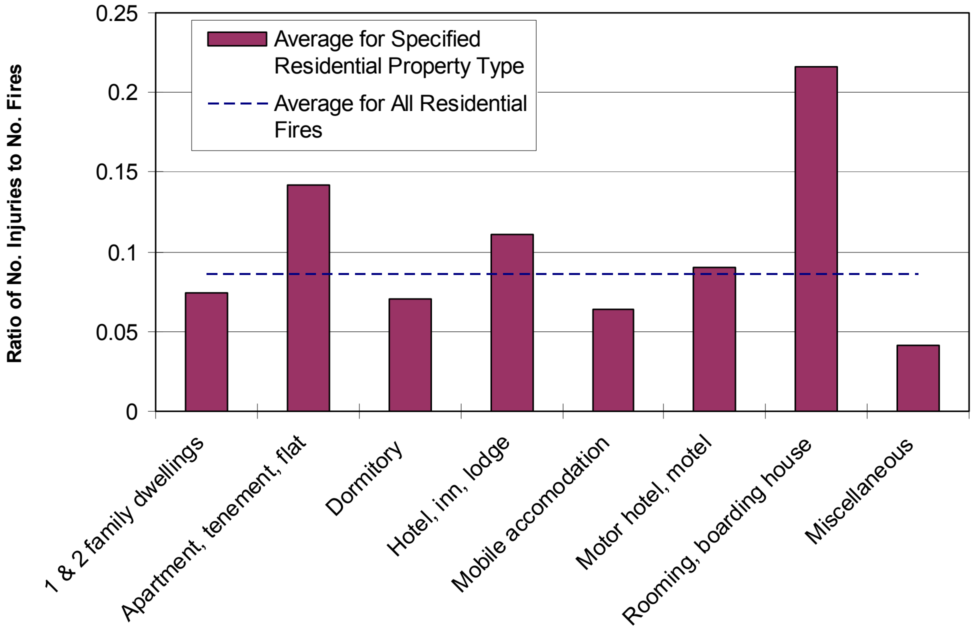


Figure 13: Ratios of the number of injuries to the number of fires that occurred in residential properties in Canada between 1986 and 2001. Adapted from (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).

3.3 New Zealand

During the period 1999–2003, there were on average 6,719 residential structure fires per annum (NZFS 2004). Of these 10% occurred in flats, home units or apartments, as shown in Figure 14. Over the same period, there was an average of 37.6 fatalities per annum, 24 (64%) of these were in residential buildings, whereas only 3.2 (8.5%) occurred within flats, home units or apartments, as shown in Figure 17.

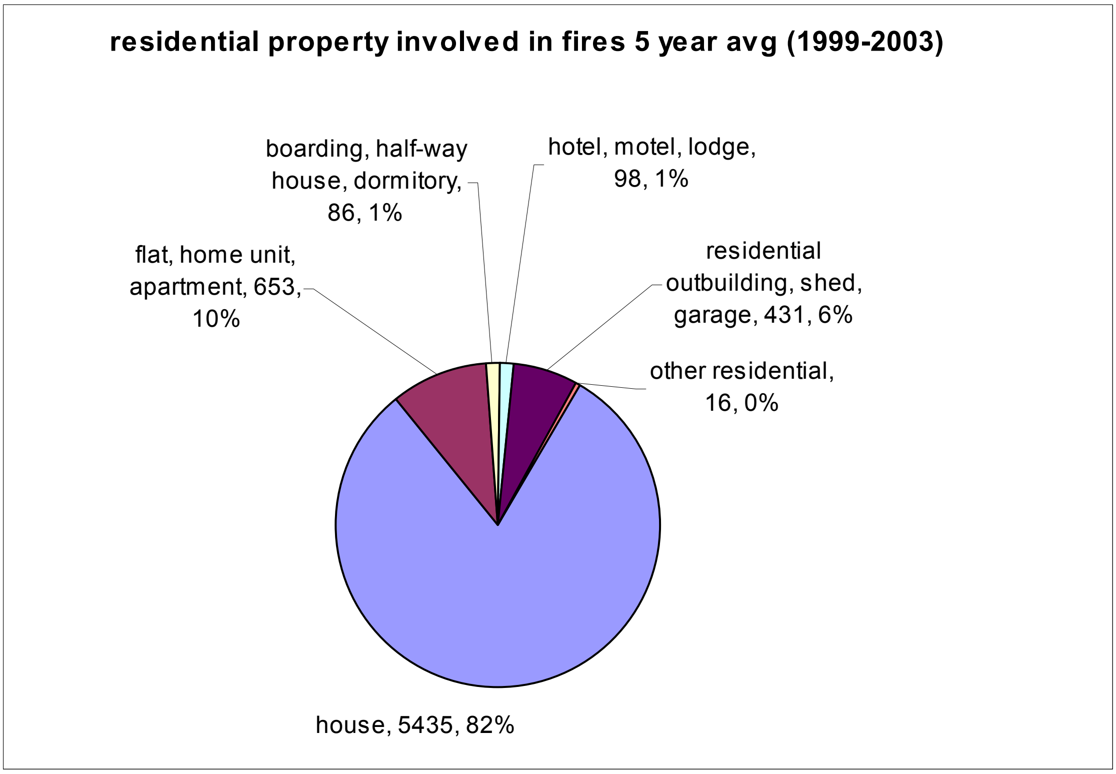


Figure 14: Residential property involved in fires (1999–2003). Adapted from (NZFS 2004).

Narayanan and Whiting (Narayanan & Whiting 1996) analysed 1986–1993 data and found apartment fires accounted for 8.3% of all residential fires. This is slightly less than the 10% from the more recent data which could be explained by the increase in the number of apartments over the last decade in New Zealand.

The New Zealand Fire Service (NZFS 2004) provided data on the area of origin for residential fires, as shown in Figure 15. The most frequent rooms of fire origin were the kitchen (31.7%), lounge (13.0%) and bedroom (10.3%). The most common types of equipment involved in ignition were cooking-related (stove top at 33%, oven at 13% and food warming unit at 3%), heating-related (portable and fixed heating, both at 4%) and appliances (including portable heating appliances, washing machine, dryer and television), as shown in Figure 16. The data indicates that 47.6% of residential structure fires involved objects first ignited typically located in a kitchen (i.e. stoves, cook tops, warming units and ovens).

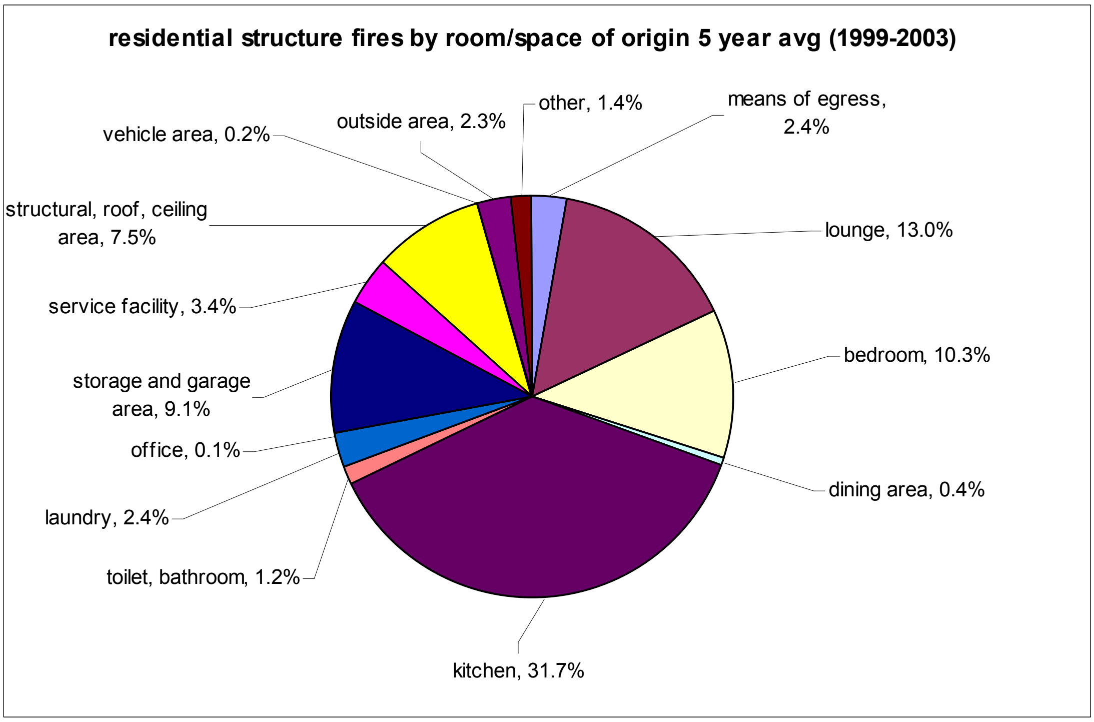


Figure 15: Residential structure fires by room/space of origin (1999–2003). Adapted from (NZFS 2004).

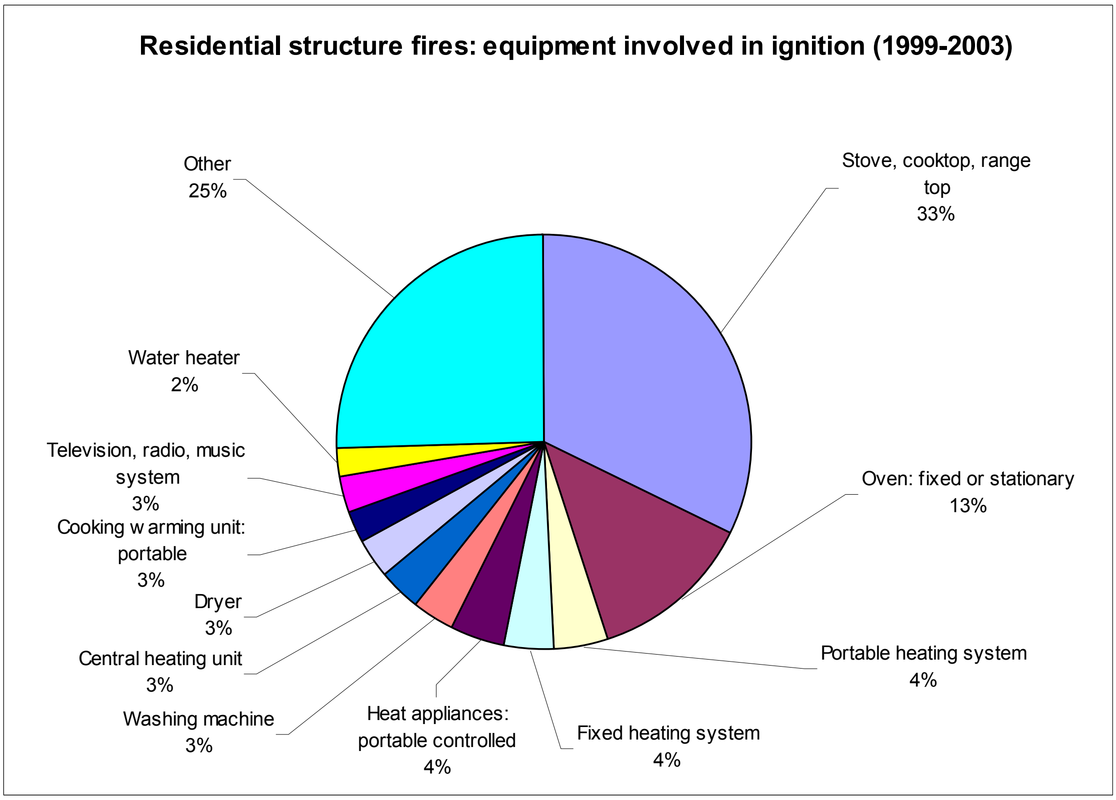


Figure 16: Residential structure fires: most common equipment involved in ignition (1999–2003). Adapted from (NZFS 2004).

3.3.1 Fatal fires

New Zealand Fire Service data (NZFS 2004) shows that 8.5% of fatal fires occur in flats, home units or apartments as shown in Figure 17.

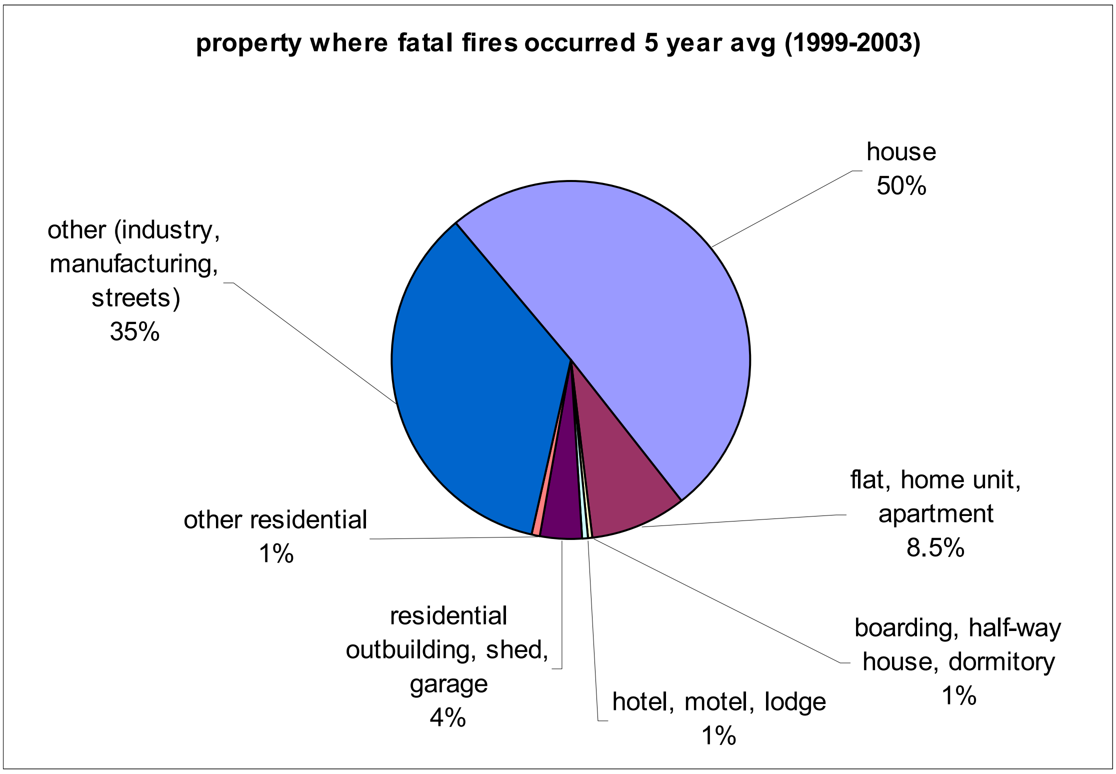


Figure 17: Property where fatal fires occurred (1999–2003). Adapted from (NZFS 2004).

Wong (Wong 2001) studied the contribution of upholstered furniture to residential fire fatalities in New Zealand and identified the most common objects first ignited in fatal fires as shown in Figure 18 and Figure 19. While upholstered furniture was reported as the item first ignited in only a modest number of fatal residential fires (1.6%), Wong showed that upholstered furniture was involved in fire incidents that accounted for 35.4% of all residential fatalities.

An analysis of earlier fire incident data presented by Wade & Duncan (Wade & Duncan 2000) showed that the kitchen was the room of origin for 24 % of fatal fires behind bedrooms (38%) and lounges (26%).

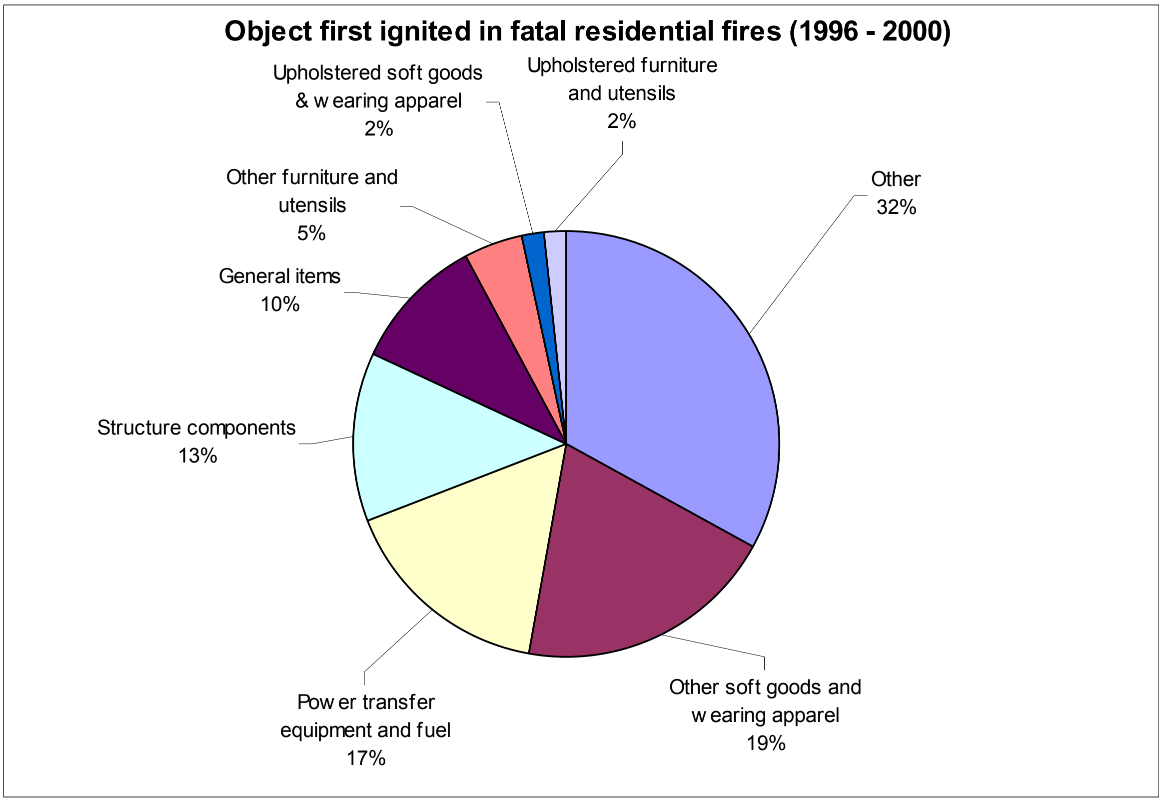


Figure 18: Object first ignited in fatal residential fires (1996–2000). Adapted from (Wong 2001).

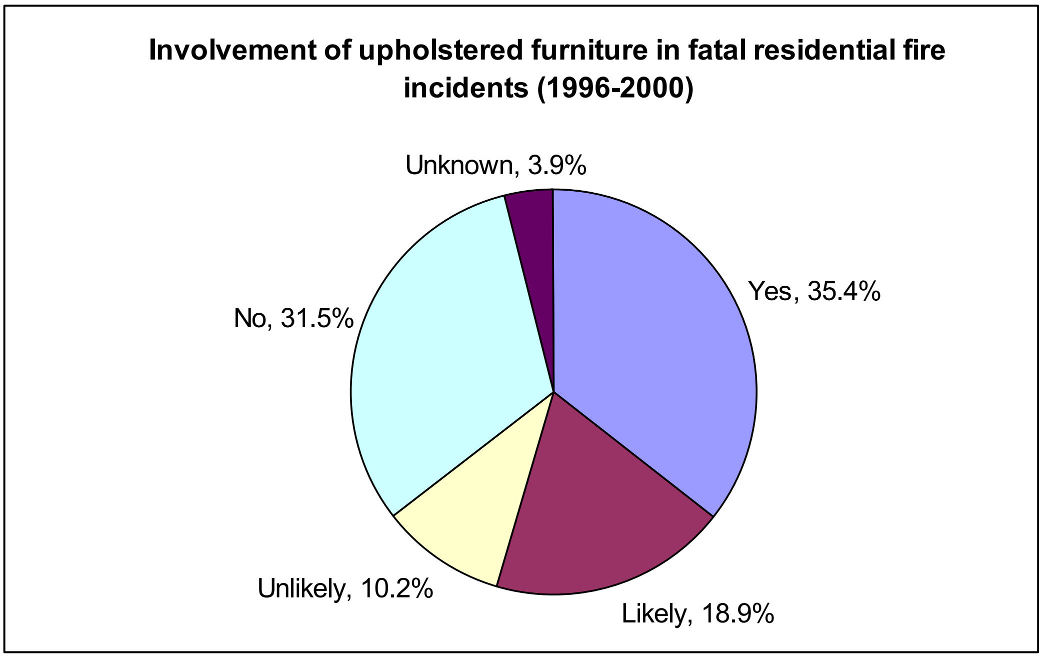


Figure 19: Involvement of upholstered furniture in fatal residential fires (1996-2000). Extracted from (Wong 2001).

3.4 United Kingdom

The Scottish Executive (Scottish Executive 2004) estimated 65,600 total fires (including primary, secondary and chimney fires) occurred in 2003, of which 65% occurred in buildings. A summary of the total number of fires and locations (dwellings, other buildings, vehicles or other locations outdoors), for the period from 1994 to 2003, is shown in Figure 20. Scottish dwelling fires (including caravans, houseboats and other non-building structures that were used solely as permanent dwellings) accounted for 69% (8,043 fires) of Scotland's total building fires in 2003. This compares with 59% for England, 56% for Wales and 65% for Northern Ireland, for the same year. The total number of fire-related injuries in Scotland in 2003 was 1,880, and of these 1,625 occurred in dwelling fires (86%). Sixty-one fatalities occurred in residential fires; this was 76% of the total number of fire-related deaths. This equated to approximately eight deaths per 1,000 residential fires, which was comparable to the other countries in the UK for the same year. The total number of fire-related injuries in Scotland in 2003 was 1,880, and of these 1,625 (86%) occurred in residential fires. For 2003, the main source of ignition reported for residential fires was smokers' materials and matches (40%), then cooking appliances (33% which was primarily attributed to chip pan fires), and candles (12%). A summary of the number of fires ignited by the top five ignition sources (which included misuse of equipment or appliances, deliberate, grease or fat fires, faulty appliances, and careless handling of fire or hot items) over the period from 1994–2003 is shown in Figure 21. In 2003, the most commonly reported source of ignition for fatal fires was smoking materials and matches (30%), followed by cooking appliances (25%), as shown in Figure 22. The most commonly reported source of ignition for fires that caused injuries was cooking appliances (60%), followed by smoking materials and matches (21%), as shown in Figure 22.

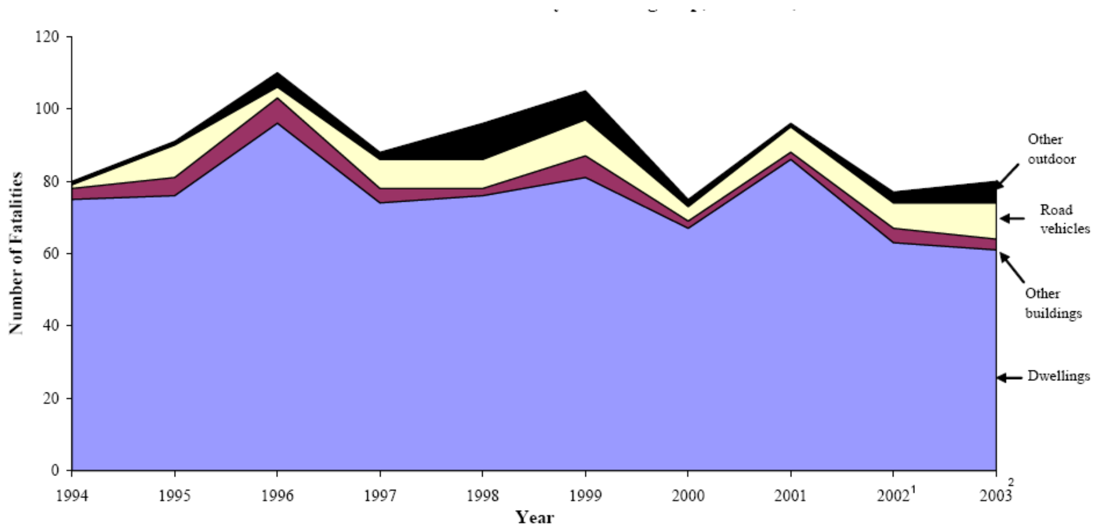


Figure 20: Number of fire-related fatalities, by location, that occurred in Scotland over the period from 1994 to 2003. Extracted from (Scottish Executive 2004).

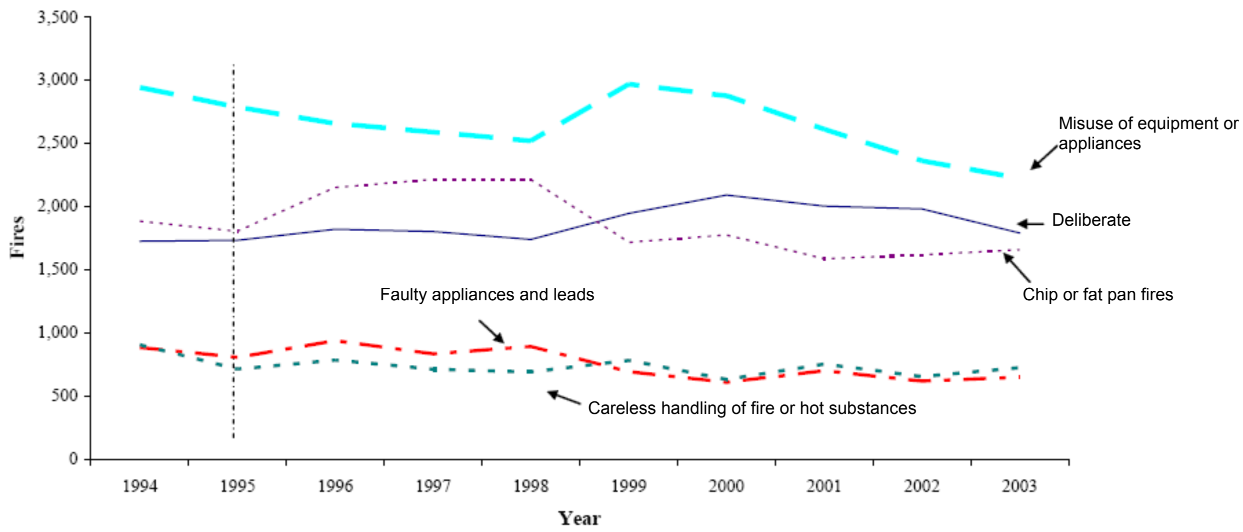


Figure 21: Number of fires in dwellings for the top five sources of ignition in Scotland (1994–2003). Extracted from (Scottish Executive 2004).

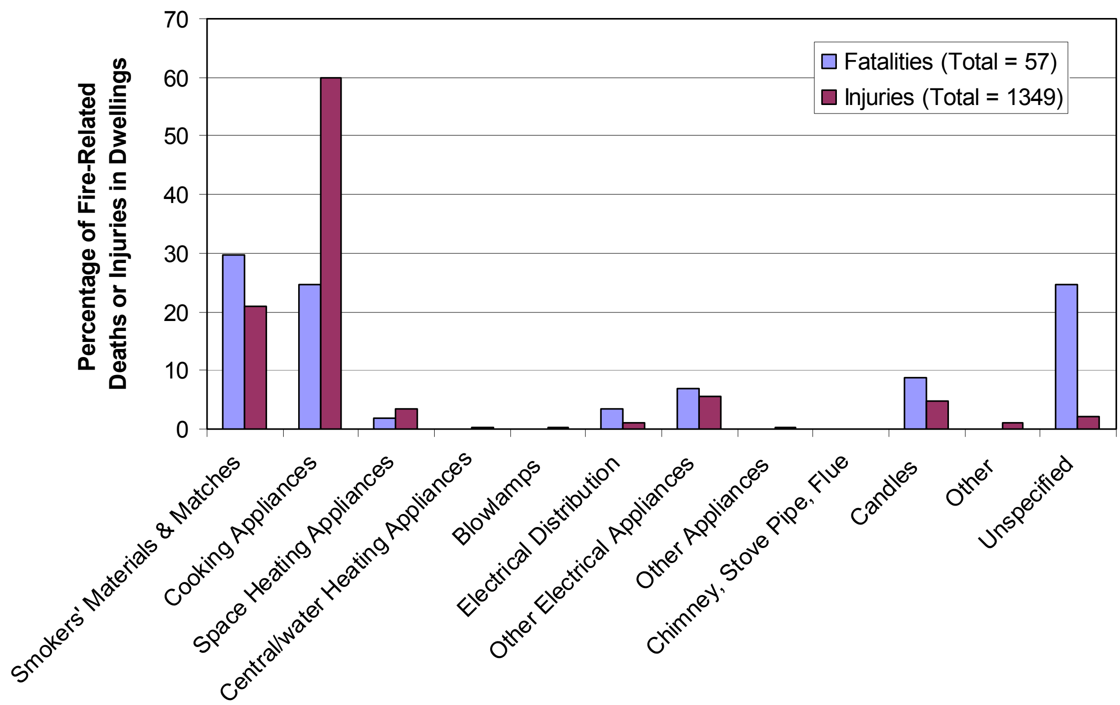


Figure 22: Percentage of fire-related fatalities and injuries that occurred in Scottish dwellings in 2003 by source of ignition. Extracted from (Scottish Executive 2004).

In the UK, from 1990–2002, 11–17% of all fires occurred in buildings, and the majority (approximately 60%) of building fires occurred in dwellings (which included caravans, houseboats and other non-building structures that were used solely as permanent dwellings) (National Statistics, U.K. 2002; National Statistics, U.K. 2003; National Statistics, U.K. 2004). The majority of fire-related fatalities and injuries also occurred in dwellings, as shown in Figure

23 and Figure 24 (for 1990–2000), respectively (National Statistics, U.K. 2002). The most commonly reported cause of fires in dwellings was the misuse of equipment or appliances (31%), followed by malicious intent (18%) and then faulty appliances and leads (12%), as shown in Figure 25. Chip or fat pan fires (11%) and careless handling of fire or hot substances (9%) also accounted for a significant proportion of the reported cause of dwelling fires. The leading cause of fire that was attributed to the highest number of fatalities was consistently the careless handling of fire or hot substances, followed by the misuse of equipment or appliances, for 1990–2000, as shown in Figure 26. A significant proportion of the number of fire-related injuries were consistently attributed to the misuse of equipment or appliances (as shown in Figure 27), which was similar to the most common cause of all dwelling fires (see Figure 25). The majority of dwelling fires initiated in the kitchen (66%), as shown in Figure 28. Bedrooms (10%) and living or dining rooms (10%) were the next most common rooms of fire origin for dwelling fires. However the largest proportion (41%) of fatalities occurred for fires that originated in the living room or dining room and another 30% were attributed to fires that had started in a bedroom, as shown in Figure 29, whereas only approximately 21% of deaths were associated with fires that had started in the kitchen. On the other hand, 60% of injuries were attributed to fires that had initiated in the kitchen and a combination of fires that originated in either the bedroom or living/dining room were associated with approximately 23% of injuries, as shown in Figure 30.

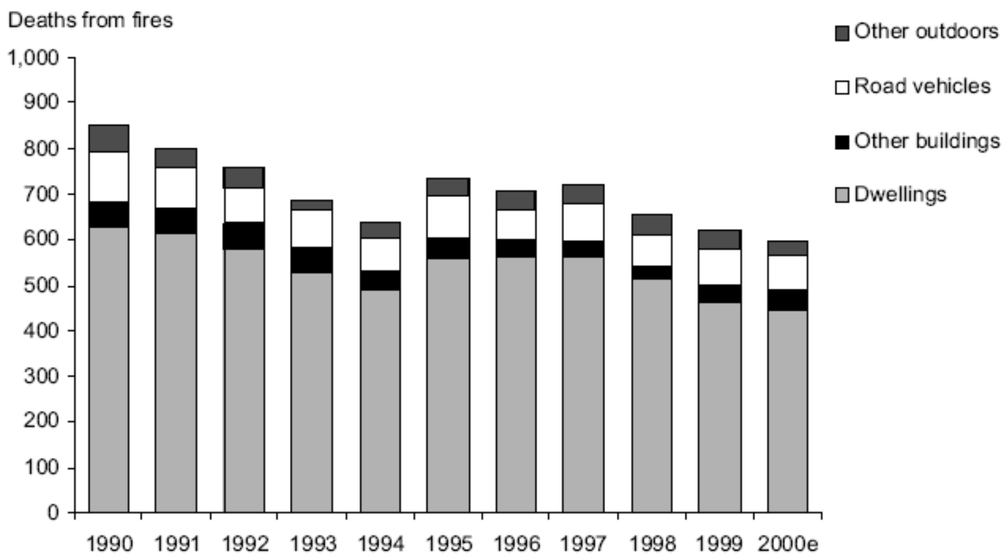


Figure 23: The number of fire-related fatalities, by location, that occurred in the UK over the period from 1990 to 2000. Extracted from (National Statistics, U.K. 2002).

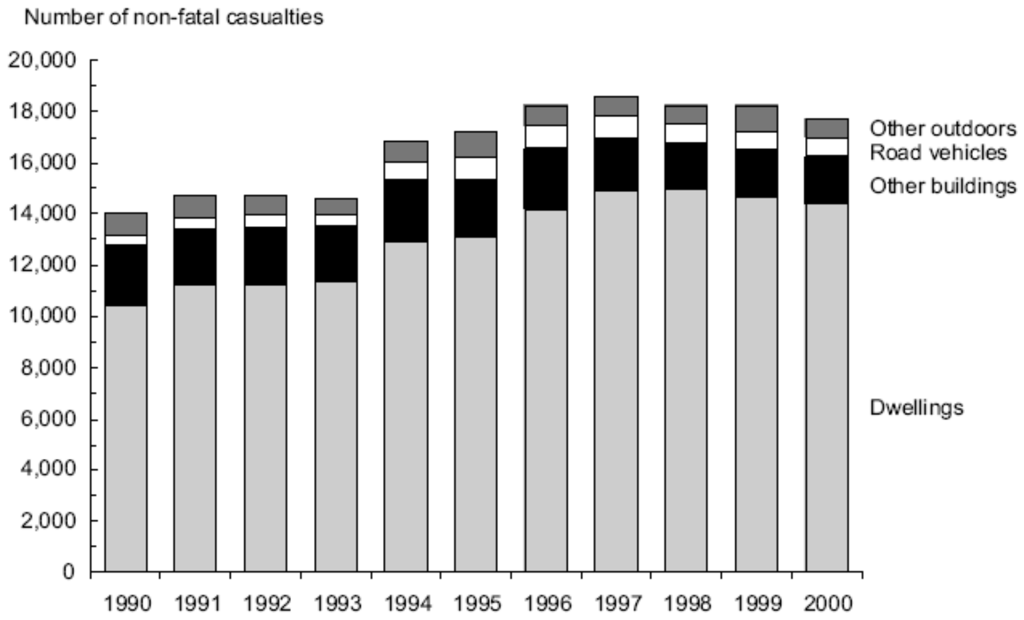


Figure 24: The number of fire-related injuries, by location, that occurred in the UK over the period from 1990 to 2000. Extracted from (National Statistics, U.K. 2002).

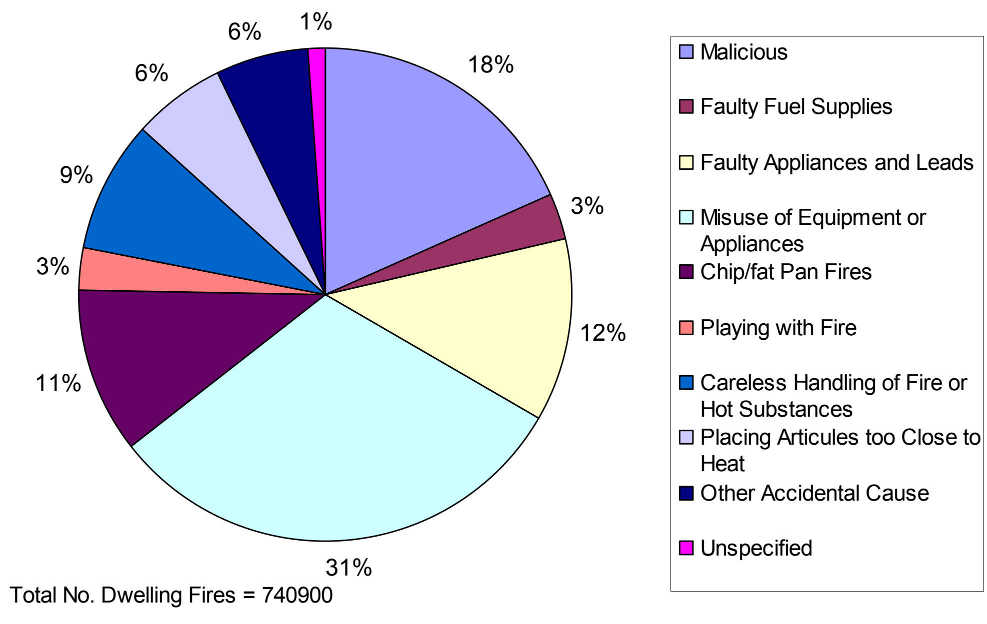


Figure 25: The proportion of dwellings fires, by cause of fire, that occurred in dwellings in the UK over the period from 1990 to 2000. Adapted from (National Statistics, U.K. 2002).

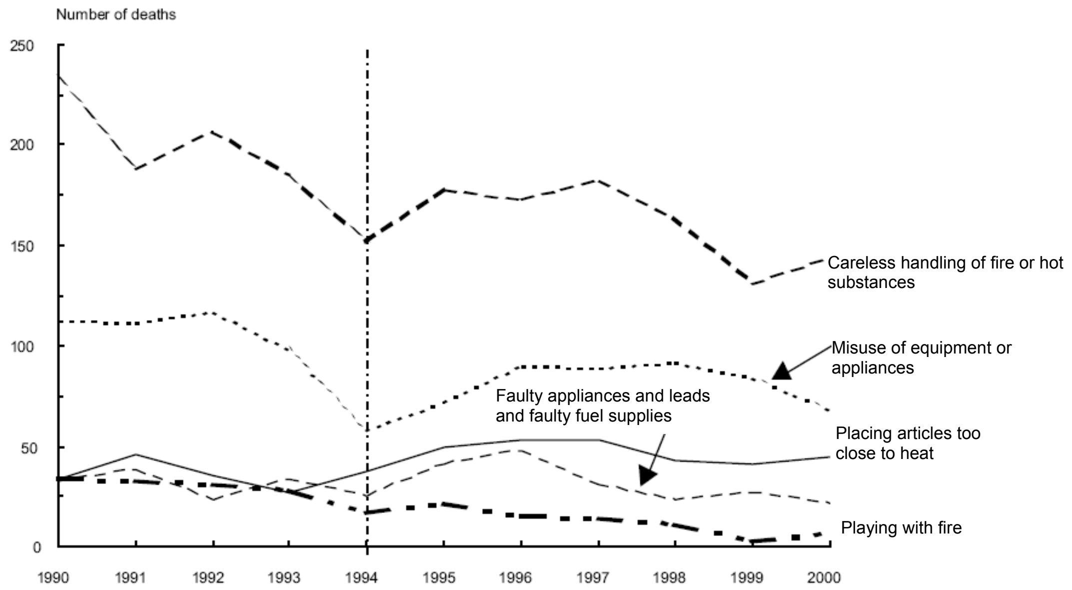


Figure 26: The number of fire-related fatalities, by cause of fire, that occurred in dwellings in the UK over the period from 1990 to 2000. Extracted from (National Statistics, U.K. 2002).

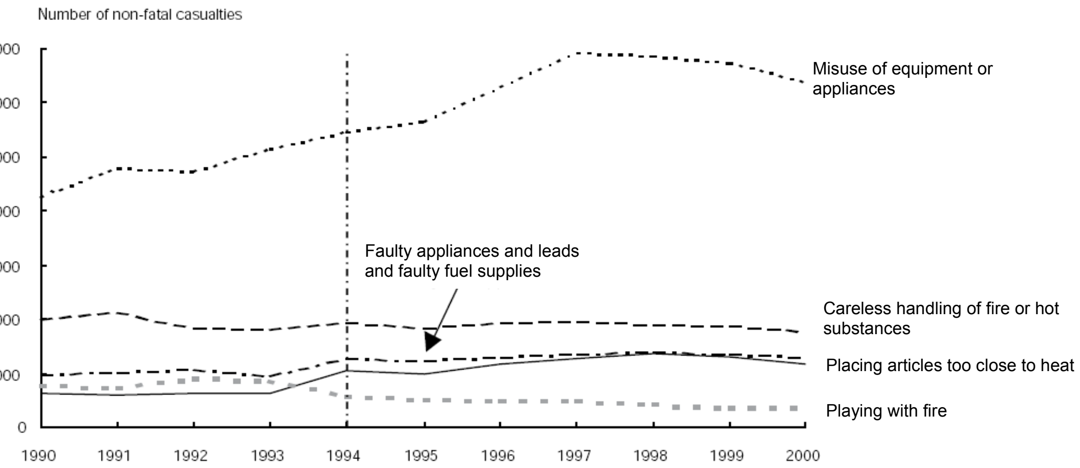


Figure 27: The number of fire-related injuries, by cause of fire, that occurred in dwellings in the UK over the period from 1990 to 2000. Extracted from (National Statistics, U.K. 2002).

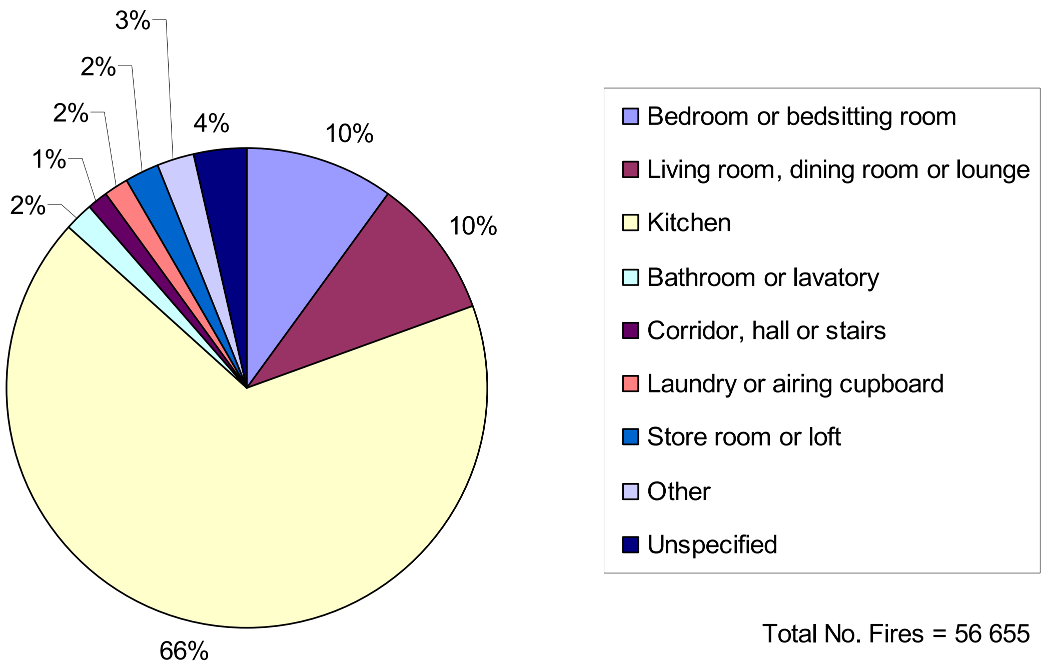


Figure 28: The proportion of dwelling fires, by room of origin, that occurred in the UK in 1999 and 2000. Adapted from (National Statistics, U.K. 2002).

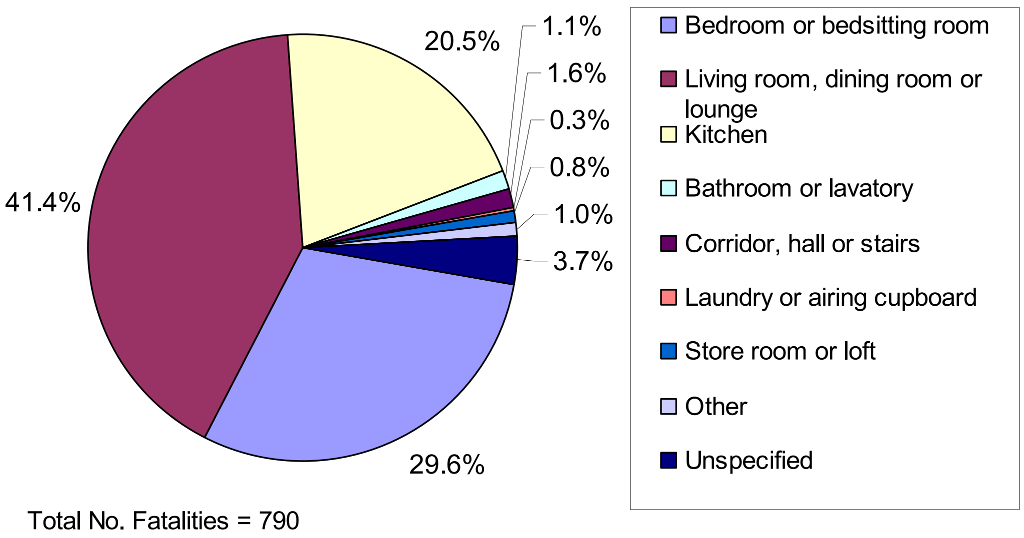


Figure 29: The proportion of fatalities, by room of origin, for dwelling fires that occurred in the UK in 1999 and 2000. Adapted from (National Statistics, U.K. 2002).

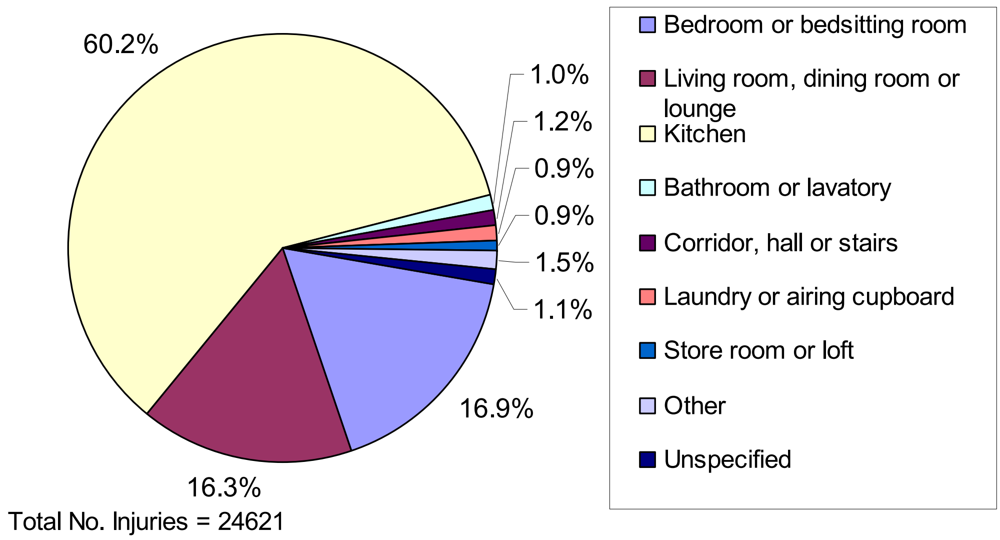


Figure 30: The proportion of injuries, by room of origin, for dwelling fires that occurred in the UK in 1999 and 2000. Adapted from (National Statistics, U.K. 2002).

The 2002/3 British Crime Survey (Office of the Deputy Prime Minister 2004) estimated 372,300 domestic fires in England and Wales. No specified proportions were reported for apartments versus other types of residences. Similar to other regions, the kitchen was the most common room of fire origin (61%), as shown in Figure 31. The lounge/dining room (13%), bedroom (6%). Miscellaneous outside areas (6%) are the next most common areas for domestic fire origin. The majority of domestic fires originated from cooking activities, as shown in Figure 32. Of these, the primary cause was associated with fats or oils catching fire while cooking, as shown in Figure 33.

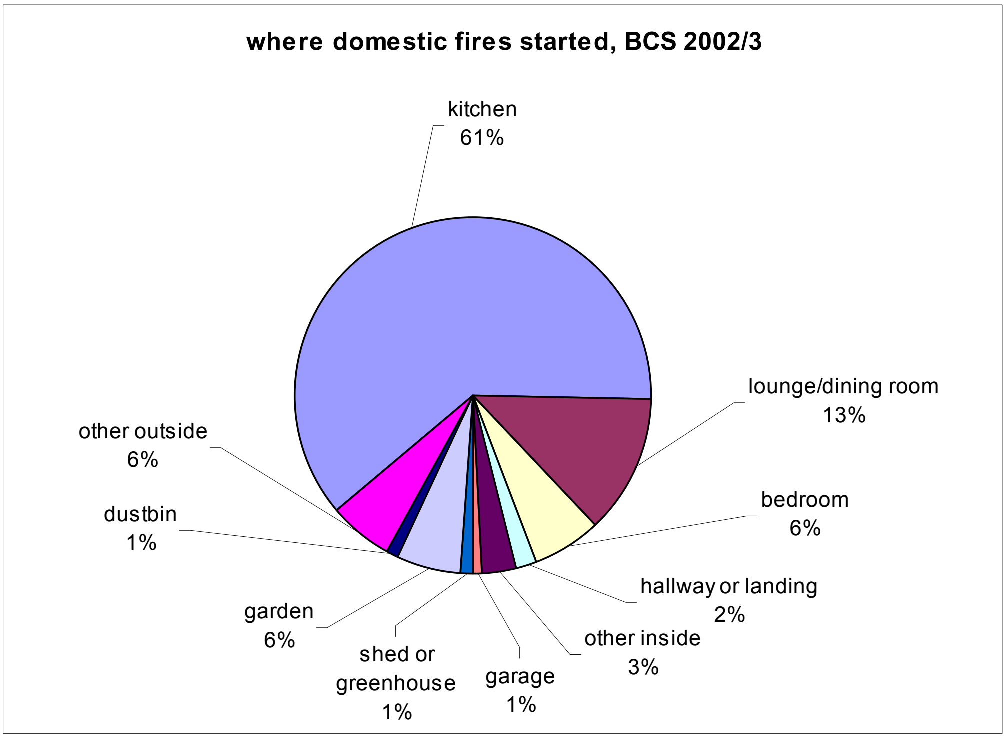


Figure 31: Proportion of areas where domestic fires started. Extracted from (Office of the Deputy Prime Minister 2004).

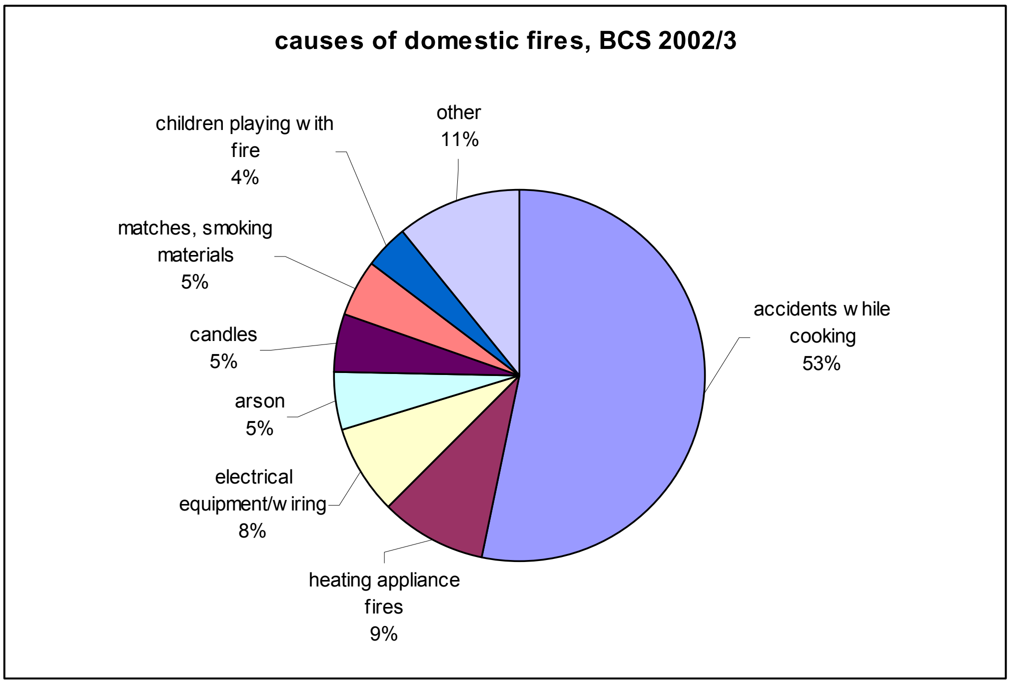


Figure 32: Proportion of causes of domestic fires in kitchens. Extracted from (Office of the Deputy Prime Minister 2004).

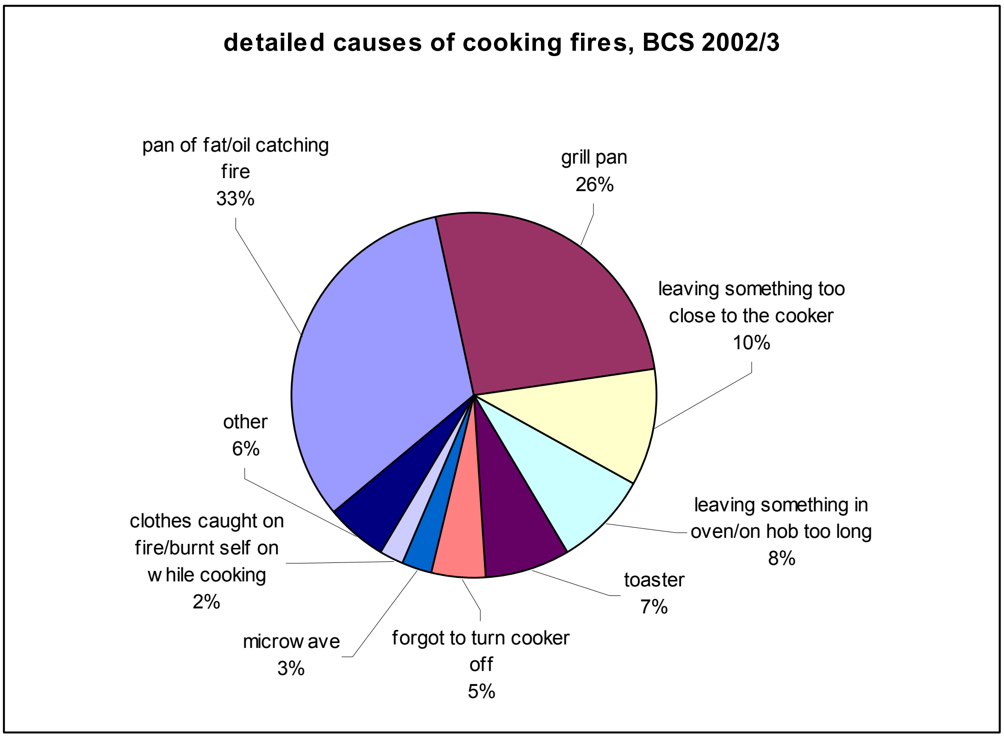


Figure 33: Proportion of causes of cooking fires. Extracted from (Office of the Deputy Prime Minister 2004).

3.5 United States

3.5.1 General

Ahrens (Ahrens 2003) analysed USA fire statistics for the period from 1980 to 1999. For apartments, condominiums or tenements, the annual average was 96,200 fires (see Figure 34), resulting in 632 civilian deaths (see Figure 35) and 5,848 injuries (see Figure 36), with an average cost of US$ 885.1 million per year.

Thomas and Brennan (Thomas, I. & Brennan 2002) conducted an analysis of injuries and fatalities in apartment building fires in the USA for the period 1983–1993 (excluding 1986). A deficiency in data was noted, in that there was no data available for those people who become involved in fires, dealt with a fire when it was small or escaped unharmed when the fire service was called. In total 420,315 fires, 26,635 injuries and 3,111 fatalities occurred during the 10 years considered. Different factors were involved in injury and fatality outcomes in apartment fires that related directly to the characteristics and behaviour of the occupants.

Thomas and Verghese (Thomas, I. R. & Verghese 2001) analysed apartment fire incident data for the years 1983 to 1993. On average, approximately 1.4 fires occurred in apartments per 1,000 apartments per year and 7.4 fatalities occurred per 1,000 apartment fires. Of the 420,315 reported apartment fires, flashover was reported as the fire type for approximately 15% of the apartment fires, 44% were reported as flaming, and 29% were reported as smouldering. Of the 3,111 apartment fire fatalities, 69% were associated with flashover-type fires, 27% with flaming, and 2% with smouldering. Approximately 17% of civilian apartment fire fatalities were intimately involved in the ignition event, 21% were located in the room of fire origin at the time of ignition, and 21% were on the storey of fire origin. Approximately 11% of civilian apartment fire injuries were reported to be intimately involved in the ignition event, 21% were located in the room of fire origin at the time of ignition, and 20% were on the storey of fire origin.

In the year 2000, there were 505,000 structure fires in the USA resulting in 3,500 fatalities, 19,600 injuries and $8.5 billion in property loss (FEMA 2004). Three-quarters of these fires occurred in residential structures, with the kitchen being the most frequent area of fire origin.

Typically, 20% of residential structure fires occur in apartments (FEMA 1999). In urban areas, in 1996, 35% of fires occurred in apartments. Furthermore, cooking fires accounted for the cause of 39% of apartment fires in urban areas, compared with 21% for one and two-family dwellings.

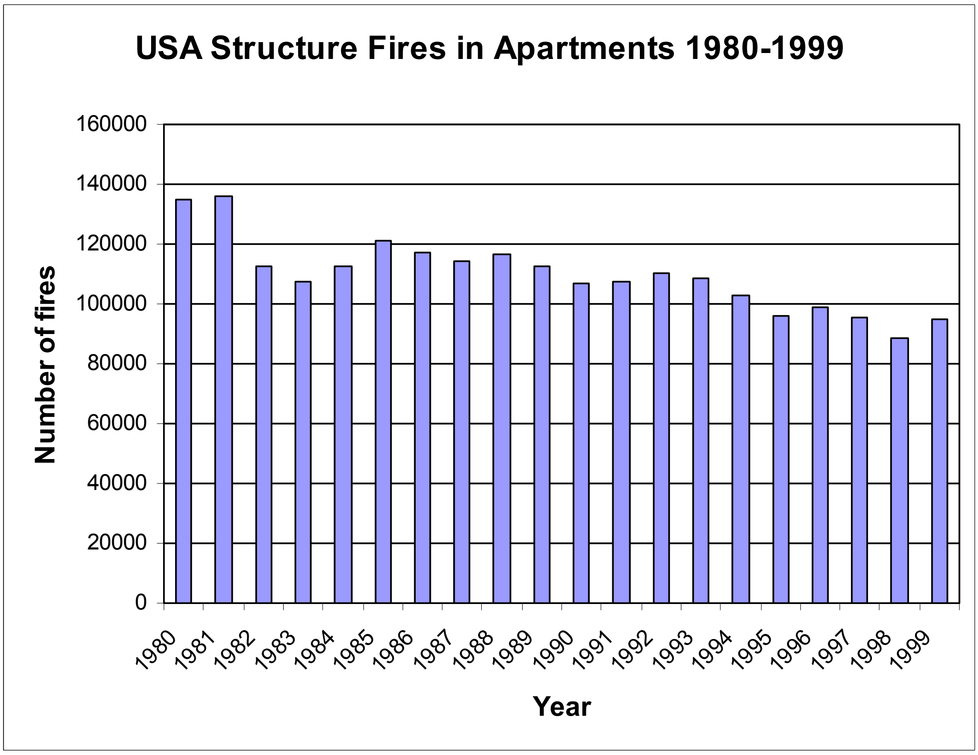


Figure 34: Number of structure fires in apartments that occurred in the USA, over the period 1980–1999. Adapted from Ahrens (Ahrens 2003).

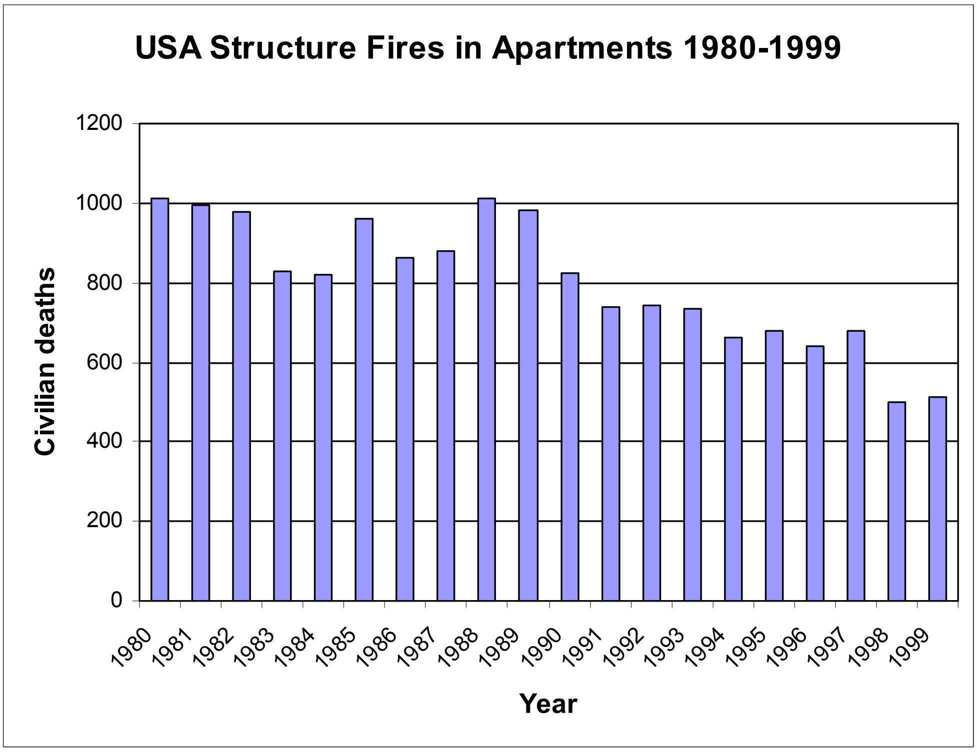


Figure 35: Number of civilian deaths resulting from fires in apartments in the USA, over the period 1980–1999. Extracted from Ahrens (Ahrens 2003).

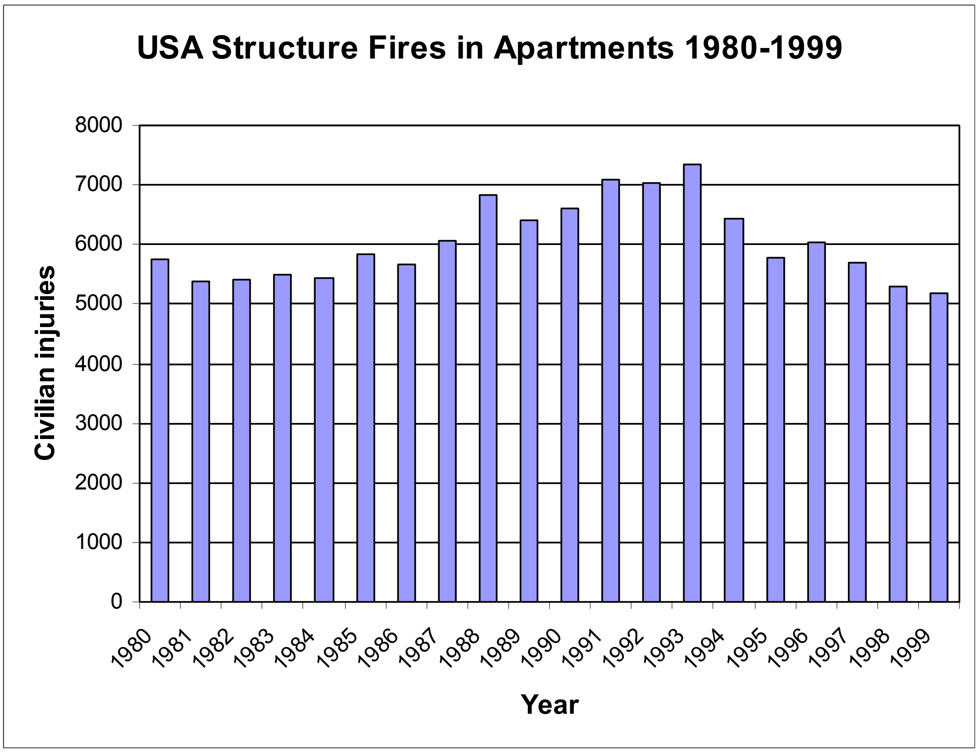


Figure 36: Number of civilian injuries that resulted from fires in apartments in the USA, over the period 1980–1999. Extracted from Ahrens (Ahrens 2003).

3.5.2 Fatal fires

The Federal Emergency Management Agency (FEMA 2005) studied fatal fires in residential buildings for the USA for the year 2002. Table 5 shows the loss measures for residential properties.

Table 5: Loss measures in residential structure fires in USA 2002*

	All	All fatal	All non-fatal
$ Loss per fire	US $11,823	US $51,795	US $11,618
Deaths per 100 fires	0.65	122.1	–
Injuries per 100 fires	3.6	40.3	3.39

* Extracted from (FEMA 2005).

Of the 3,111 apartment fire fatalities that occurred between 1983 and 1993 (Thomas, I. R. & Verghese 2001), approximately 32% of fatalities were associated with fires that originated in the lounge, 31% were associated with the bedroom as the location of fire origin, and 12% were associated with the kitchen as the room of fire origin.

3.5.3 Location of fire origin

Thomas and Brennan (Thomas, I. & Brennan 2002) presented data for the location of fire origin for the period 1983 to 1993 (see Figure 37). Similar to the other regions considered, the kitchen was the most common location for fire (41.6%). The bedroom (15%) and then the lounge room (8.5%) were the next most common location for a fire. Thomas and Brennan (Thomas, I. & Brennan 2002) also examined the ignition factor for each room of origin with their analysis shown in Table 6.

Of the 420,315 apartment fires that occurred between 1983 and 1993 (Thomas, I. R. & Verghese 2001), approximately 42% originated in the kitchen, 14% originated in the bedroom, and for 9% the room of fire origin was reported as the lounge room.

The National Fire Protection Association reported data for the location of fire origin for fires that occurred in high-rise (see Figure 38) and non-high-rise (see Figure 39) apartment buildings, from 1994 to 1998 (NFPA 2002b). A high-rise was considered as seven floors or taller. For both types of apartment building considered, the kitchen was the most common area of fire origin, then other miscellaneous areas, followed by the bedroom. A higher proportion of fires initiated in the kitchen for apartments of more than six floors (59%), compared with non-high-rise apartments (46%). Whereas, a higher proportion of fires originated in the bedroom in non-high-rise apartment buildings (14%), than in high-rise apartment buildings (9%).

Table 6: Casualty proportions by room of origin and ignition factor*

Ignition Factor	% Injuries	% Fatalities
Bedrooms		
Children playing	29.0	21.6
Abandoned or discarded material	22.4	28.1
Falling asleep	10.1	16.5
Suspicious	6.8	6.5
Short circuit, etc	6.6	4.4
Incendiary	6.5	5.5
Combustible too close to heat	4.4	3.0
Misuse of heat of ignition	3.4	3.6
Kitchens		
Unattended	45.6	29.2
Falling asleep	8.6	8.8
Misuse of heat of ignition	7.7	5.6
Combustible too close to heat	7.1	15.2
Abandoned or discarded material	5.4	10.0
Short circuit, etc	2.8	3.2
Misuse material ignited	2.8	0.4
Part failure, leak, etc	2.3	1.6
Lounge rooms		
Abandoned or discarded material	33.5	40.0
Children playing	15.9	13.0
Falling asleep	10.1	12.5
Incendiary	7.3	8.0
Suspicious	6.9	3.8
Short circuit etc	5.1	2.2
Combustible too close to heat	4.7	3.8
Misuse of heat of ignition	3.1	6.8
Other rooms		
Incendiary	24.5	38.1
Suspicious	21.0	23.0
Abandoned or discarded material	10.6	9.9
Children playing	9.6	6.6
Short circuit etc	5.9	3.3
Combustible too close to heat	4.3	2.9
Other electrical failure	3.1	1.9
Part failure, leak, etc	2.9	1.6

* Extracted from (Thomas, I. & Brennan 2002).

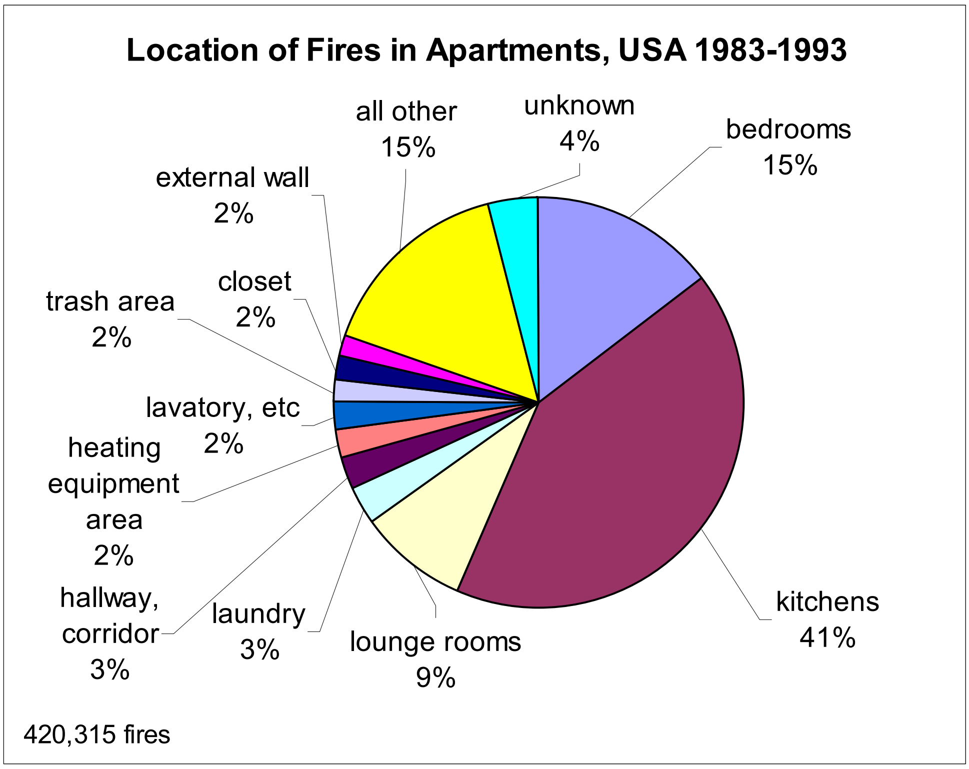


Figure 37: Location of fires in apartments in the USA, for 1983 to 1993. Extracted from (Thomas, I. & Brennan 2002).

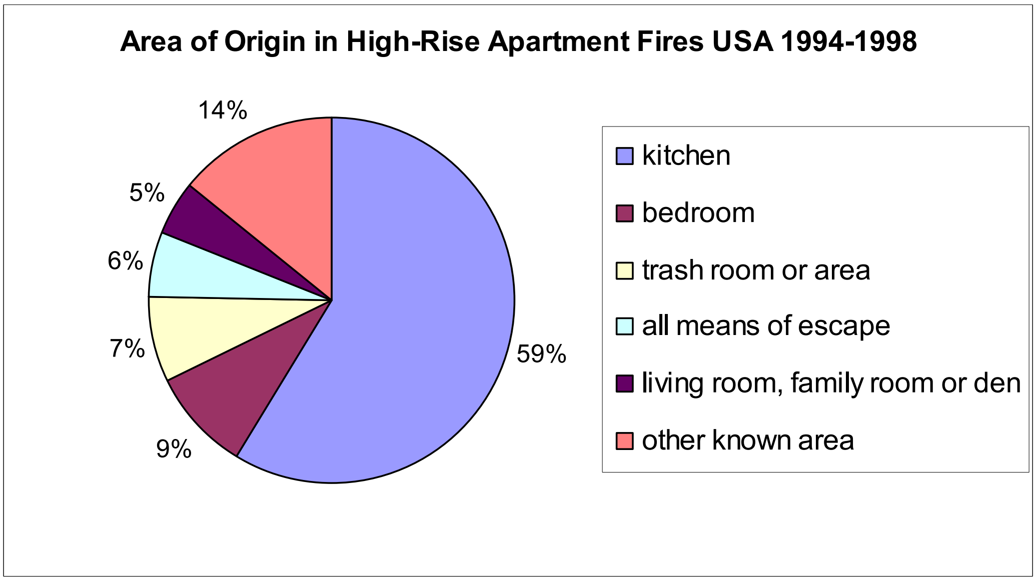


Figure 38: Area of fire origin in high-rise apartments in the USA, for the period from 1994 to 1998. Extracted from (NFPA 2002b).

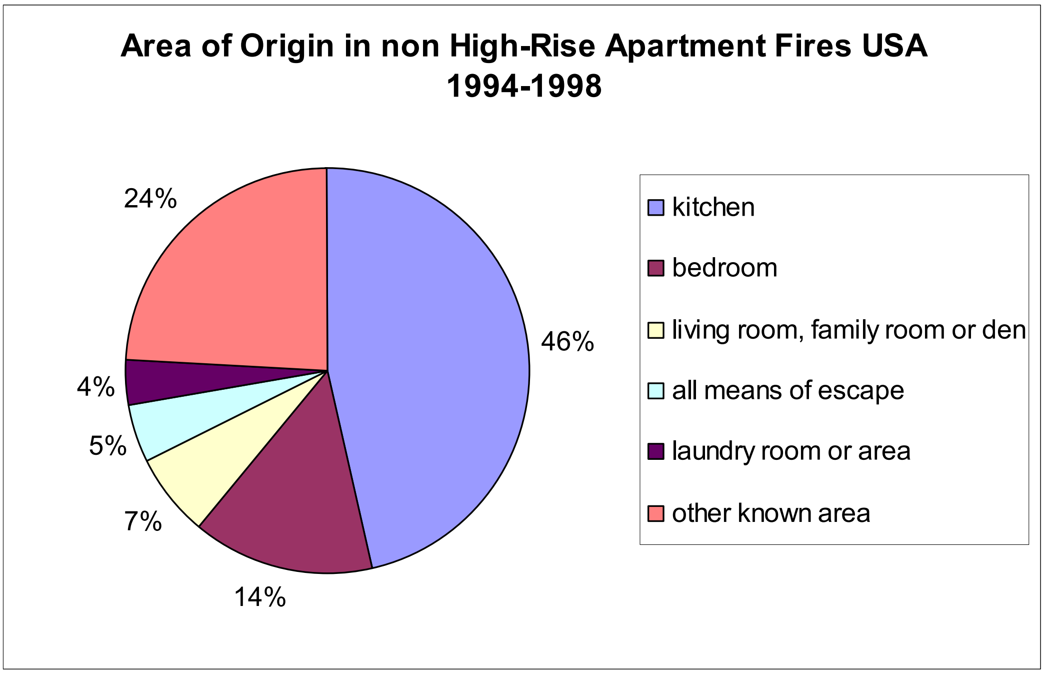


Figure 39: Area of fire origin in non-high-rise apartments in the USA, for the period from 1994 to 1998. Extracted from (NFPA 2002b).

3.6 Summary

The most relevant statistics discussed in Section 3 are summarised in Table 7 and Table 8 for each country considered. The average annual percentages of structure fires that occurred in buildings containing apartments, units and flats and all residential buildings are presented in terms of all residential fires and the total number of structure fires, respectively (see Table 7). The average yearly percentage of fire-related deaths and injuries associated with apartment buildings and all residential buildings are presented in terms of all residential fire-related fatalities or injuries and the total number of deaths or injuries, respectively (see Table 7). The statistics for the percentage of apartment and residential building fires for which the kitchen, bedroom or lounge/dining room was the room of fire origin each year are presented in Table 8. The statistics for the annual percentage of apartment and residential building fires for which the ignition source was reported to be smoking materials, cooking, heating or an open flame are also presented in Table 8.

Table 7: Summary of average yearly fire statistics for numbers of fires, fatalities and injuries associated with apartments, units and flats, and residential* buildings.

Country	Percentage of Fires (%[¶])	Percentage of Fatalities (%[¶])	Percentage of Injuries (%[¶])
Australia	16.6 [a] (77.6 [b])	18.5 [c] (95.3 [d])	22.6 [c] (-)
New Zealand	8.81 [e] (-)	13.3 [f] (-)	- (-)
Canada	22.9 [l] (-)	19.9 [l] (-)	34.3 [l] (-)
United Kingdom	- (56-69 [g])	20 [h] (80 [i])	34.2 [h] (86 [g])
United States	20 [j] (75 [k])	- (-)	- (-)

* Note: statistics related to general residential buildings are included in parentheses and a "-" is used to indicate that no data is currently available.
[¶] Apartment statistics are presented as a percentage of all residential statistics, and residential statistics (included in parentheses) are presented as a percentage of all structure fires.
[a] Average of the results presented in (Dowling & Ramsey 1997; King 1995, 1997; NSWFB 2003)
[b] Average of the results presented in (King 1995, 1997; NSWFB 2003).
[c] Average of the results presented in (Dowling & Ramsey 1997; NSWFB 2003).
[d] Average of the results presented in (QLD Dept of ES 1998; NSWFB 2003).
[e] Average of the results presented in (Narayanan & Whiting 1996; NZFS 2004).
[f] Average of the results presented in (NZFS 2004).
[g] Range of the results presented for England, Northern Ireland, Scotland and Wales (Scottish Executive 2004). Note: the percentage of injuries is calculated using the total number of fire-related injuries, not just those that occurred in structure fires.
[h] Average of the results presented in (CCFMFC 1987, 1988, 1989, 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2001, 2002).
[i] Average of the results presented in (Bounagui, Bénichou & Ederne 2004).
[j] Average of the results presented in (FEMA 1999).
[k] Average of the results presented in (FEMA 2004).
[l] (Canadian Wood Council 2000).

Table 8: Summary of average yearly fire statistics for percentages of room of fire origin and ignition source for apartments, units and flats and residential[†] buildings.

Country	Room of Origin			Ignition Source			
	Kitchen (%[¶])	Bedroom (%[¶])	Dining/ Lounge (%[¶])	Smoking Materials (%[¶])	Cooking (%[¶])	Heating (%[¶])	Open Flame or Spark (%[¶])
Australia	57.2[a] (42.8[a])	9.1[a] (13.3[a])	8.0[a] (9.6[a])	6.7[a] (4.4[a])	24.0[a] (20.9[a])	2.1[a] (4.0[a])	11.4[a] (13.8[a])
New Zealand	- (31.7[b])	- (10.3[b])	- (13.4[b])	- (-)	- (-)	- (-)	- (-)
Canada	- (61[c])	- (6[c])	- (13[c])	- (5[c])	- (53[c])	- (9[c])	- (5[c])
United Kingdom	- (25.6[d])	- (8.5[d])	- (11.3[d])	- (20[e])	- (11[e])	- (8[e])	- (-)
United States	46[f,g,h] (41[g,h])	13[f,h] (14[h])	8[f,h] (7[h])	- (-)	- (-)	- (-)	- (-)

[†] Note: statistics related to general residential buildings are included in parentheses.
[¶] Apartment statistics are presented as a percentage of all residential statistics, and residential statistics (included in parentheses) are presented as a percentage of all structure fires.
[a] Average of the results presented in (NSWFB 2003).
[b] Average of the results presented in (NZFS 2004).
[c] Average of the results presented in (Office of the Deputy Prime Minister 2004).
[d] Average of the results presented in (Yung & Lougheed 2001).
[e] Average of the results presented in (Bounagui, Bénichou & Ederne 2004).
[f] Average of the results presented in (Thomas, I. & Brennan 2002).
[g] Average of the results presented in (FEMA 1999).
[h] Average of the results presented in (NFPA 2002b). Note: In this reference, high-rise buildings were considered to be taller than seven storeys.

4. CASE STUDY FIRES

Following is a selection of summaries of case study fires that have occurred in multi-storey apartment buildings. The list is not comprehensive, but rather reflects fires that have been the subject of investigation and for which information has been published in the literature. A summary of these case studies and other selected cases is included in Appendix A, Table 15.

4.1 Multi-storey apartment buildings

4.1.1 Low-rise apartment complex

A fire occurred at the Drake Apartments complex in Davis, California on 14 March 1988 (Isner 1988b). The complex consisted of 17 two-storey and one one-storey wood-framed structures. The fire originated in the office of the apartment complex and spread to six other buildings. The fire in the office ignited the exposed walls of two adjacent buildings. Then fire spread via fire brands, igniting untreated wood shingle roofs. Twenty-nine apartments were involved in the fire.

4.1.2 Two-storey apartment building

A fire occurred in a residential apartment house in Ludington, Michigan on 28 February 1993 (Kirby 1993). No fire systems were installed in the building. The fire was suspected to have started at or near to a wall-mounted light fixture in the second floor corridor. Combustible wall and ceiling linings in the corridor limited the area involved in the fire. Nine fatalities occurred on the second floor. All deaths were attributed to smoke inhalation.

4.1.3 Three-storey apartment building

A fire occurred at a three-storey apartment building in New York (62 Watts Street, Manhattan) on 28 March, 1994 (Bukowski 1995). The building had been originally constructed in the late 1800's and consisted of one apartment on each floor. The apartments had undergone several renovations, including new doors and windows that had heavy thermal insulation. There was no central heating and the majority of fireplaces had been sealed. Sealing and caulking had also been used to limit air leakage. The building was considered as "very tight".

Smoke was visible from the chimney, but there was no other sign of fire. Fire-fighters ventilated the stairway from the roof. Two three-person hose teams were sent to clear the first and second floor apartments. When the door to the first floor apartment was opened, the first hose team reported a momentary rush of air into the apartment, a warm exhaust from the apartment and then a flame issuing from the apartment, through the upper part of the doorway, and up the stairway. Three fire-fighters located on the second floor landing were engulfed by this flame and died. From the outside of the building, the flames were seen to fill the stairway and extend out of the vent opened in the roof for at least 6 ½ min (Bukowski 1995).

The first floor apartment was the origin of the fire. The occupant was not at home at the time of the fire. Damage was evident only in the living room, kitchen and hall. All other rooms had closed doors at the time of the fire. No other apartment was involved in the fire. The cause of the fire was reported to be a plastic trash bag left on the top of a gas stove. The pilot light of the stove was assumed to have ignited the plastic bag. The only source of air for combustion was through the fireplace flue in the living room. The fire was assumed to have progressed to high alcohol content liquor bottles located on the counter top, then the heavy-plank wooden floors, before spreading to the remainder of the contents of the open space (Bukowski 1995).

4.1.4 10-storey apartment building with offices on the ground floor

A fire started in an upholstered sofa in an office on the first floor of a 10-storey apartment building on East 50th Street, New York City on 11 January 1988. The building had 120 units and had been constructed in the 1920s. Renovations had introduced decorative wood panelling into the office of fire origin that did not meet the current code. However since "the renovation did not exceed 20% of the cost of the building, the new code did not apply" (Kirby 1988). All exit and apartment entrance doors were metal fire doors, with a 17 mm gap at the bottom to promote air circulation. There was no sprinkler system, fire alarm system, emergency lighting or illuminated exit signs.

The cause of the fire was unknown. The office fire spread to involve combustible wall linings in the office. Glass doors between the area of fire origin and the lobby had melted, where the open fire doors of two stairwells allowed smoke to pass into upper floors. One stairwell in the rear of the building was available for evacuation. Four fatalities (one from smoke inhalation inside an apartment and one from smoke inhalation and burns in a stairwell) and at least two injuries occurred (attributed to smoke inhalation) and five fire-fighters were also injured (Isner 1988a; Kirby 1988).

4.1.5 12-storey apartment building

Claxton and Hurt (Claxton & Hurt 2000) reported on a fire that occurred in Pallister Plaissance apartment building in April 2000. The cause of the fire was reported as a careless smoker. Four civilians died, three from smoke inhalation and the fourth (with limited mobility) had also sustained burns to 25% of her body. Multiple injuries were also recorded. In this particular case, there was a substantial delay in the arrival of effective emergency services. Fire-fighters initially sent to the scene had not been equipped with the portable, gas-powered exhaust fan that ladder trucks carry to help clear smoke on the fire floor. Most fire-fighters on the site were not equipped with radios. In addition, no fire-fighters had in-helmet radios and the smoke on the fire floor was too thick to remove their helmets to use the hand-held radios. The three tallest ladders (including the 100-foot aerial ladder) of the aerial truck despatched to the fire had been previously known to be broken. The fire hydrant located in front of the burning building could not be opened, and it took an additional five min for another pumper truck to arrive at the next nearest hydrant.

The fire was located on the eighth floor. Smoke was reported to have logged the ninth floor, and fire-fighters reported thick smoke and poor visibility on the eighth floor. Fire-fighters on the ground reported “people pressed against eighth floor windows frantically trying to get their attention by banging against the glass” (Claxton & Hurt 2000). Some people trapped on the eighth floor attempted to jump, approximately 24 m, to the ground.

4.1.6 29-storey apartment building

A fire occurred in a fifth floor apartment of a 29-storey residential high-rise in North York, Ontario on 6 January 1995 (NFPA 2002a; Yung, Proulx & Benichou 2001). The building was not equipped with sprinklers. The voice over the loud speakers was not comprehensible. The apartment door of the initial fire location was left open. Lack of fire safety training was also attributed to the confusion. The cause of the fire was deemed to be smoking materials igniting a couch in a fifth floor apartment. The apartment door was left open. The fire spread to an exit-way corridor. Smoke entered both stairways of the building, preventing residents escaping. However the residents that stayed in their apartments and kept their doors closed until fire-fighters rescued them all survived. Six fatalities occurred on upper floors in exit stairways.

4.1.7 35-storey apartment building

Schaenman (Schaenman 1987) investigated the fire that occurred in Schomberg Plaza in Harlem, New York City on 22 March 1987. The fire started in a compactor chute of the 35-storey apartment building, between the 27th and 29th floors. A lit cigarette or hot ashes was suspected as the cause. The fire was initially mistaken to only involve a small trash fire in the basement, which had been a common occurrence. However, it was subsequently determined that the unknown fire in the upper part of the chute had spread to connected apartments on the 23rd, 33rd, and 34th floors and the public corridor on the 29th floor. The fire also spread through an open window of an apartment on the 34th floor to the 35th floor. The chute was fitted with a sprinkler system, but this failed to work. Seven residents died on the 33rd and 34th floors.

4.2 Multi-storey apartment buildings with elderly residents

Carpenter (Carpenter 1989) investigated the fire that occurred in the John Sevier Center, a high-rise residence for the elderly, on 24 December 1989 in Johnson City, Tennessee. The building was 11-storeys high and had originally been build as a hotel, then converted into a residential high-rise. When the building had been converted it had met the, then current, fire safety standards (1980). No sprinklers were installed. However because of the results of a previous fire, fire officials had been in the process of updating the building to meet present day codes.

The fire started on the first floor, in a loveseat in unit 102. The fire travelled out of the apartment and across the ceiling (above smoke detectors) and into the main lobby. Many of the occupants on the upper floors of the building were already trapped by smoke before any alarm was heard by them (Carpenter 1989).

Sub-freezing temperatures made some of the occupants resistant to leaving the building, in addition to a number of prior false alarms being attributed to the slow response of occupants after the alarm was sounded. A back-up of people trying to exit via the stairways was caused by people not wanting to venture out into the freezing temperatures. This was suggested as possibly causing some of the occupants to believe that the exit doors would not open. Fire-fighters had to force open exit doors. Some occupants hard of hearing may not have heard the alarm at all. Fire resistant doors had been installed at the entrance to each apartment, however, the automatic door closers had been removed from many of them due to resident complaints that the doors were too hard to open. Fire-fighter's air bottles could not be re-filled on site, since the pump had frozen. Inspection of the smoke towers and standpipes of the building had been conducted during the month prior, because of reports that heavier than usual accumulations of smoke had travelled to the upper floors at the time of a previous fire (that had occurred in October of the same year). The heavy smoke accumulation had been attributed to a broken pipe chase between floors, allowing the smoke to travel to the upper floors of the building. "Fire officials had attempted to correct the situation by working with building officials and engineers to convince the owner of the seriousness of this situation and bring the building into compliance." (Carpenter 1989) The fire was brought under control quickly after the arrival of emergency services. However, smoke continued to fill the building, and ventilation and rescue operations continued for at least another five hours. It was noted that although there were numerous different (both full-time / part-time fire-fighters from various) fire departments on the scene, they all worked in unison and no additional confusion was created.

This fire resulted in 16 deaths (14 residents and two visitors) and the injury of 50 others, including 15 fire-fighters. One body was found in the elevator lobby on the sixth floor, one in Room 107, and the other fatalities occurred on higher level floors in living units (Carpenter 1989).

A fire occurred in The Westview Towers in North Bergen, New Jersey, on 9 August 1998. The residential building was 22-storeys high, with 296 apartments and 400, mostly elderly, occupants. The fire started in a couch in an apartment on the fourth floor. Substantial smoke was created, which impaired rescue efforts and extinguishment of the fire. There were two fatalities from the apartment of origin, where the occupants had retreated to the apartment balcony. These fatalities included a 90-year-old woman, who succumbed to heat and smoke, and one victim, who fell while reaching for a ladder. Two other fatalities occurred in a stairwell, between the sixth and seventh floors. These two victims were residents of the 10th floor. Thirty-two people, including seven emergency workers, were transported to the hospital. Twenty-two fire-fighters and an unrecorded number of residents were treated at the scene for minor injuries. The building was not sprinklered and the stairwells were not pressurised. It was noted that "the fire resistive construction of the building limited the spread of fire, but contributed to the development of severe heat conditions on the fire floor and delayed extinguishment" (Cook 2001). Smoking was suspected to be a factor. Oxygen canisters were found in the apartment of fire origin, and one aluminium bottle was suspected to have ruptured during the fire (Cook 2001; USFA 2003; West 2003)

A fire occurred in The Council Towers Apartments in St Loius, Missouri on 12 October 1998 (Cook 2001; USFA 2003; West 2003). The building consisted of 150 apartments with 160, mostly elderly, residents and 27-storeys. The building was not fully sprinklered. The fire started in a bed in a 21st floor apartment. The fire spread out the windows on the 21st floor to an apartment on the 22nd floor. Again, the fire involved three oxygen cylinders, two of which ruptured during the fire, intensifying the fire conditions. Smoking was also suspected to be a factor. No residents died as a result of the fire, however, 13 residents were injured and one fire-fighter was permanently disabled.

A fire occurred at Kona Village Apartment Fire in Bremerton, WA on 13 November 1997 (Kimball 1997). The building provided rental accommodation for approximately 200 occupants, which comprised of a combination of both aged residents, a substantial number of which had limited mobility (and were primarily situated on the upper floors), and younger couples. The building consisted of four wings, the north wing was two-storeys and the other three wings were four-storeys. At the centre was an interior courtyard. The building was not sprinklered and there was no interconnected alarm. The fire started in a third floor apartment and spread via an external walkway and the rear window of the apartment to the fourth floor and the attic. The fire was spread vertically through pipe chases and utility shafts. The rapid fire spread was attributed to the extensive wood frame construction of the building, including the walkways, and substandard fire stopping in the walls and attic. The entrance door to the apartment of fire origin was also possibly left open. Four elderly residents died, 150 residents were evacuated and 21 residents were rescued by fire-fighters using ground ladders.

4.3 Two-storey row house

Eight lives were claimed in a row house fire in Chester, Pennsylvania on 5 December 1992 (Chubb 1992). All victims were children and siblings, ranging in age from 15 months to 11 years. The fire started in a first floor bedroom at the rear of house (behind the kitchen). The fire spread throughout the first floor, fueled by the combustible interior finish. The balloon-frame wall construction and voids of the room of fire origin aided the horizontal and vertical spread of fire. Fire-fighters found intense flames spreading up the stairway from the kitchen and dining room, which were fully involved. The cause was reported as accidental, although the misuse of smoking materials was suspected. The building was a two-storey brick duplex.

A fire occurred in a two-storey townhouse on Cherry Road, Washington DC on 30 May 1999 (Madrzykowski & Vettori 2000). The residents escaped the building after being woken by sounding smoke alarms. Fire-fighters found thick smoke throughout the first level. Smoke and some flames were observed coming from the basement. The fire originated near a light fixture on the ceiling of the basement, then spread to the floor of the basement. After sliding doors to the basement had been manually broken, the fire spread rapidly up the rear of the townhouse. Two fire-fighters died from injuries sustained during the rapid spread of the fire from the basement to the outside wall, through the broken sliding doors.

4.4 Multi-storey hotel complex

Howell (Howell 1995) investigated a fire that occurred at St George Hotel building in Brooklyn, New York on 26 August 1995. The building was part of a complex that consisted of several large interconnected buildings in a crowded neighborhood and had originally consisted of more than 2,000 guest rooms. However, some of the buildings had been deserted and others had been converted into residential apartments. Only the original St George building had been operating as a hotel at the time of the fire. The buildings were interconnected at basement level and between various floors. The fire started in a vacant ninth-story building, which had been unoccupied for at least seven years. The fire spread to several adjacent exposures. The standpipe in the fire building was found to be not functional and partly dismantled. The eighth and ninth floors of the building of fire origin were heavily involved in the fire, and flames could be seen from the outside on all 10 floors of the building. Fire brands floated onto the roofs of surrounding buildings and into open windows of taller buildings, including an occupied 31-storey apartment building. Several apartments in the 31-storey building were ignited by the fire brands or radiant heat. No fatalities were reported.

5. CHARACTERISTICS OF FUELS

5.1 General fire loads in residential buildings

Bwalya (Bwalya 2004) described a web-based survey of combustible contents in Canadian residential living rooms. Survey participants were invited to complete an online questionnaire about their home and living room contents. This included data such as room and window dimensions, wall and floor finishes, and the quantity and type of furniture items.

Specific data for mass and materials of furniture items were not collected, as this would have been a time-consuming process. The researchers obtained data about the weights, dimensions and composition of representative furniture items from manufacturers and local shops. They then assigned low, medium and high values of weight and heat of combustion for each item, and used these to calculated low, medium and high values of fire load densities. They also calculated values using randomly selected values of weight and heat of combustion (from the low, medium and high estimates).

Data for 598 Canadian living rooms was collected. All participants were employees of the National Research Council of Canada. A summary of a selection of the data follows (Bwalya 2004):

- 38% of homes surveyed were two-storey single-family detached homes
- 11% of homes surveyed were apartments
- mean fire load for apartments was 7920 MJ or 440 MJ per m² floor area (std deviation = 272 MJ/m²) based on a sample size of 64
- average living room area was 18 m²
- the eight most common items of furniture were (in order of descending frequency): side table, recliner/chair, TV, sofa, entertainment unit, coffee table, bookcase, and loveseat.

Yii (Yii 2000) surveyed four bedrooms in a New Zealand residence (flat) and calculated a mean fire load density of 724 MJ/m² (standard deviation 107 MJ/m²). The average bedroom floor area was 9.3 m². Yii also included some summary data (from Robertson and Gross) from NBS surveys carried out pre-1940 in 13 USA residences. The fire load in single occupied rooms was in the range 40-69 kg/m² or 668 to 1152 MJ/ m².

A large investigation was carried out in 1967-69, by students for the Swiss Fire Prevention Association for Industry and Trade and reported by CIB (CIB 1986). The raw data is not available, but it is suggested that at least 10 samples were used for each type of occupancy, and often at least 20. For well defined occupancies, a distribution was suggested where the 90%-fractile value is given by (1.35-1.65) × average value and the 80%-fractile value is given by (1.25-1.50) × average value. The average value for fire load density reported for some occupancies of interest in this study were:

- hotels 300 MJ/ m²
- flat 300 MJ/ m²
- youth hostel 300 MJ/ m²
- homes 500 MJ/ m²
- vacation home 500 MJ/ m²
- basement dwellings 900 MJ/ m²

Harmathy and Mehaffey (Harmathy & Mehaffey 1983) reported the mean fire load in dwellings as 30.1 kg/m², with standard deviation of 4.4 kg/m². Kose et al (Kose, et al. 1988) surveyed moveable fire load in 214 Japanese dwellings and reported an average fire load density of 33.9 kg/m² with standard deviation of 11.7 kg/m².

It is noted that there is relatively little fire load data available, particularly for New Zealand and Australian residential or apartment buildings. The Bwalya study (Bwalya 2004) in Canada appears the most comprehensive in recent years. There may be merit in carrying out a similar web-based survey for New Zealand and Australia.

5.2 Characteristics of beds and bedding fires

There are a number of standard tests and regulations regarding mattresses, beds and bedding assemblies. These include full-scale, reduced-scale and cone calorimeter tests. Some consider the mattress in isolation, while others consider the effects of bedding on the burning behaviour of the assembly. Simply testing the mattresses in isolation is not realistic for design fires in residential buildings, since mattresses are not usually found in isolation. Research has found that, while mattresses can have good fire resistance, the bedding can have a significant effect on the burning behaviour.

For a realistic fire test, the UK Crown Supplier specifications recognise the importance of disturbing or pulling back the covers (Krasny, Parker & Babrauskas 2001). A tightly made bed will have slower flame spread than a loosely made or unmade bed. The testing of bedding assemblies typically involves a made bed with the covers folded back in one of the top corners, exposing the sheets, as shown in Figure 40. Unless otherwise stated, this is the configuration of the bedding assembly tests discussed below.

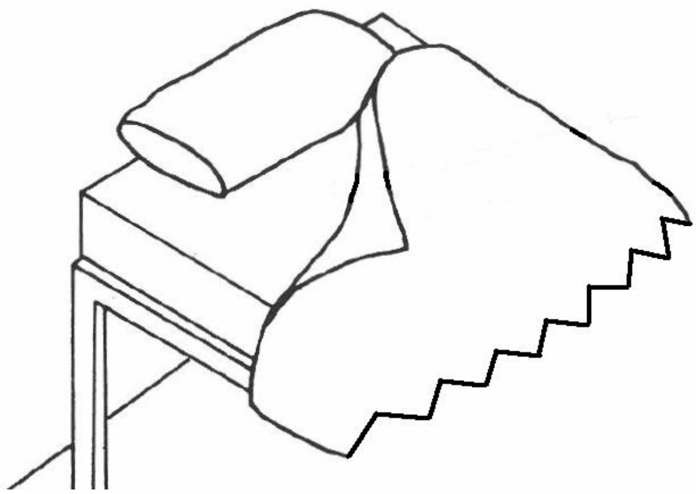


Figure 40: Bedding assembly configuration for fire testing. Adapted from (Benisek, Phillips & Paul 1985).

Some of the earlier research was performed by Woolley et al (Woolley, et al. 1976) to establish the burning characteristics of beds made up with common bedding materials. The tests were conducted in a room-corridor configuration (see Figure 41). Room temperatures, smoke production and radiation were measured within the room, and temperature and smoke measurements were taken at the end of the corridor. The HRR was not measured in this series of experiments, therefore the ceiling temperature above the bed in the test room has been used in the discussion of results. The maximum test duration was 30 min.

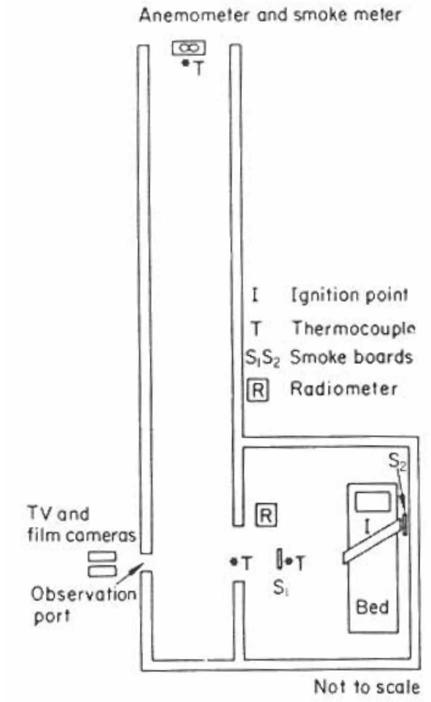


Figure 41: Room-corridor configuration. Extracted from (Woolley, et al. 1976).

Single beds were used in the bedding assembly, which was made up of a mattress, mattress cover and bedding. The mattresses were placed on a metal spring base with a laminated chipboard head board, which was placed against the wall. Typically the mattress size was 1.91 × 0.92 m and the depth varied from 0.1–0.15 m. The mattresses fillings were hair, spring interior, and a number of different foam rubbers and polyurethane foams. The mattress covers were cotton, fire retardant cotton or proofed nylon. Two interliners were also investigated: hair and glass fibre. The bedding consisted of two feather pillows with cotton covers and cases, two cotton sheets, a cotton or wool blanket and cotton bedspread.

The ignition source was crumpled newsprint with an embedded electrical element. Two ignition locations were used: on top of the bed (beneath the sheets, in the crease of the folded back covers, as shown in Figure 40) and underneath the bed. Preliminary experiments used a single double sheet (25 g) of newspaper; however, the main tests series used four double sheets of newspaper crumpled into a ball (100 g).

The bedding assembly with the standard polyurethane mattress and cotton cover was considered the control configuration. This configuration reached a maximum temperature 230°C in seven min. The tests found the larger ignition source on top of the bed was more likely to create rapidly burning fires involving the whole bed. In comparison, the small ignition source underneath the bed was found to possibly lead to a delayed, but more severe, fire. This was attributed to the bedding materials being allowed to preheat prior to flaming combustion. Since the top ignition source was located on the unmade part of the bed, there was negligible difference between the fire behaviour when a wool blanket was tested and when a cotton blanket was tested.

The results from this series of experiments showed the hair and spring interior had slow fire development compared to some of the foam rubber and polyurethane mattresses, which produced rapid fire growth. The commercial polyurethane foam mattress and cold cured polyurethane mattress had similar fire behaviour characteristics to the standard polyurethane foam mattresses. The fire retardant cotton covers increased the time before maximum involvement of the bedding assembly, but did not significantly change the maximum temperature reached for most assemblies tested. The proofed nylon cover had the worst fire performance, reaching the highest maximum temperature of 550°C in seven min. The combination of a glass fibre interliner and the control assembly (standard polyurethane mattress and cotton cover), with a fire retardant cover, improved the fire performance significantly. The time to maximum involvement was delayed (to 26 min 30 s after ignition) and the maximum temperature was restricted (to 285°C). The results using the hair interliner showed even better fire performance (21 min, 80°C). However, it was suggested that the increased risk of smouldering combustion and its associated dangers needed to be investigated in this case.

Two fire retardant treatments were applied to the standard polyurethane mattress. Both of these treatments significantly improved the fire performance. Results for the first fire retardant treatment (of which the details were not specified) showed full involvement of the mattress occurred 27 min after the test was initiated (and reached a maximum temperature of 280°C). The addition of a fire retardant cover further limited the maximum temperature to 65°C. Accelerated aging was applied to the mattress which had a negative impact on the fire performance, with a higher maximum temperature reached earlier (325°C at 13 min). The combination of the fire retardant mattress and cover produced significant quantities of smoke. The second fire retardant treatment was a standard polyurethane mattress coated with a thick layer of semi-rigid fire retardant paint, with an fire retardant cover. The maximum temperature reached was 57°C, which was reached at 22 min after ignition. However, no tests were conducted to investigate the effects of aging.

None of the beds tested would cause room flashover in isolation, except possibly the bedding assembly with the standard polyurethane mattress with proofed nylon cover. However, the thermal radiation may be sufficient to spontaneously ignite other objects in the room, causing flashover. Visibility was calculated using the smoke production measurements. Results showed that only the foam rubber moulded slab mattress with fire retardant cotton cover produced enough smoke to reduce visibility to less than 1 m (which occurred at 13 min). Other bedding assemblies that reduced visibility to 2 m during the 30 min tests were: fire retardant polyurethane foam mattress with cotton cover (at 25.8 min) and the aged fire retardant polyurethane foam mattress with cotton cover (at 14.0 min).

Paul (Paul 1980) investigated beds and upholstered furniture to address the, then current, concern that upholstered furniture was relatively easy to ignite and had rapid burning behaviour. Bedding was excluded from these experiments, because it was considered beyond the control of the manufacturer. Temperature and smoke density were measured. The primary objective of this paper was to evaluate the ability of scale mock-ups to simulate full-scale burning behaviour. Conclusions, based on the test results, suggested that the half-scale mock-ups simulated full-scale items reasonably well; however, smaller-scale model results deviated significantly from the full-scale results.

Reiber (Rieber 1983) provided detailed definitions for the components of a bedding assembly and considered different methods of determining the burning characteristics of beds. Reiber used reduced-scale beds in the tests (mattress 500 × 250 × 100 mm). The bedding assembly tested consisted of a mattress, sheet, quilted feather or fibre duvet, and feather or fibre pillow.

Cigarettes and matches were reported as the primary cause of accidental ignition of beds, whereas larger sources, like those simulated by crib fires, are rare according to accident statistics (Rieber 1983). For this reason the following ignition sources were selected for the test series: a bundle of three cigarettes, a match and one sheet of newsprint rolled into a ball. The cigarettes and the matches were placed on the bed at five different locations for each test (directly on the mattress, on the duvet, on the pillow, between the edge of the mattress/duvet and between the edge of the mattress/pillow). The newsprint was placed between the pillow and the duvet.

The results of the tests showed flame retardant cotton sheets over a mattress with cotton ticking and cellulose fibre produced sustained glowing fires. Simply using fire retardant coverings on the bedding (i.e. duvet and mattress cover and pillow case) was not sufficient to prevent fire growth. A 65/35 polyester/cotton sheet could not sustain a fire when a cigarette was used as the ignition source. Test results showed that the burning characteristics of individual components may not be the same as when tested as part of an assembly. Therefore it was suggested that the bedding assembly can only be classed as fire retardant if all components have compatible burning characteristics and are made from fire retardant materials. Furthermore, it was also recommended that fire retardants should be chosen with care, to ensure combustion products are not excessively toxic and the retardant is durable.

Ingham and Edwards (Ingham & Edwards 1984) focused on bed and bedding assemblies available in New Zealand in the 1980s. They investigated the use of wool products (ticking, overlay, blankets and duvet filling) to reduce the risk of ignition and the fire growth of polyurethane mattresses. Half-sized bed assemblies were used in the experiments. The mattress was, in most cases, a polyurethane foam mattress with a cotton or fire retardant wool cover (900 × 750 × 100 mm). A wool-filled mattress with cotton cover (900 × 914 × 122 mm) was also tested to compare the fire risks. The bedding consisted of commercially-available 50/50 polyester/cotton sheets, a blanket (made from acrylic, wool or cotton) or a duvet (with polyester fill with a polyester cotton cover or wool fill with cotton cover), and in some cases a mattress overlay (a wool blanket, fire retardant wool blanket, wool-pile (Woolrest™), wool-filled with cotton cover). The frame was an iron framed, metal based hospital bed.

The ignition source was a butane-gas flame, used to simulate a match flame. Three different-sized flames were used (in accordance with BS 5852:1979 Part 1 and 2). The flame heights and the corresponding application times were 36 mm for 20 s, 150 mm for 40 s, and 245 mm for 70 s. The tip of the burner tube was placed 40 mm from the crease of the folded covers where the sheets were exposed.

The rate of flame spread and fire intensity was reduced with the use of a wool blanket or duvet, compared to the other bedding tested. A wool overlay prevented ignition from the small ignition source, and limited the fire spread and intensity for the larger ignition sources. Wool-filled mattresses provided the best protection, only suffering surface charring even when the bedding burnt. The test results also showed that the speed of flame spread ranked from very fast to very slow for the various duvet and blankets was acrylic blankets, polyester filled duvet, cotton blanket, wool filled duvet, then wool blanket.

Benisek et al (Benisek, Phillips & Paul 1985) suggested that the only fair way to assess the burning behaviour of bed covers is by bed assembly tests. A number of half-sized and full-sized single bedding assemblies were tested in this study. Component tests were also conducted for comparison. The small-scale tests were conducted in a bay (1.25 × 1.80 × 2.95 m) within a test room (4.65 × 6.15 × 2.95 m). Each test was of at least 60 min duration to establish the presence of smouldering combustion if flaming combustion did not occur. The full-scale tests were conducted in a room-corridor facility, the room (4.6 × 3 × 2.5 m) was connected to the corridor (15 × 1.8 × 2.4 m) by a doorway.

The small-scale frame was made of metal. The full-scale bed frame was also constructed of metal (2.0 × 1 × 0.33 m), with the mattress supported by a 150 mm square wire mesh. The mattresses were constructed from a combination of the materials listed below.

Filling: polyurethane foam or metal springs
Wadding: no wadding, fire retardant wool, cotton or mixed fibre
Ticking: cotton or fire retardant cotton.

The bedding consisted of 2 × 50/50 polyester/cotton sheets, 1 × feather pillow (with primary and secondary fire retardant cotton covers, to limit their involvement), 1 or 2 × acrylic, viscose, fire retardant polyester, modacrylic, PVC, wool or fire retardant wool blankets, and a polyester, feather down or wool quilt.

Eight different ignition sources of increasing intensity were used: a cigarette, the three butane flames described in (Rieber 1983), and wooden cribs of 8.5, 17, 60 and 126 g. The ignition source was either placed in the middle of the bed on top of the covers or at the crease of the folded covers, as shown in Figure 42.

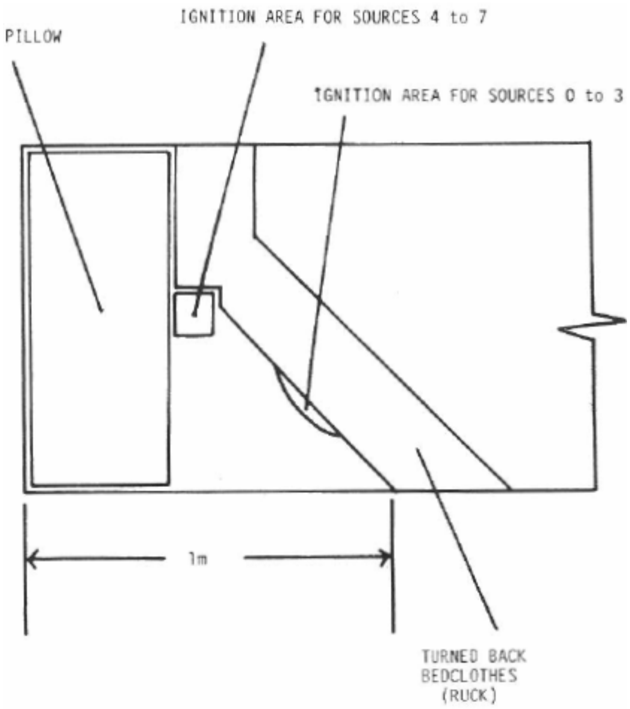


Figure 42: Location of the ignition sources. Extracted from (Benisek, Phillips & Paul 1985).

The results from a vertical component test conducted on the blankets showed no correlation to the results for bedding assemblies. The results from different combinations of bedding assembly showed that for the ignition source on top, the fire spread was dependent on the blanket or the quilt. The wool and fire retardant wool blankets and quilts formed a char, which protected the rest of the bedding assembly. The other blankets, which melted, exposed the bedding to the fire, causing substantially more damage. The results for the polyester and feather down quilt filling showed the flame spread rapidly over the bed covers. In comparison, the wool quilt delayed the flame spread.

For bedding assemblies that contained mattresses with fire retardant wool wadding and/or wool blankets, the overall flame resistance improved when the ignition source was located at the crease compared to other locations tested. These tests confirm results found by Rieber (Rieber 1983) and Ingham and Edwards (Ingham & Edwards 1984), that wool products are effective in increasing the fire resistance of a bedding assembly. The ability of wool to char reduces flame spread and smouldering. When ignition occurred on top of the covers, it was observed that the covers determined the burning behaviour of the assembly. When the ignition source was at the crease, then all components (sheets, mattress wadding, ticking, filling and bedcovers) affect the burning behaviour. Benisek et al (Benisek, Phillips & Paul 1985) recommended that more attention needed to be paid to mass loss rate, to assist in the assessment of smouldering combustion and the production of toxic gases.

Lee (Lee 1985) performed a number of tests to determine the burning behaviour of bedroom fires in USA park service lodging facilities. A number of free burn tests were conducted, as well as room tests that were performed in the set-up shown in Figure 43. A number of the free burn test and room test results are available on FASTData (NIST 1999), including the HRR curves and upper and lower layer temperatures for the room tests. The bedrooms consisted of a double bed, bedding assembly (with a head board), a night table and a waste paper basket that was used as the ignition source.

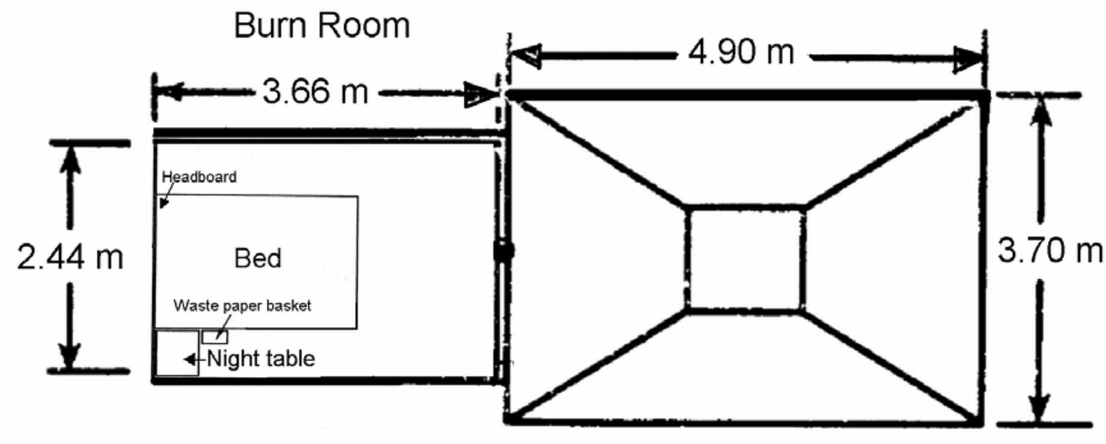


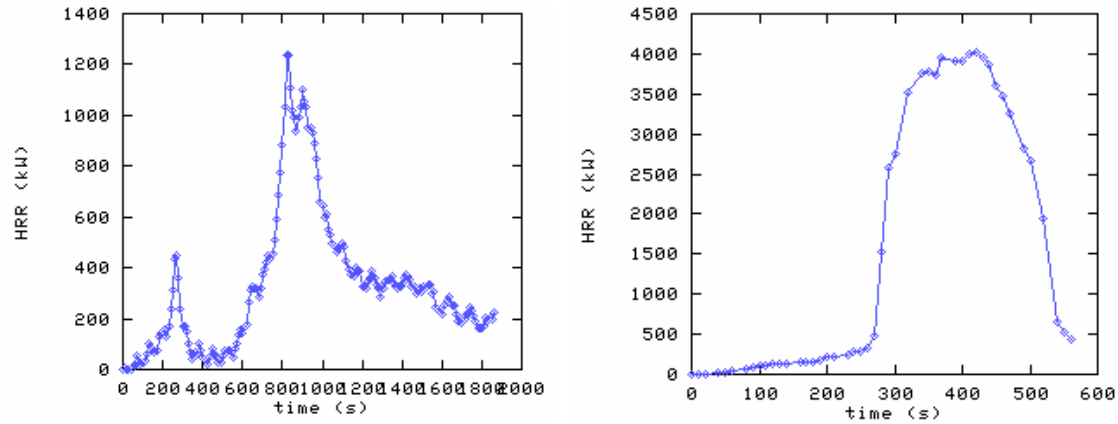
Figure 43: Schematic of the set-up for the room tests conducted by Lee (Lee 1985).

The spring mattress and the box spring base had a wooden frame with a steel wire grid and a polyester quilted cover. The padding was polyurethane over fire retardant cotton felt with sub-layers of cotton felt and synthetic cellulosic fibre pad. The bedding consisted of two polyester/cotton sheets, two pillows (with polyester fill, polypropylene olefin covers and polyester/cotton pillow cases) and an acrylic blanket.

A single wall located behind the headboard with a combustible (plywood) or incombustible wall lining (gypsum) was also installed in both the free burn and the room burn experiments. The ignition source was a 0.34 kg polyethylene wastepaper basket with 0.41 kg of trash, consisting of different paper items. The trash was ignited with a match. The wastepaper basket was located adjacent to the night table and against the bed.

All the free burn experiments showed similar burning characteristics, with an initial peak, which corresponded to the bedding being consumed and exposing the mattress. A period of slower burning and/or smouldering then occurred until there was sufficient heat to support flaming combustion of the mattress and base, which corresponded to a second peak. The tests containing the plywood wall had an extended period of burning associated with the second peak. This was attributed to the full contribution of the plywood wall to the fuel load. The presence of the incombustible wall had negligible effect on the burning behaviour of the assembly.

The characteristics of the fire in the early stages of the room tests were similar to the free burn tests, however the later stages of the fire were more severe. The hot combustion gases trapped under the ceiling radiated back onto the burning furnishings. This was observed in the heat flux measurements taken from the end of the bed. The heat flux increased from 20 kW/m^2 in the free burn tests to 130 – 220 kW/m^2 in the room tests. The room test with the combustible plywood linings resulted in flashover at 290 s after ignition. This was attributed to the significant increase in combustible material and enhancement in burning rate due to radiation feedback. A comparison of heat release rates (HRR) associated with the free burn and room burn, with the plywood wall lining, is shown in Figure 44.



a) Free burn test **b) Room test**

Figure 44: Heat release rate profiles of a bedroom with plywood wall linings. Note the change in scale. Extract taken from (Lee 1985).

The peak carbon dioxide (CO) concentration also increased in the room tests (1.5 – 2.1 g/s) compared to the free burn tests (4.6 – 23.5 g/s). This is a significant increase when considering life safety, however there was negligible difference in the total CO produced 1.39 – 1.71 kg and 1.48 – 2.38 kg, for the free burn and room tests, respectively. The difference in the results from the free burn tests and the room burns with the noncombustible gypsum wall linings was also insignificant when comparing peak smoke concentration and total smoke production measurements (1.3 – 1.5 OD/m and 1850 – 2430 m^2). However, in the plywood room burns the peak smoke concentration and the total smoke production was double that of the other tests (2.1 – 3.0 OD/m and 4,190 m^2).

Paul (Paul 1989) investigated the burning behaviour of bed assemblies, with reduced flammability for use in hospitals, using a room-corridor arrangement, as shown in Figure 45. Temperature, smoke volume and density, gas concentrations (CO, CO_2 and O_2) and mass loss rate were measured during the tests. The HRR was estimated from the mass loss rate resulting in very approximate HRR profiles.

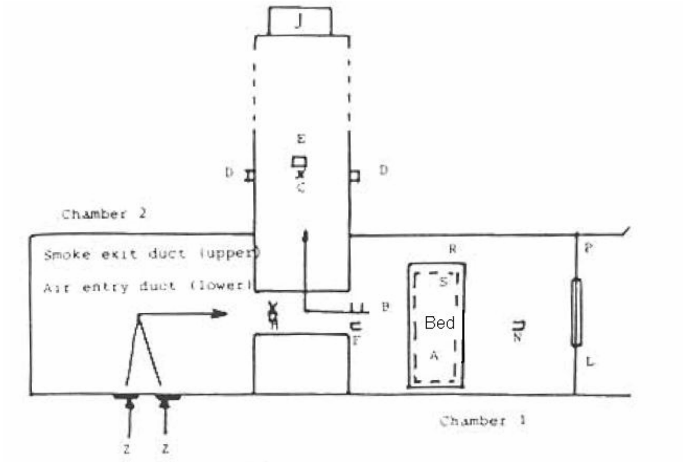


Figure 45: Room-corridor arrangement used in the experiments by Paul. Extracted from (Paul 1989).

Two different bed bases were tested: a solid metal base or a wire mesh base. Mattresses were made of standard hospital contract foam or polyurethane barrier foam. The bedding consisted of three pillows (made from polyurethane foam, with a fire retardant cotton cover and polyester pillow case), two polyester sheets, a blanket and a bedspread (made from fire retardant cotton, modacrylic or polyester). A limited number of tests were conducted using untreated cotton bedding on a barrier foam mattresses.

A No. 7 crib was used to ignite the bedding. Two ignition locations were used. One at the crease of the covers and the other against the pillows, as shown in Figure 46.

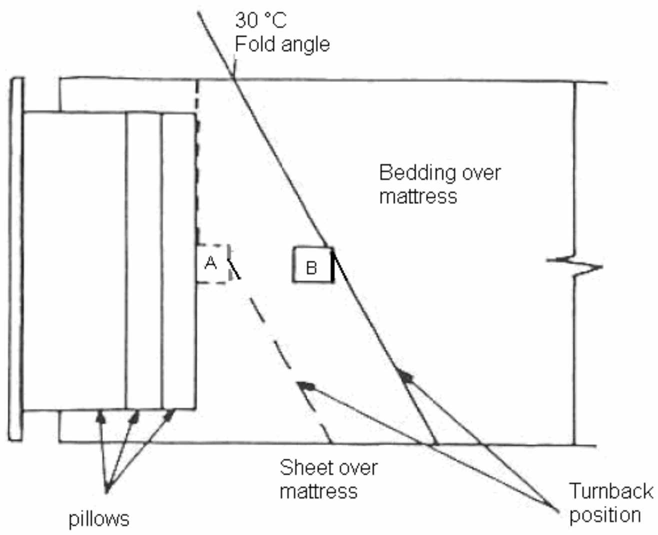


Figure 46: Location of ignition sources. Extracted from (Paul 1989).

The results from these tests showed that the wire bed base produced a more severe fire than the solid bed base, if the mattress melted or disintegrated during the test. The severity of the bed assembly fire was dependent on the type of mattress tested. The polyester bedding produced more smoke and fire gases than the other types of bedding. The polyester bedding was also observed to burn with a small flame.

The modacrylic and fire retardant cotton burned with similar characteristics. Flame spread over the bed assembly was aided by the sheets and pillow cases. Fire spread more extensively and steadily with the untreated cotton bedding on the barrier foam mattress than the other tests with the barrier mattress. The bed assembly also produced a highly irritant light grey smoke.

While the pillow case burned, the fire retardant case around the pillow filling formed a char layer. When the char layer broke, the pillows burned rapidly and significantly contributed to the production of heat and smoke. The total bedding assembly had a significant effect on the burning behaviour, especially when the ignition source was remote from the pillows. When the fire was able to spread to the pillows and ignite them, the heat released and the smoke produced was considerably increased. This was attributed to the combustible mass of the pillows and the ability of the heat released to ignite other components.

The Combustion Behaviour of Upholstered Furniture (CBUF) study (Sundström 1994) looked at mattresses in isolation, since the focus was on the manufacturing requirements of upholstered furniture and the manufacturer has no control over the bedding used on mattresses. Mattresses were tested on a slat mock-up bed. The CBUF database contains furniture calorimeter data and room burn data for six commercially available mattresses (solid foam and innerspring, ranging from domestic foam to high risk foam) and two mock-up mattresses (solid foam and innerspring). The results of the study were that solid foam mattresses showed flame propagation and significant burn out, whereas innerspring mattresses did not propagate flames, but smouldered and self-extinguished.

The results of a comprehensive study on the burning behaviour of full-scale mattresses and bedding assemblies were published by Damant and Nurbakhsh (Damant & Nurbakhsh 1992). Approximately 40 full-scale tests were conducted in 1991 in a Bureau of Home Furnishings and Thermal Insulation (BHFTI) fire facility test room (3.05 × 3.66 × 2.44 m). The room had an open doorway (0.97 × 2.06 m). During the tests, the temperature, gas concentrations (for O_2, CO and CO_2), smoke opacity, mass loss of the bed and HRR were measured and recorded. Four series of test were conducted:

- control tests, using standard bedding components over an inert fibreglass mattress, with ignition by burner only
- mattresses in isolation (the author of this review was not able to verify this, but it has been assumed the mattress was on an inert frame)
- mattresses on a box spring base
- full bedding assemblies with mattress, base and bedding components.

The bedding components tested comprised of 50/50 polyester/cotton sheets and pillowcases, a pillow (either 100% loose polyester fibre filling or 100% cotton ticking), and a 100% acrylic blanket. The mattresses tested had innersprings or solid foam cores, the foams can be characterised into five different groups, these were:

- standard polyurethane foam
- TB 117 fire retardant polyurethane foam
- melamine treaded polyurethane foam (highly ignition resistant)

- neoprene or polychloroprene foam, or
- other fire retardant foam.

The ignition source for these tests was a T-shaped propane gas burner positioned parallel to the bottom horizontal surface of the mattress (1 inch from the vertical side panel). The burner was applied for 3 min. The general observations were recorded for the tests, as well as the maximum HRR, temperatures and CO concentrations. However, it appears the corresponding times were not published.

A number of general conclusions were made, those relevant to this literature review have been summarised:

- The burning behaviour of a mattress was largely dependent on its combination of filling material, style and construction.
- Overall, different cover fabrics did not alter the burning behaviour significantly, unless the fabric was treated with a fire retardant.
- A fire retardant ticking was effective in improving the fire performance, and some non-fire retardant tickings were also capable of slowing the rate of burning and delaying the fire spread to rest of the bedding assembly.
- Mattresses containing neoprene and chloroprene foam had very good fire performance, even when used in combination with cotton batting, which has no fire resistance. However, when properly treated with boric acid, cotton batting performed well as a fire block component.
- Flaming combustion usually ceased once the burner was removed, but the development of smouldering combustion was common and this fire hazard needs to be considered.
- The combination of materials used in mattresses needs to be considered carefully. As the tests found, if one component was a fire barrier or a fire blocking material good fire performance was still obtained even though other materials were not fire retardant. Conversely, positive effects of fire retardant components could be neutralised when used in combination with other components.
- When evaluating the fire hazard, the study found mattresses and bedding assemblies containing standard polyurethane foam contained enough fuel to rapidly lead to flashover. It was also noted that replacing standard polyurethane foam with foams which complied with TB 117 did not necessarily improve the fire performance.
- The bedding contributed significantly to the fuel load of the bedding assembly, however their overall effect was dependent on the nature of the other components used.
- The effect of different types of bases was also dependent on the components in the bedding assembly.
- The fuel load of a mattress in isolation was concluded to be insufficient to determine the fire performance of a bedding assembly.

Luo and Beck (Luo & Beck 1996) conducted a multi-room test with a mattress (polyurethane foam slab) fire to compare experimental results with Computational Fluid Dynamics (CFD) models. The set-up can be seen below, in Figure 47. Quantities measured were temperature, radiation, gas composition, smoke optical density and soot concentration, CO, CO_2, and O_2 concentrations in both the room of origin and at the remote locations.

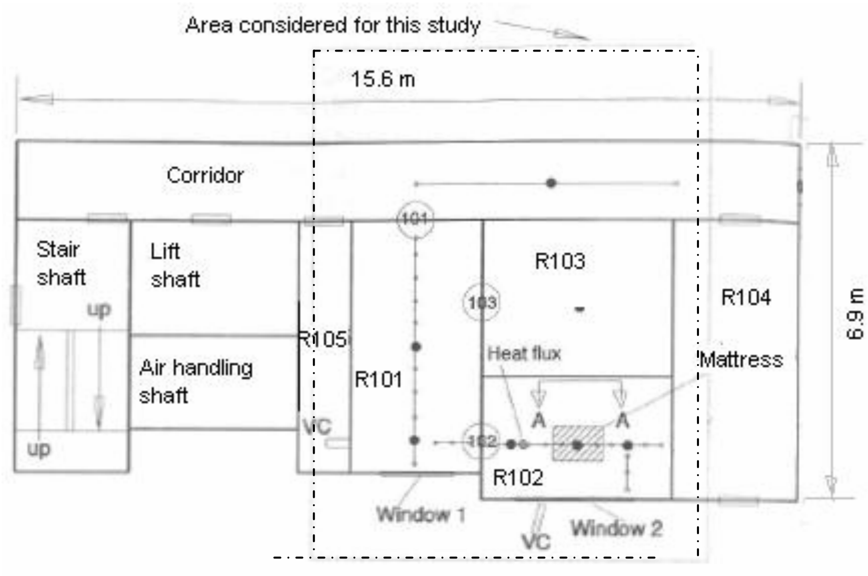


Figure 47: Multi-room arrangement used for mattress fire testing by Luo and Beck. Extracted from (Luo & Beck 1996).

Two fuel loads were used in the experimental part of the study. The smaller load was a polyurethane foam slab (0.95 × 0.94 × 1.5 m) equivalent to half a mattress. The larger load was three polyurethane foam full-sized single mattresses (two were 1.88 × 0.95 × 1.50 m and the other was 1.88 × 0.95 × 1.0 m). The fuel configuration is shown in Figure 48. In both cases, the base was a steel frame with the mattresses supported by a steel mesh. An electrical igniter, set at 800°C, was used to initiate combustion of the mattress.

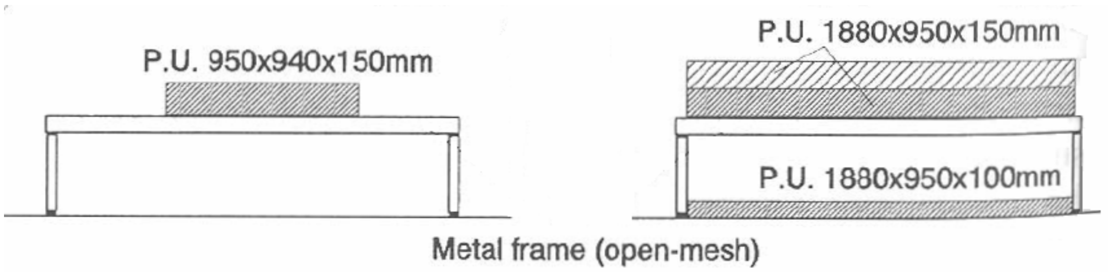


Figure 48: Fuel configuration used by Luo and Beck. Extracted from (Luo & Beck 1996).

The fire associated with the smaller fuel load developed slowly and lasted approximately 7 min. The temperatures within the burn room reached 500°C at 1.9 m around 4 min after ignition. The temperature reached approximately 200°C in adjacent rooms and 100°C in the hallway. The concentration of O_2 decreased to 12 mol% in the burn room and to 17 mol% in the corridor. The concentration of CO_2 increased to 3 – 6 mol% and CO concentrations increased to 0.35 mol% in the burn room.

The larger fuel load, designed to cause flashover in the burn room, burned slowly for the first 3 min, with rapid fire growth leading to flashover in the 4th minute. The duration of the fire was similar to the smaller fuel load (7 min). The window present in the burn room cracked at 3.5 min and fell out before flashover at 4.5 min. In the burn room, the temperatures exceeded 900°C at 1.9 m. Temperatures reached between 700°C and 400°C in the adjacent room and 200°C in the corridor, at approximately 4.5 min after ignition. The O_2 concentration dropped to < 5 mol% in the burn room and 10 mol% in the adjacent room. Concentration of CO_2 increased to 10 mol% and 7.5 mol%, as did the CO concentrations to 3 mol% and 1 mol%, in the burn room and adjacent room, respectively.

These results showed the significant changes in conditions with increasing fire load, with untenable condition developing in rooms adjacent to the room of origin. Both fires had a similar duration, providing some indication of possible radiation feedback effects for bed assemblies and the level of combustion products produced by polyurethane foam mattresses. Luo and Beck also presented CFD results that showed this scenario successfully simulated in the CESARE-CFD model by using a solid fuel and predicting the mass loss rate and the HRR.

Nurbakhsh and McCormack (Nurbakhsh & McCormack 1998) reviewed the California Technical Bulletin, TB 129 – *Mattresses for use in public occupancies*. TB 129 is a room fire test for a single mattress and currently has three pass/fail criteria:

- a maximum heat release rate of 100 kW or greater
- a total heat release of 25 MJ or greater in the first 10 min of the test
- a total weight loss of 3 pounds or greater in the first 10 min of the test.

The test can be conducted in the BHFTI room, an ASTM room or under an open calorimeter, as shown in Figure 49. HRR, smoke production rate, total heat released, total smoke released, and weight loss were all recorded during the tests. This study tested 126 mattresses, innerspring, non-innerspring, different fillings, some containing interliners and a range of cover materials. A T-shaped propane gas burner placed parallel to the lower edge of the mattress was used to ignite the bottom and side of the mattress.

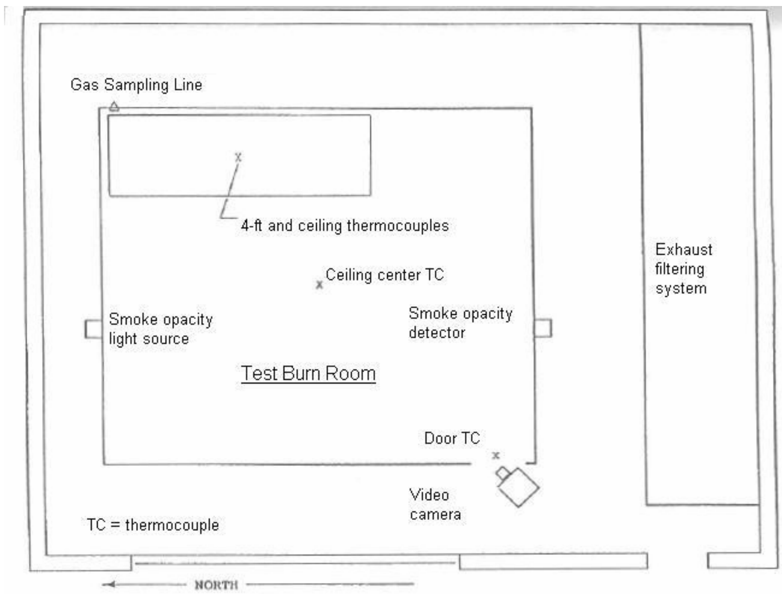


Figure 49: TB 129 experimental set-up. Extracted from (Nurbakhsh & McCormack 1998).

The results were summarised in Krasny et al (Krasny, Parker & Babrauskas 2001). The summary of the test results from the 126 mattress showed:

- 63 had vinyl ticking, of which 56 passed all three criteria.
- 24 mattresses had cotton ticking, of which 15 passed.
- All mattresses which had no innersprings made with Combustion Modified High Resiliency Polyurethane Foam (CMHR) passed, regardless of the presence of interliners.
- In contrast all foams modified to meet TB 117 failed, unless an interliner was present.
- The innerspring mattresses had similar results to the non-innerspring mattresses. Two mattresses failed because they reached flashover conditions before 10 min. These were the non-fire retardant polyurethane foam and low density foam, which complies with TB 117.

Ohlemiller performed extensive research into beds, bedding and mattresses (Ohlemiller 2003; Ohlemiller & Gann 2002, 2003; Ohlemiller, et al. 2000). Ohlemiller's series of reports systematically investigated the burning characteristics of bedding assemblies. Figure 50 shows the mattress and foundation structure used in all tests discussed by Ohlemiller, unless otherwise stated.

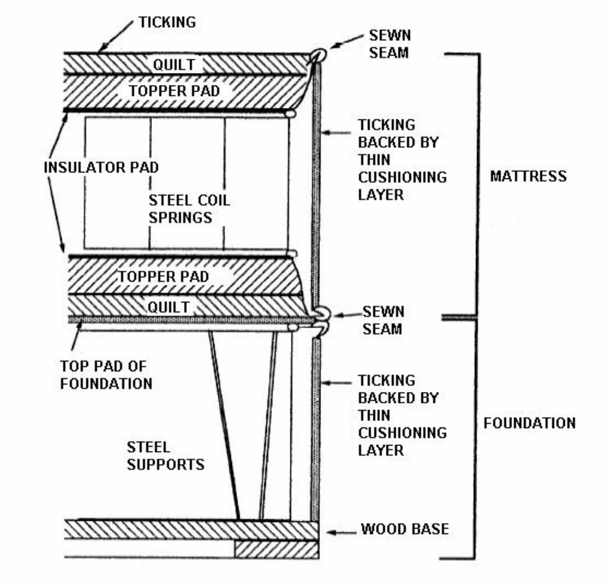


Figure 50: Schematic of the cross-sectional view of the mattress and foundation structure. Extracted from (Ohlemiller 2003; Ohlemiller & Gann 2002, 2003; Ohlemiller, et al. 2000).

Ohlemiller et al (Ohlemiller, et al. 2000) looked specifically at the bedding and the simulation of the burning bedding using gas burners. Ohlemiller and Gann (Ohlemiller & Gann 2002) also tested mattresses with varying burning characteristic (from low to high HRR), to estimate the resulting fire risks associated with each type of mattress. Ohlemiller and Gann (Ohlemiller & Gann 2003) also investigated the burn characteristics of different types and combinations of bedding possible on bedding assemblies. The effect of these modifications on the characteristics of the whole bedding assembly was then assessed. Ohlemiller (Ohlemiller 2003) further compared the burning behaviour of bedding assemblies resulting from the use of gas burners developed in (Ohlemiller, et al. 2000) and actual bedding.

Ohlemiller et al (Ohlemiller, et al. 2000) investigated the thermal impact on mattresses created by burning bedding in order to produce a reproducible simulation. Twelve different bedding sets were tested on an inert mattresses in a furniture calorimeter. HRR, flame spread and heat flux data was measured and recorded. Using an infrared imaging technique, six sets were further characterised by the heat flux patterns they imposed on the mattress. Propane burners were then used to simulate the burning bedding in terms of peak heat flux, duration and area. From these results, a series of tests were conducted comparing bedding assemblies, mattress, base and bedding, and mattress and base sets with the propane burners.

The bedding ranged from two sheets and a pillow only, to a mattress pad, two sheets, a blanket, a heavy bedspread and a pillow. The materials of the bedding were:

- sheets: polyester/cotton or cotton
- pillows: polyester fibrefill or latex foam
- blankets: acrylic, polyester, polyurethane, cotton or wool
- bedspreads: polyester fibrefill of medium weight or heavyweight.

The bedding was ignited using a gas burner simulating a match flame. The arrangement for the inert tests is shown in Figure 51.

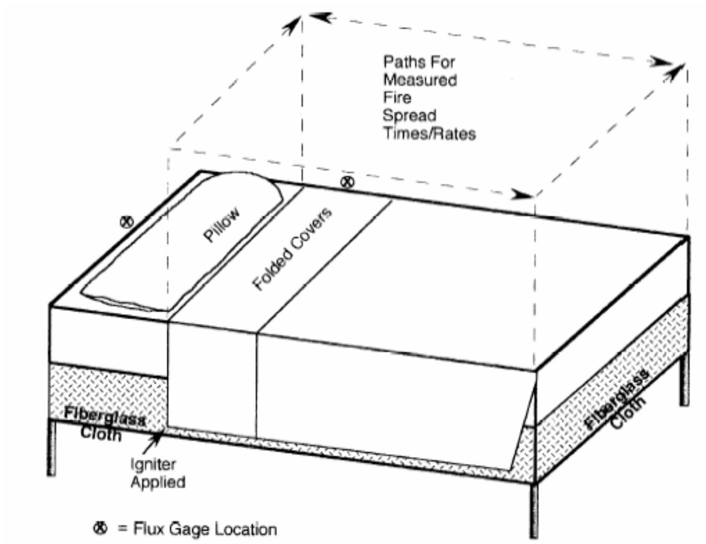


Figure 51: Schematic of the set-up and igniter position for bedding tests on inert mattresses. Extracted from (Ohlemiller, et al. 2000).

The maximum peak HRR reported from the 12 combinations tested was 200 kW and the minimum was 130 W. Even though 130 W was relatively small, it was still a significant increase of heat released compared to the initial ignition source, increasing the risk of the mattress igniting. For a small room, it was assumed that flashover would occur at 1.1 MW (Ohlemiller, et al. 2000). In isolation, the bedding combinations tested produce insufficient heat to cause flashover. To prevent flashover in a room, the heat released by the mattress would need to remain under 900 kW and other items in the room would not ignite.

The data was selected from six combinations of bedding burn tests to characterise the bedding using propane burners (which produced a heat flux on the top and side of the mattress). Peak HRR rates, time to peak HRR, average rate of flame spread and incident heat flux were given for each bedding combination, as well as the HRR curve for one of the bedding combinations.

Five types of twin bed-sized mattresses were tested: one representing commercially available residential mattresses and four experimental reduced-flammability designs. The mattresses were also tested using the heat flux produced by the propane burners and with one of the bedding sets. The propane burners simulated the burning bedding well in four out of the five mattresses. However a phenomenon described as internal over-pressurisation (Ohlemiller, et al. 2000) occurred in the 5th mattress with the bedding. The heating of the mattress surface produced a flammable gas mixture within the mattress. This caused the seams to rupture, which allowed the fire to penetrate the interior of the mattress. The characteristics of the over-pressurisation was not well simulated by the propane burners.

The mattresses were improved as follows:

- Mattress 2 employed more flame resistant ticking and moderately flame retardant foam.
- Mattress 3 contained a ticking with a fire barrier material.
- Mattress 4 contained flame retardant polyester batting instead of polyurethane foam.
- Mattress 5 combines flame retardant foam with boric acid treated cotton batting.

A description of each of the mattress tests is given in the report comparing the residential mattress (Mattress 1) with the four altered mattresses. The difference between the five mattresses varied from delayed/slowed fire growth, with equal severity to appreciably reducing the HRR, but still consuming the mattress and base, to reducing the HRR by limiting the mattress involvement.

Ohlemiller and Gann (Ohlemiller & Gann 2002) attempted to quantify the change in fire risk resulting from the change in fire intensity of a bedding assembly fire. Free burn and room tests were conducted for the different types of mattress, while the bedding remained constant. The free burn tests measured the HRR and mass loss rate. Radiant heat flux and flame length/reach were also measured to assess whether a remote object could ignite. The room tests were instrumented with heat flux gauges and thermocouple trees. CO concentrations were estimated using CFAST. Flashover was assumed to occur when the HRR exceeded 1 MW in a normal-sized bedroom.

King and twin-sized beds, with three different constructions, were tested: one replicating the design most common in residential buildings with a relatively high HRR, and two experimental designs with intermediate and low HRRs. Bedding consisted of a polyester/cotton mattress pad (which covered the top and sides), a fitted and flat 50/50 polyester/cotton sheet, an acrylic blanket, a polyester fibre fill bedspread, and polyester pillows in polyester/cotton cases (one for the twin bed and two for the king-sized bed). The ignition source and location was the same as used previously (Ohlemiller, et al. 2000).

The relationships between the peak HRRs achieved with the king-sized beds and the twin beds appeared to be based on the mattress designs. For the residential mattress, there was a large effect on the peak HRR due to the bed size. The intermediate HRR mattress did not show an obvious effect due to the bed size. However, the room tests accentuated the differences in peak HRR and other burning characteristics between the different bed sizes. The king-sized beds generated a more severe fire due to the increase in fuel. The two experimental mattresses often had two peaks in the HRR profile, for both the open hood and room tests. Table 9 shows the results of one of the tests of the king-sized beds.

Table 9: Results from the king-sized bedding assembly tests*

Mattress/Foundation Design	Test Location	Peak HRR [a] (kW/m^2)	Time from Ignition to Peak [a] (s)
Low design	Open hood	290	380
Intermediate design	Open hood	755 (660)	700 (1160)
Regular (high) design	Open hood	3,850	305
Low design	Room	420	525
Intermediate design	Room	880 (955)	445 (970)
Regular (high) design	Room	4,620	334

* Adapted from (Ohlemiller & Gann 2002).
[a] Numbers in parentheses are associated with the second peaks.

Smouldering combustion then occurred in the bedding assembly with the mattress designed to have a low HRR. Flaming combustion spontaneously resumed 4 min after the initial peak. This behaviour was not investigated in this report, and the fire was extinguished.

From these experiments and previous experiments (Ohlemiller, et al. 2000) it was clear that a room containing a bed with a regular mattress would be at high risk of flashing over. The bed fire was severe enough to cause flashover, even before secondary items were considered. The focus of this report was to determine the risk of flashover, if the experimental mattresses were in a room fire. The intermediate mattress also showed a high risk of room flashover, when the bed was burned in isolation. When the bedding assembly with the low mattress was ignited, only the bedding burned with the king-sized bed in the room, however the HRR still reached 400 kW.

One of the concerns in room fires was the risk of a second item igniting due to the radiant heat flux of the first item (in this case the bedding assembly). By comparing the open hood and room tests it was shown that the room environment enhances both the HRR and the radiant flux fields (Ohlemiller & Gann 2002). The risk of ignition of secondary items was estimated using the cone calorimeter data of seven surrogate materials. The most important material was cotton cloth, which could represent the ignitability of curtains or upholstered furniture in close proximity to the bed. The heat produced from the regular and intermediate assemblies indicated the capacity of the ignition of a second item, as they could cause flashover in isolation. Even the heat produced by the low assembly (400 kW) would have been sufficient to ignite a second item in close proximity to the bed.

The CFAST results showed that conditions in room of origin and other rooms in the model house could become untenable in the upper layer of the room within a few minutes of ignition for the intermediate-HRR mattress. Results for the low-HRR mattress also indicated incapacitating and lethal concentrations within the upper layer of the room; however, the layer remained high, presenting a much lower threat to occupants.

Ohlemiller and Gann (Ohlemiller & Gann 2003) used twin-sized mattresses of the same composition as previous investigations (as shown in Figure 50) and modified some of the bedding components to monitor the effect on the overall burning behaviour of bedding assembly. Tests were conducted in a NIST 6 m hood calorimeter. The mattress pad, bedspread and pillow were modified by increasing the flame resistance of the fibrefill and adding one of two types of charring barrier inside the shell. The bedding assembly also comprised of two sheets, a blanket and a solid base. Ignition was from a match-sized flame impinging on the overhanging sheets and blanket, similar as that used in previous tests (Ohlemiller & Gann 2002; Ohlemiller, et al. 2000).

The modified mattress pads with the protecting sides improved the bedding assembly performance by reducing the HRR and increasing the time to reach the peak. The difference was significant when comparing the results with mattress pads that did not have side barriers. The mattress pads with no sides did not noticeably improve the performance of the bed assembly. Based on these results, it was suggested that a modified bedspread can protect the top and sides of the bedding assembly, however the unmodified components are still partially exposed and the bedspread is not always part of a bedding assembly. Pillows have a big influence on the burning behaviour of the assembly. Pillows can increase the severity of a bedding assembly fire in two ways:

- Contributing a significant portion of the HRR, especially if more than one pillow is present.

- Increasing the HRR can compromise the mattress, increasing the amount of fuel involved in the fire. This occurs because pillows are typically long burning and are generally located where there is little fire resistance over the mattress, due to the absence of charring materials like blankets.

There were often two peaks in the HRR of a bedding assembly, which were more distinct when the mattress had a higher fire retardant. The first was a peak associated with the bedding and was controlled by the bedding characteristics. The second peak was associated with the mattress and base. When the mattress and base became involved in the fire, the bedding had often completely burned away.

Ohlemiller (Ohlemiller 2003) discussed the validity of using gas burners to simulate the burning of bedding in a bedding assembly for testing purposes. Gas burners are used to improve the repeatability of the tests because the consistency of bedding can not be assured over a long period of time. Tests were conducted in a NIST 6 m hood calorimeter.

Results showed that the peak HRRs reached using the gas burners were an adequate comparison to those recorded when bedding was used. However the time to peak HRR was 15 – 30 min slower. The length of the gas burner test was crucial in determining late hazards (occurring after 1 h). Tests with bedding should still be conducted to identify subtle differences in burning behaviour. As found in previous investigations (Ohlemiller & Gann 2002, 2003), for mattresses with improved fire resistance there are two distinct peaks, one associated with the bedding, the other associated with to mattress and base. Table 10 presents a summary of the differences in the two methods (Ohlemiller 2003).

Table 10: Features of burning bedding and gas burners as ignition sources*

Burning Bedding	NIST Duel Gas Burners
Progressive burning (spread flames over bed surface)	Localised burning to one area
Rapid exposure to all vulnerable surfaces	Slow spread to surfaces beyond that exposed
Highly variable heat flux to all bed surface locations	Worst case heat flux to representative locations only
Variable burning and heat flux from identical sets in successive tests	Reproducible heat flux exposure to successive tests
No provision for obtaining identical bedding sets over extended time periods	Uses a simple, reproducible fuel (high grade propane)
Real world exposure condition for mattress/foundation	Simplified exposure condition can miss or under-estimate some failure modes

* Extracted from (Ohlemiller 2003).

Babrauskas (Babrauskas 2002), in the *SFPE Handbook*, summarised research on mattresses, excluding bedding. Babrauskas noted that the burning behaviour of polyurethane mattresses is very sensitive to the surrounding environment. This is due to the fuel acting like a liquid pool once the polyurethane foam melts. This behaviour can be enhanced or reduced, depending on the type of bedding used in a bedding assembly. The effect would be enhanced if the bedding propagated the fire, further increasing the liquid pool. On the other hand, the effect can be reduced by preventing ignition of the mattress.

Pillows can have a significant effect on the burning behaviour of a bedding assembly. If they do not ignite, then the HRR and fire intensity of the bedding assembly is reduced. However, if the pillow ignites it may produce sufficient heat to ignite other bedding components, which would not otherwise ignite. Therefore the burning characteristics are important when considering the whole bedding assembly. Babrauskas (Babrauskas 1985) quantified the HRR of pillows made of five different materials, as shown in Figure 52. Ignition was by six balls of newspaper placed inside the pillowcase opening.

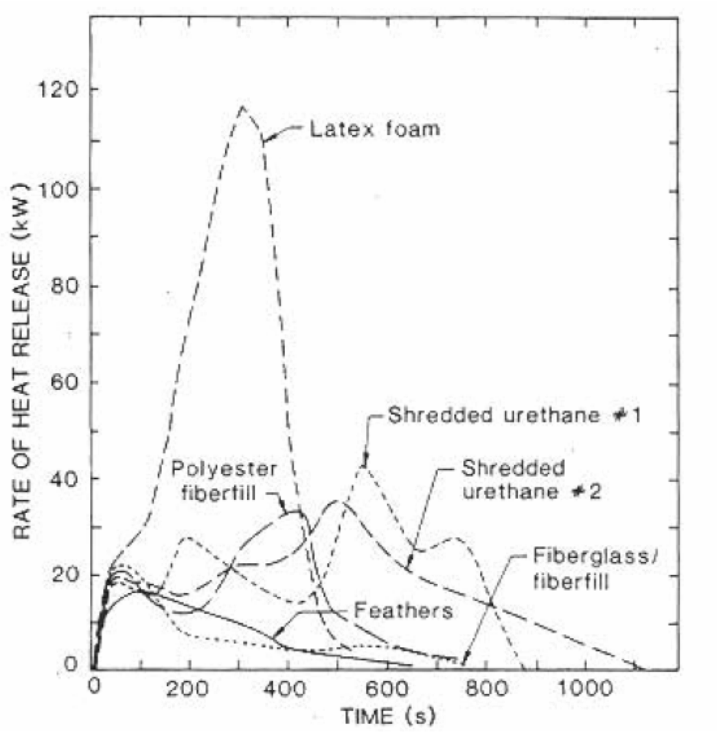


Figure 52: HRR curves for various pillows. Extracted from (Babrauskas 1985).

Each pillow, as shown in Figure 52, had an initial peak HRR of 20 kW. This was attributed to the ignition source. The ranking from best to worst in terms of performance (where the best is considered the lowest HRR and total heat released) was: fibre-fill with fibreglass cover, feathers, fibre-fill, polyurethane foam and latex foam. The latex pillow performed the worst, burning the most rapidly, with a peak HRR of 117 kW and total heat release of 27.5 MJ. The peak HRR for other pillows ranged from 16 – 43 kW, with a total heat release of 3.1 – 18.9 MJ.

Krasny and Parker (Krasny & Parker 1995) examined the peak heat release rate of various types of mattresses, including innerspring and foam. Mattresses were examined in both a furniture calorimeter and an ISO 9705 room. For each item studied, a detailed description of the cover fabric, padding, fibre wrap, use, and peak heat release rate was also listed in tabular format. For all mattresses tested, reproducibility and repeatability were reported as acceptable but "not that good". The authors report that above a threshold of 460 kW, the peak heat release rates observed in the ISO room were consistently higher than those obtained for the same mattress tested in the furniture calorimeter. This was concluded to be as a result of the radiation reinforcement exhibited by the walls and ceiling of the room.

The largest interaction reported by Krasny and Parker (Krasny & Parker 1995) with the room was exhibited by the two solid core mattresses examined. The flame spread rate over the surface of the mattresses was concluded to play a large part in this fact. Justifying this conclusion was the peak heat release rates obtained for these mattresses that were four times larger in the ISO room tests than in the furniture calorimeter.

5.2.1 Summary of beds and bedding fires

The following is a summary of the results and observations presented in the reviewed literature for investigations of beds and bedding flammability data:

- A tightly made bed has slower flame spread than a loosely made bed or an unmade bed (Krasny, Parker & Babrauskas 2001).

- Results from tests using small-scale models (i.e. models smaller than half-scale) deviated significantly from full-scale results (Paul 1980). This is an indication that an incorrect combination of parameters have been used to scale the models.

- Cigarette and matches are the primary cause of accidental ignition of beds (Rieber 1983). Larger sources, like those simulated by crib fires, are rare according to accident statistics.

- A fire retardant covering on bedding components was demonstrated to be insufficient to prevent fire growth (Rieber 1983).

- Bedding assemblies can only be classed as fire retardant if all components have compatible burning characteristics and are made from fire retardant materials (Rieber 1983).

- Vertical component tests on blankets showed no correlation between the component tests and results from testing the entire bedding assembly (Benisek, Phillips & Paul 1985).

- Wool products were shown to be effective in increasing the fire resistance of a bed assembly (Rieber 1983). This was attributed to the ability of wool to char, which reduced flame spread and smouldering.

- Solid foam mattresses showed significantly more flame propagation and burn out than innerspring mattresses which smouldered and self-extinguished (Sundström 1994).

- The burning behaviour of polyurethane mattresses was shown to be highly sensitive to the surrounding environment (Babrauskas 2002).

- The flame spread across blankets varied, depending on the material. The flame spread across some representative blankets on a bedding assembly was ranked from very fast to very slow: acrylic blanket, polyester filled duvet, cotton blanket, wool filled duvet, wool blanket (Ingham & Edwards 1984).

- The burning behaviour of bedding assemblies in the early stages of a room fire was reported as similar to a free burn fire (Lee 1985).

- Pillows may significantly affect the burning behaviour of a bedding assembly (Babrauskas 1985).

- For fire spread to pillows, on ignition, the HRR and smoke production increased considerably (Paul 1989). This was attributed to the availability of a greater combustible mass and the additional heat released increases the risk of other items igniting.

- Conditions were observed to change significantly with increasing fire load. The relationship between resulting conditions and fire load was greater than linear (Luo & Beck 1996).

- Untenable conditions have been observed to extend past the room of origin (Luo & Beck 1996).

- Room fire scenarios have been successfully modelled using a CFD approach (Luo & Beck 1996).

- Mattresses containing foams, which comply with TB 117, do not necessarily comply with full-scale tests (Damant & Nurbakhsh 1992; Nurbakhsh & McCormack 1998). For example, TB 129.

- Fire retardant treatments can delay or slow fire growth, but have equal severity; reduce the maximum HRR, but still consume most of the (combustible) mass; or they can limit the mattress involvement (self-extinguishing) (Ohlemiller, et al. 2000).

- Unique failure modes of mattresses can occur when bedding is used (Ohlemiller, et al. 2000). For example, over-pressurisation of the mattress has been observed, where a flammable gas mixture was created within the mattress causing the seam to rupture and allowing fire penetration into the interior of the mattress. These effects could not be simulated when testing mattresses with gas burners simulating the bedding.

- There are often two peaks in the HRR for bedding assemblies (Ohlemiller & Gann 2003). The first is due to the bedding and the second is due to the mattress and base.

- Solid core mattress have been shown to have a higher interaction with the room as a result of radiation reinforcement in comparison to innerspring mattresses (Krasny & Parker 1995).

In summary, experimental results from investigations of the burning characteristics of mattresses and bedding were shown to be influenced by:

- *Inclusion of bedding in a mattress test* – inclusion of bedding provides more realistic design fire data. For example, pillows may significantly affect the burning behaviour of a bedding assembly.

- *Configuration of the bedding* – for example, a tightly made bed had slower flame spread than a loosely made bed or an unmade bed.

- *Type of mattress* – for example, solid foam mattresses showed significantly more flame propagation and burn out than innerspring mattresses, which smouldered and self-extinguished. In addition, solid core mattress have been shown to have a higher interaction with the room as a result of radiation reinforcement in comparison to innerspring mattresses.

- *Combination of the bedding and mattress material* – for example, if one component of mattress material was a fire barrier or a fire blocking material, good fire performance could still be obtained even though other materials were not fire retardant. Conversely, positive effects of fire retardant components could be neutralised when used in combination with other components. Furthermore, bedding assemblies can only be classed as fire retardant if all components have compatible burning characteristics and are made from fire retardant materials.

- *Type of test used* – for example, experimental results from room experiments of mattresses and bedding differ from free burns, with increased HRR and CO concentrations, due to radiative feedback. However, the burning behaviour of bedding assemblies in the early stages of a room fire was reported as similar to a free burn fire.

- *Ignition source* – for example, cigarettes and matches were the primary cause reported for accidental ignition of beds, whereas larger sources like those simulated by crib fires are rare, according to accident statistics.

5.3 Characteristics of upholstered furniture fires

Combustion properties of upholstered seating can be extrapolated from data for small-scale tests in the cone calorimeter, and larger-scale tests, for example, chair mock-ups and full-scale chair burns. Chair mock-ups are made up of cushions, as shown in Figure 53, where armchairs are represented four cushions to represent a back, a seat and two arm cushions. Similarly, loveseats and three-seater sofas can be represented by six and eight cushions, respectively. There are a number of different styles of armchairs and two- and three-seater sofas. Details, including the chair size, type, design and construction materials, can have a significant effect on the ignition propensity and resulting fire.

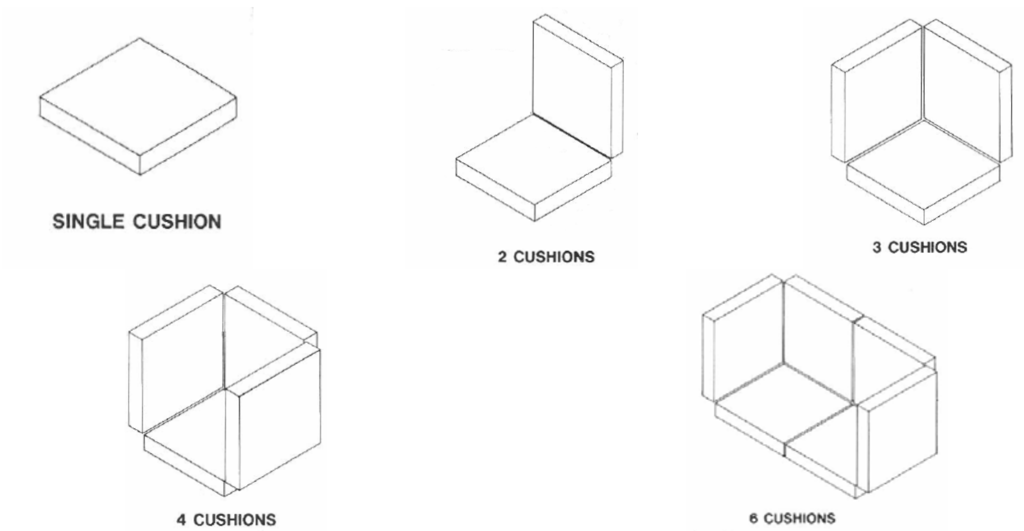


Figure 53: Configurations of chair mock-ups. Extracted from (Krasny & Babrauskas 1984).

The results of a number of furniture items tested in the NBS furniture calorimeter in 1983 were reported by Lawson et al (Lawson, Walton & Twilley 1984). The HRR, mass loss rate, thermal irradiance, carbon monoxide and smoke concentration were measured and recorded. The upholstered items investigated were five easy chairs, one sofa and two loveseats, as described in Table 11.

Table 11: Upholstered furniture items tested by Lawson et al[*]

Upholstered Item [a]	Frame	Foam	Fabric
Easy Chair (45)	Wood	Cal 117	Polyolefin
Easy Chair (48)	Polystyrene-plywood	polyurethane	Polyurethane with polyolefin backing
Easy Chair (49)	Wood	polyurethane	Cotton
Easy Chair (64)	Cold moulded polyurethane foam/ wood/springs	polyurethane	Imitation leather/polyester batting
Easy Chair (66)	Wood	polyurethane -polyester fibrefill	Cotton and paper welted cord
Sofa: three-seater (38)	Wood	Cal 117	Polyolefin
Loveseat (54)	Metal	polyurethane	Plastic-coated fabric
Loveseat (57)	Oak wood	polyurethane	Plastic-coated cotton

[*] Adapted from (Lawson, Walton & Twilley 1984).
[a] Numbers in parentheses indicate the number of items tested.

A number of office/waiting room type chairs were also tested. The office chairs/waiting room type chairs were made of different combinations of the following materials:

- fabrics: polyolefin, cotton, synthetic fibre, polyester fibre, plastic-coated fabric
- padding/foam: Cal 117, polyurethane foam, latex foam rubber, vegetable fibre
- frame: wood, polypropylene, polyurethane.

Unless otherwise specified, the ignition source was a 50 kW gas burner, which was located 25 mm from the side of the chair.

The easy chairs were all different styles and, unfortunately, the details of the designs were not specified with the corresponding results. The easy chairs have been characterised by construction materials: frame/padding/cover material. The relevant investigation results for the burning characteristics have been summarised:

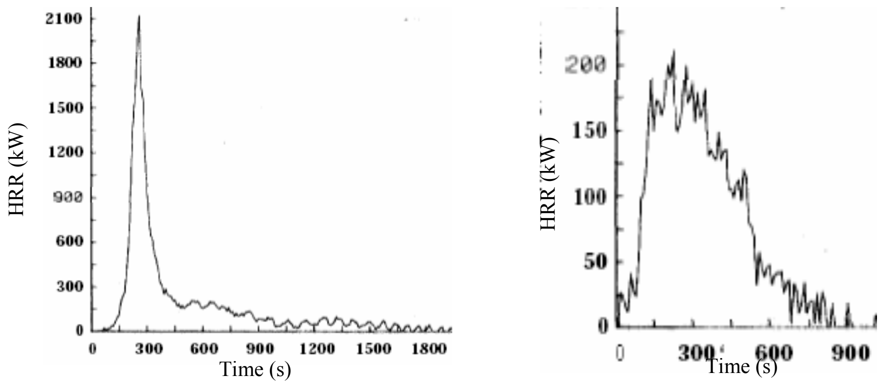
- The peak HRR value for both the 'wood/Cal 117/polyolefin' and 'polystyrene-plywood/polyurethane/polyurethane with polyolefin backing' (of 2,100 kW and 960 kW, respectively) indicated that room flashover would be likely. The HRR increased rapidly, reaching the peak around 300 s from ignition.
- The 'polystyrene-plywood/polyurethane/polyurethane with polyolefin backing' easy chair also had the greatest smoke production and thermal irradiance.
- The 'wood/polyurethane/cotton' easy chair had the most favourable burning characteristics with a peak HRR of 210 kW.
- The ignition source for the 'wood/polyurethane-polyester fibrefill/cotton and paper welted cord' easy chair was a smouldering cigarette located in the seat-arm crevice. The easy chair smouldered for 3,700 s before flaming combustion occurred. The HRR then increased rapidly to reach a peak of 640 kW within 200 s.

- The loveseat with the metal frame had a lower peak HRR than the other loveseat and the sofa, 370 kW at 450 s.

- The loveseat with the wooden frame was the most difficult to ignite due to plywood panels at the ends of the loveseat where the ignition source was located. Flaming combustion was established once the seat and back cushions were involved, causing rapid fire growth and a peak HRR of 1,100 kW at 800 s.

- The sofa ('wood/ Cal 117/ polyolefin') had a peak HRR of 3,000 kW in 250 s, which was the highest of all the furniture items tested in this paper; it also produced the highest total heat released, thermal irradiance and CO concentrations.

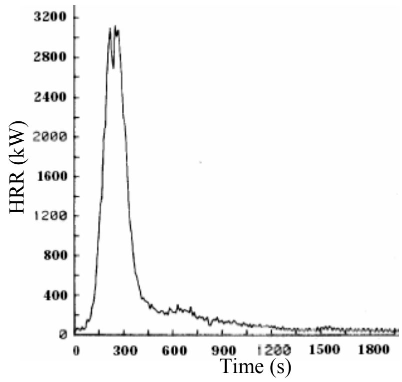
In general, two types of burning behaviour were observed for the easy chairs: a short sharp peak HRR or a lower peak HRR with a period of steady burning after the peak HRR was achieved. Examples of these two types of HRR measurement are shown below in Figure 54. Figure 54 (a) shows the results for a 'wood/Cal 117/polyolefin' easy chair, with a short sharp peak in the HRR measurement. Figure 54 (b) shows the results for a 'wood/polyurethane/cotton' easy chair, with a lower peak HRR measurement followed by a period of steady burning.



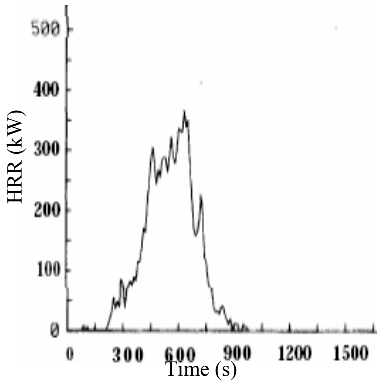
(a) 'Wood/Cal 117/polyolefin' easy chair **(b) 'Wood/polyurethane/cotton' easy chair**

Figure 54: Examples of HRR profiles for easy chairs. Note the difference in scale between (a) and (b). Extracted from (Lawson, Walton & Twilley 1984).

In particular, the results for the loveseat with the wooden frame showed that a delay before the onset of rapid fire growth would probably have been shorter or absent by moving the ignition source to the seat or back cushion. With this in mind, the location of the ignition source could be significant when considering life safety in fire engineering design. Similar to the results for the easy chairs, the HRR measurements showed one distinct peak HRR for each of the above tests, with either a high sharp peak or a lower peak followed by steady burning (see Figure 55). Figure 55 (a) shows the results for a 'wood/Cal 117/polyolefin' sofa, with a short sharp peak in the HRR measurement. Figure 55 (b) shows the results for a 'metal/polyurethane/plastic-coated fabric' loveseat, with a lower peak HRR measurement followed by a period of steady burning.



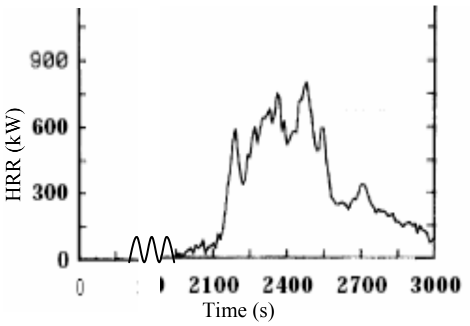
(a) 'Wood/Cal 117/polyolefin' sofa



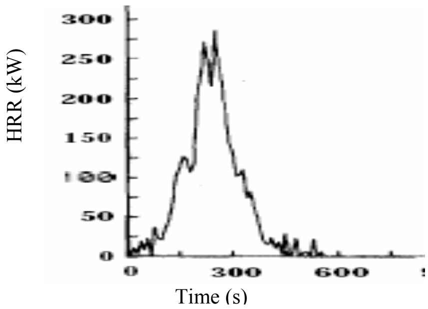
(b) 'Metal/polyurethane/plastic'-coated fabric loveseat

Figure 55: Example of HRR profiles for a sofa and loveseat. Note the difference in scale between (a) and (b). Extracted from (Lawson, Walton & Twilley 1984).

The office/waiting room type chairs that were investigated were commonly used in commercial buildings, but could often be found in residential buildings. The amount of combustible materials on these chairs was often significantly less than the easy chairs, which were discussed earlier. The smaller amount of combustible materials was attributed to very low peak HRR measurements. For example, a metal frame chair with an upholstered seat cushion peaked at 3 kW. The office/waiting room type chairs were constructed from similar materials to the easy chairs or from moulded plastics frames, with varying amounts of upholstery. Examples of the burning behaviour of office chairs are shown in Figure 56. Figure 56 (a) shows an example of the HRR measurements for a moulded plastic office chair. Figure 56 (b) shows an example of the HRR measurements for an office chair, with a metal frame and foam cushions.



(a) Moulded plastic office chair



(b) Office chair, with a metal frame and foam cushions

Figure 56: Example HRR profiles for office chairs. Note the difference in scale between (a) and (b). Extracted from (Lawson, Walton & Twilley 1984).

Sardqvist (Sardqvist 1993) collated the results from a number of experiments for items ranging from building materials, warehouse stock to furniture and furnishings. The database included furniture calorimeter tests, different-sized room tests and room tests with varying degrees of ventilation. The range of information from the tests included a detailed description of the item, HRR profile, mass loss profile, CO concentrations, smoke concentrations, etc. There were tests with mock-ups, armchairs, easy chairs, loveseats and sofas. The results showed a wide range of burning behaviour from poor to excellent.

The CBUF study (Sundström 1994) tested a number of full-scale chairs and sofas, which were commercially available, and a number of full-scale models, which were constructed specifically for the furniture tests. Single item tests were conducted in the furniture calorimeter, ISO 9705 room and a larger test room (5.7 × 7.37 × 4.0 m). The commercially available items varied from fully-upholstered armchairs, loveseats and sofas to basic office chairs and executive swivel chairs. The full-scale models of upholstered chairs, loveseats and sofas tested changed for different variables, for example, fabrics, interliners, foams, gaps between cushions, framing material and design. Parameters reported in both graphical and tabular form include: peak heat release rate, time to peak heat release rate, total heat release, effective heat of combustion, peak smoke production rate, total smoke production, smoke yield, test duration, HCN peak concentration, HBr peak, CO peak, NO peak, all of the previous mentioned parameters when the door to the room was opened (door was shut for previous parameters), SO_2 peak, total CO produced, HF peak, H_3PO_4 peak, oxygen minimum level, sample mass, mass loss, peak rate of mass loss, time to peak rate of mass loss, and heat flux and temperature at various heights of the room 30 s after ignition.

The test results showed the presence of arm rests could increase the radiation feedback onto the seat. If ignition was within the seat area, a higher HRR was achieved and the fire growth was also faster with the peak HRR reached 60 – 120 s faster than similar chairs with no arm rests. A higher backed chair produced a slightly higher HRR, which was attributed to the extra combustible mass present. If there were gaps between the seat cushion and other cushions, the fire growth was slower but the peak HRR was similar. Chairs, where the cushions were supported by webbing, showed faster fire development and higher HRR values. The fire was observed to burn through the interior structure, producing a pool fire to form on the floor below the chair. Chairs of a similar design with solid wood panelling had slower fire growth and significantly lower peak HRR values (361 kW compared to 821 kW). Button tufting was another variable tested using the full-scale models. However, no detectable difference in burning behaviour was caused by button tufting.

The framing used in chairs was usually no frame or it was made of wood, metal, thermoplastic or thermosetting materials. Chairs with no frames were not tested in the CBUF study, since earlier studies had found chairs with no frames were very hazardous due to large amounts of easily combustible material, for example, bean bags and foam-block chairs. Sundström (Sundström 1994) noted that wooden framed chairs were the most common in the commercial market.

During the tests, it was observed that the frame was not usually involved until the later stages of the fire. Therefore the peak HRR was not affected by the combustion of the framing material. However the construction of the frame did affect the burning behaviour. For example, if corrugated metal plates or similar connectors were used, the frame sometimes collapsed in the early stages of the fire. Early failure sometimes exposed large quantities of concealed material to the fire, resulting in rapid fire growth and a higher peak HRR. The chairs with metal frames had similar burning characteristics to the wooden frame chairs, however the joints in the metal frames did not fail from the thermal effects of the fire. The thermoplastic frames performed worse than the wooden frames, but better than the thermosetting frames. The office chairs tested often had metal frames with hard plastic shells. In these cases, the performance depended on the burning behaviour of the plastic. Plastic that melted tended to form a pool fire under the chair, accelerating the burning rate and increasing the peak HRR.

The results of the study indicated that the peak HRR and combustible mass correlation for armchairs, loveseats and sofas was greater than linear, with the high HRR resulting from an increased amount of combustibles. However, in a room environment the armchair was the worst case scenario in the early stages of a fire. This was attributed to the acceleration in the growth rate due to radiation feedback.

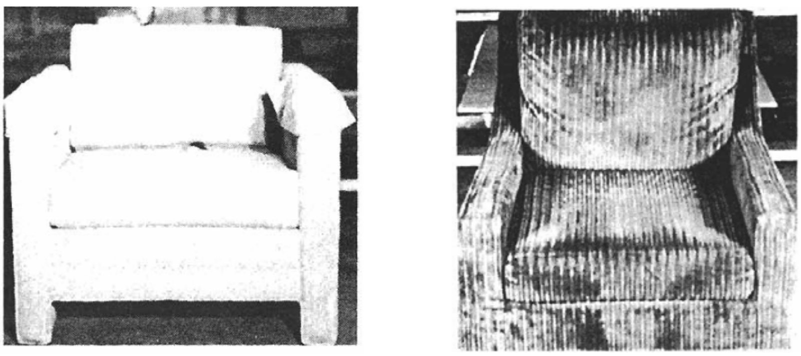
Babrauskas, in the *SFPE Handbook* (Babrauskas 2002), referred to NBSIR 82-2064 (Babrauskas, et al. 1982), Babrauskas (Babrauskas 1983) and a *Flammability Information Package* published by the Bureau of Home Furnishings of the State of California (Bureau of Home Furnishings, California 1987). The package included TB 21, 106, 116, 117, 121, and 133, and illustrated the general burning behaviour recorded for full-scale tests (Bureau of Home Furnishings, California 1987). The information available for upholstered furniture in this chapter also summarised some of the findings published in the CBUF report (Sundström 1994); specifically, CBUF Model I, which predicts burning behaviour from small-scale cone tests. However, this model is not within the scope of this literature review.

The development of the furniture calorimeter has been described by Babrauskas (Babrauskas 1983). Before the development of the furniture calorimeter, room tests were used to assess the burning characteristics of items. Barbrauskas identified the differences between room tests and furniture calorimeter tests. The peak HRR, and the time to peak HRR, were considered the most important variables when considering the burning characteristics.

The burning characteristics of 13 upholstered seats were identified. These included: maximum burning rate, maximum HRR and the time this occurred, total heat generated, average heat of combustion, and the peak target irradiance. Experimental data was presented in tabular form and also included the results of two repeat experiments. Experimental data was additionally presented in tabular form to compare the effects of fabric, padding, mass and frame type on the peak HRR obtained. The HRR profile of the item was determined using oxygen consumption. Ten armchairs were constructed in a combination of the materials listed below.

- frame: wood, polypropylene or polyurethane
- padding/foam: Cal 117, fire retardant cotton batting, non-Cal foam or foam/cotton/polyester
- fabrics: polyolefin or cotton.

Cotton was the representative material for cellulosic fabrics, while polyolefin was the representative material for thermoplastic fabrics. Two loveseats and a three-seater sofa were also tested. The ignition source was a gas burner simulating a wastepaper basket fire. The propane porous burner was located adjacent to the left arm of the chair. Examples of the chairs used in the tests are shown in Figure 57.



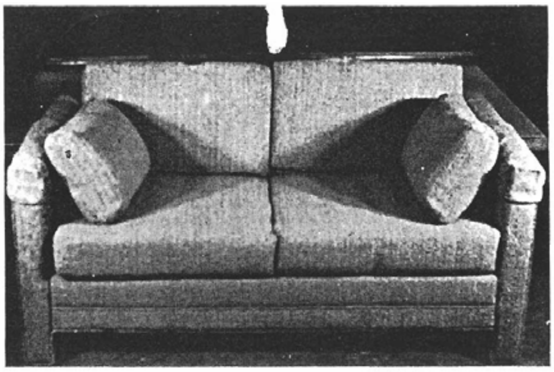


Figure 57: Examples of chair designs used in testing. Extracted from (Babrauskas 1983).

In general, it was observed that the flames spread along the left arm to the outside back of the chair, then to the seat and inside back of the couch. Flame spread to the right arm of the chair was dependent on the fabric. For the polyolefin (thermoplastic fabric), the ignition was due to radiation caused by the rapid involvement of the foam. For the cotton (cellulosic fabric) covers, the ignition was due to flame spread across the couch. In all cases, the front of the chair was the last to ignite and in most cases pool burning occurred under the chair, created by the melted padding. All furniture items ignited within 15 s, and most specimens were observed to have pool burning occur. Tests were terminated once flaming ceased, therefore the smouldering potential was not considered in these tests. In all cases, the active burning period did not last beyond 1,800 s, and at this time a HRR of around 50 – 100 kW was reported.

Barbrauskas concluded that the main advantage of furniture calorimeter tests over room tests was the ability of the furniture calorimeter tests to calculate the HRR using oxygen consumption calorimetry. Some of the HRR results are summarised below.

The results showed that seats constructed out of cotton fabric and cotton batting had the slowest developing fire (920 s to peak HRR) and the lowest peak HRR (370 kW). The cotton fabric with polyurethane foam, polyolefin fabric with cotton batting padding, and the seats containing mixed cotton batting and foam padding, all had fires that developed at an intermediate rate (420 s – 650 s). The peak HRR values ranged from 700 to 1060 kW, which was also considered in the intermediate range of HRR values. The loveseat, constructed with mixed padding and cotton fabric, showed a comparable growth rate of 560 s, with a peak HRR of 940 kW, which was within the range of the armchairs.

The seats containing foam padding and polyolefin fabric had rapid fire growth (220 s – 280 s) and high peak HRR values ranging from 1950 kW to 1990 kW. The results from these tests also indicated that the framing material did not significantly affect the burning behaviour of the chairs. The loveseat and the sofa, constructed from polyurethane foam and polyolefin fabric, reached the HRR peaks at similar times to the single armchairs of the same construction (230 and 250 s, respectively). Increased fuel load were attributed to the higher peak HRR values (2,890 kW and 3,120 kW, respectively).

The tests analysed by Krasny and Babrauskas (Krasny & Babrauskas 1984) formed part of a development of test methods to quantify the burning characteristics of furnishings and furniture. The tests were conducted in a furniture calorimeter and the temperature, CO, CO_2 and O_2 concentrations, total gas flow, smoke development, mass loss, radiation 0.5 m in front and 0.2 m above the font edge of the seat cushion and HRR were measured.

Five different configurations of full-scale mock-ups were analysed, as shown in Figure 53. The results for the four cushion and six cushion mock-ups represent an armchair and a loveseat respectively. These results have been included in the summary table.

The cushions were 610 × 610 mm with a fabric cover over all foam surfaces. Different fabric/foam combinations were tested and no interliners were included in these tests. The fabrics tested were heavyweight olefin with back-coating, lightweight olefin with back-coating, heavyweight cotton with back-coating and lightweight cotton. The foams tested were standard polyurethane foam, fire retardant polyurethane foam and neoprene foam. Two thicknesses of each type of foam were tested. For the polyurethane foams, thicknesses of 100 and 50 mm were tested. For the neoprene, thicknesses of 80 and 40 mm were tested.

Two ignition sources were used. The first ignition method was a 150 mg methenamine pill, which was placed either in the centre of the seat offset from the back by 100 mm or in the crevice of a seat/back/arm junction. The second ignition source was 25 × 50 mm strips of alpha-cellulose chromatography paper (4.5 or 9.0 g). These strips were stacked and folded to sit against the seat and the back cushions. The strips of paper were ignited by a match.

The olefin fabric over the standard polyurethane foam burned rapidly. As the olefin fabric melted away it exposed the foam. This combination resulted in the highest peak HRR in the shortest time after ignition. Cotton covers over the standard polyurethane foam had slower burning rates, because the cotton charred. However, once the charring split and exposed the foam, the fire grew rapidly to peak HRR values comparable to the combinations with the olefin covers. The fire retardant foam did not ignite or burn as readily as the standard foam. As a result of this, the mock-ups containing fire retardant foam burned more slowly than the standard foam mock-ups, but reached similar peak HRR values. The neoprene foam mock-ups did not support flaming combustion, and instead the foam around the ignition source smouldered. However for the neoprene foam covered by olefin fabric, the olefin melted and formed a small pool fire.

The mock-ups performed differently, depending on the type of foam. The neoprene foam did not sustain flaming combustion. The standard polyurethane foam ignited and burned readily. The fire retardant polyurethane foam burned more slowly than the non-treated foam, but eventually reached similar peak HRR values. The fabric affected the fire growth and flame spread until the foam was exposed. The burning characteristics were then dominated by the characteristics of the foam. The thinner cushions burned more rapidly than the thicker cushions.

Andersson and Magnusson (Andersson, B. & Magnusson 1985) described a study of 53 reduced-scale experiments and 11 full-scale experiments carried out in 1978 and 1979. The HRR and smoke production results were presented. The experiments were conducted in a test room, which was instrumented to measure temperature, smoke production, heat flux and mass loss rates. This review focused on the results from the full-scale tests. Different combinations of the fabric, interliners and foams were used to construct full-scale three-seater sofas on a steel frame. The materials that were used are listed below.

- fabrics: wool, acrylic and 61% wool/39% acrylic
- interliner: fire retardant polyurethane, modified neoprene foam and novoloid fibres
- foam: standard polyurethane foam, fire retardant polyurethane foam and HR polyurethane foam.

The ignition source used was a 20 – 30 kW liquid fuel burner. It appears the burner was located near the seat-back crevice.

As some of the earlier experiments in the fire behaviour of upholstered furniture, the HRR was calculated using two methods: (a) using the temperature and gas flow out of the room, and (b) using the mass loss rate and an averaged heat of combustion. The peak HRR for an acrylic/-/standard polyurethane was reported as 1,400 kW, at 240 s. When the sofa was constructed out of wool-viscose/-/fire retardant polyurethane foam the peak HRR reduced to 580 kW and the time to peak HRR increased to 1,320 s (22 min). The HRR values were calculated using the mass loss rate and a heat of combustion of 18.7 $MJ.kg^{-1}$.

The conclusions drawn from these tests included:

- The fabric used for the covers can significantly influence the burning behaviour of the sofa.
- The fabric can affect the ignitability, rate of fire spread and the HRR profile.
- From observations, the interliners considerably decrease the rate of fire spread and fire growth of the sofas.
- Smoke density measurements indicate that the total amount of smoke produced depends on the combination of materials used.

California has a number of regulations regarding the flammability of upholstered furniture sold within the state. The furniture was tested using TB 116 and TB 117. "TB116 is a voluntary standard which tests the whole furniture item for total resistance of cigarette ignition. TB 117 is the mandatory standard involving small-scale tests of the filling/stuffing materials requiring both flame retardancy and smoulder resistance." (Damant, Williams & McCormack 1983) There is ongoing testing of furniture manufactured within California and furniture imported into the state to ensure compliance. Imported items are tested by purchasing items at random from retail outlets, items range in price, construction, materials and origin. Damant et al (Damant, Williams & McCormack 1983) published findings for 171 furniture items. McCormick et al (McCormack, Damant & Williams 1986) discussed the propensity to cigarette ignition of 450 items including those tested. McCormick et al (McCormack, Damant & Hilado 1988) presented results from furniture purchased from 1986 to 1988 and included the findings from 1981–1986. The total number of chairs tested was 700 of those 679 were tested using TB 116.

The 450 chairs investigated by McCormick et al (McCormack, Damant & Williams 1986), purchased between 1981 and 1986, were manufactured in the USA. The foams used in the furniture varied from those which complied with TB 117 to those that either failed or had not been tested. The variety of padding materials tested included:

- shredded polyurethane foam
- polyurethane foam pads
- cotton batting
- cellulose pads, and
- synthetic fibre and cotton mixed batting and pads.

A few chairs containing hair or vegetable fibre were tested. However, as chairs made of these padding materials are rarely available, the results were disregarded and removed from the data set.

The chairs purchased from 1986 to 1988 (McCormack, Damant & Hilado 1988) were manufactured in Europe (Italy, Denmark, Norway, Belgium, Romania), Asia (Taiwan) and Canada. The designs varied from dining room chairs, office chairs, recliners, bar stools and armchairs. The majority of the chairs contained some polyurethane foam. Cover fabrics were identified as 100% cellulosic (89 chairs), 100% thermoplastic (256 chairs), blends (295 chairs), and leather (39 chairs). The fabrics were grouped into cellulosic fabrics and thermoplastic fabrics.

Cellulosic: cotton, rayon and linen

Thermoplastic: acrylic, polyester, PVC, nylon, polypropylene, acetate, wool, and silk.

The ignition source for TB 116 was a cigarette placed under a 152 x 152 mm square of cotton sheeting. The cigarettes were placed on the chair at one or more of the following locations (as shown in Figure 58):

- top of the back
- tuft
- seat/back crevice
- seat/arm crevice
- top of arm
- quilting welt cord
- decking (seat platform)
- footrest
- headrest, and/or
- seat.

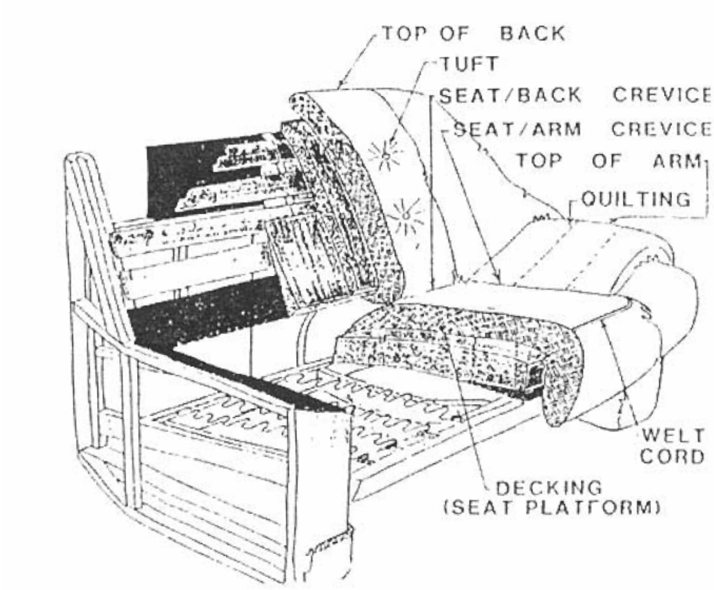


Figure 58: Locations of ignition used for the testing of various chairs. Extracted from (McCormack, Damant & Hilado 1988).

A chair was considered to have ignited if the char spread more than 50.8 mm from the cigarette in any direction.

Of the 700 chairs tested 480 did not ignite from any of the cigarettes, the remaining chairs had ignition at 1, 2 or 3 of the ignition locations listed above. A summary of the relevant conclusions of the study results include (McCormack, Damant & Hilado 1988).

- The most venerable ignition location for an upholstered chair was at a crevice and along the welt cord.
- The fabric used influenced the ignitability of the chair by cigarettes.
- The susceptibility to cigarette ignition appeared to relate to the cellulosic content of the chair
    - chairs which had 100% thermoplastic fabric covers were the most resistant to smouldering – 31 of the 256 chairs smouldered
    - chairs which had 100% cellulosic fabric covers were the least resistant to smouldering – 60 of the 89 chairs smouldered
    - only two of the leather-covered chairs smouldered.
- Heavier fabrics were more likely to ignite and smoulder than lighter weight fabrics.
- The probability that smouldering would occur increased as the cellulosic content of the fabric increased.
- Smouldering cigarette ignition was most likely to occur in the crevice area of an upholstered chair with a heavyweight fabric 100% cellulosic cover with cotton batting directly beneath the fabric and with no resin back-coating present.

Schumann and Hartzell (Schuhmann & Hartzell 1989) characterised the flaming combustion of upholstered furniture by burning specially made armchairs in a room calorimeter. The room calorimeter was 2.74 × 2.74 × 2.74 m. The inlet air was supplied by an external blower and distributed through hoses on the room floor. The air was exhausted through a stack in the centre of the ceiling. The armchair was placed on a load cell and the room and stack was equipped with thermocouples, photometer, flow meters, and a gas analyser measuring CO_2, CO, O_2 and CH_x. A schematic of the layout for the testing is shown in Figure 59.

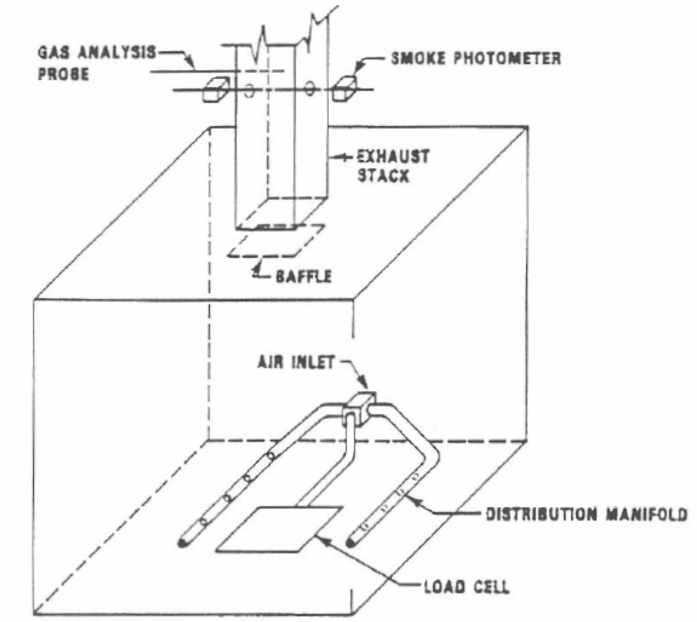


Figure 59: A schematic of the layout used for testing armchairs in a room calorimeter. Extracted from (Schuhmann & Hartzell 1989).

The chairs were constructed with a wooden frame with foam cushions and a cover fabric. Some chairs contained interliners. The design was the same for each test specimen with 10 different cover/interliner/foam combinations tested. The materials used were:

Fabrics: polypropylene, cotton, or vinyl on cotton

Interliner: fibreglass

Foam: standard polyurethane foam, high-resilience (HR) polyurethane foam, melamine-treated polyurethane foam, or combustion modified polyurethane foam.

The ignition source was a premixed natural gas flame with a calculated output of 70 W. The ignition source was located at the centre of the chair, against the back cushion, 16 mm above the seat. The effects of background heat flux of 0.125, 0.22 or 0.9 W/cm^2 on approximately 75% of the seat and back cushions was also tests for six of the combinations.

It was observed that the ignition resistance and the rate at which the fire spread was dependent on the fabric cover. Polypropylene ignited rapidly, while the cotton initially smouldered before spontaneously changing to flaming combustion. The vinyl on cotton required an additional heat flux before it would ignite. A number of the chairs showed two distinct peaks in their HRR profiles. The first peak was smaller attributed to the cover fabric. The second, larger, peak was attributed to the foam as the main contributor to the fuel. The modified foams (melamine treated and combustion modified) only ignited when the heat flux was added. The fire performance was also improved by decreasing peak HRR values by 20–40% with the use of the melamine treated and combustion modified foams, respectively. Significant increases in the time to peak HRR were also measured. When interliners were present, the involvement of the foam in the fire was either prevented or delayed.

In the analysis of the results, time t = 0 s was considered to be the time at which flaming combustion started. In the cases where two peaks were observed, the second higher peak was recorded, unless the first peak was greater than 90% of the second peak. The peak HRR was predominantly dependent on the foam, with the peak HRR for the standard and HR foams around 600 kW. Lower HRR values occurred when the chairs had interliners or vinyl on cotton fabric covers (220 – 350 kW). The modified foams had peak HRR values ranging from 100 – 530 kW, depending on the heat flux applied to the chair. The time to peak HRR varied from 210 to 450 s. When interliners or modified foams were used, the time to peak HRR increased from 20 min to over two hours.

Fesman and Jacobs (Fesman & Jacobs 1989) looked at upholstered furniture intended for public occupancies. The study used three different test methods to evaluate the same combinations of materials:

- *California Technical Bulletin*, which is a room test (3.7 × 3.0 × 2.4 m) with a doorway (0.87 × 2.0 m) for ventilation. Mock-ups or full-scale chairs can be used. Five double sheets of loosely wadded newspaper are used as the ignition source. Temperature, smoke opacity, CO concentration and mass loss rate are monitored.

- City of Boston Fire Department Procedure BFD IX-10 is also a room test (3.7 × 2.4 × 2.4 m). A two cushion mock-up or a full-scale chair can be used in this test. The ignition source was a brown paper bag filled with four double sheets of loosely wadded newspaper. The flaming behaviour, excessive smoke production, time fire self-extinguishes and mass loss rate are monitored.

- British Standard BS-5852 Part II, requires a room greater then 20 m^3 with inlet and exhaust airflows. A two-foam-fabric cushion mock-up is tested on a steel and wire mesh frame. The ignition source is a size 7 wood crib. Various flaming behaviour properties are monitored during the test.

No interliners were used and the foam used in all test specimens was melamine HR polyurethane foam. For each test, five cover fabrics were used:

- 55% wool/45% nylon with acrylic backing

- 75% modacrylic/25% nylon with fire retardant backing

- nylon with latex backing

- fire retardant treated PVC with a treated backing, or

- standard PVC with a standard backing.

There were a number of observations common to all three tests. The ‘wool/nylon’, ‘modacrlyic/nylon’ and ‘treated PVC fabric’ passed all three tests. The fabrics formed a char layer when burnt, limiting the involvement of the foam and much of the cover fabric. The ‘nylon’ fabric and the ‘standard PVC’ fabric specimens failed all three tests. The ‘nylon’ fabric had a slow growth rate, however it did not self-extinguish and eventually led to foam involvement and a more serious fire. The results of this investigation showed that in these cases the different test methods were comparable.

Paul and King (Paul & King 1990) presented the test results of a representative group of armchairs that complied with UK furniture requirements up to and including regulations made in the 1990s. The requirements of these regulations included:

- cigarette resistant composites
- covers resistant to matches
- combustion Modified High-Resilience (CMHR) polyurethane foams.

Tests were conducted in a brick room (3 × 4.5 × 2.5 m), with a single domestic door connecting the room to a hallway. Ceiling temperature, smoke density and volume, and concentrations of CO, CO_2, O_2, NO and HCN were measured and recorded. There was also an attempt to calculate the HRR from the oxygen depletion. The data was logged every 15 s.

The armchairs were constructed from a single fabric. No interliner was used. Polyurethane foam was used with a wooden frame. There were three series of chairs built using a constant design with different fabric/foam combinations. Other chairs tested were three used chairs, taken from scrap, and three chairs of non-standard test design. The fabrics and foams used are listed below.

Fabrics: acrylic pile, woven cotton, woven fire retardant cotton, woven cotton/wool, viscose pile, or woven polypropylene.

Foam: standard polyurethane foam, high-resilience (HR) polyurethane foam, a medium density CMHR polyurethane foam or high density CMHR polyurethane foam.

The test set was relatively small (18 chairs), with no replicate test performed, so the repeatability of the results is uncertain. No detailed descriptions of the chairs tested were reported.

A gas flame specified by BS5852: Part 1 – ignition source 1, was used for most tests, since it readily ignited most of the composites in small-scale tests. Three other ignition sources, which increased in duration and theoretical heat of combustion, were also tested. It is assumed that these were BS5852: Part 1 – ignition sources 4, 5 and 7. The chairs were ignited at the seat/back junction or the seat/back/arm junction.

The results indicated that the chairs burned in a similar manner, independent of fabric, when made with standard or HR polyurethane foam. The ‘polypropylene’ and ‘acrylic’ fabrics burned rapidly and split open early, allowing the foam to burn directly. The other fabrics (‘wool’, ‘cotton’ and ‘viscose’) charred and burned more slowly, exposing the foam only after the charred fabric split open. The chairs containing the HR foam burned more slowly than the standard foam, however the difference was small (1–2 min), which would result in an insignificant advantage in a real fire. However HR foam produced a higher smoke density and peak CO concentration. The used chairs, which contained standard or HR foam, had similar burning characteristics to the new chairs of similar construction.

It was found that when ‘acrylic’ fabric was used in combination with the medium density CMHR foam, the chair had a similar burning profile to the chairs containing standard and HR foam, with a slight delay reaching the peak HRR. The ‘cotton’ fabric over the standard and HR foams produced similar results to the acrylic fabric with the high density CMHR foam. A ‘cotton’ fabric in combination with the high density CMHR foam did not sustain burning with the small gas flame ignition source. When fire retardant fabrics were used over CMHR foams, the smaller ignition sources could not sustain burning. The larger sources caused slow flame spread over the surface of the chair, delaying the onset of rapid burning. The fire then burned steadily, until, it was thought, the foam melted and created a secondary fire under the chair. However this was not observed during the experiments. Rapid burning then occurred destroying the chair.

Ohlemiller and Villa (Ohlemiller & Villa 1992), summarised the findings from a previous study (Ohlemiller & Villa 1990). TB 133 tested the flammability of seating, and Ohlemiller and Villa investigated the reproducibility of the ignition source used and compared it with a gas burner that had a similar heat flux pattern. Mock-up and full-scale tests were performed in the furniture calorimeter. The materials used were:

Fabrics: polyolefin, nylon, wool and PVC

Interliner: fibreglass

Foam: melamine-treated polyurethane and TB 117 polyurethane foam.

Seven combinations of fabrics and foams were used in the chair mock-ups. These did not include the use of polyolefin or PVC, the most flammable and least flammable fabrics, respectively. Cushions were assembled according to TB 133. To test for repeatability, each ignition source was tested twice. Therefore four mock-ups were made of each of the different combinations. The full-scale chairs were constructed out of solid hardwood frames. Ten 'fabric/interliner/foam' combinations were tested. No batting wraps were used in any of the chairs. In some cases, no interliner was present either. No repeats were performed for the full-scale tests. The configuration of the full-scale chair is shown in Figure 60.

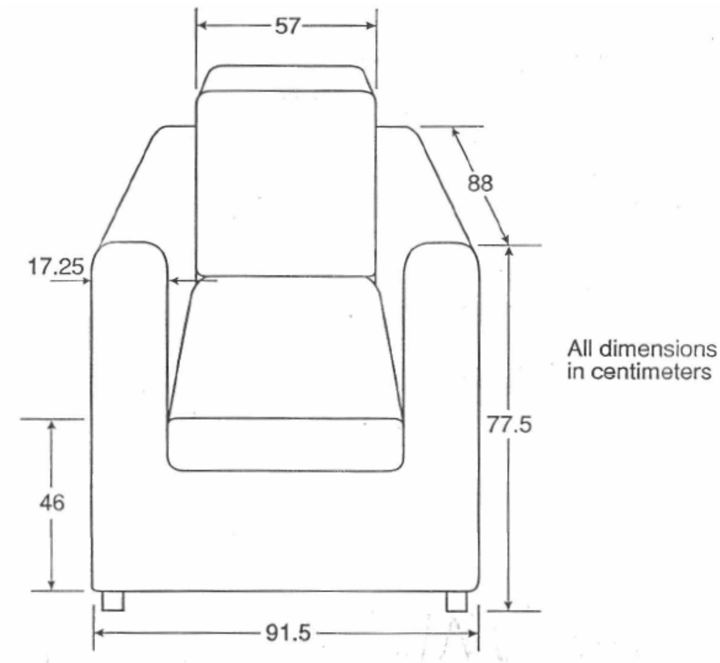


Figure 60: Configuration of the full-scale chairs. Extracted from (Ohlemiller & Villa 1992).

The two main differences between the mock-ups and the chairs were:

- The width of the mock-up seat was appreciably larger than the full-scale chair (70 cm and 57 cm, respectively).

- The cushions used in the mock-ups left part of the back of the foam block exposed. Whereas all foam surfaces on the full-scale chairs were fully encased by the 'fabric/interliner'.

The first ignition source (TB 133) was five sheets of crumpled newsprint covered by a sheet metal/wire mesh box, as shown in Figure 61. This was centred between the arms on the seat, offset approximately 25 mm from the chair back. The paper was ignited by a match and burned for approximately 7 min, with approximately 2 min of flaming combustion and approximately 5 min of smouldering. The second ignition source was a propane gas torch, mimicking the first source by producing a comparable heat flux on the back and sides of an inert mock-up.

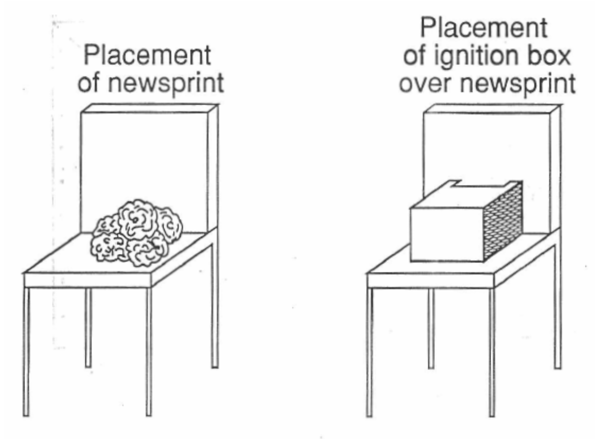


Figure 61: TB 133 Ignition Source 1. Extracted from (Ohlemiller & Villa 1992).

The mock-up results were compared to the full-scale results. The results associated with the two ignition sources used were also compared. The chairs and mock-ups have been described as 'fabric/interliner/foam' combinations. The results for the 'nylon/-/melamine' combination showed a noticeable difference between ignition sources in mock-up form, but similar performance in the full-scale test. In contrast, 'nylon/fibreglass/TB 117' produced comparable results between the two ignition sources in the mock-ups, but the results varied in the full-scale tests. Late fires developed in the 'PVC/-/melamine' mock-ups, which did not occur in the full-scale tests. It was suggested that the late fire was due to the exposed cushion back present in the mock-up configuration.

The following combinations had comparable results for the two ignition sources in the full-scale tests:

- 'wool/-/TB 117'

- 'nylon/-/TB 117'

- 'nylon/-/melamine', and

- 'polyolefin/-/TB 117'.

These combinations ignited early and had low fire resistance resulting in rapid flame spread. Peak HRR values exceeded 1 MW and there was high mass loss. The ‘nylon/-/melamine’ combination was a slow developing fire, delaying the time to peak HRR. Both ignition sources on the ‘wool/fibreglass/TB 117’ combination resulted in insignificant fire development.

For both ignition sources, the ‘polyolefin/fibreglass/TB 117’ combination resulted in a late developing fire. However, the peak HRR and the time to peak HRR depended on the ignition source. Ohlemiller and Villa (Ohlemiller & Villa 1990) suggested the two ignition sources are comparable due to the randomness of late developing fires. The ‘PVC/-/TB 117’ combination generated a late developing fire with the TB 133 source, but minimal burning when exposed to the gas burner. The difference between the results for the different ignition sources for the ‘nylon/fibreglass/TB 117’ combination was attributed to the variability of the TB 133 source. The ‘nylon/fibreglass/melamine’ and ‘PVC/-/melamine’ combinations resulted in weak fires, with noticeable differences between ignition sources. The ‘nylon/fibreglass/melamine’ combination was the only full-scale test in which the gas burner produced a more severe fire than the TB133 ignition source. It was concluded that this was not a consequence of the material combination, but of the variability inherent in the TB133 ignition source. The reduced severity was due to one arm of the chair failing to ignite, compared to the gas burner which ignited both arms of the chair.

The fibreglass interliners significantly reduced the fire severity. The TB 117 foam produced a more severe fire than the melamine treated foam. The fabrics in increasing order of flammability were:

- PVC
- wool
- nylon
- polyolefin.

The flammability of the combinations was dependent on the interactions between all three components. The combinations containing interliners were the least flammable, with the exception of the ‘PVC/-/melamine’ combination, which had low flammability without an interliner. The combinations without interliners were more flammable and were dependent on the flammability of the fabric and then the foam. The nature of the TB 133 ignition source meant variability of results was inevitable and repeats of the full-scale tests may be necessary to determine whether the HRR profiles are typical of the material combinations. The gas burner was a more repeatable ignition source, however these experiments found it resulted in fires that were less severe compared to TB 133. The gas burner was also a less realistic ignition source when considering design fires for residential buildings. However, when the chair materials ignited early and had low resistance to flame spread the results from the two ignition sources were similar.

Nurbakhsh et al (Nurbakhsh, Mikami & Damant 1991) summarised a previous report (Nurbakhsh 1991). The test results of full-scale upholstered chairs in three different test locations were compared. Ten sets of upholstered chairs were tested in the California Bureau of Home Furnishings (CBHF) test room, ASTM room and furniture calorimeter. The instrumentation was identical in each room. Measurements were recorded for CO concentrations, temperature rise, heat flux, smoke opacity, weight loss and HRR.

The chair design and ignition sources were the same as that used by Ohlemiller and Villa (Ohlemiller & Villa 1990). In total, 70 chairs were obtained, of which 55 were tested. These chairs were made of various fabric/interliner/foam combinations. The materials used are shown below:

Fabrics: wool, nylon, PVC, vinyl, or polyolefin

Interliner: fibreglass

Foam: melamine-treated polyurethane, or TB 117.

The ignition sources used were crumpled newspaper (TB 133) and the equivalent gas burner.

During testing, four of the chairs were excluded from the CBHF room tests due to the possibility of flashover, which was beyond the safety margin of the room. The excluded chairs were the 'wool/-/TB 117', 'nylon/-/TB 117', 'nylon/-/melamine' and 'polyolefin/-/TB 117' combinations. In the ASTM room, the chairs were ignited by the newspaper (TB 133). In the furniture calorimeter, each chair was ignited by the newspaper, then the tests were repeated using the gas burner. In the CBHF room, both ignition sources were used and tests were conducted with each ignition source, for comparison. A single test was conducted with a 'nylon/-/TB 117' chair in the CBHF room using the newspaper ignition source. The resulting fire exceeded the capabilities of the exhaust system. Mass loss rate, temperature, CO concentration and HRR measured in the ASTM room tests were compared to the results in the CBHF room. The results were comparable when equivalent chairs tested.

Figure 62 shows the HRR curves for the 'nylon/fibreglass/TB 117'. It is typical of the HRR curves produced by most of the chairs in the three testing facilities. There are two peaks which have been identified. The first dominated by the burning fabric and the second, larger, peak dominated by the foam.

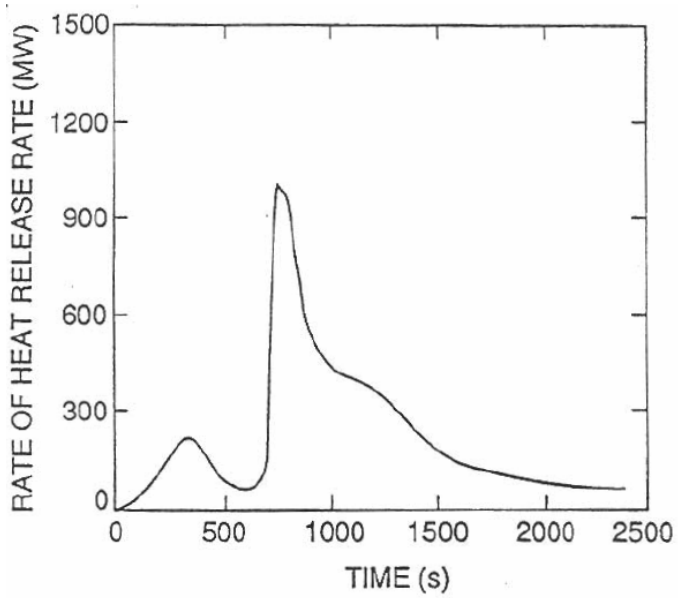


Figure 62: The HRR curve for a 'nylon/fibreglass/TB 117' combination chair. Extracted from (Nurbakhsh 1991).

The first peak was similar in magnitude in the two test rooms, however the second larger peak was significantly higher in the ASTM room. The radiation feedback present in the ATSM room accounted for the enhanced HRR. Overall, the tests found that when the peak HRR was below

600 kW there were no significant compartment effects. This condition may not be true for smaller rooms or rooms with low thermal conductivity.

Cleary et al (Cleary, Ohlemiller & Villa 1994) investigated the influence of five common ignition sources on the flaming fire hazard of upholstered furniture. The tests were carried out in a furniture calorimeter using the same full-scale chair as Ohlemiller and Villa (Ohlemiller & Villa 1992). Five different fabrics were used to cover conventional non-fire retardant polyurethane foam, and these are described below:

- cotton, non-fire retardant cotton batting
- 63% nylon/26% olefin/11% acrylic with latex backing
- 100% olefin, latex backing
- acrylic, rayon/cotton backing, and
- expanded vinyl.

There were five ignition sources tested: a cigarette, match-sized flame, incandescent lamp, space heater and a large flaming source. An 85 cm non-filtered cigarette, which had burned for 2 min, was placed in the same position as the match flame and was not removed for the duration of the test. The match flame was simulated using a small propane gas burner. An established flame was placed in the crevice of the seat and the arm cushions for 20 s and then removed. The incandescent lamp was a 55 W quartz-halogen lamp with a typical desk lamp fixture to simulate a reading lamp. It was placed near the corner of the chair on the seat and then tipped onto the chair arm, so the bulb was 5 cm from the covering fabric. An electric spark at 10 s intervals tested the ignitability of the pyrolysed material. The large flaming source was the gas burner characterised by Ohlemiller and Villa (Ohlemiller & Villa 1992) centred between the arms, on the seat, offset from the back cushion by 25 mm. The space heater was initially placed with the front grill 10 cm from the front of the seat. It was eventually tipped so the grill touched the front of the seat cushion. An electric spark was used in the same manner to test for pyrolysed material, as had been used for the lamp.

HRR rates and combustion gas species were recorded for each test, however it appears only the peak HRR and time to peak HRR were published. Detailed results of the HRR profiles, mass loss rates, concentrations of CO and CO_2, and smoke yields are given in Cleary et al (Cleary, Ohlemiller & Villa 1992). Time, t = 0 s, was been taken as the time when flaming combustion began. When sustained burning was achieved, a replicate test was performed. These repeats produced similar ignition behaviour.

The cotton/non-fire retardant cotton batting chair was the only chair to ignite from the cigarette, after smouldering for approximately three hours. However the same cover did not ignite with the lamp or match ignition source. The peak HRR varied from 400 – 500 kW, with the time to peak varying from 1,000 – 2,200 s. The '63% nylon/26% olefin/11% acrylic with latex backing' chair and the '100% olefin with latex backing' chair did not produce sustained burning from the lamp or cigarette ignition source. The peak HRR was 1,000 – 1,500 kW and time to peak was 300 – 600 s, and 800 – 1,200 kW and 250 – 550 s, respectively. The '100% olefin' chair test was repeated seven times with the match ignition source, but only developed into flaming combustion during one of the tests. The 'acrylic with rayon/cotton backing' chair burned for all ignition sources, except the cigarette, with a peak HRR 900 – 1,300 kW in a time of 150 – 950 s.

When sustained burning was achieved, the peak HRR for each type of chair was independent of the ignition source. However, the time to peak HRR varied considerably (up to 1,500 s), depending on ignition source. The larger ignition sources (the gas burner and space heater) resulted in sustained burning for all chairs. It was concluded that the fire hazard of upholstered furniture can be minimised by placing limitations on peak heat release, plus the speed at which the peak heat is reached.

Ohlemiller and Shields (Ohlemiller & Shields 1995) tested 27 full-scale fabric/interliner/foam mock-ups. The configuration of the mock-up is shown below in Figure 63, using TB 133 to investigate the effects of different fabrics and barriers. A number of cone calorimeter tests were also conducted, however they are not relevant to this review. The full-scale mock-up tests were conducted in a furniture calorimeter. The HRR and heat flux were measured and camera observations were taken for each test.

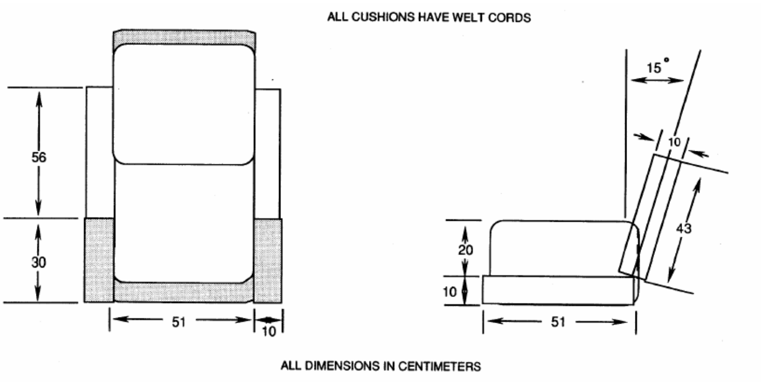


Figure 63: Mock-up configuration. Extracted from (Ohlemiller & Shields 1995).

The cushions were attached to a steel frame, with a steel mesh under the arm cushions to prevent them falling off the frame. The cushions were constructed with a fabric cover/interliner/foam padding. The materials used are shown below:

Fabrics: polyester, nylon, cotton, two densities of polypropylene, two densities of polypropylene with fire retardant back-coat, 75% modacrylic/25% nylon, or 62% cotton/38% polyester

Interliner: aramid fibre, knitted glass/charred fibre, knitted glass/charred fibre embedded with halogen fire retardant resin, or fibreglass

Foam: melamine-treated polyurethane or Cal 117 polyurethane foam.

Initial samples were made with nylon zippers; however these failed during testing, prematurely exposing the foam. In subsequent samples, the cushions were sewn closed to prevent this type of failure. The ignition source was a square-ring propane gas burner, which was positioned so it did not touch any of the surfaces. It was located on the centreline of the seat cushion offset from the back cushion.

The test results showed that there were often two peaks in the HRR, the first occurring while the burner was still on. The second, often larger, peak occurred once the burner was extinguished. With the exception of the polypropylene fabrics, the first peak appeared to be more dependent on the cover fabric than the interliner. With increasing HRR ranging from 40 to 180 kW, the fabrics were modacrylic/nylon, cotton, polyester, polyester/cotton, and nylon. The interliners with the polypropylene fabrics interacted differently depending on the combination. The peak HRR varied from 80 to 240 kW.

The camera observations showed that typical flaming stared on the seat back and on the seat cushion, below the burner. From there, the flaming area increased rapidly. The thermoplastic fabrics (for example, nylon and polyester) curled back from the flames, eventually melting and dripping off the cushions or forming small pool fires, exposing the materials underneath. The cotton fabric formed a char layer, which split while the burner was still on, exposing the material underneath.

Once the burner was extinguished, most of the sample continued to burn with flames spreading along the crevices between the cushions. For the mock-ups made with modacrylic/nylon covers and interliners, the first peak HRR was greater than the second peak. The cotton and polyester cover with the knitted glass or the fibre glass interliners did not have a secondary peak HRR. With the aramid fibre interliner, the second peak HRR for the cotton and polyester fabric covers was limited to less than 120 kW. The polyester and nylon fabric covers did not show a second peak with the fibre glass interliners, but a significantly higher second peak occurred when the other interliners were used (over 350 and 450 kW, respectively). The polypropylene fabric showed a high second peak HRR (200 – 750 kW), regardless of the interliner used; the exception being the knitted glass/charred fibre embedded with halogen fire retardant resin interliner, where the second peak HRR was consistently less than 80 kW. The high density polypropylene with fire retardant backing over the melamine foam also controlled the HRR to less than 80 kW, once the burner was extinguished.

The test found that interliner failure was due to the melting of the foam. In these cases, the heat transfer through the cushion was sufficient to melt the foam. The melted foam seeped through the pores of the interliner. The melted foam could then ignite, increasing the HRR, which in turn melted more foam, while the interliner remained intact. In some cases, the heat transfer was sufficient to ignite the foam within the interliner without causing it to break. A single test was performed using a two cushion mock-up, which removed a major source of radiation feedback (the arm rests). This produced a significant reduction in HRR and chair involvement, showing radiation feedback as a major contribution to the burning characteristics of an upholstered item.

The influence on the size of the ignition source of the burning characteristics of items in the furniture calorimeter was investigated by Söderbom et al (Söderbom, van Hees & Meirsschaert 1996). All the HRR profiles start (at time, t = 0 s) at the point where the HRR reaches 50 kW. Two sets of experiments were discussed. The first experiments were conducted earlier by the University of Gent. In these experiments, two types of armchair were tested:

- an armchair constructed with a solid beech frame, '65% acrylic – 35% viscose/polyether fibre/polyether foam (27.5 & 17 $kg.m^{-3}$)', and

- a fire retardant armchair constructed with a solid beech frame with wooden lathes, '69% acrylic – 31% cotton/polyester fibre/CMHR foam (37 and 35 $kg.m^{-3}$)'.

The ignition source was a square gas burner set at four different intensities:

- 40 kW for 120 s

- 30 kW for 120 s

- 30 kW for 180 s, and

- 20 kW for 300 s.

The results showed there was no significant difference between the ignition sources. The armchair had a peak HRR ranging from 463 – 511 kW after 150 – 200 s. The fire had a growth rate similar to a t^2-fire. The fire retardant armchair had higher peak HRR values, ranging from 918 to 1182 kW. However, the peak was reached later (300 – 400 s) and there was a period of steady burning at approximately 20 kW before the fire rapidly grew to its peak HRR.

The second set of experiments used six different armchairs available commercially on the European market. All chairs had upholstered arm rests and the following combinations of materials:

- acrylic with fire retardant back-coat/fire retardant polyester/CMHR seat – fire retardant polyester back
- leather/-/HR foam
- polyester/polyester fibre/polyether foam
- fire retardant treated cotton/fire retardant polyester fibre/CMHR foam
- polyester/polyester fibre/polyether foam, or
- fire retardant polyester/-/HR foam.

Lower ignition sources were used for this series of experiments, by using a smaller gas burner. The heat outputs used were:

- 1.7 kW for 90 s
- 5.8 kW for 90 s
- 30 kW for 120 s.

If the item did not ignite with the 1.7 kW ignition source, then the heat output was increased to 5.8 kW and applied for a further 90 s. Initial match-sized flame tests were also conducted to ensure the furniture encompassed a large range of fire resistance. The first four items did not ignite using the smallest ignition source. However the 'polyester/polyester fibre/polyether foam' armchair ignited with the smaller match-sized flame. This was thought to be due to the local geometry of the chair at the location where the burner was applied. The other two items ignited when the 1.7 kW source was used, so the 5.8 kW source was not applied.

The 'acrylic with fire retardant back-coat/fire retardant polyester/CMHR seat – fire retardant polyester' armchair had the best performance. It did not ignite with the 1.7 kW or the 5.8 kW ignition sources. The growth rate was slow when the 30 kW ignition source was used and the peak HRR was relatively low, 730 kW, compared to the other armchairs. The 'fire retardant treated cotton/fire retardant polyester fibre/CMHR foam' armchair had a steady state burning (less than 150 kW for over 1,000 s), before rapid fire growth to its peak HRR. The HRR of other armchairs grew rapidly to peaks exceeding 1,000 kW.

Once the results were shifted, so t = 0 s was associated with the HRR reaching 50 kW, comparison of results indicated that the growth rate and the peak HRR were very similar for both ignition sources. These results showed that if the ignition source was sufficient to ignite the item, then the size of the ignition source did not significantly affect the HRR profile of an item.

Enright et al (Enright, Fleischmann & Vandevelde 2001) conducted a study on exemplary New Zealand (NZ) upholstered furniture following the CBUF protocol. The purpose was to examine the goodness of fit of NZ furniture with CBUF model II. A number of cone calorimeter tests were completed to input into the CBUF model, however these results will not be discussed in this review. Thirteen full-scale items were then tested in the furniture calorimeter to validate the CBUF model II results.

There were three styles of armchair and one style of two-seater sofa tested, as shown in Figure 64. The materials used in the upholstered items were:

Fabrics: polyester & blends, nylon with polyester backing, polypropylene, nylon with 65% polyester – 35% cotton backing, nylon

Interliner: general fibre

Foam: polyether foam, standard polyurethane foam.

Figure 64: Upholstered furniture designs tested by Enright et al. Extracted from (Enright, Fleischmann & Vandevelde 2001).

The HRR was recorded for each of the full-scale tests and these were compared with the predictions made by the CBUF model II. The analysis found the model did not predict the burning behaviour of the exemplary NZ furniture very well. The results for the furniture were then compared with results from comparable items in the CBUF study. The CBUF items had a similar style/design, fabric, interliner and foam. It was found the NZ furniture consistently produced a significantly higher peak HRR, although the total heat released was similar.

Fleischmann and Hill (Fleischmann & Hill 2004) described the burning behaviour of upholstered furniture based on tests on 55 single upholstered chairs and upholstered two-seater sofas. The designs of the chairs were the same as the CBUF Series II. The tests were conducted in a furniture calorimeter, according to the CBUF protocol. The chairs were made of combinations of the fabric and foams shown below, with no interliners.

Fabrics: wool, cotton, polyester, or polypropylene.

Foam: domestic (standard polyurethane foam), commercial (HR polyurethane foam), or aviation (CMHR foam).

The materials used were those typically available commercially in New Zealand, where there are currently no fire regulations on upholstered furniture. The ignition source was a 30 kW burner, as specified in TB 113 (Ohlemiller & Villa 1992).

The tests identified four distinct phases during burning, excluding the ignition phase. These were (1) Spread, (2) Burn Through, (3) Pool Fire and (4) Burn out.

- The spread phase was identified by the flame spread from point of ignition over the seat and back of the chair, then on to the arm rests.

- The burn through phase occurred once flames had spread over the surface of chair and steady state burning occurred. This phase ended once the fire had burned through the seat of the chair.

- The pool phase occurred if the fire burned through the chair, causing molten foam and fabric to form a pool of fuel below the chair. The HRR then increased rapidly to the peak HRR, due to the increase in oxygen available to the fuel pooled on the floor.

- Once the peak HRR had been reached, the chair entered the burn out phase, which continued until all the fuel was exhausted or the fire was extinguished.

When the chairs were constructed out of readily combustible materials with low ignition resistance, the burn through phase was non-existent. The fire grew so rapidly that the pool phase followed the spread phase, bypassing burn through. If the chair had high fire resistance, the pool phase did not occur due to insufficient heat production preventing burn through of the chair. The burn through phase was also shortened when the chair self-extinguished.

Most of the published results from tests do not report the concentrations of the combustion gases. Kallonen et al (Kallonen, et al. 1985) conducted toxicity tests for 11 cover fabrics and six foams/fillings. The materials were tested under temperature conditions at approximately 500 and 700°C. Rats were used for an indication of tenability. The chemical composition of the combustion products was also measured. The components measured were CO, HCN, CO_2, O_2 and HCl. The fabrics and fillings tested were widely used commercially and often tested in upholstered furniture tests (as presented in Table 12).

Table 12: Fabrics and foam/fillings tested by Kallonen et al*

Fabrics	Foams/Fillings
modacrylic	fire retardant polyester fibrefill
wool	neoprene foam
fire retardant cotton 1	HR polyurethane foam
fire retardant viscose	fire retardant polyurethane foam
fire retardant cotton 2	flame laminated polyurethane foam
fire retardant cotton/viscose blend	standard polyurethane foam
fire retardant cotton 3	
PVA/ PVC	
fire retardant polyester	
cotton	
waterproofed cotton	

* Adapted from (Kallonen, et al. 1985).

Kallonen et al presented a detailed analysis of the combustion gases of wool, modacrylic, polyester fabric and fire retardant polyester fibrefill, however this is not discussed in this review. From the toxicity tests, it was found that HCN and CO were the main cause of toxicity. The chemical analysis of the materials found that in the non-flaming tests the CO, CO_2, and O_2 were essentially constant for the duration of the toxicity tests (30 min). More CO_2 was produced at 700°C compared with 500°C. The fire retardant cottons produced more CO than the untreated cotton. In the untreated and treated case, the CO concentrations increased at the higher temperature, but the waterproofed cotton showed no change at the two test temperatures. At 700°C, the following materials produced lethal concentrations of CO: fire retardant viscose, two of the fire retardant cottons and the fire retardant cotton/viscose blend. HCN was produced when the materials or the fire retardant treating contained nitrogen. At both temperatures, lethal concentrations of HCN were produced with the modacrylic, wool, one of the fire retardant cottons and the polyester fibrefill. The following materials produced high concentrations of HCl for at least one of the test temperatures: PVA/PVC, modacrylic and neoprene. The concentrations of HCl were greater than 1,000 ppm, but were not lethal to the experimental animals.

In general, the materials became more toxic as the temperature increased. The health of the test animals indicated that exposure to the hot gases at the higher temperature (700°C) resulted in death during the exposure. At 500°C, test animals deaths also occurred up to one week after the exposure. The most toxic materials tested at 500°C, in order of decreasing toxicity, were:

- modacrylic
- fire retardant cotton, then
- fire retardant polyester fibrefill.

The most toxic materials tested at 700°C, in decreasing toxicity, were:

- modacrylic
- wool
- fire retardant cotton

- fire retardant viscose, then

- fire retardant polyester fibrefill.

Andersson et al (Andersson, P., et al. 2004) presented a summary of results from the *Fire Life Cycle Assessment (LCA) Model* study for a furniture case study. The study was part of a larger study that was initiated in 1995 to determine the environmental impact of methods used to improve fire safety. To obtain the inputs for the Fire LCA model, one non-fire retardant sofa and two fire retardant sofas were tested in an ISO 9705 room. The HRR was measure in each test as well as the yields of:

- inorganic compounds: CO_2, CO, HCN, HCl, NH_3, NO, Sb, Br and P

- volatile organic compounds (VOCs); 10 different compounds

- polybromide diphenyl ethers (PBDE); eight different compounds

- (PAHs); 20 different compounds, and

- dioxins and furans; 12 different groups of compounds.

The sofas were two-seaters with a wooden frame, polyurethane foam padding and cotton cover. The non-fire retardant sofa was made with standard foam and an unmodified cotton cover. Fire retardant sofa 1 was made with melamine foam and a phosphorous (P) treated fire retardant cotton cover. Fire retardant sofa 2 also had melamine foam and the cotton cover had a brominated (Br) back-coating. The ignition source for the non-fire retardant sofa was a utility lighter. The fire retardant sofas were ignited using a 30 kW burner initially in one corner of the sofa for 10 min and then the opposite corner for 5 min.

The peak HRR for all the sofas tested was 690 – 750 kW. Fire retardant sofa 2, treated with bromide, was the only one that produced detectable levels of HCN. This was probably due to the Br inhibiting combustion, thereby promoting the formation of HCN. There were significant concentrations of HCl produced by the non-fire retardant sofa. The source of Cl was found to be the adhesive used on the sofa. Tests found Br in the combustion gases of all three sofas. For the non-fire retardant sofa and the fire retardant sofa 1 (P treated), the only possible source of Br was from impurities in the foam. Br inhibits combustion, so a high concentration of chlorinated dioxins/furans was found in the combustion gases of fire retardant sofa 2. Also due to the Br in fire retardant sofa 2, significant concentrations of PBDEs and brominated dioxins/furans were produced.

Gallagher (Gallagher 1993) studied the effect of an interliner on the burning behaviour of upholstered materials. Small-scale tests were conducted on various 'fabric/interliner/foam' samples. Two foams were looked at: a polyurethane foam that complied with TB 117, and a melamine modified foam that complied with TB 133 (a more stringent standard). The materials used for the covers and interliners were:

Fabric: nylon A, nylon B, polypropylene (7.7 oz/yd^2, 8.23 oz/yd^2, 13.1 oz/yd^2), or cotton (8 oz/yd^2, 16 oz/yd^2)

Interliner: none, glass cloth, Kevlar, polyester batting, or cotton batting.

A heat flux of 1.0 W/cm^2 was applied to the samples within a calorimeter (ASTM E 906). The pilot flame was extinguished after 80 s.

The results of these tests showed that the behaviour of a sample was dependent on the combination of the materials, such that the performance of an upholstered item cannot be accurately predicted using individual component tests. For example, the nylon fabric samples showed no significant differences between the two fabrics and, as expected, the heat released from the 'nylon/-/Cal 117' was considerably more than the 'nylon/-/Cal 133' sample. However, when a glass cloth interliner was included in the sample the heat released from the Cal 117 and Cal 133 samples was remarkably similar. The interliner in the 'nylon/glass cloth/Cal 117' samples acted as a thermal barrier decreasing the heat released. Conversely the interliner in the 'nylon/glass cloth/Cal 133' samples appeared to form a heat trap causing the Cal 133 foam to melt and char under the interliner, increasing the heat released. The polypropylene sample showed the same behaviour as the nylon samples. When the interliner was present in the polypropylene samples, the peak heat release was proportional to the weight of the fabric. In the cotton samples, the glass cloth interliners resulted in a decrease in total heat released. Without the interliners, the burning behaviour of the cotton samples appeared to change, and due to the depletion of melamine in the foam the flaming characteristics changed to a more sustainable burning and the levels of smoke produced reduced.

The Kevlar interliner produced similar burning behaviour to the glass cloth. The polyester and cotton batting, when used in combination with melting fabrics, appeared to exacerbate burning behaviour. The melting material absorbed into the upper layer of the batting, allowing it to burn more readily. In general, these tests showed the fire performance was improved with the interliner when the Cal 117 foam was used. However, the performance deteriorated when the glass cloth interliner was used in conjunction with the Cal 133 foam.

D'Silva and Sorensen (D'Silva & Sorensen 1996b, 1996a) investigated the flammability of decorative trimmings on upholstered furniture. The experimental results indicated cellulosic trimmings had a tendency to smoulder, which could lead to progressive smouldering of the upholstered furniture. However, trimmings that were made from fire retardant materials continued to have good fire resistance. The trimmings on an upholstered item contributed insignificantly to the total fuel, therefore having a negligible effect on the burning characteristics of an item. However, depending on the materials used as trimmings, they could act as a secondary ignition source, increasing the ignitability of the item. While developing a new method to test trimming flammability, D'Silva and Sorenson (D'Silva 1998) found the flame spread was dependent on the fibre type and the angle of the trimming from the ignition source. Furthermore, ignition of an upholstered item from the flaming trimming depended on the trimming material and the cover fabric.

Krasny and Parker (Krasny & Parker 1995) examined the peak heat release rate of various types of upholstered furniture, including two and three seater sofas, fully upholstered chairs, office chairs, executive chairs and sofa beds. In total, 43 items of furniture were examined in both a furniture calorimeter and an ISO 9705 room, and for each a detailed description of the cover fabric, padding, fibre wrap, use, and peak heat release rate was listed in tabular form. Reproducibility and repeatability were reported as being good for the chairs for both the ISO room and furniture calorimeter. The authors report that above a threshold of 460 kW, the peak heat release rates observed in the ISO room were consistently higher than those obtained for the same item of furniture when tested in the furniture calorimeter. This was concluded to be as a result of radiation reinforcement, however an exception was observed with one of the office chairs and two of the sofas. These items exhibited similar peak heat release rates in both test environments due to the burning becoming ventilation limited at the 460 kW level.

Krasny and Parker also reported the peak heat release rates from 10 fully upholstered chairs varying in fabric and foam combinations obtained from a prior study conducted by NIST and the California Bureau of Home Furnishings. These are presented for use as a comparative tool with the experimental results generated by Krasny and Parker; however it should be noted that the peak heat release rates for the two studies were collected at different times, thus diminishing the power of the comparative analysis performed.

The ignitability and fire behaviour of upholstered furniture was also studied in detail by Mizuno and Kawagoe (Mizuno & Kawagoe 1984). In their study, the burning tests of several wood cribs and modern chairs with soft foam upholstery was carried out in a full-sized room to examine their respective contributions to the pre-flashover stage in a compartment-sized fire. An excellent description of the instrumentation used to fit out the room is given by the authors, and measurements taken in the course of the burns included the mass burning rate, gas temperatures inside and outside of the plume, smoke density and radiant heat flux. In comparison to the wood cribs burnt in the study, the burning behaviour of the upholstered chairs tested was reported as very irregular, with some upholstered chairs showing an extreme peak in the graphical representation of the mass burning rate over time while others showed no peak at all. In all cases, the upholstered furniture produced substantial residual weights in comparison to the wooden cribs examined and this was reported to be due to the unburnt parts of the furniture including wooden frames. The authors additionally report that from the results obtained, it is clear that the burning behaviour of a piece of furniture depends on its configuration and component materials. Although several upholstered chairs and settees are examined, only one set of experimental mass burning rate, residual rate, smoke generation and radiant heat flux is reported, which may be seen as a downfall of the report. Smoke generation produced by the upholstered chairs is reported as being greater than that produced by the wooden cribs.

Mizuno and Kawagoe (Mizuno & Kawagoe 1985) then conducted a further project examining the burning rate of chairs in fire tests, with specific emphasis on the effect of fire location in a room on several fire burning characteristics including mass burning rate, radiative heat transfer to the surroundings, heat transfer to the wall and optical smoke density. Two series of fire tests on upholstered chairs were carried out in a full-sized room, with one series having the specimen burn in the middle of the room (17 samples examined), while the other had the test specimen located at the side of a wall erected within the test room (23 samples examined). As in the authors' previous mentioned study, an excellent description of the instrumentation used was reported, however no details or descriptions were afforded as to the composition of the samples used in the tests. Also no details are given to enable comparisons to be made directly with chair from the two different series, and subsequently no direct comparisons are reported. All results are reported in graphical format, and specifically include the residual weight over time for all chairs in both series tested, temperature contour maps of burning chairs (one for both series however reported at different times), and radiant heat flux for all chairs in both series. Although the authors report that optical smoke density was recorded, it is not reported in the results of the study. As a conclusion to the study, it is reported that the mass burning rate is one of the key factors which describe the burning behaviour of an item. In the case of the individual burning chair, the authors conclude that from an engineering point of view, the burning rate of an upholstered chair may be assumed as the same regardless of its location during a fire (centre of room or against compartment wall).

Experimental work performed by Babrauskas (Babrauskas 1992) examined the fire burning characteristics of two different types of upholstered chairs. One chair was reported as being non-fire retardant (chair T), with a foam density of 25 kg/m3, while the other chair (chair S) was reported as being fire retardant with a foam density of 64 kg/m3. The same nylon fabric cover was used for both chairs. A furniture calorimeter was used to examine the two chairs, and reported tabular data collected included: total mass, combustible mass, mass lost, peak heat release rate and time, total heat released, average heat of combustion, average CO generated, average CO2 generated, average HCN generated, and average smoke extinction.

Dietenberger (Dietenberger 1992) examined a four cushion, fabric/polyurethane, chair mock-up with piloted ignition in a furniture calorimeter for the purposes of data comparison with data previously obtained from a cone calorimeter. Reported graphical data included the area of burning over time, burn rate over time, mass loss rate (g) over time, and soot extinction area (m^2/kg) over time. An excellent description is given by the author as to the behaviour of the fire and fire spread during the experimentation. Dietenberger concludes that the processes of flame spreading and thermal ignition needs to be simulated in a furniture calorimeter (in comparison to a cone calorimeter) to obtain good agreement with the cushion's burn area data.

A range of 16 infill/cover combinations of upholstered chairs was tested and reported on by Ames, Babrauskas and Parker (Ames, Babrauskas & Parker 1992). A buoyancy driven, chimney type furniture calorimeter was used to measure the full-scale peak heat release rate, and the specimen mass for all of the 16 chairs was also reported.

Ames, Babrauskas, and Parker (Ames, Babrauskas & Parker 1992) additionally reported on the results of ten sets of chairs tested in the NIST furniture calorimeter, the ASTM room, and the TB 133 room. The chairs tested were plain, of rectilinear construction with wooden frames, and varied only in the type of fabric, foam and the presence or absence of a fibreglass interliner. The total heat release rates were reported for each chair combination for all three testing facilities used in the study. The authors also reported the general observation that the total heat release rate curves of upholstered furniture have two major peaks, one being associated with the burning of the fabric, and the other the burning of the underlying foam or padding.

Parker, Tu, Nurbakhsh and Damant (Parker, Tu, Nurbakhsh & Damant 1992) reported on the burning characteristics of 10 sets of upholstered chairs that were tested in the TB 133 room, the ASTM room, and the NIST furniture calorimeter. The chairs varied only in the type of fabric, type of foam, and whether or not there was a fibreglass interliner present. For all burn environments, the total heat release rate was measured and reported graphically against peak temperature rise of the individual environments, as well as against the upper layer temperature (25 mm below ceiling and directly above the chair). It should be noted, however, that heat release rates reported from the TBC 133 room were generated from cone calorimeter data and thus should be treated with caution (see Hirschler 1999). For all of the upholstered chairs examined, the heat release curves generated (peak heat release rate versus peak temperature rise) all exhibited a double peak, which the authors associated with the individual contributions of both the fabric (first peak) and underlying foam (second peak) during combustion.

5.3.1 Soiled and unsoiled fabrics

Only a few fire tests have been conducted on used furniture, so the fire performance of used furniture in general is unclear. Wanna et al (Wanna, Polo & Schettino 1996; Wanna, et al. 1996) conducted two studies into the smouldering potential of unsoiled and soiled upholstery fabrics and then characterised the behaviour. The first study looked at fabric obtained from 60 used chairs; armchairs, recliners, sofas etc from stores around Richmond, Virginia, USA. The average age of the chairs was 15 years. The second study was conducted with a similar sample size in the state of Georgia. Samples (127 mm square) were taken from each chair, representing both unsoiled and soiled fabric. The unsoiled samples were taken from the underside of cushions and from deep crevices. The soiled samples were from the tops of the cushions and the arm rests. The fabrics were divided into three categories: cellulosic, synthetic and cellulosic/synthetic blends.

The smouldering potential was tested using a 3 s exposure to a small butane flame. Ignition was considered possible if the fabric continued to smoulder for over 2 min after the flame was removed. The flaming combustion generated with the synthetic fabrics was blown out, allowing the smouldering potential to be studied. Five repeat tests were conducted for each sample.

Increasing smouldering potential due to oil stains was not considered in these studies. Quantities of sodium and potassium ions in the fabrics were measured. These were indications of how much sweat had been absorbed into the fabric. The highest sodium and potassium ion concentrations were found on the arm rests of the chairs. Other species measured were calcium, magnesium, and six different anions including chloride and sulphur. None of the synthetic fabrics smouldered once the flames were extinguished. The material melted, curled and blackened. Overall, findings in both studies indicated that soiling did not increase smouldering potential. Depending on the nature of the soiling, the smouldering potential was even observed to decrease, particularly if the sulphate anion concentration was high.

5.3.2 Summary of upholstered furniture fires

The following is a summary of the results, suggestions and observations presented in the reviewed literature for investigations of upholstered furniture fires data:

- Easy chairs can contain enough combustible mass to cause flashover in a room, even in isolation (Lawson, Walton & Twilley 1984).

- Upholstered furniture items containing wooden panels within the frame were found to be more resistant to ignition than for items without wooden panels, when using a 50 kW gas burner as the ignition source that was located 25 mm from the side of the chair (Lawson, Walton & Twilley 1984).

- In general, easy chairs and loveseats with rapid fire growth rates had one distinct peak HRR (Lawson, Walton & Twilley 1984).

- Office chairs had lower peak HRR values than easy chairs, sofas or loveseats (Lawson, Walton & Twilley 1984). This was attributed to the significantly smaller amount of combustible materials of an office chair.

- Arms on upholstered items increased the HRR and fire growth rate (Sundström 1994). This was attributed to the increased radiation feedback onto the seat of the chair.

- Cushions supported by webbing showed higher HRR and faster fire growth rates (Sundström 1994). This was attributed to the cushion burning through the webbing and forming a pool fire inside the chair, which significantly enhanced radiation feedback.

- Chairs with no frame caused the most hazardous conditions, because of the large amount of combustible materials available (Sundström 1994).

- The most common framing material for upholstered furniture items was wood (Sundström 1994).

- The combustible mass of the frame was inconsequential to the burning behaviour of an upholstered item in early stages of the fire, as it does not become involved until the later stages of the fire. However it was shown that if the frame failed it could adversely affect the burning behaviour, because large quantities of combustible material can suddenly become exposed (Sundström 1994).

- It was generally found that the correlation between peak HRR values and combustible mass, for armchairs, loveseats and sofas, was greater than linear (Sundström 1994).

- In the early stages of a fire, an armchair fire still represented the worst-case room scenario (Sundström 1994). This was attributed to greater radiation feedback effects between the item and itself, and the item and the room.

- The most vulnerable area of an upholstered seat, to cigarette ignition, was found to be along a crevice or welt cord (McCormack, Damant & Williams 1986).

- Heat resistant foam gives a higher peak CO and smoke density, compared to standard polyurethane foam (Paul & King 1990).

- For some armchairs, two HRR peaks were identified (Ames, Babrauskas & Parker 1992; Schuhmann & Hartzell 1989). The first peak was associated with the burning fabric, and the second peak with the foam.

- It has been found that a peak HRR below 600 kW, within a standard-sized room, would not be appreciably affected by radiation enhancements and compartment effects (Nurbakhsh, Mikami & Damant 1991).

- It has been found that if an ignition source is sufficient to cause flaming combustion in an upholstered chair, different-sized ignition sources produce comparable peak HRR, with differing times to reach the peak (Cleary, Ohlemiller & Villa 1992).

- No matter how small the ignition source, there is always some statistical probability it will ignite a larger item (e.g. an upholstered chair) leading to a sizeable fire (Cleary, Ohlemiller & Villa 1992).

- Upholstered furniture that is smouldering may have a time delay of several hours before flaming combustion initiates spontaneously (Cleary, Ohlemiller & Villa 1992).

- Preliminary experiments have found nylon zippers used on fabric covers can fail before the covering fabric fails, exposing foam (Cleary, Ohlemiller & Villa 1992). This could severely compromise the fire resistance of an upholstered item and change its burning behaviour.

- Cover fabrics can affect the burning behaviour of an item:

    - cotton fabrics can char, slowing fire growth and lowering the HRR, while the char layer remains intact (Krasny & Babrauskas 1984)

    - thermoplastic fabrics tend to melt and form pool fires, exposing the material underneath (Ohlemiller & Shields 1994).

- General observations of upholstered chair fires indicate that flames tend to spread along the crevices (Ohlemiller & Shields 1994).

- Interliners can fail without breaking (Ohlemiller & Shields 1994). The heat transfer through the interliner can be large enough to cause the foam underneath to melt or even ignite.

- It was found that the CBUF model did not predict the burning behaviour of NZ furniture well (Enright, Fleischmann & Vandevelde 2001). The NZ furniture consistently produced higher HRR values than the model predicted.

- Tests monitoring combustion products found that more CO_2 was produced at higher temperatures (700°C compared with 500°C) (Kallonen, et al. 1985). The study also found that fire resistant cottons produced more CO than non-fire resistance treated cottons.

- The most toxic cover fabrics in decreasing order at 500°C and 700°C were found to be (Kallonen, et al. 1985):

- at 500°C: modacrylic, fire retardant cotton, and then fire retardant polyester fibrefill
- at 700°C: modacrylic, wool, fire retardant cotton, fire retardant viscose, fire retardant polyester fibrefill.

- Furniture trimmings can increase the ignitability of upholstered items, due to the trimmings increased smouldering potential (D'Silva & Sorensen 1996b, 1996a).

- Soiling of materials (excluding oils) was shown not increase the smouldering potential of upholstered cushions (Wanna, Polo & Schettino 1996; Wanna, et al. 1996).

- In general, the fire performance of an upholstered item was improved when an "interliner/Cal 117 foam" combination was used. However, the performance was shown to possibly deteriorated when the glass cloth interliner was used in conjunction with the Cal 133 foam (Gallagher 1993).

- The radiation reinforcement of room walls and ceiling does have an impact on the peak heat release rate of various types of upholstered furniture (Krasny & Parker 1995).

- The burning behaviour of a piece of upholstered furniture depends on both its configuration and component materials (Mizuno & Kawagoe 1984).

- From an engineering point of view, the burning rate of an upholstered chair may be assumed as being the same, regardless of its position in a burning room (Mizuno & Kawagoe 1985).

In summary, investigations of the burning characteristics of upholstered furniture showed the experimental results to be influenced by:

- *Frame materials* – for example, the combustible mass of the frame was shown to be inconsequential to the burning behaviour of an upholstered item in the early stages of the fire, as it does not become involved until the later stages of the fire. However, it was shown that if the frame failed it could adversely affect the burning behaviour, because large quantities of combustible material can suddenly become exposed. In addition, upholstered furniture items containing wooden panels within the frame were found to be more resistant to ignition than for items without wooden panels (Lawson, Walton & Twilley 1984). Furthermore, chairs with no frame caused the most hazardous conditions, because of the large amount of combustible materials available.

- *Cover and interliner materials* – for example, cotton fabrics can char, slowing fire growth and lowering the HRR, while the char layer remains intact (Krasny & Babrauskas 1984), whereas thermoplastic fabrics tend to melt and form pool fires, exposing the material underneath (Ohlemiller & Shields 1994).

- *Combination of cover, foam and interliner materials* – in general, easy chairs and loveseats with rapid fire growth rates had one distinct peak HRR. For some armchairs, two HRR peaks were identified. The first peak was associated with the burning fabric, and the second peak was associated with the foam. Furthermore, interliners can fail without breaking. The heat transfer through the interliner can be large enough to cause the foam underneath to melt or even ignite (Ohlemiller & Shields 1994).

- *Size* – for example, office chairs had lower peak HRR values than easy chairs, sofas or loveseats. This was attributed to the significantly smaller amount of combustible materials of an office chair.

- *Geometry of the furniture* – for example, arms on upholstered items increased the HRR and fire growth rate. This was attributed to the increased radiation feedback onto the seat of the chair. Furthermore, general observations of upholstered chair fires indicate that flames tend to spread along the crevices (Ohlemiller & Shields 1994).

- *Internal construction* – for example, cushions supported by webbing showed higher HRR and faster fire growth rates. This was attributed to the cushion burning through the webbing and forming a pool fire inside the chair, which significantly enhanced radiation feedback.

- *Type of test* – for example, the radiation reinforcement of room walls and ceiling does have an impact on the peak heat release rate of various types of upholstered furniture (Krasny & Parker 1995).

- *Location of ignition* – for example, the most vulnerable area of an upholstered seat, to cigarette ignition, was found to be along a crevice or welt cord.

- *Fire retardant treatments* – for example, heat resistant foam gives a higher peak CO and smoke density, compared to standard polyurethane foam. In addition, fire resistant cottons have been shown to produce more CO than non-fire resistance treated cottons (Kallonen, et al. 1985).

- *Number of tests (especially for a "no ignition" result)* – no matter how small the ignition source, there is always some statistical probability it will ignite a larger item (e.g. an upholstered chair), leading to a sizeable fire.

- *Duration of test* – for example, upholstered furniture that is smouldering may have a time delay of several hours before flaming combustion initiates spontaneously.

- *Inclusion of zippers* – for example, preliminary experiments found nylon zippers used on fabric covers can fail before the covering fabric fails, exposing foam (Cleary, Ohlemiller & Villa 1992). This could severely compromise the fire resistance of an upholstered item and change its burning behaviour.

- *Inclusion of trimmings* – for example, furniture trimmings can increase the ignitability of upholstered items, due to the trimmings increased smouldering potential (D'Silva & Sorensen 1996b, 1996a).

- *Temperatures achieved during testing* – for example, tests monitoring combustion products found that more CO_2 was produced at higher temperatures (700°C compared with 500°C) (Kallonen, et al. 1985).

5.4 Characteristics of room burns

Hirschler (Hirschler 1999) conducted a study that examined the efficiency of the cone calorimeter in predicting actual full-scale fire test results. Twenty-six fabrics commonly used in the production of upholstery furniture and mattresses were subjected to both cone calorimeter and standard room full-scale fire tests. Reported experimental data included fabric weight, fabric description and peak heat release rate for each of the fabric samples tested in the full-scale burns. Peak heat release rate is additionally reported for the same fabric samples tested using the cone calorimeter.

Kim and Lilley (Kim, H. J. & Lilley 2002) reported various fire parameters of many common apartment building furnishings including beds, chairs, Christmas trees, curtains, mattresses, sofa, wardrobes, wardrobes and electrical equipment. Although reported as data sourced from another reference, experimental values of the time taken after ignition to reach 1 MW, time at which heat release rate began to decay, time at which heat release rate was zero, maximum heat release rate, growth time and fire growth and decay coefficients were reported in a tabular format. For each item, the ignition source for the experimental test was also reported. Data was provided so that it could be used as input into a fire modelling program called 'HAZARD'.

Three full-scale fire tests were carried out by Kim (Kim, A. K. 1988) to study the incremental fire hazard in a university dormitory room furnished with three different types of fibreglass reinforced plastic furnishings. Room burns were performed in a standard ASTM room, and for each test, fuels common to each of the three scenarios examined were arranged differently. For example in one test, a pair of jeans was placed on the bed, and in another, the jeans were hanging in the wardrobe. An excellent description of the instrumentation used in the experiments is given. The experimental data presented includes:

- room temperatures, heat release rate over time, optical density in exhaust duct over time, toxicity of gases measured (all tests)
- temperature over time for upper layers of room
- concentration of O2 and CO in room over time, and
- results of analysis using ion chromatography (HCl and HBr concentration and generation rate for all three tests).

In concluding remarks, Kim made mention of the difference between the three types of fibreglass reinforced plastic furnishings examined on the basis of their individual contributions to the overall heat release rate in the room fire (Kim, A. K. 1988). The first style of furnishings (methyl methacrylate and styrene) examined resulted in an incremental contribution to the heat release rate by 0.3 MW, while the next two styles (benzofurandione and styrene, and another methyl methacrylate and styrene mix) resulted in incremental contributions of 0.45 MW and 0.40 MW respectively. The benzofurandione and styrene furnishings were reported to produce very heavy smoke in comparison to the other two styles examined. Fire retardant in one style of plastic furnishing was reported to delay ignition times and resulted in a reduced contribution to the overall fire severity.

The experimental results obtained from realistic fires set in a prototype apartment building are presented by Luo, He and Beck (Luo, He & Beck 1997). Fires in a three-storey multi enclosure building fitted out to resemble an apartment building were studied. Two groups of fire experiments were presented, the first conducted to estimate the effects of ventilation conditions on the fire development and environment, and the second group conducted to examine the effect of a varying fuel load with common ventilation conditions. In the first group of experiments, the fuel load was a single mock-up chair made from polyurethane foam and a cotton linen cover. The second group of experiments included a plain polyurethane slab fire, a mock-up chair and a commercial chair.

Results presented by Luo, He and Beck, for both sets of experiments, were limited to mass release rates and compartment temperatures, although it was not expressed clearly which location these temperatures were recorded from within the compartment. All results were presented graphically, and additionally included measured interface heights for each of the rooms for each of the tests performed against time. From the experimental results obtained, the authors were able to show (based on the mass release rates obtained) that fire growth on a horizontal plain polyurethane slab was faster than any of the other fuels tested in the project.

5.4.1 Summary of room burns

- Fire retardant used in one style of plastic furniture examined has been shown to delay ignition time and result in a reduced contribution to the overall fire severity (Kim, A. K. 1988).

5.5 Characteristics of miscellaneous type fires

Hadjisophocleous, Benichou and Tamim (Hadjisophocleous, Benichou & Tamin 1998) have addressed the current trend of building codes shifting from prescriptive to performance based. The authors report second-hand experimental data covering nominal radiant heat flux values required for the ignition of a variety of common building materials. Also reported in their paper, again sourced elsewhere, are common fire growth parameters for typical apartment style furnishings including items such as desks, mattresses, wardrobes and upholstered chairs.

Data from real-scale fire tests on stacked chairs was presented by Hirschler and Treviño (Hirschler & Treviño 1997). In their study, the authors focussed on stacks of chairs as opposed to single chairs with the intention of studying a fuel type common to large assembly areas. Fire testing was performed in three different configurations, including two different-sized rooms, and with a furniture calorimeter. Very high heat release rates were observed in all testing environments. Six different types of chairs were used in the testing, with each type tested in each of the three configurations. For each test performed, tabular experimental data – comprising of the mass of the chairs, the mass loss after burning, peak heat release rate, peak smoke release, total heat release, total smoke release, and the time to peak rate of heat release – was reported.

For each type of chair examined, experiments were conducted in the room calorimeter as well as the furniture calorimeter. Hirschler and Treviño (Hirschler & Treviño 1997) reported that re-radiation from the walls of a room is an important consideration for products that release a large amount of heat at a fast rate.

Chow (Chow 1996) discusses the use of two fire models, and refers to experimental data by Soderbom (Söderbom 1992) and Luo and Beck (Luo & Beck 1994). Chow assumes a fire of size 5 MW, confined to a 3 x 3 m compartment, and burning for a period of 600 s, and uses the data as input into two commonly used computer models (CFAST and BRI2T) to estimate other burning characteristics not already reported including smoke temperature, lower layer temperature, and smoke interface height for different rooms within an apartment.

Data presented by Soderbom (Söderbom 1992) includes the results of two smoke spread experiments performed at the Swedish National Testing and Research Institute. More specifically, this data covers the results of two experiments; burns in a single level building with three rooms and in a three level building. For each of the two situations, the smoke temperature and smoke layer interface height over time is represented in a graphical form. The mean smoke temperature from smoke spread experiments carried out by Luo and Beck (Luo & Beck 1994) in a compartment 0.3 x 0.3 m in area with a heat release rate of 300 kW is also presented by Chow, 1996.

Twenty full-scale fire experiments were conducted by Dembsey, Pagni and Williamson (Dembsey, Pagni & Williamson 1995) in a test compartment, 2.5 x 3.0 m by 2.5 m high. The objective was to develop a database of experiments to advance the development of compartment fire models. For each compartment fire test performed, the interior wall and ceiling surfaces were covered with a stainless steel sheet-coated with a heat resistant paint, the walls and ceiling behind the sheet were ceramic fibreboard backed by gypsum wall board and plywood, and the floor was composed of gypsum wallboard backed by plywood. A propane burner was placed into the compartment at two locations, and generated a steady heat release rate between 330 – 980 kW over the duration of the experiment. For each experiment, the authors report the duration, fire size (kW), floor pressure difference, maximum ventilation enthalpy flow, ventilation bulk centreline temperature, average upper layer gas temperature, mean flame height, average upper layer gas temperature, average surface temperatures (upper and lower wall, and floor), average net heat flux, interface elevation, and average ventilation mass flow rate. An excellent description of the instrumentation used and its location during the burn time is made.

Dembsey and Williamson (Dembsey & Williamson 1997) presented research into the role of combustible interior finish materials in fire growth. PVC foam as a wall lining was studied in an ISO room using a propane burner as the ignition source. In total, four experiments were performed, and the authors report a net heat release rate. Data is presented in graphical form for the four tests, with the higher ignition source strengths resulting in a higher net heat release rate.

Shields, Silcock and Flood (Shields, Silcock & Flood 2002) performed research to test the performance of a single glazing exposed to a fire in the centre of an enclosure. Using an ISO 9705 room, the authors replaced one of the walls with a wall that had three different-sized glass panels in it. Pan fires of various sizes, using methylated spirits as fuel, were used as an ignition source. Pan sizes of 0.6 x 0.6 m, 0.7 x 0.7 m, 0.8 x 0.8 m and 0.9 x 0.9 m were used, and for each fire the total heat release rate was recorded. For each pan size, three repetitions were performed and consistent results were achieved. HRR was reported using both mass loss rate and oxygen depletion calorimetry. A general trend of increase in HRR was observed with an increase in pan fire size, and in all cases the mass loss technique reported a higher HRR than then oxygen depletion technique. The main conclusions were based around the integrity of the glass panels throughout each of the different pan fires, and detailed observations were given for times at which cracking and deformation of the glazing occurred. No comment was made by the authors as to whether they hypothesized or determined the thermal failure of the glass panels to impact on the HRR obtained in each test.

Shields, Moghaddam, Azhakesan and Zhang (Shields, et al. 1999) conducted full-scale fire experiments in an ISO 9705 room using four wood based wall linings (fire retarded, melamine faced, plywood and medium density fibre board). In all experiments, the fuel source used was a 0.55 x 0.55 m pool of methylated spirits located in one corner of the room. The four linings were comparatively examined on the bases of ignition time, flame spread, HRR at ignition time, and the time to flashover. These results obtained from the experiments were reported in a tabular form for each of the four common wall linings examined. Various observations were also made, including visual observations for each of the wall linings during the tests. As an example, the fire retarded chip board was reported to ignite after 11 min and 45 s of heating, while the plywood and medium density fibre board which were not fire retardant had reached flashover stage after only 4 min of heating.

5.5.1 Summary of miscellaneous type fires

- Re-radiation from the walls of a room is an important consideration for products that release a large amount of heat at a fast rate (Hirschler & Treviño 1997).

5.6 Characteristics of fire tests performed by the CSIRO

CSIRO has conducted a variety of 'in-house' and published experimentation that specifically examines fuel loadings commonly associated with apartment buildings. A thorough survey of the literature produced by the CSIRO over the last 20 years was undertaken to establish the extent of fire test data that would be of assistance to the Design Fires Project. The focus was on large-scale fire data, such as compartment and furniture calorimeter type experiments. Seventeen CSIRO experimental studies are detailed below, and a table summary is additionally presented as Table 13 in section 5.6.3.

5.6.1 Furniture items

A comparative investigation to quantify differences in the burning behaviour of furniture items tested under two different ventilation conditions was undertaken (CSIRO 2005g). The two different ventilation conditions used were a furniture calorimeter (open ventilation), and an ISO room (closed ventilation). Furniture items that were examined in both environments included a three seat mock-up sofa, a single seat mock-up chair, and a commercial armchair. Three repetitions were performed for all furniture items, resulting in a total of 20 burns. Specimens were conditioned at 23^{o}C and 55% relative humidity prior to testing, and were ignited using a timber crib or alcohol tray. Data collected from the experiments performed included peak HRR, total HRR, peak rate of mass loss, and time to peak HRR from 50 kW. Also reported are room temperatures in some of the enclosures examined. The results showed no obvious distinction between the two different burning environments examined. For example, the average total HRR for the commercial armchair tested in free ventilation conditions was reported at 173 MJ, and for enclosed 262 MJ, while the three seat sofa's average total HRR was in both environments 107 MJ.

An assessment of the HRR and smoke production from single bed mattresses used in police cells was reported by McArthur and Bradbury (McArthur & Bradbury 1996). Using a fire room of dimensions similar to that of standard prison cell, two mattresses composed of polyurethane foam and coated with a rubberised cotton fabric were ignited by paper in a wastebasket within the test room. HRR was measured using oxygen depletion calorimetry. Other data reported for the test burns includes smoke height within the room, and carbon monoxide concentration. A detailed description of the fire behaviour in both burns was afforded by the authors in the results and discussion section of the report. An interesting observation made between the two fires is that the first mattress burn went on for longer than the second and obviously resulted in a higher total heat release being observed (20.0 MJ in comparison to 7.7 MJ for the second mattress). This latter total heat release value is consistent with observations made that the mattress in that instance did not sustain ignition for as long as the first mattress, and that most of the total heat release was from the burning of the paper in the wastebasket (ignition source).

Three experiments examining the heat release rate of mock-up sofas have been performed in the CSIRO ISO burn room (CSIRO 2005c, 2005b, 2005a). For each experiment, a three seater mock-up sofa was used, with each sofa containing six polyurethane cushions. Each test also included a section of polypropylene carpet placed under the sofa, which was 2.4 x 2.4 m in area for the first test, and 3.1 x 3.1 m in area for the second and third tests. In the first test, the walls were lined with unburnt paper faced plaster, however the second and third tests were reproduced in the same environment, and thus the wall linings were pre-burnt plaster in these instances. Data collected for each test included temperatures at three locations throughout the testing period, oxygen and carbon monoxide concentrations collected in the exhaust, and HRR over time (graphical). A peak HRR of 6 MW was observed in the first test using the smallest area carpet; however for the second and third tests a peak HRR value of approximately 2.8 MW was observed. For both the second and the third tests, a double peak of HRR was observed. This was not observed in the first experiment, indicating that the second peak may have been as a result of the larger area of carpet's contribution to the HRR.

Another series of three tests examining the fire parameters of mock-up chairs has been performed by the CSIRO using an ISO 9705 room (CSIRO 2005f, 2005e, 2005d). In this set of experiments, mock-up chairs of varying construction type were ignited with crumpled newspaper. Tests one and two involved two one-seater mock-up chairs constructed with FR polyurethane foam, while test three examined the burning characteristics of one mock-up chair. In this latter experiment, the previous ignition source was replaced with a gas torch, and was constructed from grey foam. For each of the three experiments, total heat release, total smoke, and CO, CO_2, and O_2 concentrations were reported. Hood temperature and differential pressure was also reported for the duration of the experiment.

Barnett (Barnett 2002) conducted a series of 11 burn tests using the CSIRO ISO 9705 room. Each experiment involved the same furniture fuel loading, however the location of the furniture was varied for each test performed. The fuel loading consisted of a mock-up polyurethane foam three seater sofa, two chairs and a table. Extensive data was recorded for each burn, and included the HRR, room gas temperatures, room surface temperatures, room surface heat flux, and door way gas temperatures.

Bradbury (Bradbury 2004) conducted a fire experiment in the CSIRO ISO 9705 burn room to gather burning characteristics of furniture and typical fuel loads commonly associated with a living room. Furniture used as a fuel load included a chair that was placed in the corner of the room, a glazed window in the wall of the burn room with curtains, two small tables, a lampshade and newspapers. Experimental results presented included the total HRR, room gas and surface temperatures (various locations), room surface heat flux, and doorway gas temperatures.

5.6.2 Compartment burns

CSIRO has conducted a full-scale house burn (White, et al. 2000), in which a three bedroom, double fronted one-storey home was used for the purposes of both data analysis and fire-fighter training. Due to limited time and resources available, data collection was kept to a minimum, however data regarding temperature gradients through wall plaster, temperature variation in different rooms (open and closed), CO concentration, and times to untenable conditions within the house were recorded. Temperature-time curves are also presented. The house was fitted with a fuel load representative of a typical Australian home, and included couches and chairs, timber, two fridges, and a three seat mock-up sofa. This sofa served as the ignition point, with the ignition source a lighted match. Although no HRR was measured, a chronology of observed events (such as time to flashover in various locations of the house) is presented, and gives an indication of the fire behaviour during the course of the experiment.

Large-scale fire experiments in a simulated two bed hospital ward were performed by Dowling, Knight, McArthur and Webb (Dowling, et al. 1999). An ISO 9705 room was set up as a staged two bed hospital ward and included hospital beds and manchester, personal items and floor coverings. Two different scenarios were explored in this research. In the first situation, ignition of one of the beds was achieved by a smouldering source, while in the second, a small flame was used. In each scenario, the ISO room was instrumented to measure the rate of heat release, rate of smoke production, smoke obscuration, CO concentration, radiation at floor level and temperature. The room was also fitted with smoke and thermal detectors. Mechanical ventilation was installed, and for one of the burns, a dry sprinkler was included.

The burn characteristics reported by Dowling, Knight, McArthur and Webb demonstrated that based on the typical fuel load in a hospital ward, there is sufficient loading for the ward to go to flashover in the event of a fire. The main components of the fire load were found to be the bedding, privacy screens and window curtains, however the authors report that the beds alone were sufficient fuel loading to result in flashover. It was also concluded in the report that the testing of materials, such as mattresses in isolation, do not provide sufficient information for safe fire engineering judgements to be made.

McArthur, Webb, Bradbury and Dummett (McArthur, Webb & Bradbury 1996a, 1996b; McArthur, et al. 1996) conducted three comparative assessments of the fire burning characteristics of various floor coverings in a 10 m corridor. The first comparison examined the behaviours of various carpets including polypropylene, wool, polyamide and wool-pile carpet, while the second compared two different polypropylene carpets. The third and final comparison performed in the series of experiments looked at a nylon carpet against a wool benchmark carpet. For all three comparisons, the fire environment was a 10 m long corridor constructed with a steel frame, erected on a concrete slab, and clad on the inside walls and ceiling with a cellulose cement sheet. At the end of the corridor, attached at 90^o, was a fire test room containing a three seat sofa and 5.5 m^2 of the carpet under observation. A detailed description of the locations of thermocouples and radiometers used was reported, as well as the experimental procedures performed. The distance burnt along the carpet in the corridor was measured and the burn patterns recorded. The time at which flames ran across the carpet in the burn room was recorded, as was the time to flashover, and ultimately to burn out. Floor level radiant flux was reported in three points along the corridor for each scenario, as was CO, CO_2 and O_2 concentrations. Replicates were performed for each scenario, and where similar results were not achieved, a third experiment burn was performed.

Webb et al (Webb, Dowling & McArthur 1999) performed 37 experiments that examined the burn characteristics of various room wall and ceiling linings. Materials studied included plasterboard, two types of plywood (one fire retardant), polyurethane foam and polystyrene. Burns were conducted in both an ISO 9705 room, a corridor, and as well an ASTM standard room. For 35 of the experiments, a gas propane fired burner was used as the ignition source, and for the other two a lounge chair was used to examine the different effects of the two ignition sources. Data reported by the authors include graphs of gross heat release over time and smoke production rates for both the ISO and ASTM room fire tests, including tests performed with the furniture ignition point. A graph of the radiation levels for the room experiments performed with the chair ignition source highlights the differences observed for the two different wall linings used (plasterboard and plywood). Similar experimental data for the small-scale testing performed of the wall and ceiling linings using a cone calorimeter were also reported.

'Operation Live Fire' conducted by the CSIRO in 1989 covered a section of a multi-storey office building that was instrumented for experiments with small fires (Dowling 1987-1989). Experimental data is available in hardcopy and chart format, and cover thermocouple and radiometer readings over time for various tests performed. Both hot and cold smoke tests were performed. It was concluded that standard cold smoke tests used to determine fire protection principles do not model a real life fire.

5.6.3 Summary of fire tests performed by the CSIRO

- The fire testing of several furniture items has shown no obvious distinction between the two (open and closed ventilation) types of fire burning experiments examined (CSIRO, 2005g).

- A typical hospital ward contains sufficient fuel loading for a fire to proceed to flashover. A single, dressed hospital bed alone contains sufficient fuel loading for a fire to proceed to flashover (Dowling, et al. 1999).

- Standard cold smoke tests, historically used to determine fire protection principles do not model a real life fire (Dowling 1987-1989).

Table 13: A summary of CSIRO experiments related to design fires

Test Number/Project	Test Description	Measurements	Data File	Reference
Freencl , 1998	A series of furniture calorimeter experiments conducted under free and enclosed ventilation conditions – 21 experiments	HRR + Mass Loss + some temperatures in enclosures	Data files available on CSIRO archives	(CSIRO 2005g)
Prison cell mattresses	Assessment of HRR and smoke production from single bed mattresses used in police cells – eight experiments	HRR, smoke production	Hardcopy data. Mattress did not burn, HRR mainly from waste paper basket ignition source	(McArthur & Bradbury 1996)
RB0113, 2001	Mock-up three seat sofa with six polyurethane cushions, 2.4 x 2.4 m polypropylene carpet in ISO 9705 Burn room with unburnt paper faced plaster – one experiment	HRR	Data files available on CSIRO archives	(CSIRO 2005c)
RB0114, 2001	Mock-up three seat sofa with six polyurethane cushions, 3.1 m^2 carpet in ISO 9705 Burn room plaster lined (pre-burnt plaster) – one experiment	HRR	Data files available on CSIRO archives	(CSIRO 2005b)
RB0115, 2001	Mock-up three seat sofa with six polyurethane cushions, 3.1 m^2 polypropylene carpet in ISO 9705 Burn room plaster lined (pre-burnt plaster) – one experiment	HRR	Data files available on CSIRO archives	(CSIRO 2005a)
Two seat test, 2004	Two mock-up chairs using FR polyurethane foam under hood ignited	HRR	Data files available on CSIRO archives	(CSIRO 2005f)

	with crumpled newspaper – one experiment			
Two seat test 2004	Two mock-up chairs using non FR polyurethane foam under hood ignited with crumpled newspaper, Conducted under ISO hood – one experiment	HRR	Data files available on CSIRO archives	(CSIRO 2005e)
One seat test 2004	One chair under hood ignited with gas torch mock-up chair using grey foam. Conducted under ISO hood – one experiment	HRR	Data files available on CSIRO archives	(CSIRO 2005d)
RB0211–RB0221 2002	Series of similar Burn room tests involving mock-up polyurethane foam three seat sofa, two chairs and table placed at different locations in ISO 9705 Burn room – 11 experiments	HRR, room gas temperatures, room surface temperatures, room surface heat flux, doorway gas temperatures	Data files available on CSIRO archives	(Barnett 2002)
Mock-up living room corner	One chair in corner of ISO Burn room with window curtains, glazed window, two small tables, lampshade and newspapers. Conducted in ISO Burn room – one experiment	HRR, room gas temperatures, room surface temperatures, room surface heat flux, doorway gas temperatures	Data files available on CSIRO archives	(Bradbury 2004)
Kilsyth House Burn, 2000	Full-scale fire experiment run in conjunction with CFA fire training. No HRR. Mainly temperature and gas analysis for tenability – one experiment	Lounge, kitchen and bedroom temperatures at three heights; CO concentrations in bedrooms, video footage, smoke detector activation	Data files available on CSIRO archives	(White, et al. 2000)
Royal Children's Hospital, 1999	Mock-up experiments on children's hospital	HRR, smoke production, CO concentration,	Hardcopy	(Dowling, et al. 1999)

	ward room in ISO Burn room – four experiments	radiation at floor, temperatures, smoke and thermal detector activation		
10 m corridor tests on floor coverings, 1996	Comparative assessment of floor coverings in a 10 m corridor. Three seat sofa in carpeted ISO room joining onto 10 m carpeted corridor	HRR, burn length along corridor. Corridor flame temperatures (to determine spread)	Data location to be found	(McArthur, Webb & Bradbury 1996b)
10 m corridor tests on floor coverings, 1996	Comparative assessment of floor coverings in a 10 m corridor. Three seat sofa in carpeted ISO room joining onto 10 m carpeted corridor. Two polypropylene carpets – eight experiments	HRR, burn length along corridor. Corridor flame temperatures (to determine spread)	Hardcopy data	(McArthur, Webb & Bradbury 1996a)
10 m corridor tests on floor coverings, 1996	Comparative assessment of floor coverings in a 10 m corridor. Three seat sofa in carpeted ISO room joining onto 10 m carpeted corridor. Nylon vs wool benchmark – six experiments	HRR, burn length along corridor. Corridor flame temperatures (to determine spread)	Hardcopy data	(McArthur, et al. 1996)
FCRC Linings, 1999	A series of Burn room tests on various wall and ceiling linings, 37 experiments	HRR + smoke production	Electronic files available	(Webb, Dowling & McArthur 1999)
Operation live fire, 1989	A section of a multi-storey office building was instrumented for experiments with small fires, numerous experiments		All data is chart recorder and handwritten	(Dowling 1987-1989)

Table 14: A summary of the papers reviewed by CSIRO

Reference	**Test Description**	**Date**	**No. of Expts**	**Measurements**	Graph or Numerical Data	Comments
(Babrauskas 1983)	Furniture calorimeter test 13 upholstered chairs	1983	13	Time to peak RHR, max burning rate, max RHR, total heat, heat of combustion, peak target irradiance, graph of RHR vs time, graph of mass loss rate vs radiant flux	Mainly numerical	
(Chow 1996)	Fire size 5 MW in compartment 3 m x 3 m	1996	2	Smoke temp, interface height, and mean smoke temp	Graphical	Second-hand data. No fuel in rooms for burns
(Cleary, Ohlemiller & Villa 1994)	Five different upholstered chairs subject to different ignition sources. NIST furniture calorimeter	1994	5	Peak heat release for various ignition sources vs time	Graphical	
(Dembsey, Pagni & Williamson 1995)	Full-scale compartment fire experiments	1995	20	Fire duration, burner location, fire size, ambient temp, max vent enthalpy flow, vent bulk centreline temp, entrainment height, mean flame height, average upper layer gas temps, average surface temps, ambient temp, average net heat fluxes, wall and floor surface temps	Numerical	Compartment 2.5 x 3.7 m plan and 2.5 m height. Porous surface propane burner used
(Dembsey & Williamson 1997)	Combustible interior finish materials	1997	4	Net RHR for PVC foam over time for fires of 43, 64, 75 and 150 KW	Graphical	Only of use if considering PVC foam in experiments
(Hadjisophocleous, Benichou & Tamin 1998)	Look at movement from prescriptive based codes to performance based	1998	0	Heat flux range for ignitability of easy, medium and hard materials (gives examples), typical fire growth parameters with reference to household furniture	Numerical	Second-hand experimental
(Hirschler 1999)	Standard room testing using 26 fabrics commonly used in production of upholstery furniture	1999	26	RHR for each of the 26 fabrics used	Numerical	Refers to ‘mock-up testing’; not sure if this includes entire furniture structure
(Hirschler & Treviño 1997)	Real-scale fire testing of stacks of chairs	1997	3	Mass loss, RHR peak, rate of smoke release, total heat release, total smoke	Numerical	Only important if considering large assembly area where chairs may be

				release, time to peak rate of heat release		stacked
(Kim, H. J. & Lilley 2002)	Furniture calorimeter test	2002	1	Time to reach 1 MW, max RHR, growth time	Numerical	Second-hand data obtained from Building and Fire Research Laboratory
(Kim, A. K. 1988)	Full-scale fire testing on plastic furnishings	1988	3	Temp vs time in upper layers of room, average room temp, O_2, CO conc vs time, RHR bs time, average room temp, optical density, HCL and HBR concs	Numerical and graphs	Not all data available for all tests, carried out in ASTM standard test room
(Krasny & Babrauskas 1984)	Furniture testing in furniture calorimeter	1984	Numerous	RHR, total heat, irradiation, smoke deviation, CO, CO_2%, O_2 depletion, total heat at 300 s	Numerical	Full-size cushions used in different set-ups
(Luo, He & Beck 1997)	Experimental results for flaming fires using a prototype apartment building	1997	2 groups	Mass release rates and temperatures	Graphical	Varied ventilation conditions and fuel loads used
(Parker, et al. 1991)	Upholstered chairs in furniture calorimeter	1991	10	RHR vs temp, temp vs upper temp layer	Graphical	ASTM test room
(Shields, Silcock & Flood 2002)	Glazing exposed to a fire in compartment	2002	1	HRR from fire, mass loss rate and oxygen depletion	Tabular	ISO room, HRR may have been affected by thermal failure of glass
(Shields, et al. 1999)	ISO room experiments of different wall linings	1999	4	HRR at ignition, and time to flashover	Tabular	Only useful if considering wall linings

6. CONCLUSIONS

From the results of this literature review, as well as current fire engineering practices, it is clear that a citable set of credible design fires for use in determining the appropriateness of apartment building designs for the event of fire using modelling approaches would be useful.

ISO standards provide general guidelines for design fires and scenarios, but do not recommend design fires for specific occupancies or scenarios, thus justifying the need for this project.

Fire incident statistics, for all regions considered (Section 3), show that cooking fires were consistently the most common but not the most hazardous of residential apartment fires in general. Fires involving bedding or soft furnishings have been the most commonly reported fires to cause death. In general, statistics for apartment and all-residential buildings were similar, however due care must be employed when analysing small sample sizes. More detailed information would be useful in identifying the most common and the most hazardous fire events. Fire incident statistics and case studies can assist with construction of a range of realistic fire scenarios, forming a basis for the development of design fires.

The data sets available for large-scale experimental fires from literature, and from tests conducted at CSIRO and University of Canterbury cover mainly furniture calorimeter, room fire and room-corridor tests on various types of bedding and furniture items used in apartments. Measurements included heat release rate, smoke, combustion species concentrations, heat fluxes, temperature distributions etc, however all experiments do not consistently cover these measurements.

Relatively little fire load data is available, particularly for New Zealand and Australian residential or apartment buildings (Section 5.1). In recent years, the Bwalya study of Canadian residential living rooms appears the most comprehensive. There may be merit in carrying out a similar web-based survey for New Zealand and Australia.

Experimental results from investigations of the burning characteristics of upholstered furniture, mattresses and bedding were shown to be influenced by several factors, including materials, combinations of materials, construction, configuration, geometry and size, inclusion of associated items, source and location of ignition, type of test used, etc. Therefore care must be applied when selecting appropriate experimental data sets for specific applications. Furthermore, the results of the study by Enright et al (Section 5.3) showed that the CBUF model did not predict the burning behaviour of New Zealand furniture well. Therefore due care must be applied when selecting burn characteristics appropriate to the region of interest for inclusion in a design fire.

7. FURTHER WORK

Whilst compiling this literature review, we have identified the following items for further work, either as part of this project or as a potential further project:

Fire incident data

- Development of a generic event tree for fire occurring in an apartment building, making use of fire incident statistics for the scenario development.

- Using the ISO methodology – event trees, risk analysis and so on, develop design fires based on the available sources of data.

- Define how common apartments are in relation to other types of residential buildings for different regions. Apartments more common in Japan, Hong Kong etc with high population densities as against houses in Australia, New Zealand, USA etc.

Fire loads in residential or apartment buildings

- Consider the fuel loadings of individual rooms as opposed to the apartment building/unit as a whole to enable appropriate probabilities to be determined. For example, the bedroom has a lower probability of fire, but a significantly higher fuel loading in comparison to the kitchen.

- Development of a web-based fire load survey for apartment buildings in New Zealand and Australia, similar to the Canadian study of residential living rooms (Bwalya 2004).

Database development for experimental data

- Undertake further detailed analysis and tabulation of the type of available data.

- Design an excel worksheet format to store data required for design fires. This will form a basis for the web-based database.

- Digitise data wherever necessary.

- Input the data into the database.

Experimental work

- Define missing conditions/tests in the current data sets to determine further experiments to be undertaken.

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APPENDIX A: SUMMARY OF CASE STUDIES OF MULTI-STOREY APARTMENT FIRES

A summary of some of the available information for a selection of case studies of fires that have occurred in multi-storey buildings is presented in Table 15.

Table 15: A summary of case studies of multi-storey apartment building fires *

Year	Location	No. Storeys	No. Deaths/ Injuries [a]	Fatality Info.	Fire Origin	Fire Spread	Fire Safety Precautions in Building
1987 [b] 22 Mar	Schomberg Plaza, Harlem, NY, USA	35	7/-	On 33rd and 34th floors	Lit cigarette (or similar) ignited trash in a chute between the 27th and 29th floors	Through a window from 34th floor to the 35th floor	Sprinkler system installed in chute, but was not operational
1988 [c] 14 Mar	Davis, CA, USA	1 & 2	0/-		Office in the one-storey building	Fire brands 6 of 17 other buildings in the complex (29 units) involved in the fire	-
1988 [d] 11 Jan	New York City, NY, USA	10	4/2 (0/5)	1 in 9th floor apartment, 3 in stairwell	Cause unknown Started in a professional office on ground floor	Smoke-filled stairwells through open fire doors	All exit and apartment doors were metal fire doors with 17 mm gap at bottom No sprinkler system, fire alarm system, emergency lighting or illuminated exit signs
1989 [e] 24 Dec	John Sevier Center, Johnson City, TN, USA	11	16/50 (0/15)	1 in unit on fire floor, 1 in elevator lobby on 6th floor, 14 in units on higher floors	Loveseat ignited in an apartment on 1st floor	Number of prior false alarms Sub-freezing temperatures – residents did not want to leave	No sprinklers Officials were updating building Fire resistant doors installed on all apartment entrance ways, but many closers removed
1992 [f] 5 Dec	Chester, Pennsylvania, USA	2	8/-	Smoke inhalation, all were children from one family	Bed ignited in 1st floor bedroom, smoking materials suspected	Balloon frame wall construction Combustible interior finish	One inoperable smoke alarm – batteries removed
1993 [g] 28 Feb	Ludinton, MI, USA	2	9/-	All smoke inhalation, on 2nd floor in units	On or near a wall-mounted light fixture in 2nd floor corridor	Leakage of smoke into apartments through vents in corridor	No fire systems installed
1994 [h] 28 Mar	Manhattan, NY, USA	3	0/- (3/-)	Backdraft, on landing above unit of fire origin	Plastic trash left on a stove top in the open plan kitchen of the 1st floor apartment	High alcohol bottles and floor boards in kitchen/dining/lounge/hall Renovations – "very tight" building Occupant was not at home at the time of the fire	-

Table 15 continued.

Year	Location	No. Storeys	No. Deaths/ Injuries [a]	Fatality Info.	Fire Origin	Fire Spread	Fire Safety Precautions in Building
1995 [i] 6 Jan	North York, Ontario, Canada	29	6/-	On floors above the fire, in exit stairways	Smoking materials ignited a couch in a 5th floor apartment	Apartment of fire origin entrance door was left open Fire spread to an exit-way corridor Residents that stayed in their apartments with the door closed were all unharmed	Loud speakers – but not audible No sprinkler system No fire safety training
1995 j 26 Aug	Brooklyn, NY, USA	31	0/-		Cause unknown, started on 9th storey of an adjacent deserted building	Fire spread to adjacent exposures Fire brands or radiant heat caused fires in the 31-storey building, 1 in an apartment on the 31st floor	Standpipe in fire origin building not functional
1997 [k] 13 Nov	Kona Village, Bremerton, WA	2 & 4	4/-	All elderly	Cause unknown, started in an unoccupied 3rd floor apartment	Entrance door of fire apartment possibly left open Fire spread to external walkway, and through window to unit on 4th floor and attic	Individual smoke alarms No sprinkler system No interconnected alarm system
1998 [l] 9 Aug	The Westview Towers, New Jersey, NY, USA	22	4/25 (0/7)	2 in unit of fire origin, 2 in stairwell between 6th and 7th floors	Couch ignited in apartment on 4th floor		No sprinkler system No stairwell pressurisation
1998 [m] 12 Oct	The Council Towers, St. Louis, MO	27	0/13		Bed ignited in an apartment on 21st floor	Fire spread out windows to the 22nd floor	Not fully sprinklered
1999 [n] 30 May	Washington DC, USA	2	0/0 (2/-)		Light fixture on ceiling in basement	Fire spread to the floor of the basement	Smoke alarms
2000 [p] Apr	Detroit, MI, USA	12	4/many	3 smoke inhalation (2 in unit on fire floor, 1 in stairwell), 1 burns and smoke in stairwell	Started in an apartment on 8th floor	-	Faulty hydrant outside building

* A "-"indicates a lack of information available.
[a] The numbers in parentheses are associated with fire-fighter or emergency services.
[b] Taken from (Schaenman 1987).
[c] Taken from (Isner 1988b).
[d] Taken from (Isner 1988a; Kirby 1988).
[e] Taken from (Carpenter 1989).
[f] Taken from (Chubb 1992).
[g] Taken from (Kirby 1993).
[h] Taken from (Bukowski 1995).
[i] Taken from (NFPA 2002a; Yung, Proulx & Benichou 2001).
[j] Taken from (Howell 1995).
[k] Taken from (Kimball 1997).
[l] Taken from (Cook 2001; USFA 2003; West 2003).
[m] Taken from (Cook 2001; USFA 2003; West 2003).
[n] Taken from (Madrzykowski & Vettori 2000).
[p] Taken from (Claxton & Hurt 2000).