STUDY REPORT

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Timeline for Incipient Fire Development

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The work reported here was jointly funded by Building Research Levy, whose logo is shown above

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Preface

This is a report prepared from a literature search and experimental programme measuring the incipient spread timeline of fire for a selection of ignition sources and locations on items of upholstered furniture. The resulting fire-spread development period was analysed statistically and recommendations made regarding the inclusion in fire engineering designs.

Acknowledgments

This work was funded by the Building Research Levy.

Note

This report is intended for:

- The Department of Building and Housing (DBH) as a technical basis for a proposed framework for performance-based fire engineering and/or updating provisions contained within their approved documents

Timeline for Incipient Fire Development

BRANZ Study Report SR 194

PCR Collier and PN Whiting

Reference

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Abstract

This study has evaluated the incipient fire development of a series of purpose-built chairs with polyester fabric-covered flexible polyurethane (PU) seat and back cushions and three sofa chairs. The results of the measurement of heat release rate (HRR) from ignition to beyond the peak HRR, and smoke extinction area (SEA), were analysed and presented as statistical distributions. The findings indicate that the incipient fire development period is variable, depending on the size and location of the ignition source. It is also likely to be relatively short in duration for the furniture tested, such that its inclusion in the fire development time adds very little additional time available from detection to potential escape time or intervention that would benefit fire engineering design.

Keywords

Fire-spread, incipient, statistical distribution, polyurethane foam, upholstered furniture, HRR.

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1. INTRODUCTION

This project has measured the time from ignition to 'sustained' flaming in a series of HRR furniture-scale laboratory experiments using slabs of polyester fabric-covered flexible PU foam in the form of typical New Zealand economically manufactured upholstered chairs and a variety of small flaming ignition sources. A statistical distribution for the incipient fire development period from ignition to 'sustained' flaming for this series experiments has been determined. The results are intended to be used to help inform whether there is merit in including an incipient fire development period in design fires used in performance-based fire engineering, and if so, what period of time would be appropriate.

1.1 Background

The DBH is currently reviewing the New Zealand Building Code including the fire safety provisions. They are developing a conceptual framework for fire engineering design in New Zealand that may include specified input parameters for design fire characteristics (fire loads, fire size, growth rate, production rates of CO and smoke), occupant behaviour (travel speeds, pre-movement times) and acceptance criteria for life safety (exposure dosages for toxic gases and heat).

Ideally, this framework would be applied to demonstrate the adequacy of the current Acceptable Solution (DBH 2005) or to highlight areas of needed change. It is generally accepted that the overall level of safety implicit in the Acceptable Solutions is appropriate. However, initial benchmarking studies indicate that proposed design fire inputs in total produce results that are overly conservative, and therefore if adopted as is may stifle performance-based design solutions.

One important assumption that is traditionally made in fire engineering design is to ignore any period of incipient fire development and to assume the fire growth follows a time-squared relationship ($Q=\alpha.t^2$) commencing at ignition. If more realistic times for occupant pre-movement activity when calculating required safe egress time (RSET) are included, consideration of more realistic incipient fire development assumptions should be investigated to avoid possible excessive conservatism in design calculations for available safe egress time (ASET).

The period of incipient fire development is expected to be variable in practice (depending on air currents, ignition source location, orientation etc) and ideally should be characterised with a statistical distribution. The period describes the time while the fire is becoming established before it reaches a size after which the fire growth becomes more predictable. HRR experiments of items of furniture (chairs, sofas) using standard test methods almost always use strong ignition sources such as 30 kW gas burner or similar to initiate the fire (BHFTI 1991). The incipient period could then be described as the time from ignition until a size of 30 kW is reached and we have applied this definition for the purposes of this study. Typically, t^2 fires for upholstered furniture are characterised as ‘fast’, partly based on experiments by the University of Canterbury (Denize 2000), and reviewed by Young (2007) and others (Wade et al 2003). A ‘fast’ fire is defined as one that reaches a HRR of 1 MW in 150 seconds. This means that the time to reach 30 kW (the incipient period) would be assumed to be just 26 seconds as shown in Figure 1. The purpose of this project was to determine how reasonable this assumption is in relation to upholstered furniture ignited with small flaming ignition sources, and to provide an experimental basis for the selection of a different value if appropriate.

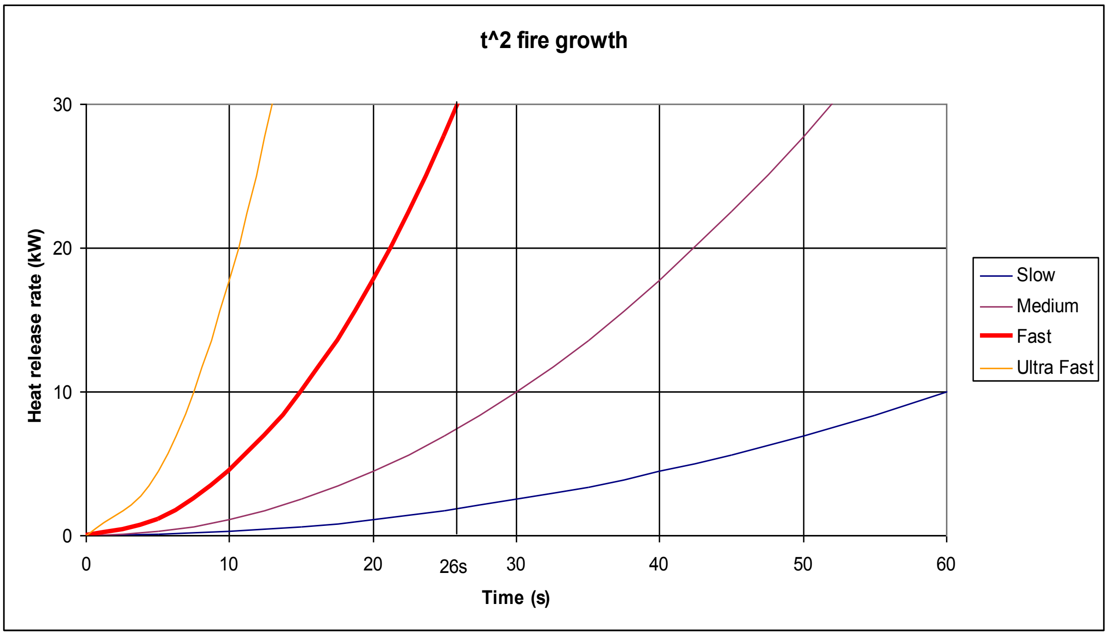

Figure 1. t^2 fire growth rates

2. LITERATURE REVIEW

There has been a great deal of research into the many varied methods of fire ignition. However, very little work has been done that strictly considers the duration of the incipient fire development phase of a fire.

In fire engineering design, specified input parameters for design fire characteristics such as fire loads, fire size, growth rate, production rates of CO and smoke are required. Traditionally, when specifying the fire development timeline, the period of incipient fire development is ignored and it is assumed that the fire growth follows a time-squared relationship ($Q=\alpha.t^2$) commencing at ignition.

The general assumption is illustrated in Figure 2 where t_0 is the incipient growth phase and the fire growth period for modelling purposes is simplified to a t^2 curve.

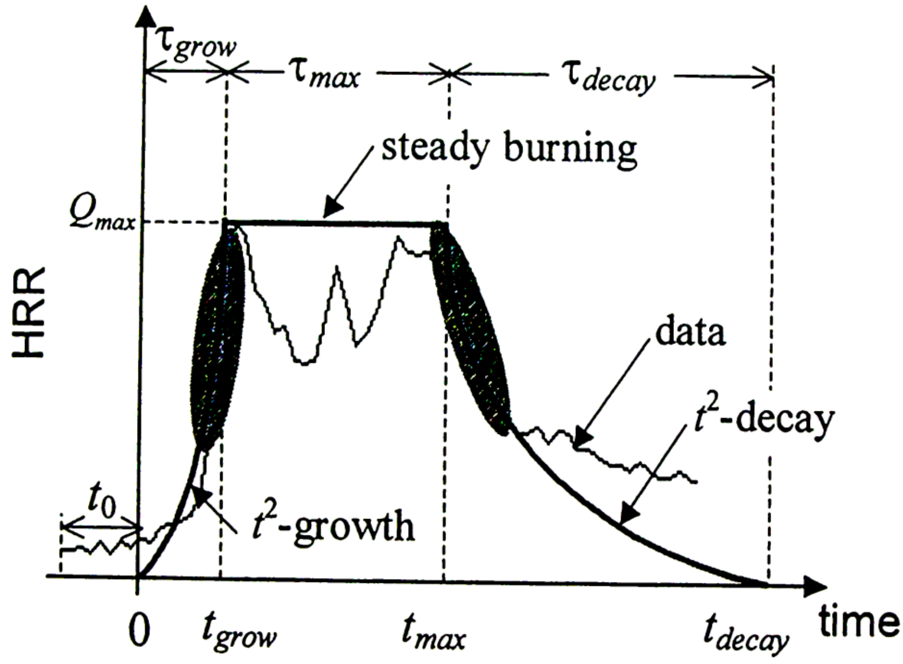

Figure 2. HRR data and approximated curve (Natori 2006)

No two fires are ever the same, with differences caused by factors such as air currents, ignition source location, and orientation. In order to develop a statistical distribution to characterise the incipient fire development period, the period has to be defined

Alternative measures of the t_0 period for relating the incipient phase prior to a t^2 fire growth are the:

- Period up to when 25 kW HRR is exceeded (Bukowski 1995 and Ristic 2001), or
- Period up to when 30 kW HRR is exceeded (Ahrens 2007).

2.1 Real fire data

Typically, studies of real fire starts identify the item first ignited and the cause. Fire starts commonly fall into one or more of the following categories:

- Cooking
- Smoking materials
- Heating equipment
- Candles
- Electrical
- Mechanical failure
- Intentional fires, including arson.

According to statistical studies in the USA, fires that originate from cooking activities were identified as the leading cause of home fires and home fire injuries (Ahrens 2007). Cooking by its very nature could be described as operating in a state of managed incipient fire development. It was identified by Ahrens that a clearly identifiable yet un-managed incipient phase is difficult to define and was therefore not considered further in this report.

Fires started by cigarette smoking was identified as the leading cause of home fire deaths (Ahrens 2007), and 80% of the home smoking material fire fatalities resulted from fires originating with upholstered furniture, mattresses or bedding, or clothing.

Home heating equipment and intentional fires were the second and third leading causes of home fire fatalities respectively, with candles being the second leading cause of home fire injuries (Ahrens 2007). In these fires it was often an item of furniture that was ignited by the heating equipment or candle.

2.1.1 New Zealand fire data

Analysis of the New Zealand Fire Service (NZFS 2005) database of fire incidents indicates that in this country the most common recorded types of first material ignited for all residential fires were fat or food, polymers, finished timber products, and fabric, respectively as shown in Figure 3.

The top three most common recorded types of material initially ignited for residential fire fatalities were fabric, flammable or combustible liquids, and polymers.

The top three most common recorded types of material initially ignited for residential fire injuries were fat or food, flammable or combustible liquids, and fabric.

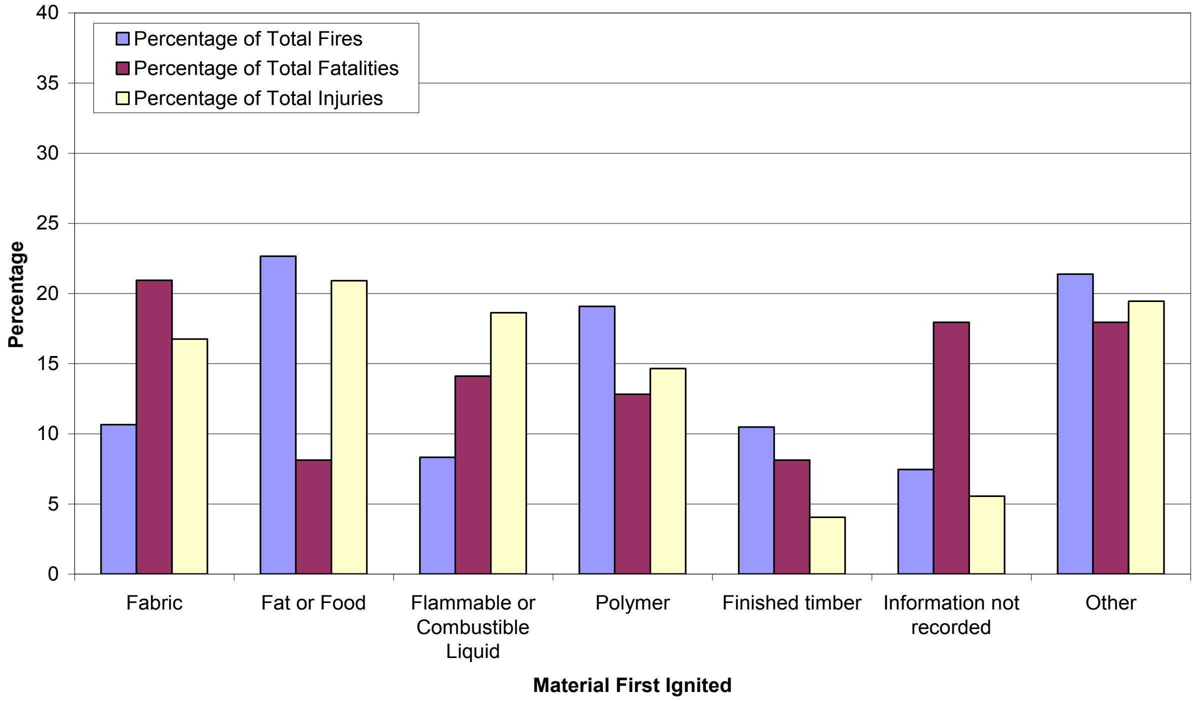

Figure 3. Percentage of totals for fires, fatalities and injuries that occurred in all residential structures as recorded for each group of first material ignited (1995–2005)

The most common types of causes recorded for all residential fires were unattended kitchen fires, carelessness, electrical failure, and deliberate, respectively as shown in Figure 4.

The top three most common recorded types of cause recorded for residential fire fatalities were unattended kitchen fires, falling asleep in bed, and deliberate.

The top three most common types of causes recorded for residential fire injuries were unattended kitchen fires, carelessness, and play or recklessness.

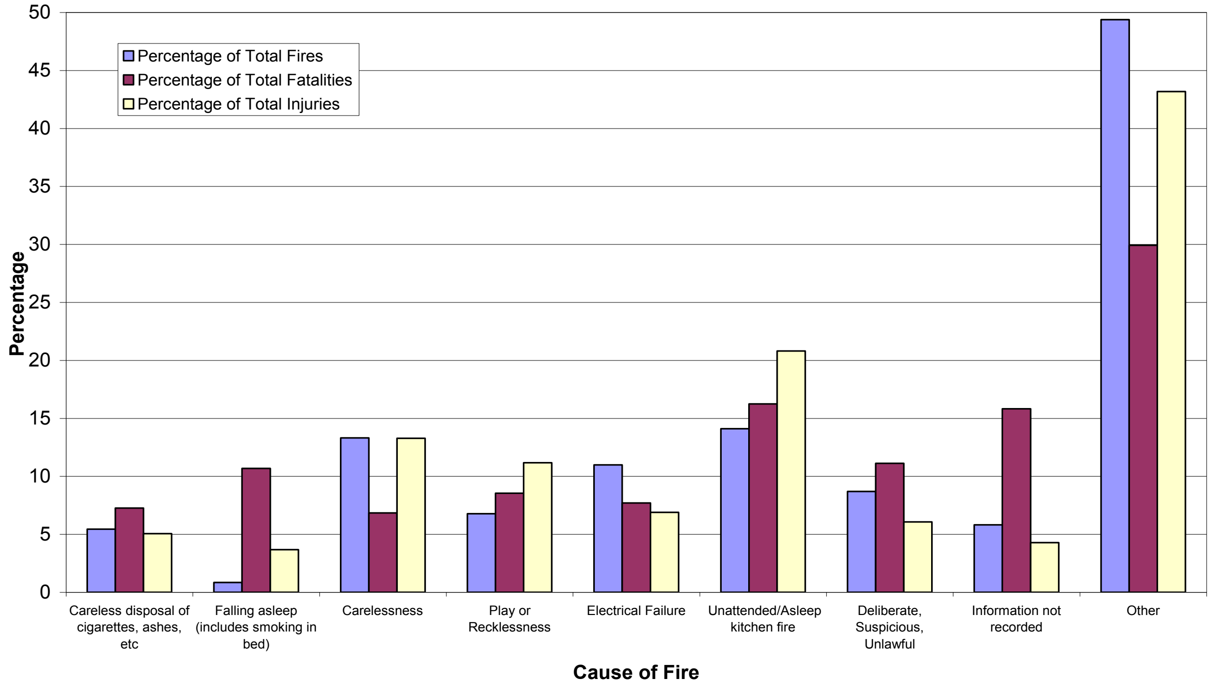

Figure 4. Percentage of totals for fires, fatalities and injuries that occurred in all residential structures as recorded for each group of cause of ignition (1995–2005)

2.2 Incipient fire-spread process

A study by Artim (1998) into fire risks to historic religious buildings highlights the risk of the incipient fire-spread as a process that may begin with a slow growth, smouldering process that may last a few minutes to several hours. The duration is dependent on several factors such as the fuel type, its physical arrangement and available oxygen. This period is characterised by heat generation and an increasing production of smoke, which may be noticed as the first indication that incipient fire development is underway. At some point there may be enough heat to initiate the onset of open visible flames. At this stage, the fire dynamic changes from a relatively minor incipient development phase to a more serious event with rapid fire development.

The life safety protection provided by sprinklers or heat detectors may be delayed for most or all of the incipient stage of the fire-spread due to insufficient temperature rise at the sprinkler or detector head until the fire size increases. On the other hand, smoke detectors or smoke alarms may give a significantly earlier warning of fire before the rapid growth phase commences (Collier 1996).

2.2.1 Cigarette ignition

A literature review of the cigarette ignition of soft furnishings in the USA was carried out by Krasny (1987). It was reported that substrates covered with thermoplastic fabrics tend to resist cigarette ignition because some of the heat transferred to the item is absorbed by the fabric melting. Alternatively, cigarettes generally induce smouldering of medium to heavy cellulosic fabrics, with consequent heat transfer to the padding. It was emphasised that while some materials may have good cigarette ignition resistance, these may not necessarily have good small flame ignition resistance and vice versa.

The thermoplastic was observed to consistently shrink, curl and melt upon contact with an open flame and expose the padding, whereas cellulosic fabric charred and until the char broke, protected the padding. Generally the findings indicated that increasing the amount of cellulosic materials (cotton, rayon, linen, hemp in fabrics, cotton batting) in the substrate decreased cigarette ignition resistance. Increasing the amount of thermoplastics nylon, polyester, and polyolefin in fabrics and thermoplastic fibres typically found in polyester batting, increases the cigarette ignition resistance. It was identified that cotton batting (cellulosic padding) ignited readily in contact with a cigarette, while PU foam needed a smouldering cellulosic fabric cover before it ignited on exposure to a cigarette.

A further point of note was that the tension of the fabric affected the degree to which it was in contact with the substrate. The higher the tension, the more intimate the contact between the fabric and substrate and the more effectively the substrate was able to act as either a heat sink or smoulder, depending on the type of fabric covering.

2.2.2 Other mechanisms of ignition

In a New Zealand study (Chen 2001), the radiant ignitability of locally sourced furniture composites was examined using the ISO Ignitability Test (ISO 5657 1997). The results of this study corroborate the findings of Krasny (1987). Fourteen types of fabrics and a single type of foam were tested. This selection represented combinations most commonly used in the manufacture of upholstered furniture. These fabric-foam composites were subjected to a range of imposed heat fluxes from 6 to 40 kW/m^2. The time to ignition data was analysed statistically. As expected, the greatest variance in the times to ignition occurred at the lowest heat fluxes. The study concluded that for the purposes of fire engineering design, it was reasonable to apply the “thermally-thin” theory to predict times to ignition.

In Chen’s study, ignition was defined as flaming sustained for at least 4 seconds in accordance with ISO 5657. While incipient fire development data was not recorded for the tested specimens, the behaviour of each fabric subjected to the imposed heat flux was characterised into two categories: those that ignited with charring, and those that melted at first, then ignited. The 14 fabrics chosen ranged from 100% polypropylene, polyester, acrylic, cotton, olefin and nylon pile to blends of these and in two fabrics the blend included viscose. Of the seven that ignited with charring, four were composed of at least 40% cotton, one was 100% nylon pile, one a polyester/viscose blend, and the last (a blend of polyester/acrylic/olefin) also melted at higher heat fluxes. Typically, at the lower imposed heat fluxes (10 kW/m^2 or less), times to ignition were substantially greater for those fabrics that ignited with charring.

Bukowski (1995) reported that with small sources there was an incubation period before established flaming which can influence the response of smoke detectors (resulting in an underestimate of time to detection). Bukowski suggested that could be simulated by adding a slow, linear growth period until the HRR reaches 25 kW.

The mechanism of ignition noted in experiments and confirmed by the NFPA Committee (2003) reports (for users of NFPA 130) that ASTM E 1537 and ASTM E 1590 have very low intensity ignition sources. Therefore it is not unusual to find materials that gain a favourable result for the above tests (including “passing” by melting away from the source of ignition), yet burn quite vigorously when subjected to a different ignition source.

2.3 Variations of incipient ignition

A huge variation of the incipient fire development time was reported by Mitler and Tu (1994), depending on the location of a 10 kW propane gas flame ignition source on upholstered furniture. Locations of the ignition source considered by Mitler and Tu were:

1. Centre of chair cushion
2. Seat back
3. Seat side
4. Seat front.

The average times for incipient fire development ranged from:

- 10 minutes for locations (1) and (2)
- 14 minutes for (3)
- 36 minutes for (4).

The study concluded that the location of the initial ignition can have a significant effect on the elapsed time to reach the peak HRR. It was found that the duration of the incipient stage had the dominant effect on the timing of the peak HRR, the magnitudes of which are similar and independent of where the fire started.

Ohlemiller and Villa (1990) reported that measurements (of ignition time and HRR) using newspaper-based ignition sources were subject to appreciable variations when placed on:

1. Flat surfaces such as the side arms of chairs, or
2. A vertical surface such as the area of the seat back, where the high heat flux impinged more directly on the surface resulting in more rapid ignition and growth.

Also there are upholstery combinations for which this variability (location of source) was found to be irrelevant, because the combination was so flammable or non-flammable that the ignition source location makes minimal difference in the overall outcome.

The gas burner was generally a less severe igniter (than newspaper), and on marginally ignitable substrates resulted in no ignition at all. Trials in the preliminary stage of this project (Section 3.2.2) supported this finding.

A further investigation into the influence of ignition sources on the flaming fire hazard of upholstered furniture by Cleary, Ohlemiller and Villa (1994) summarised the main findings as:

1. Some of the weak ignition sources did not have sufficient energy input to yield sustained spreading flames for all of the chair types.
2. There can be substantial differences in the time to the peak HRR for different ignition sources.
3. The magnitudes of the peak HRRs for the different ignition sources, given the same chair type, were close and appeared to be within the scatter of the data.

In other words, when ignition and sustained burning did occur as the result of an ignition source, the effects of extent-of-preheat and the size of initially ignited area did not appear to significantly impact the peak HRR, but did affect the time to reach the peak for these chair types.

2.3.1 New Zealand studies of furniture fires

A study of the combustion behaviour of upholstered furniture in New Zealand (Denize 2000) tested a variety of chairs with a range of PU foam types and polypropylene and then woollen fabric coverings. Attempts were made to match the HRR curves to t^2 fire growth rate curves. The majority of foams with the polypropylene fabric covering were found to approximate a 'fast' growth rate. The findings were:

- The public auditorium seating using fire-retardant foam exhibited a delay time of approximately 140 seconds before rising to a lower HRR peak compared to standard foams.
- With the woollen fabric covering, all of the combinations tested produced later HRR peaks characterised by an initial growth to a minor peak before dipping and then a rapid increase to a second peak that was lower than the initial peak.

It was suggested that if an incipient growth/development stage were included before the rapid growth stage (the latter lends itself to a t^2 curve), then a much better fit would be obtained and the proposed curves would not need to be so conservative.

Studies by Denize (2000) and Coles (2001) showed the combination of fabric and foam has the most significant influence on the ignitability of the furniture. The fabric and foam interaction was shown to be important in determining the time to ignition, the time to the peak HRR and the magnitude of the peak HRR. The most significant characteristics were:

- whether the fabric melted or charred
- the level of heat flux required for that to happen
- the level of fire retardancy of the foam, determining the growth of the HRR with respect to time.

A study by Young (2007) considered a large database of furniture fires. Although the data did not directly consider the incipient spread stage, the wide range of time to peak HRR is unmistakable. The growth rate and the length of the incipient phase was shown to be dependent on a number of factors including:

- The materials involved in the upholstered item, in particular the foam fabric interactions
- Burner type (igniter)
- Burner location.

Because of the natural variability of the burning characteristics it is difficult to predict the incipient phase and whether the point of ignition (t = 0) should be shifted, making growth rates hard to quantify.

Young considered the distribution of the time to peak HRR for 138 armchairs as shown in Figure 5. In some experiments time (t = 0) was taken as when the ignition source was started and in others time (t = 0) was taken once the HRR of the fire had reached a certain level (either time of ignition or when the HRR was 50 kW or 100 kW), so the fire development may include some or all of the incipient stage. However the incipient stage was treated, it can be concluded that it may take up a considerable period of the fire duration in cases where the time to peak HRR exceeds say 600 seconds or more. Young recommended a 98 percentile period of 60 seconds (compared with a 95 percentile period of 90 seconds) for the peak HRR to be reached for armchairs when these are the first burnt item under consideration.

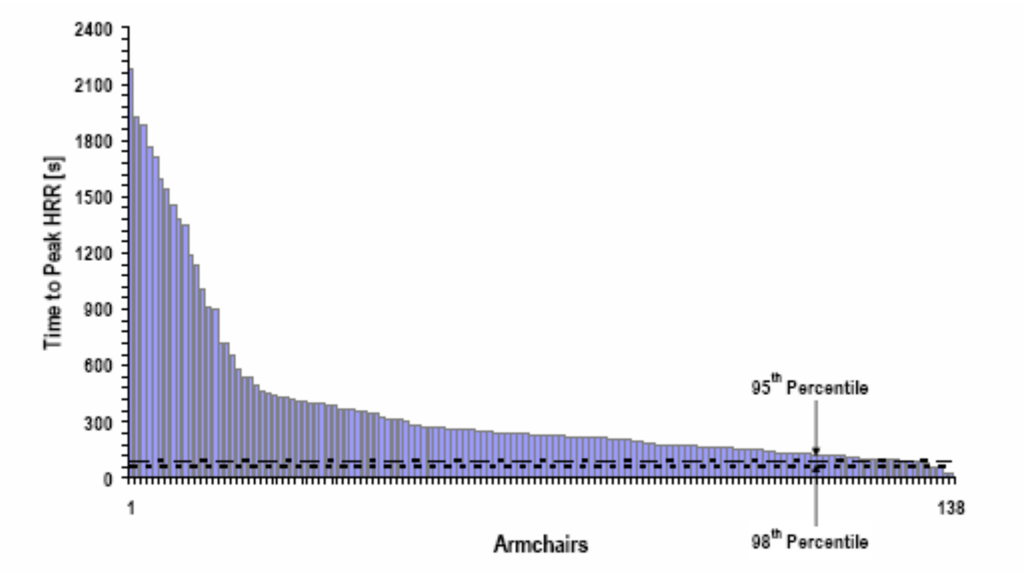

Figure 5. Time to peak HRR for armchairs (Young 2007)

It was also noted (Enright, Fleischmann et al 2001) that New Zealand-produced furniture resulted in noticeably more severe fires than those tested in Europe in the CBUF study (Sundström 1994). In recognition of the increased severity of New Zealand furniture, the 98th percentile for "Time to Peak HRR" was recommended by them for modelling purposes.

2.3.2 Incipient phase not always included

Satoh and Mizuno (2006) analysed the combustion of initial fire sources and found that by utilising statistical data for various representative combinations of the ignited material, and the ignition source from the test results (they developed), a model could be established that predicts the early stages of fire development. Five types of fire source that have five different HRR curves were identified and matched to t^2 curves with accompanying maximum HRR and durations. Although the authors noted that several of the sources tested showed clear delays in the emergence of a t^2 curve, they did not identify the duration of any incipient stage.

The authors noted that although several of the sources tested showed clear delays in the emergence of a t^2 curve, an incipient stage was not included or otherwise identified.

The CBUF study (Sundström 1994) concluded that the ignition time (incipient fire development) should not be included in the available safe egress time. The ignition time was found to vary substantially, depending on the point of ignition and the size of the source for a given furniture item. For small flame sources, the difference in the length of the ignition period between various source positions on a chair could be 50 minutes. The time to peak HRR for a chair ranged from about three minutes for a larger burner to about 12 minutes for a match-like flame. The authors concluded that in reality there are an unlimited number of different ignition possibilities. If one ignition source was picked on an arbitrary basis, then the results of the analysis of the hazard would be equally arbitrary if the ignition time was included in the available escape time. It was proposed that in order to solve the problem of variability the worst case scenario could be selected to ensure a required level of safety.

3. EXPERIMENTAL

The experimental phase of this study included:

- Initial burning of a sofa chair to verify that an incipient phase did indeed occur
- Trials with smouldering and flaming ignition sources to determine consistent start of incipient phase
- Trials with purpose-made upholstered chairs of typical (economical) New Zealand manufacture
- Three trials with identical sofa chairs
- Statistical analysis of results.

3.1 Characterising the incipient fire development phase of an upholstered chair fire

A preliminary trial of a single sofa (upholstered) chair weighing 31 kg was conducted using the ISO 9705 oxygen consumption calorimetry apparatus, in this case being used as a furniture calorimeter with the chair positioned directly beneath the exhaust hood. The ignition source was a small piece of paper towel lightly soaked in methylated spirits placed in the centre of the seat. The HRR is shown in Figure 6 with a best fit t^2 curve, whereby the growth rate α and the start time t_0 (or delay from 0 seconds) are adjusted to obtain the best fit (Natori 2006).

$$HRR = \alpha (t - t_0)^2$$ **.....Equation 1**

The best fit is achieved when:

t_0 = 24 seconds and α = 0.015

by least squares fit where r^2 = 0.986.

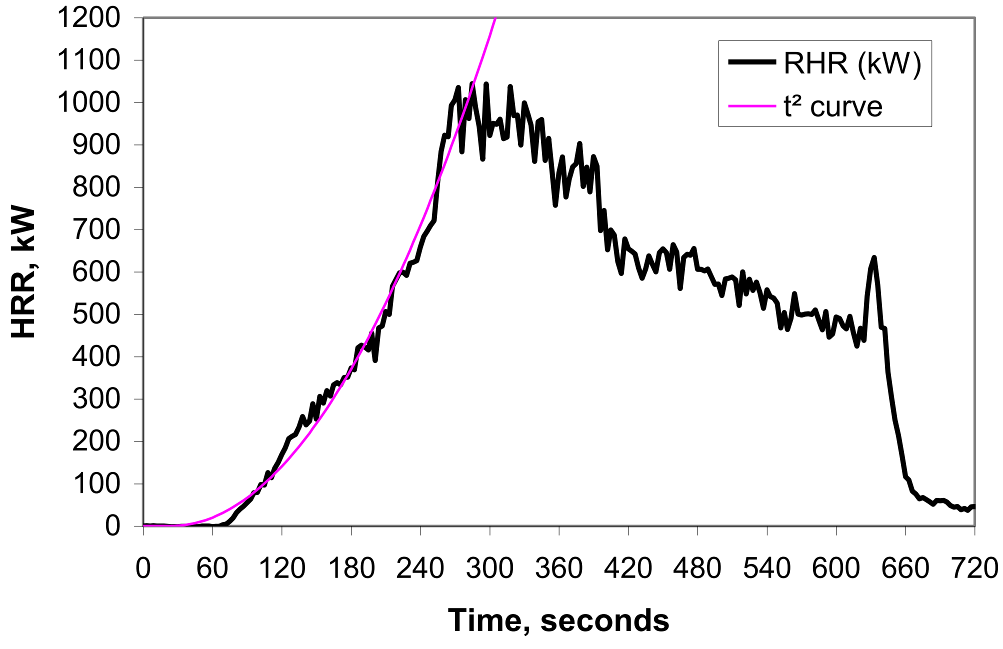

Figure 6. Example of sofa burn with delay time t_0 of 24 seconds to t^2 (medium+)

The sofa burn would be marginally above a medium t^2 fire where α = 0.015 in accordance with Table 1 and with a delay t_o of 24 seconds.

Table 1. Classifications of t^2 fires

Fire growth rate	
Slow	α = 0.00293
Medium	α = 0.0117
Fast	α = 0.0466
Ultra-fast	α = 0.1874

Alternative measures of the t_0 period for the sofa burn are:

- Period up to when 25 kW (Bukowski 1995 and Ristic 2001) is exceeded: 65 seconds, or
- Period up to when 30 kW (Ahrens 2007) is exceeded: 69 seconds.

The results of the various methods for assessing incipient fire development are summarised in Table 2.

Table 2. Summary of incipient fire development times for sofa chair

Criterion	Time, seconds
t_o by correlation to t^2	24
Exceeding 25 kW	65
Exceeding 30 kW	69

3.2 Preliminary experiments with ignition sources

The preliminary experimentation was carried out to evaluate the respective performance of various ignition sources. The experiments typically used reduced scale non-fire-retardant treated PU foam blocks measuring 200 x 200 mm. In some instances, the foam blocks were additionally covered with cotton, brushed cotton and polyester upholstery fabrics.

3.2.1 Smouldering ignition source – typically a cigarette

In 1985 it was calculated that some 600 billion cigarettes were consumed in the USA. This meant that approximately one in 12 million cigarettes caused a fire (Krasny 1987). This study reported that the temperature distribution in a free-burning cigarette ranged from greater than 775°C at the core to less than 600°C at the outer layer.

The smouldering ignition sources considered in this BRANZ study were:

- A lit cigarette
- A simulated cigarette (comprising an electric coil inside a clear glass test-tube and controlled to provide a constant temperature on the exterior of 600°C
- A bare wire ignition coil.

In the experimentation the free-burning cigarettes were laid horizontally onto the surface of fabric-covered PU foam blocks. Each of the cigarette tests was run for approximately 14 minutes (the typical duration for an undisturbed smouldering cigarette). No ignition of the foam was recorded without intervention such as using a flint lighter.

The simulated cigarette was trialled for ease of repeatability and monitoring. Like the cigarette, it was also placed horizontally onto the surface of fabric-covered PU foam blocks. Each of these tests was run for at least 10 minutes, with any extended duration determined on the combustion temperature and observation of the quantity of smoke. In these tests, the covering and PU foam did have a tendency to melt away a distance (based on the inverse square law) from the heat source such that the heat flux had reduced to a level that was less than what was required to melt the material any further and/or ignite it. The simulated cigarette in the glass tube was also considered representative of other ignition sources such as incandescent light bulbs, electric blankets, power cords and space heaters. Each of these types of ignition source can vary enormously, depending on the particular circumstances. These are therefore difficult to quantify experimentally and were not modelled in the testing program.

The bare wire ignition coil resulted in instantaneous ignition and was abandoned as it was considered too severe to be used as a possible smouldering ignition source.

A summary of the smouldering ignition source scenarios that were trialled is presented in Table 3.

Table 3. Preliminary trials of smouldering ignition sources

	Description	**Result**
1	Smouldering cigarette laid horizontally on the top of the uncovered foam block	Charred a channel into the top of the foam block – no ignition
2	Smouldering cigarette sandwiched against the side of the block between a non-combustible aluminium foil and the vertical side face of the uncovered block	Charred a channel into the foam block – no ignition
3	Smouldering cigarette placed horizontally into a channel cut in the top of the uncovered foam block	Charred a channel into the foam block – no ignition
4	Smouldering cigarette placed horizontally onto fabric over the block of foam	Charred a channel into the foam block – no ignition
5	Smouldering cigarette placed horizontally onto heavy cotton fabric over the block of foam	Charred a channel into the foam block – no ignition
6	Simulated cigarette placed horizontally onto flannelette brushed cotton fabric over the block of foam	Charred a channel into the foam block – some sparks of ignition early on and flaming ignition after approximately 12 minutes*
7	Repeat of #6, simulated cigarette placed horizontally onto flannelette brushed cotton fabric over the block of foam	Charred a channel into the foam block – some sparks of ignition early on but no ignition*
8	Smouldering cigarette placed horizontally onto flannelette brushed cotton fabric over the block of foam	Charred a channel into the foam block – some sparks of ignition early on but no ignition
9	Smouldering cigarette placed horizontally into an internal 90° corner formed between two foam blocks with a continuous flannelette brushed cotton fabric covering	Charred a channel into the foam block – some sparks of ignition early on but no ignition
10	Smouldering cigarette placed horizontally onto pile of shredded paper	Almost instant ignition

* At the conclusion of these trials a flint lighter was struck 50 mm above the charring/smouldering region and the resulting sparks were sufficient to cause ignition of the pyrolysed gases and flaming combustion of the heated PU foam.

3.2.2 Flaming ignition sources

Flaming ignition sources involved in upholstered furniture fires cover a considerable range from arson, children playing with lighters and matches to simply accidental ignition e.g. the careless use of candles.

The flaming ignition sources considered in this BRANZ study were:

- Matches
- A gas flame as a simulated match.

In the experiments, the regular size matches were placed on the specimen surface while the head of the match was still flaming. The simulated match comprised a propane gas flame approximately 25 mm in height from a horizontal 7.4 mm internal diameter stainless steel tube. The simulated match was ignited and then placed horizontally onto the surface of the specimens.

Four specimens of PU foam blocks were trialled, two covered with an olefin fabric cover and two with a cotton fabric (red in photos). The events following placement of the ignition sources are described in Table 4.

Table 4. Ignition trials with matches and simulated match by gas flame

Trial #	Ignition source	Covering/base	Observations	Timeline
1	Gas flame	Olefin/PU	Covering melted and ignited burning outwards in a circle forming a crater in the PU	All much the same for # 1 2 3 4
2	Match	Olefin/PU	Ditto	
3	Gas flame	Cotton/PU	Covering scorched and burnt outwards in a circle forming a crater in the PU	
4	Match	Cotton/PU	Ditto	

In the flaming ignition trials, it was concluded that the rate of spread of flaming was independent of the ignition source whether it was a gas or match flame, so either was found to be equally satisfactory for the experimental trials. The trials are illustrated in Figure 7 and Figure 8. In the case of the gas flame, it pointed directly upwards with minimal impact on the fabric below (the effect was similar to that of a lighted match). However, with the match there was a just perceptible amount of downward flaming from the match's lower surface to the fabric compared with the totally upward flow of gas and flame from the burner tube.

Figure 7. Gas flame and match ignition of olefin-covered PU foam

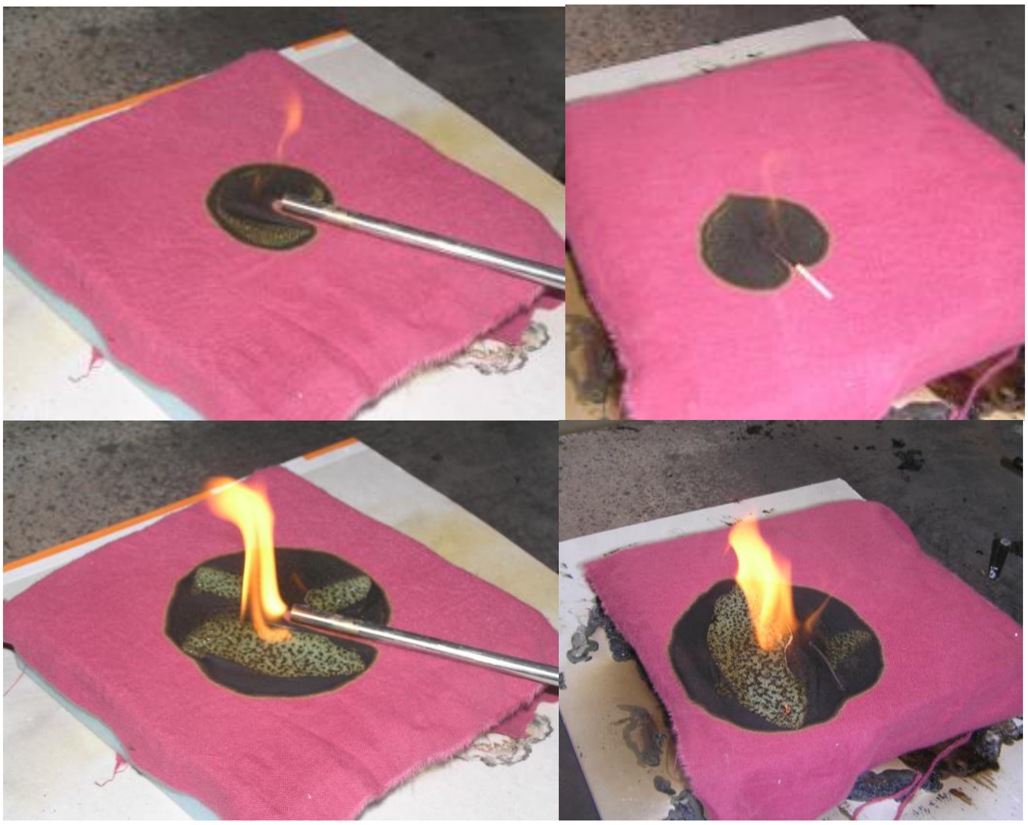

Figure 8. Gas flame and match ignition of cotton fabric-covered PU foam

3.2.3 Selection of ignition source

On completion of the preliminary trials, it was concluded that the smouldering ignition sources were too unreliable and inconsistent to be used as the ignition source for the full-scale tests. The underlying aim of the project was to examine the period of incipient fire development, and to determine statistically if this phase was sufficient to modify a predicted ASET. It was therefore concluded to use only flaming ignition sources. Two were selected: the regular match; and a much stronger flaming ignition source, a solid fuel domestic 'fire starter'. The regular match was considered to be representative of a small flaming source, of a size that was reliable enough for the purposes of this project, whilst still easily susceptible to being prematurely extinguished given relatively light wind drafts. The fire starter represented a considerably higher energy flaming ignition source with an exceptional reliability. Once ignited, not one of the fire starters became extinguished before its fuel supply was exhausted.

3.3 Design of specially made upholstered chairs typical of New Zealand manufacture

Twelve sets of seat and back cushions were fabricated for the experimental trials.

3.3.1 The construction of the seats

To investigate the incipient development phase of a chair fire, the project only considered the initiation component of the fire and details of the seat frame and construction techniques were therefore not considered relevant. The critical components of the chair were therefore the covering and padding. A steel chair sub-frame was used for all tests to support a seat cushion and back in the basic geometry of a conventional sofa chair.

The seat base and back used in the test programme were constructed to replicate the construction and materials used in chairs sold into the lower end of the market in New Zealand, and therefore are representative of the large volume sales units. To that end, materials were sourced from New Zealand furnishing manufacturers and importers.

The typical sofa chair construction replicated for this study comprised a non-fire retardant treated PU foam with a polyester wadding overlay and polyester covering fabric over that. The wadding acts to give the seat a plusher feel, and also to prevent friction damage that would otherwise occur if the outer covering fabric was in direct contact with the foam.

3.3.1.1 Foams used in the seat base and back

The seat base foam is typically both thicker and a higher density to that used in a seat back. The seat base foam measured 600 x 600 x 100 mm thick and that for the seat back measured 600 x 600 x 60 mm thick. The densities for the foams measured approximately 28 kg/m^3 and 21 kg/m^3 for the seat base and back respectively.

3.3.1.2 Wadding

The wadding used was a thermally bonded polyester blanket approximately 20 mm thick with a nominal density of 170 g/m^2 and is illustrated in Figure 9.

Figure 9. Polyester blanket wadding

3.3.1.3 Fabric covering

The fabric used to cover the seat base and back was supplied as an "entry point" 100 % polyester, without a backing. This was identified as typical of fabric coverings on the cheaper imported furniture. The fabric had a suede-like surface finish, a woven underside and was red in colour. The fabric is illustrated inFigure 10.

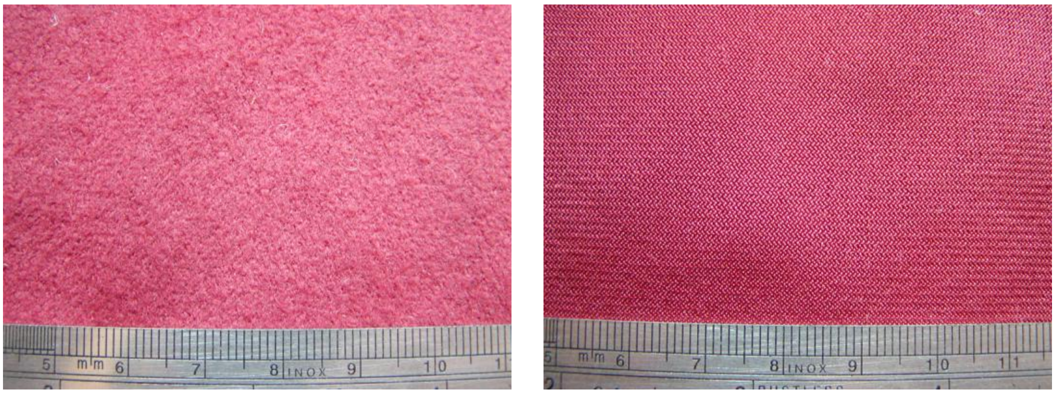

Figure 10. Polyester fabric covering left to right, suede-like top surface and woven underside

3.3.2 Construction

The fabric and wadding were cut to size, sufficient to cover the top and sides of the foam blocks. The fabric was pulled taut and secured to the back of the foam blocks with paper-grade metal staples.

The average weight of the seat bases and backs are recorded in Table 5 and a complete chair is shown in Figure 11

Table 5. Masses of seat combustibles averaged across the 12 test specimens

Material	Seat base (g)	Seat back (g)	Total (g)
Foam	1005	461	1466
Wadding	92	77	169
Fabric	116	88	204
Total	1213	626	1839

Figure 11. Purpose-built upholstered chair

4. TESTING PURPOSE-BUILT CHAIRS

The 12 purpose-built chairs were subjected to various ignition sources under an extraction hood and the products of combustion were analysed using oxygen consumption calorimetry to determine HRR. Also recorded were smoke production and mass loss. The ignition sources and locations used in the trials are listed Table 6.

Table 6. Ignition sources and locations

Source	Location	Number of trials
Match	seat centre	3 (2 attempts self-extinguished)
Match	seat back	3
Match	seat front	2 (self-extinguished, chairs able to be re-used)
Fire starter*	seat centre	2
Fire starter*	seat back	2
Fire starter*	seat front	2
Total number of tests		14**

* The fire starters were a typical domestic type measuring approximately 25 mm cube and weighing 10 grams and were selected so as to provide a consistent intensity of ignition.

** The total number of trials on the purpose-built chairs was increased to 14 following four trials in which the match ignition source extinguished without igniting the chair.

4.1 Results and analysis

With the following series of trials the time of the incipient fire-spread was evaluated using two methods:

- Time to exceed 30 kW HRR
- $\mathbf{t_o}$ by correlation to t^2.

The time to exceed 25 kW was not used as it gives a close time to 30 kW (refer to preliminary trial results in Table 2) and the 30 kW criterion is more widely used (BHFTI 1991) than 25 kW.

4.1.1 Series 1 – ignition source in centre of seat

With the ignition source placed in the centre of the seat of the first five chairs as illustrated in Figure 10, the HRR results are summarised in Table 7. Each of the two ignition sources produced consistent results for that particular source, but clearly fires initiated with the fire starters progressed more rapidly than those with the single matches due to their larger size.

Table 7. Incipient fire-spread on purpose-built chairs with fire source in seat centre

Fire source type and location	Match in centre of seat	Match in centre of seat	Match in centre of seat	Fire starter in centre of seat	Fire starter in centre of seat
Time to exceed 30 kW after ignition, s	106.8	109.9	101.7	81.4	88.0
HHR peak, kW	392	529	435	515	544
Time of peak, s	159	153	156	141	135
Fire growth rate, αt^2 where α =	0.125	0.192	0.089	0.109	0.169
t_o, s	88.5	98.0	76.6	65.7	76.6
Correlation of t_o to t^2	0.9962	0.9964	0.9885	0.9968	0.9964

The HRR is shown by the graphs in Figure 12, all base-lined to the time when the ignition source was placed on the centre of the seat at zero seconds. No appreciable rise in the HRR is evident until more than 60 seconds has elapsed, indicating the duration of the incipient development phase.

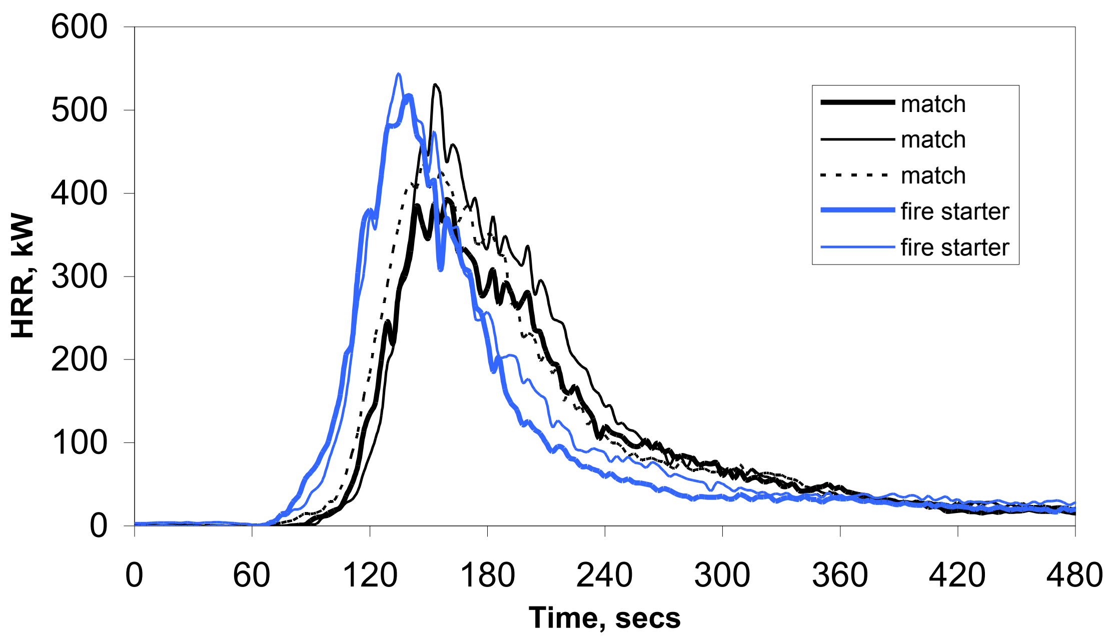

Figure 12. HRR with source at centre of seat cushion

The further progression of the incipient stage of fire development to the peak HRR is illustrated in Figure 13. In this trial, the match burning on the surface of the seat first melted the polyester fabric covering and then proceeded to melt through the polyester wadding, during which time the match had fully burned out. Small spheres of flaming charred polyester fabric dropped through the wadding and continued to melt and burn, enlarging the hole until the PU foam was reached. Once the PU foam became involved the available fuel increased markedly, as did the progression of the fire accompanied by an increase in the HRR. The fourth photograph, taken at approximately 69 seconds, shows the fire has involved an area approximately 200 mm in diameter and represents the initiation of the t^2 growth phase. Another 30 seconds later, the fire-involved area had spread to include the seat back. The rapid increase in the HRR continued past

120 seconds onto the peak at 156 seconds. Once the seat back had been largely consumed, an equally rapid decay commenced down to about 100 kW before levelling off to a more gentle decrease.

The difference between the ignition sources of the matches and fire starters equates to approximately 20 seconds for the incipient spread times and the time to reach the peak HRR.

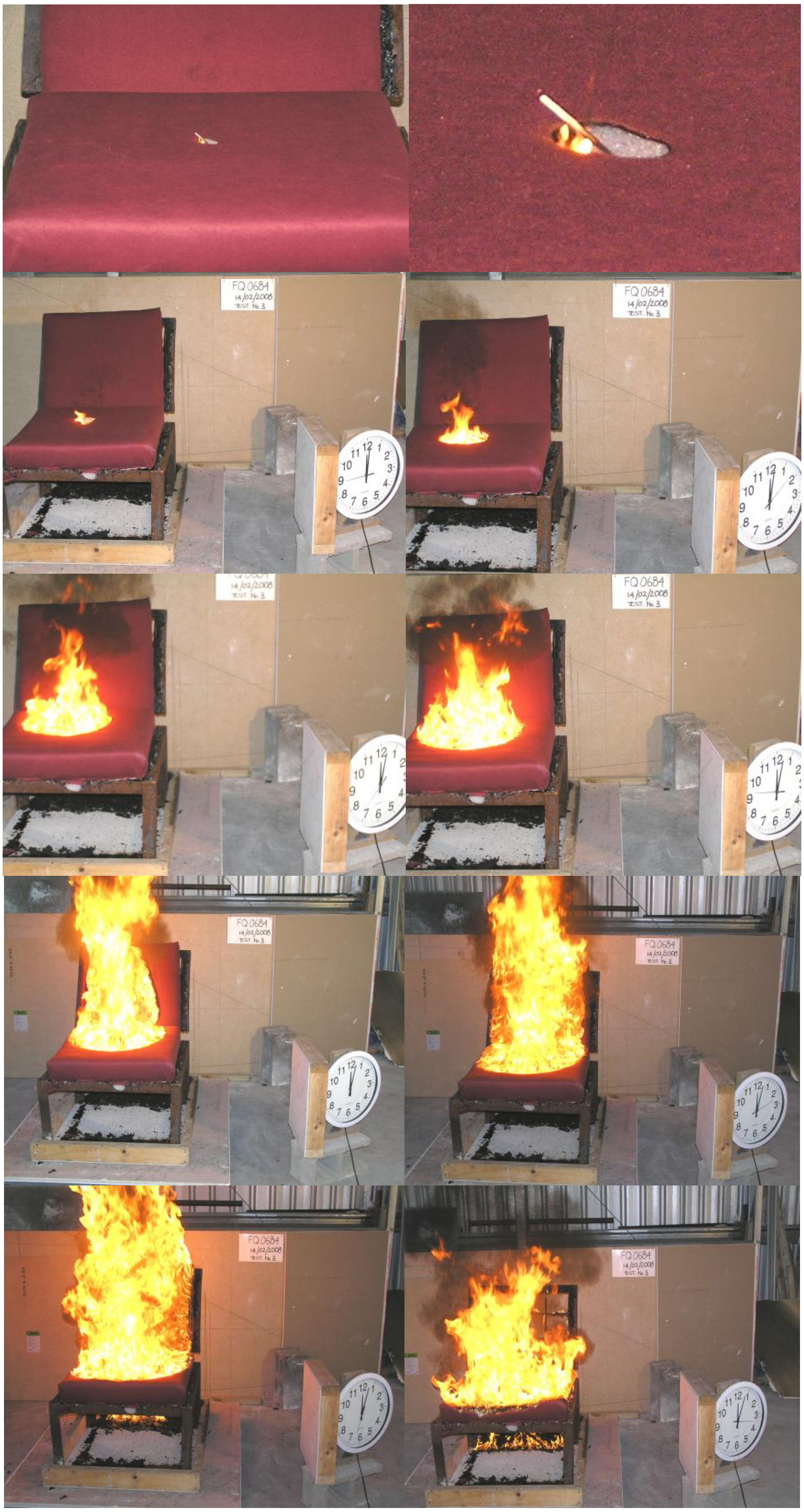

Figure 13. **Fire growth with match in centre of seat cushion in Test 3, t^2 rate of fire growth begins after approximately 69 seconds (fourth photo), and 30 kW was exceeded at 102 seconds, between fifth and sixth photos in sequence**

4.1.2 Series 2 – ignition source at junction of seat cushion and chair back

Placement of the ignition source at the junction of the seat base and back produced a slightly different fire-spread scenario where the seat back was involved from the beginning. This resulted in shorter incipient spread times and earlier peak HRRs. The logical reason for this was the ease of fire-spread up the inclined seat back. The magnitude of the peak HRRs were lower than with the seat centre ignition because the seat back had burnt out completely by the time the fire had only covered about 33% of the seat base as shown in Figure 14. The results are summarised in Table 8 and Figure 15.

Figure 14. **Fire growth with fire lighter at junction of seat base and back in Test 7, t^2 fire growth rate was reached after 26 seconds, and 30 kW was exceeded at 53 seconds, third photo in sequence**

In the case of the match-initiated ignition, the progress of the fire was delayed slightly due to the exact placement of the match. In initial attempts the lighted match was dropped into the gap between the seat base and back and, because of the confined space and lack of air, the match was quickly extinguished. The subsequent attempts with the match placed about 25 mm away from the seat back resulted in ignition of the seat base followed soon after with a spread to the seat back. On the other hand, the burning 25 mm cube 10 gram fire starters were placed at the top of the gap and immediately the fabric on both surfaces began burning. The effective time-shift for the more advanced burning of the fire starters meant similar events to the match ignition occurred some 50 to 60 seconds earlier.

The shapes of the HRR curves were similar, except those initiated by the fire starters appeared to be slightly flattened-out with a lower peak HRR. It is feasible that this is due to the earlier involvement of the seat back compared with the base. It follows also that the rate of decrease in the decay phase is less due to the continuing contribution of the seat base after the peak HRR. The photographs in Figure 31 in Appendix 1 confirm the differences in the fire development between the two ignition sources. Where the match ignition established a small fire on the seat base before the back became involved, the fire starter caused considerable fire development on the seat back before any spread onto the seat base. Once the respective 30 kW thresholds were reached, considered the end of the incipient phase, the difference is apparent in Figure 13 when comparing the relative involvement of the seat and back. The earlier involvement of the seat back in Figure 14 with the fire starter resulted in a lower peak HRR as there was less contribution from the seat base, at the peak HRR. Once the base was burning over its entire surface the seat back was completely burnt out and the only remaining burning was then confined to the seat base.

Table 8. Incipient fire-spread on purpose-built chairs with fire source at junction of seat cushion and chair back

Fire source type and location	**Match at back**	**Match at back**	**Match at back**	**Fire starter at back**	**Fire starter at back**
Time to exceed 30 kW after ignition, s	100.0	102.7	135.0	53.0	55.5
HHR peak, kW	334	351	374	298	277
Time of peak, s	135	144	180	99	105
Fire growth rate, αt^2 where α =	0.107	0.101	0.087	0.061	0.053
t_o, s	80.4	81.0	111.7	25.6	25.7
Correlation of t_o to t^2	0.9973	0.9960	0.9951	0.9932	0.9860

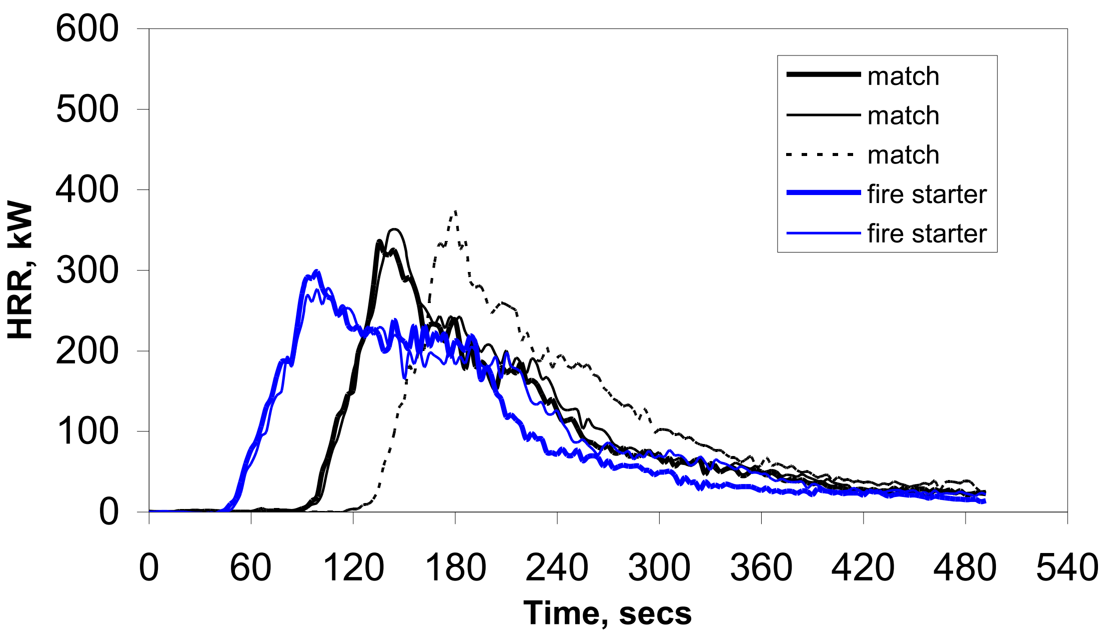

Figure 15. **HRR with ignition source at junction of seat cushion and chair back**

4.1.3 Series 3 – ignition source at front edge of seat cushion

In this series the only trials where successful burns were achieved were with the fire starters. In the attempts with matches, sustained burning of the seat fabric did not occur due to the air currents caused by the extraction hood and fan at the edge of the seat causing the flame to extinguish before the fabric was alight.

For the two trials with the fire starters, the results are shown in Table 9 and Figure 16. Due to the relatively remote location of the ignition source compared with the Series 1 and 2 trials, the times of the incipient spread and peak HRR are longer simply because the ignition source was further from the centre of mass of the combustibles.

Table 9. Incipient fire-spread on purpose-built chairs with fire source on front edge of seat

Fire source type and location	Match at front of seat	Match at front of seat	Fire starter at front of seat	Fire starter at front of seat
Time to exceed 30 kW after ignition, s	*	*	123.0	138.0
HHR peak, kW	*	*	502	479
Time of peak, s	*	*	189	195
Fire growth rate, αt^2 where α =	*	*	0.086	0.081
t_o, s	*	*	111.4	118.0
Correlation of t_o to t^2	*	*	0.9961	0.9966

* Match extinguished with no incipient development

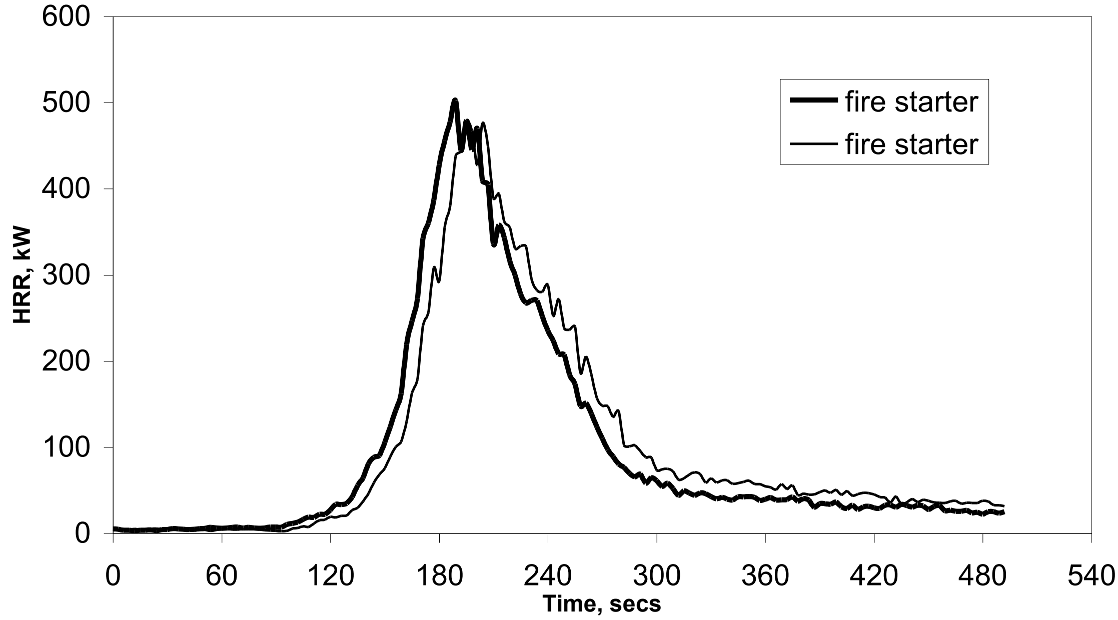

Figure 16. HRR with ignition source on front edge of seat

The magnitude of the peak HRR was comparable with the fire source in the centre of the seat (Series 1) trials. However, the fire developed more slowly with the peak occurring at least 30 seconds after those in the Series 1 trials. The peak HRRs in both Series 1 and 3 trials were greater than the Series 2 trials with the source at the junction of the seat and the back.

4.2 Statistical distribution of fire-spread results

The results of the trials were statistically analysed using small sampling theory and in particular the student t distribution method. A 95% confidence interval was selected with degrees of freedom of 2 or 3 depending on the number of trial runs for each ignition scenario.

The results for the mean, standard deviation and 5% and 95% confidence intervals of the student t distributions best fitting the sample results for incipient spread of fire based on time to exceed 30 kW HRR are shown in Table 10. The time to exceed 30 kW HRR was selected as the basis for the incipient fire development time on the basis that it gave more consistent times compared with the t_o correlated to t^2 even though the correlation coefficient was 0.99.

Table 10. Distribution of incipient fire development times for various fire sources and locations

Time to exceed 30 kW HRR after ignition, s	5%	Mean	95%	Sample standard deviation	No. degrees of freedom
Match in centre of seat	100.4	106.1	111.8	4.2	3
Fire starter in centre of seat	75.0	84.7	94.4	4.7	2
Match at back	86.1	112.6	139.1	19.5	3
Fire starter at back	50.6	54.2	57.9	1.8	2
Match at front*	-	-	-	-	2
Fire starter at front	108.6	130.5	152.4	10.6	2
All scenarios	87.2	101	114.4	26.9	12

* Did not establish fire – match extinguished

The resulting distributions are plotted in Figure 17.

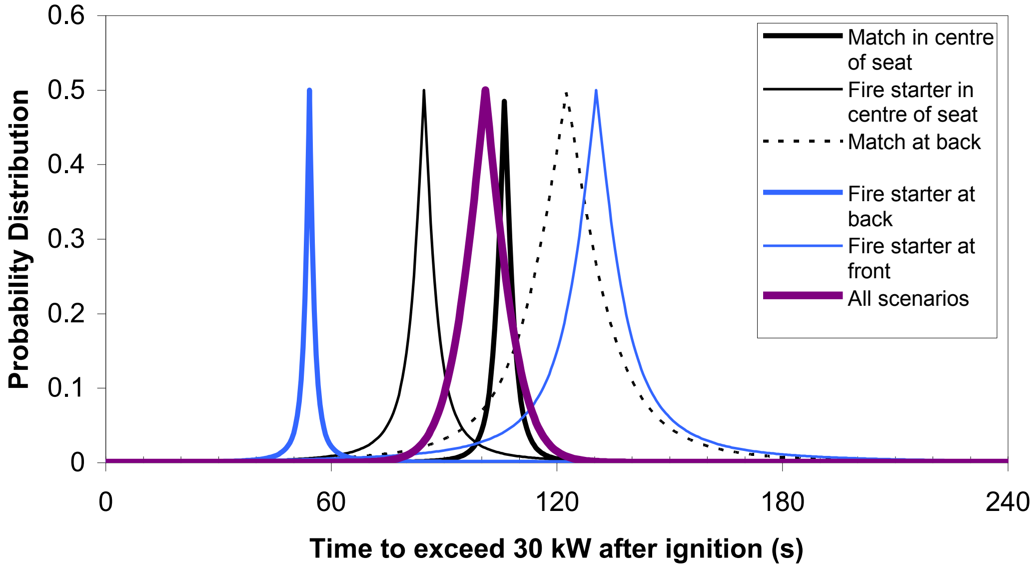

Figure 17. Distribution of likely incipient spread times for upholstered chairs

The individual distributions based on the fire source type are separated into Figure 18 and Figure 20.

4.2.1.1 Statistical distribution of trials with matches

For the match ignition with three trials in each of the three locations shown in Figure 18, the spread in the distribution between the two successful ignition locations is quite different and the third one failed to ignite at all.

The fire-spread response when the match was placed at the junction of the two cushions (see Figure 19) was shown to be highly dependent on exactly where the match is placed. This then influenced how quickly the seat back became involved. The key factor was how soon the flames crossed the gap and spread up the seat back.

Conversely the exact location of the match on the seat centre is not critical, as the mechanism of fire growth is from the centre outwards, unimpeded by any boundaries for the time it takes the fire to become well established.

The fires from the match at the front did not spread as the match extinguished.

The results indicate how variable the progression of a relatively small ignition source, such as a match, may be and that the location has a significant influence.

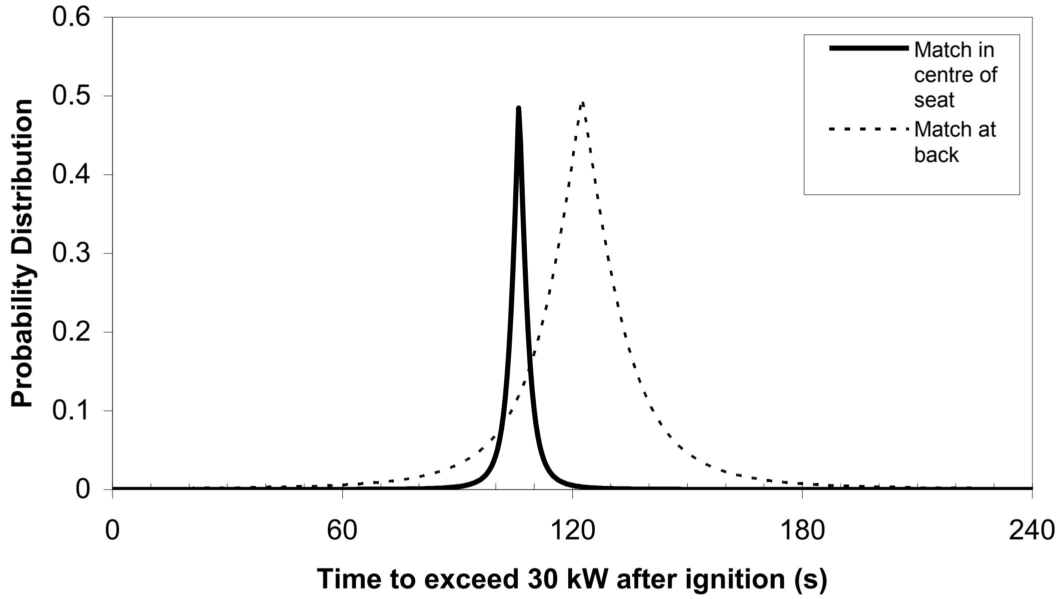

Figure 18. **Distribution of likely incipient spread times for upholstered chairs for match ignition**

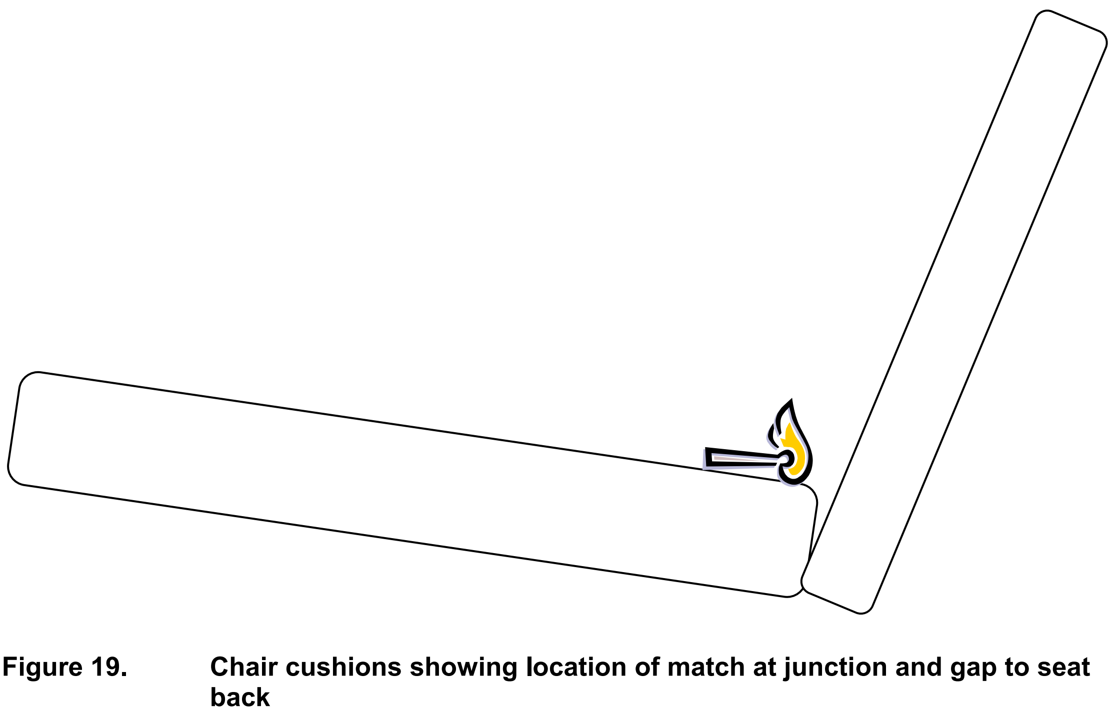

Figure 19. **Chair cushions showing location of match at junction and gap to seat back**

4.2.1.2 Statistical distribution of trials with fire starters

The trials with the fire starters did not have the same delay effect with the seat back as the matches. The physical dimensions of the fire starter meant it happened simultaneously. This resulted in consistent incipient spread times and the compact distribution as illustrated in Figure 20 compared with the wide spread of times for those trials with the match in the same location.

The distribution for the trials ignited using a fire starter located in the centre of the seat base was relatively narrow, similar to that of the match in the same location, albeit with the mean time shifted about 20 seconds earlier.

With the fire starter on the front of the seat base, the time taken for incipient fire-spread is increased and the distribution is wider. It was not possible to complete a comparable analysis for the match fire source as that did not result in any fire-spread.

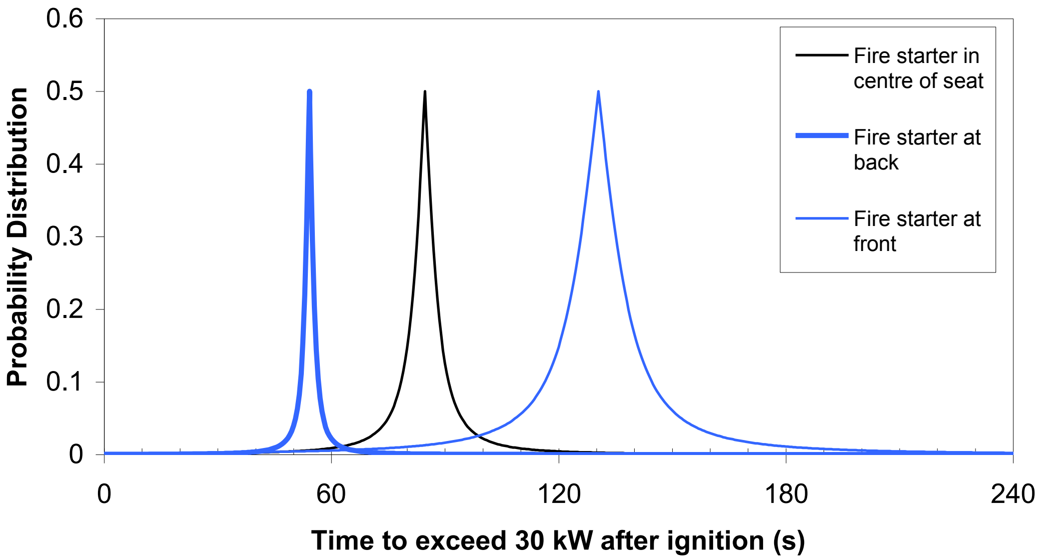

Figure 20. **Distribution of likely incipient spread times for upholstered chairs for fire starter ignition**

4.3 Statistical distribution of time to maximum HRR results

Statistical analysis of the times to reach maximum HRR from the data in Table 7, Table 8 and Table 9 follows a similar pattern to the incipient spread times as shown in Table 11.

Table 11. Distribution of times to maximum HRR for various fire sources and locations

Location	5% (s)	Mean (s)	95%	Sample standard deviation (s)	No. degrees of freedom
Match in centre of seat	151.9	156	160.1	3.0	3
Fire starter in centre of seat	129.2	138	146.8	4.2	2
Match at back	120.6	153	185.3	23.8	3
Fire starter at back	93.2	102	110.8	4.2	2
Match at front	–	–	-	–	2
Fire starter at front	183.2	192	200.8	4.2	2
All 12 scenarios	133.9	149	164.6	29.8	12

The distributions are plotted in Figure 21, and one noticeable trend is the reduced time of the match at the back of the seat to reach peak HRR compared with the match in the centre of the seat, and compared with the relative times of the incipient spread phase. This supports the observations that the rate of fire development was greatly assisted by the orientation of the inclined surface of the seat back, and the earlier the seat back became involved in the fire, the earlier the peak HRR occurred.

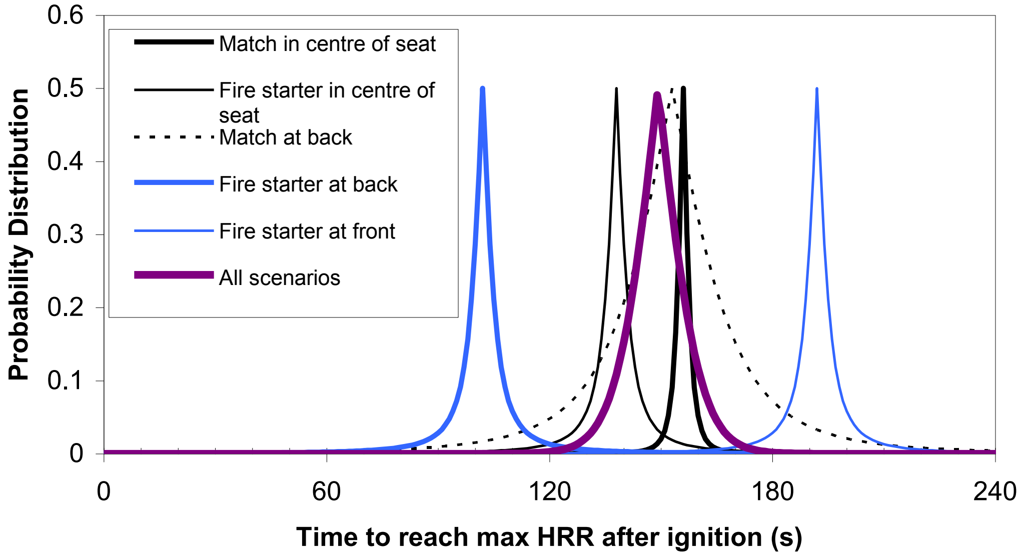

Figure 21. Distribution of likely times to reach maximum HRR for upholstered chairs

5. TESTING WITH REAL SOFA CHAIRS

In addition to the 12 purpose-built chairs burnt, three further sofa chairs of predominantly foam construction with an average weight of 21 kg were burnt, as shown in Figure 22. The method of ignition was a single match placed in the centre of the seat cushion. In two of the three trials the match went out and a second match placed on the slightly charred spot of the first match then resulted in a sustained fire. In the other case, just a single match was required. This observation supports the earlier decision (Section 3.2.3) by indicating that a single match is close to the minimum size ignition source required to reliably initiate a fire.

Figure 22. Sofa chair

5.1 Results and analysis

The results of the three burns with the sofa chairs are shown in Table 12. The incipient fire development period, as defined by the time to 30 kW, was almost identical for the first and third chairs while the second chair lasted 25 to 28 seconds longer.

Table 12. Incipient fire-spread on sofa chairs

Fire source type and location	Chair match in centre of seat (1)	Chair match in centre of seat (2)	Chair match in centre of seat (3)
Time to exceed 30 kW after ignition, s	146.7	172.2	144.3
HRR peak, kW	913.8	734.0	745
Time of peak, s	321.0	345.0	270
Fire growth rate, αt^2 where α =	0.054	0.067	0.065
t_o, s	117.1	149.0	119.1
Correlation	0.9964	0.9962	0.9985

The HRR for the three sofa burns are graphed in Figure 23, where the incipient spread stage for two of the burns are identical as indicated by the closeness of the HRR curves in the early stages up to 300 kW. The other burn had the same upward slope, but lagged behind due to a longer incipient fire development stage.

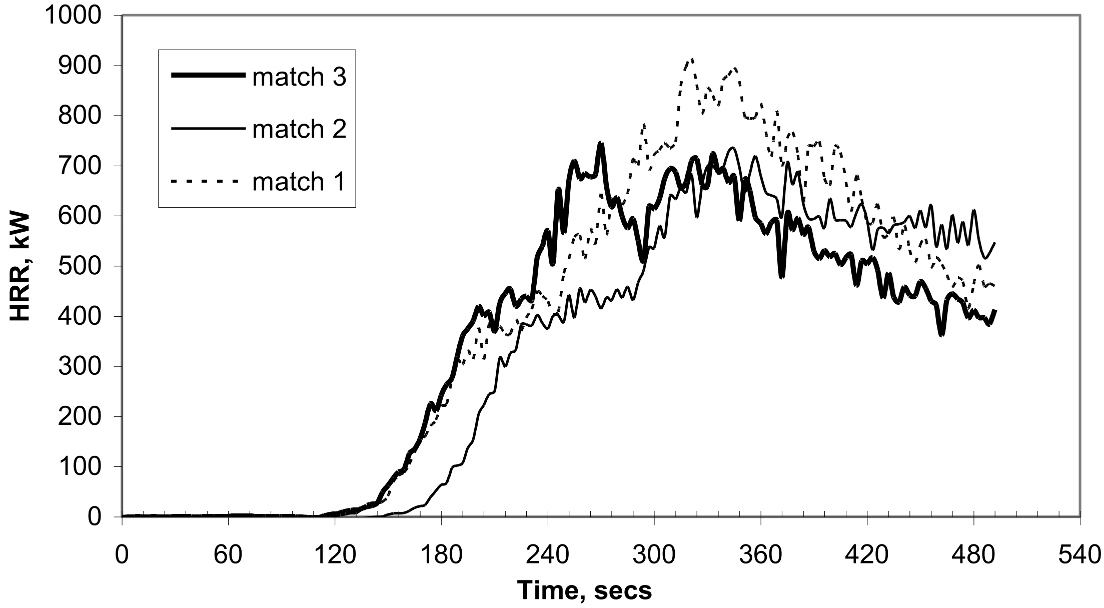

Figure 23. HRR with ignition source in centre of seat of sofa chair

It was observed that during the initial fire growth period, the HRR partially plateaued in the region between 350 and 450 kW before increasing again. This was because the burning of the seat base approached a plateau before the seat back became involved and the rate of increase in HRR accelerated towards the eventual peak. The sequence of pictures in Figure 24 typically shows the incipient fire development to 30 kW and subsequent spread to the seat back leading to the peak HRR and subsequent decay.

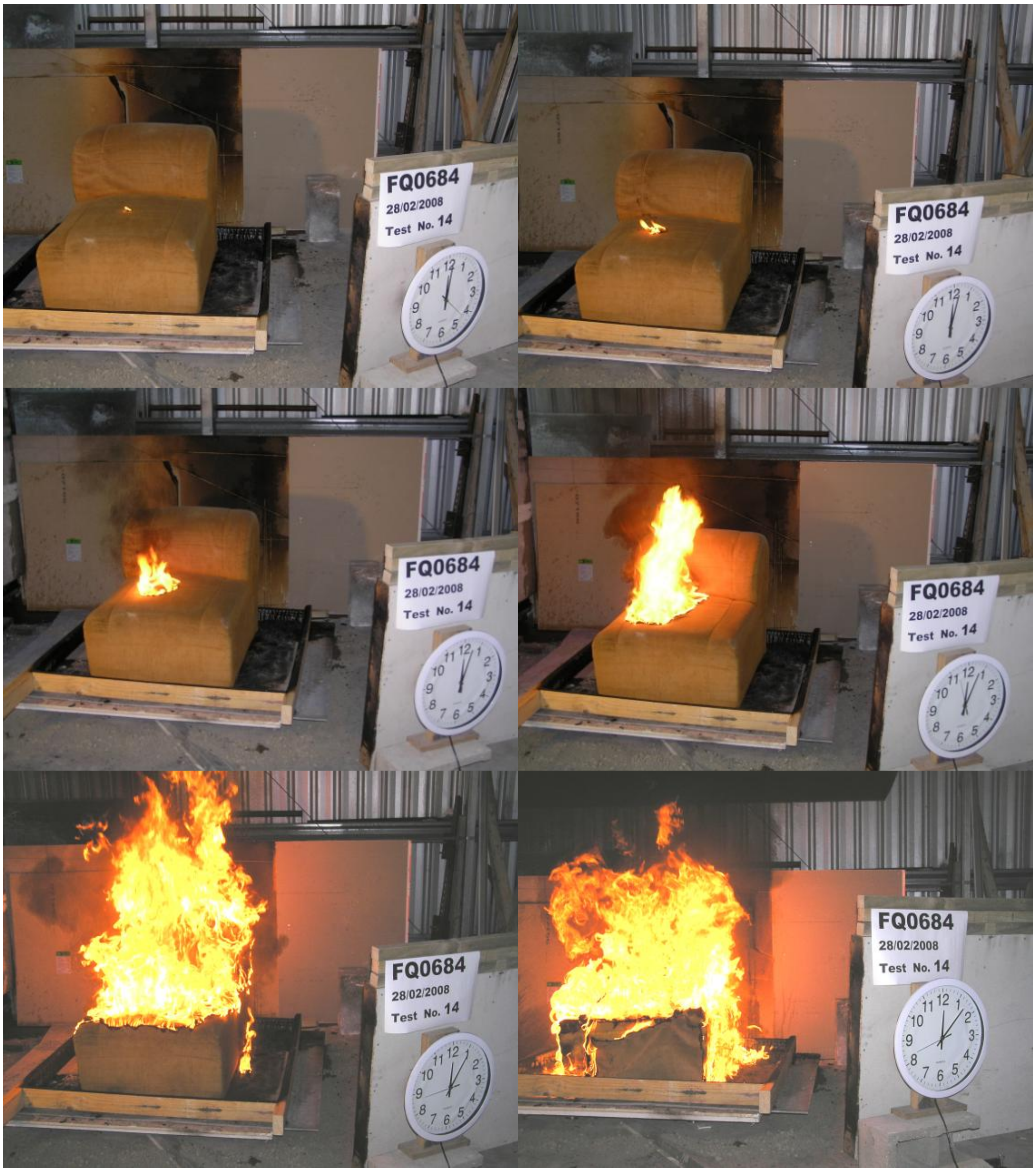

Figure 24. **Fire growth with match in centre of sofa seat, 30 kW was exceeded at 172 seconds, fourth photo in sequence**

5.1.1 Statistical distribution of incipient fire-spread

Table 13 shows the results for the mean, standard deviation and 5% and 95% confidence intervals of the student t distribution that best fits the sample results for incipient fire development based on the time to exceed 30 kW HRR.

Table 13. Distribution of incipient fire development times and time to peak HRR for sofa seats with match ignition in the centre of sofa seat

Parameter	5%	mean	95%	Sample standard deviation	No. degrees of freedom
Incipient spread (s)	133.3	154.4	175.4	15.5	3
Time to peak HRR(s)	259.9	312	364.0	38.3	3

The resulting distribution for the sofa chair with 95% confidence for incipient spread time and time to peak HRR is plotted in Figure 25 and Figure 26.

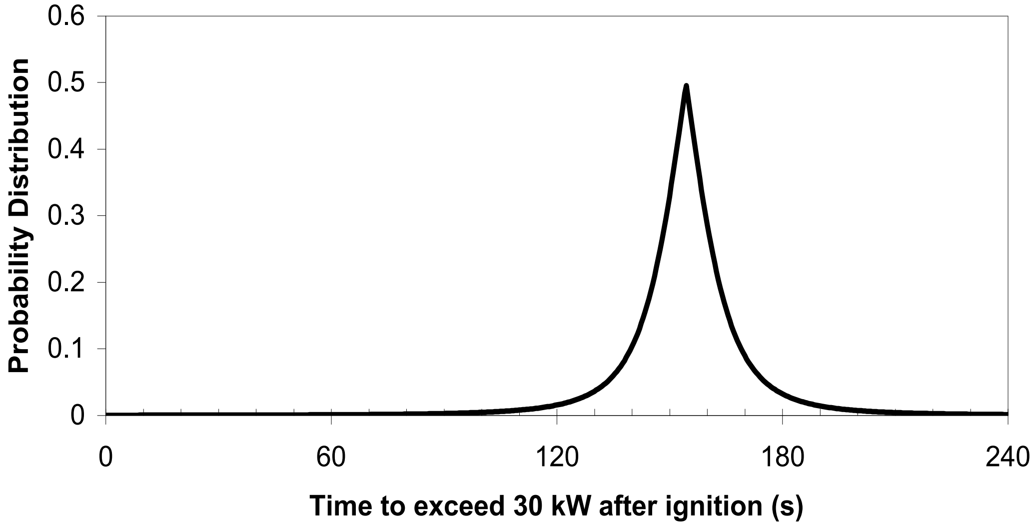

Figure 25. Distribution of likely incipient spread times for sofa chairs

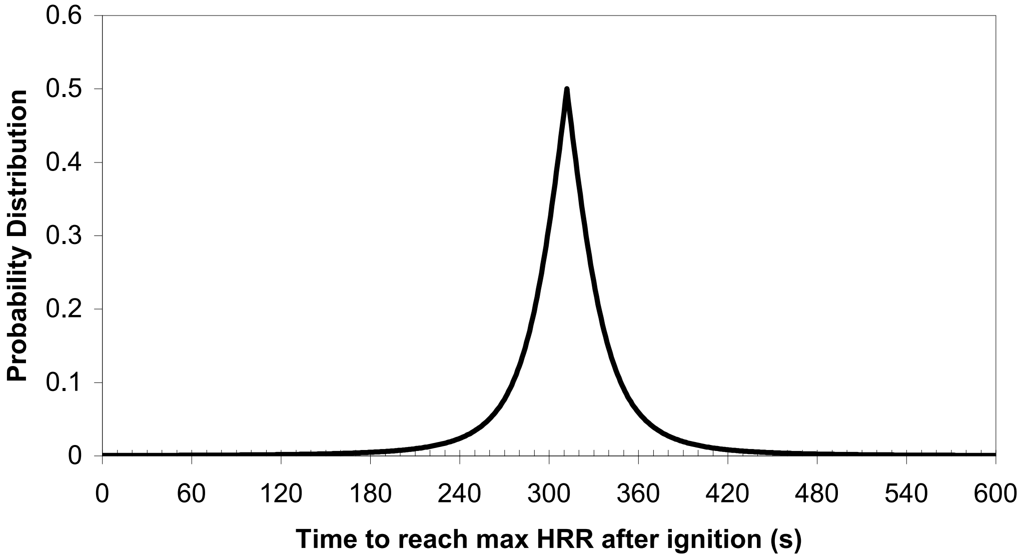

Figure 26. Distribution of likely times to peak HRR for sofa chairs

6. SMOKE LEVELS

In considering the smoke levels generated during the incipient fire development phase, and whether the smoke is of sufficient level to activate smoke detection equipment, the SEA and the HRR of two trial burns are compared in Figure 27 and Figure 28 for the early stages of fire development and beyond. In the two examples considered, there was a presence of smoke detected (SEA) prior to the HRR reaching 30 kW. On this basis, it could be predicted that smoke detectors in the compartment with the burning item may activate and give warning prior to 30 kW being exceeded. However, there are other variables, such as compartment size and smoke filling rate, as well as individual smoke detection system responses that make it not possible to comment on detector responses for the instances trialled here.

The challenge in evaluating the merits of including the incipient fire development time is to determine how much warning would be given in practice.

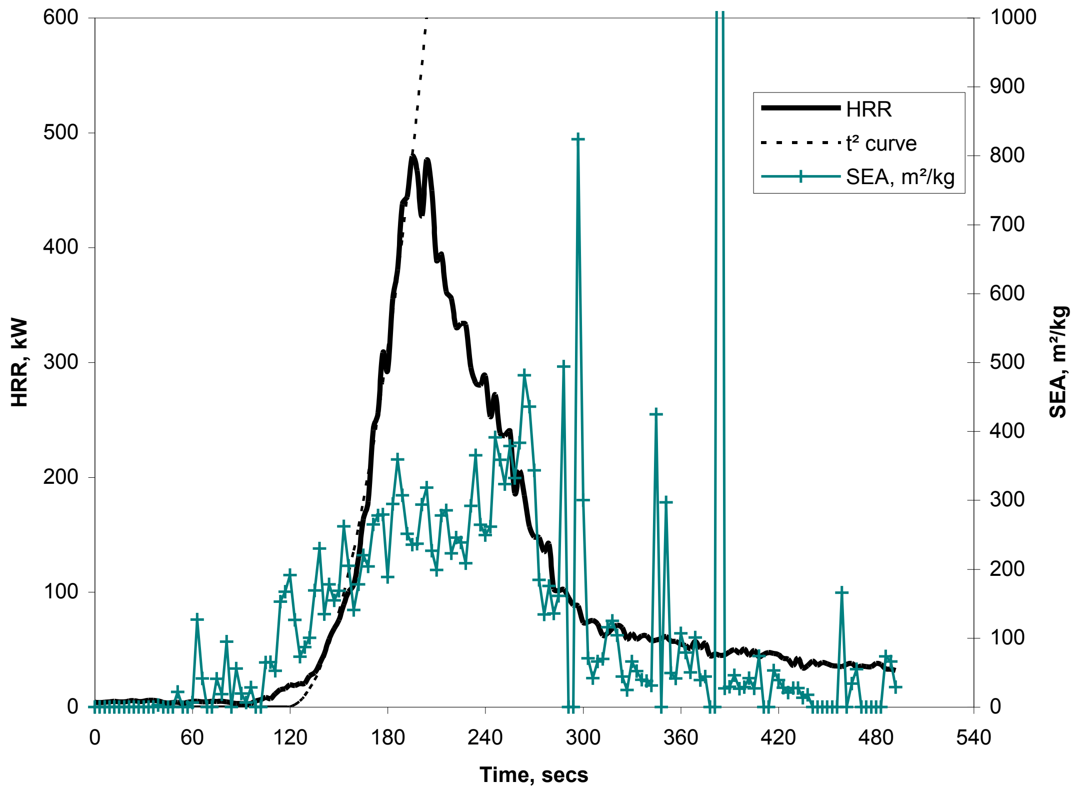

Figure 27. Comparison of HHR and SEA for purpose-built seat burn with fire starter ignition and incipient fire development time of 135 seconds (30 kW)

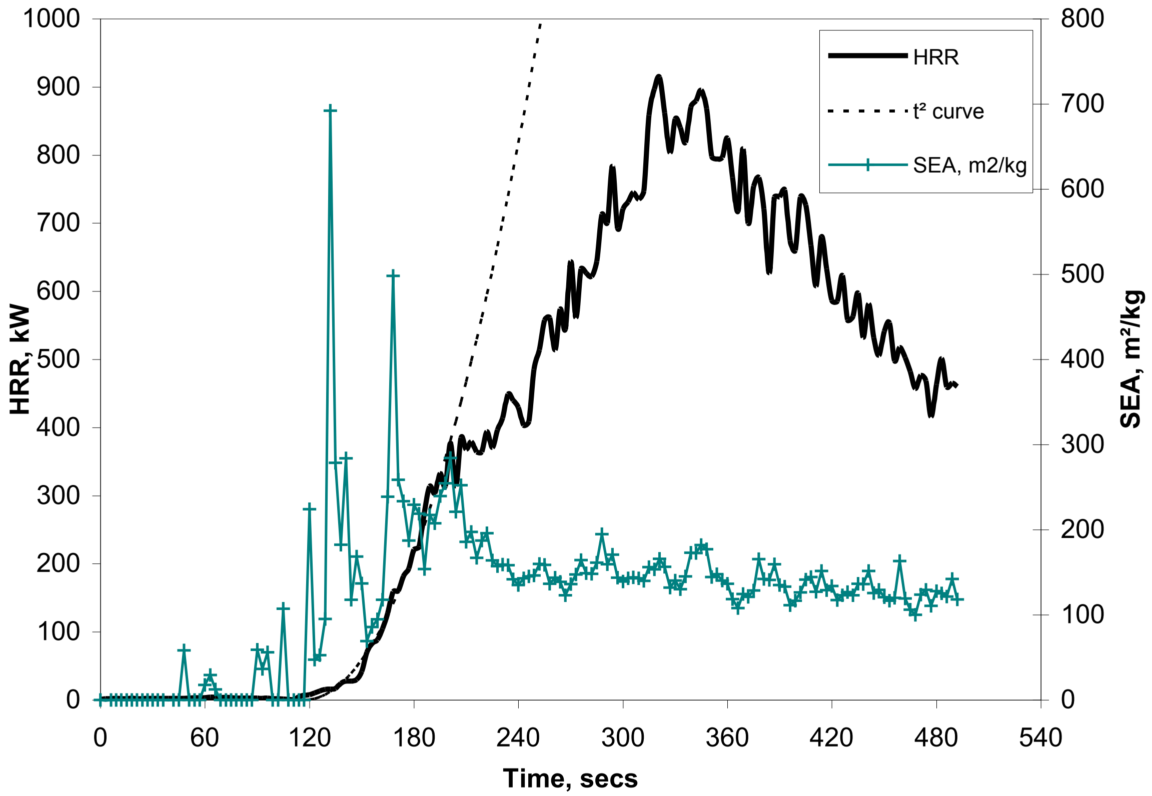

Figure 28. Comparison of HHR and SEA for sofa burn with match ignition and incipient fire development time of 146.7 seconds (30 kW)

The oscillating nature of the SEA is attributable to the noisy nature of the mass loss data from the load cell the chair was positioned on.

7. SUMMARY OF INCIPIENT FIRE DEVELOPMENT

For each scenario considered in the trials, the lower confidence limit at 5% is selected such that there is 95% confidence that the incipient spread time will be equal to or exceed the values in Table 14 for the selected scenarios.

Table 14. Summary of incipient spread times

Location and type of ignition source	Lower 5% limit, (s)	Mean,(s)	Standard deviation(s)
Match in centre of seat	100.4	156	3.0
Fire starter in centre of seat	75.0	138	4.2
Match at back	86.1	153	23.8
Fire starter at back	50.6	102	4.2
Match at front	No ignition	No ignition	No ignition
Fire starter at front	108.6	192	4.2
All 12 scenarios	133.9	149	29.8
Sofa chair, match in centre	133.3	154.4	15.5

Considering the incipient fire development time from ignition to sustained flaming of 30kW, the length of this period needs to be compared with the total burn time of the chair item, the subsequent spread to other items and eventual full room involvement/flashover and the time to untenable conditions.

All 15 scenarios trialled are combined in Table 15 for the distribution of the incipient fire development times and the time to peak HRR. The distributions are plotted in Figure 29 and Figure 30.

Table 15. Distribution of incipient fire development times and time to peak HRR for all scenarios

Location all scenarios including sofa chair	5%	mean	95%	Sample standard deviation
Time to exceed 30 kW (s)	88.3	110.2	132.1	33.3
Time to peak HRR (s)	133.2	181.2	230.3	73.8

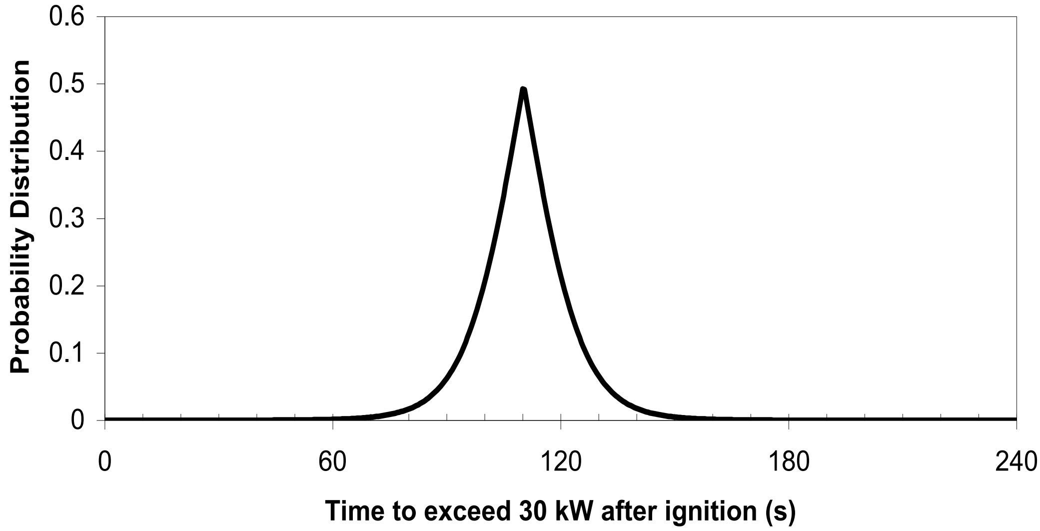

Figure 29. Distribution likely times to exceed 30 kW for all scenarios

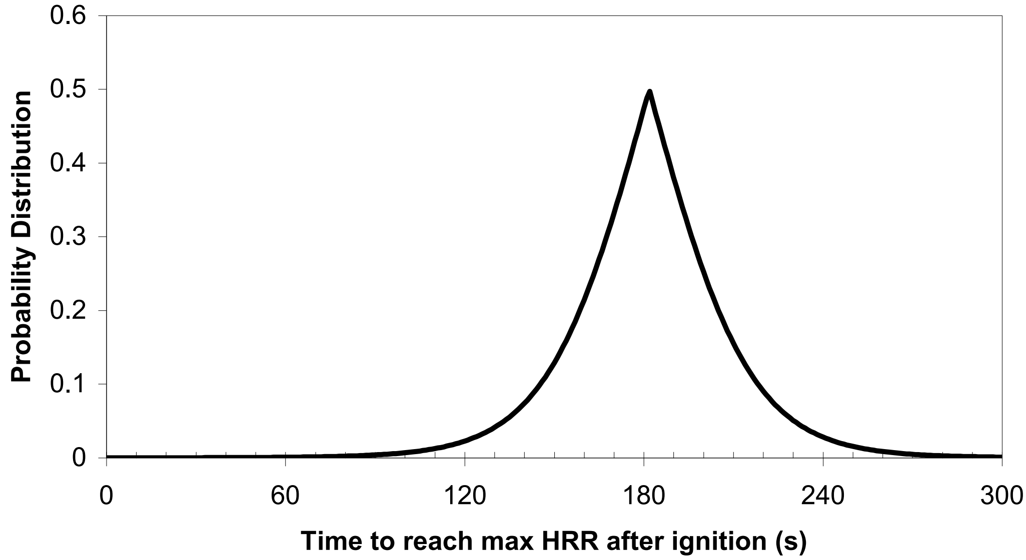

Figure 30. Distribution likely times to peak HRR for all scenarios

Given the additional uncertainty of the type of ignition source, its location and the particular item of furniture that will be first ignited, then the lower 5% incipient fire development time of 88 seconds is representative of a likely lower bound time for an incipient fire development period.

Another likely scenario at the opposite end of the spectrum is an incipient fire development that takes longer, and perhaps considerably longer to develop, and may even extinguish before the onset of a rapid growth phase. Such an outcome would not develop to a fire and therefore it is unlikely to be recorded in the statistics.

8. CONCLUSIONS

Based on the results of the series of tests conducted under the extraction hood of the ISO9705 room apparatus of 12 purpose-built typical New Zealand upholstered chairs and three sofa seats, the timeline of the incipient fire development and complete combustion was analysed from ignition through the peak HRR and into the decay phase. The following conclusions were drawn:

- The end of the incipient phase was shown to be most satisfactorily characterised by the HRR exceeding 30kW.
- The determination of the duration of the incipient phase time $\mathbf{t_o}$ by correlating a t^2 curve to the actual HRR curve up to the first peak where $\mathbf{t_o}$ is the difference between application of the ignition source and commencement of t^2 fire growth produced close correlations of the order of 0.99 but produced wider variations for $\mathbf{t_o}$ than the previous method where HRR reaches 30 kW
- The location of the ignition source was shown to influence the incipient fire development.
- The closer the ignition source was to the centre of mass of the combustibles, the shorter the incipient fire development.
- The type or size of fire source influenced the incipient fire development. However, larger fire sources (such as the fire starters) resulted in more rapid fire-spread compared with matches and small smouldering sources (such as discarded cigarettes) failed to progress at all in the preliminary trials attempted.
- Student t distributions to 95% confidence were prepared for the trials that resulted in ignitions, and the lower end 5% value is recommended for use in modelling applications.
- The lower 5% incipient fire development time assessed in the trials would be significantly less than the 5% applicable to a more representative sample of furniture found in buildings. This is because a selection of worse-case furniture was used and that smouldering fire scenarios were ignored for the experiments.

The experimental trials conducted in this project resulted in relatively short times for incipient fire development compared with much longer times in the range of 10 to 36 minutes in the study by Mittler and Tu (1994) (that used a gas flame for ignition). This indicates a much longer initial phase, perhaps involving a considerable period of smouldering before any flaming of the furniture item develops.

The findings in this study indicate incipient spread times in the range 50 seconds to 133 seconds based on the lower 5% of the distributions for the narrow range of samples burnt. It is acknowledged that the furniture samples selected were a small subset representative of low-cost upholstered furniture and were ignited using flaming ignition sources. It is unknown what the distribution would be based on a representative cross-section of furniture in buildings with a realistic range of ignition sources, except to recognise that the incipient spread times would be greater and cover a larger range.

This study did not include experiments involving smouldering ignition sources in the dataset generated. The experimental furniture items trialled were mock-up upholstered furniture components (fabric/foam) on metal frames that were at the poorer performing end of the range of furniture existing in New Zealand, and three ‘used’ PU foam sofa chairs. Both these factors mean that estimates of the incipient fire development period derived from this study are likely to be underestimates, compared to what might be observed for the total population of upholstered furniture in the building stock and for the total range of actual ignition sources and scenarios (flaming and smouldering) that occur in practice. Consequently, it is expected these results would be conservative estimates of the incipient fire development period.

The analysis of the incipient fire development obtained for the individual scenarios showed a degree of repeatability between some pairs of results, but also some statistical spread, indicating a predictable degree of randomness and uncertainty characteristic of the statistical distributions.

The results obtained here also reconfirm that the current practice of ignoring the incipient fire development period is conservative for the purpose of calculating ASET based on a fast t-squared design fire.

9. RECOMMENDATIONS

On the basis of the relatively short time of the incipient fire development observed in the experiments, it is recommended that NO allowance for incipient fire development be included in the timeline of fire development in the period up to the establishment of a t^2 growth rate.

However, there is a need for a case study analysis to be undertaken for a range of buildings, with calculations of ASET and RSET including detection times and an incipient period in the design fire. Perhaps then conclusions can be drawn about whether the advantages (if any) of including an incipient period are justified from the point of view of recommending changes to current fire engineering design practice.

10. FUTURE WORK

The experiments conducted in this project intentionally focused on a narrow range of likely incipient fire development outcomes for the express purpose of determining a statistical distribution. There is clearly a need for further experiments using a wider range of representative furniture and ignition sources, to provide a more comprehensive and statistically significant data set.

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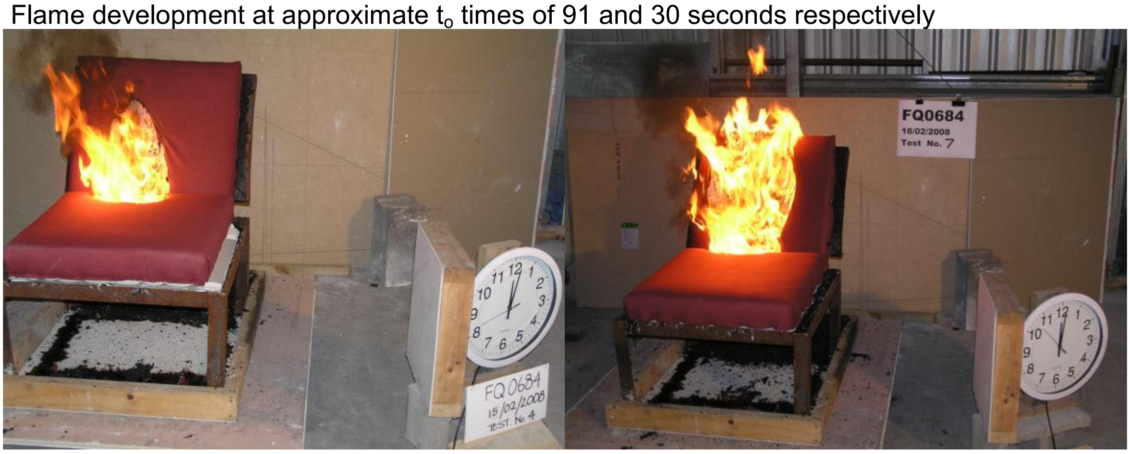
12. APPENDIX 1: COMPARISON OF MATCH AND FIRE STARTER IGNITION

Equivalent flame size after 72 seconds from ignition with match vs 14 seconds from ignition with fire starter

Flame development at approximate t_o times of 91 and 30 seconds respectively



Fire development when HRR had reached 30 kW

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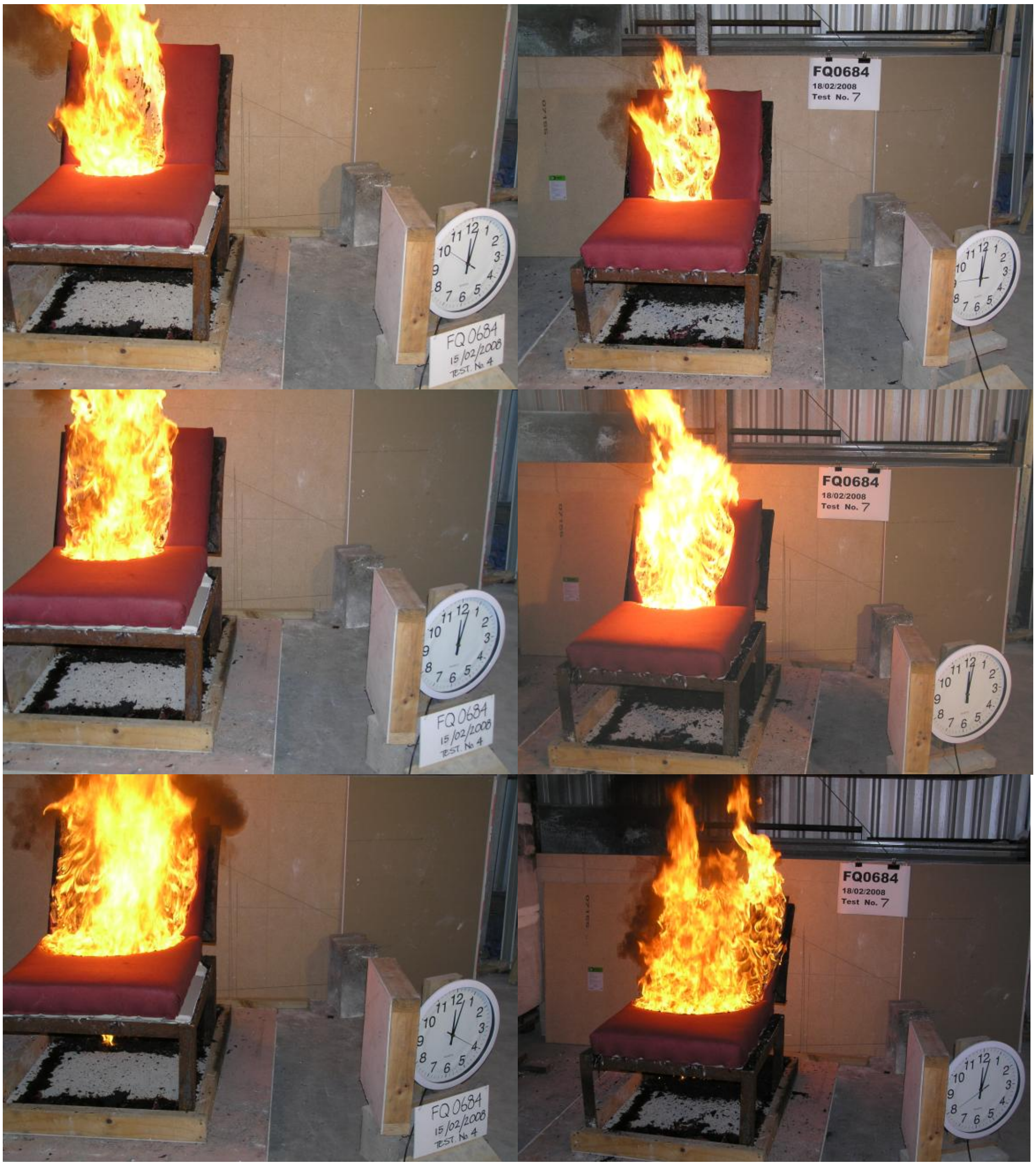

Extent and location of flaming at peak HRR of approximately 334 and 298 kW respectively

Figure 31. Comparing ignition by match and fire starter