

Development of Low-Cost Fire Blocking Inter-Liners for New Zealand Furniture

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ABSTRACT

Over the past 20 years soft furniture in New Zealand has followed the same global trend of incorporating an ever increasing proportion of synthetic polymeric materials. Despite the proven flammability potential of the products, the willingness to introduce regulations controlling the threat of flammability of these household items has been absent.

During the same period substantial improvements have been made in the field of fire retardant or fire and heat resistant fibres, however, application of these in the furniture market has not been widely supported. This research project aims to demonstrate that relatively simple and low-cost fire barriers can be produced which substantially reduce the heat release rate and delay the time to peak heat release rate of polyurethane filled soft furniture.

The approach taken here considers the reduction of the thermal contribution from the polyurethane inner core that forms the major proportion of the products' fire load. This research does not consider or seek to eliminate the threats created by a flammable upholstery layer. It is noted that the latter threat is also an important consideration and the achievement of a truly fire resistant furniture product can only be obtained by the fire resistance of all of its components.

The research described in this report has shown that an effective low-cost fire barrier for furniture is achievable using blends of readily available fibres and additive treatments, combined in a non-woven substrate.

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Abbreviations

| | | |
|-----------------|---|-------------------------|
| APHRR | Average Peak Heat Release Rate | (kW/m ²) |
| ASTM | American Society of Standards and Materials | |
| B | Basofil | Fibre |
| BS | British Standard | |
| CO | Carbon monoxide yield | (g/g fuel) |
| CO ₂ | Carbon dioxide yield | (g/g fuel) |
| CPSC | Consumer Protection Safety Committee | USA |
| CTB | California Test Bulletin | |
| ΔH _c | Net Heat of Combustion | (kJ/g) or (MJ/kg) |
| EHC | Effective Heat of Combustion | (kJ/g) or (MJ/kg) |
| FAR | Federal Aviation Regulations | USA |
| FB | Fire Blocker | |
| FR | Fire Retardant | |
| FRST | Fund for Research, Science and Technology | NZ Government |
| FRV | Fire Retardant Viscose | Fibre |
| G | Grafil | Fibre |
| HR | Heat release | (MJ) |
| HRR | Heat Release Rate | kW or kW/m ² |
| IWS | International Wool Secretariat | |
| LOI | Limiting Oxygen Index | % |
| OD | Optical Density | - |
| P | Panox | Fibre |
| PAHRR | Peak Average Heat Release Rate | (kW/m ²) |
| PHRR | Peak Heat Release Rate | (kW/m ²) |
| PP | Polypropylene | Fibre |
| PU | Polyurethane | Foam |
| RSR | Rate of Smoke Release | (m ² /s) |
| SEA | Specific Extinction Area | (m ² /kg) |
| s.d. | Standard deviation | - |
| TPI | Thermal Protective Index | (s) |
| TSR | Total Smoke Release | (m ²) |
| TTP | Time to Peak | (s) |
| UFAC | Upholstered Furniture Action Council | USA |
| w/w | Weight for weight | (kg/kg) or (g/g) |
| Z | Zirpro treated wool | Fibre |
| Z/P or z/p | Zirpro/panox blend | Fibre blend |

1.0 INTRODUCTION

1.1 Scope of this research

Independent studies [1, 2] of the New Zealand burn related deaths and injury data, spanning the last 30 years from the 1970's until 2000, have determined that a relatively constant percentage of between 20% and 30% of deaths and injuries can be related to fires involving bedding and upholstered furniture in residential buildings. It is a well established and documented fact that common, untreated or unmodified upholstered furniture exhibits rapid flame spread and fire growth characteristics leading to considerable risk to life and property [3-8]. At present, in New Zealand, there are still no mandatory rules or regulations governing the manufacture and sale or importation of upholstered furniture, in terms of fire safety.

Some countries, notably the UK, and the State of California in the USA, have introduced mandatory regulations and minimum standards, such as BS 5852 [9] and the California Technical Bulletin 117 [10], while some trade organisations such as the Upholstered Furniture Action Council (UFAC), USA and the Consumer Protection Safety Commission (CPSC), USA have implemented voluntary standards in response to the risk, such as Technical Bulletin, TB 116 [11], but not all Associations of Furniture Manufacturers are in agreement as to which standards should be adopted [12].

The difficulties of regulating the improvement of the fire safety of NZ upholstered furniture can be attributed to the issue of 'Cost'. For governing bodies this is the Cost/Benefit outcome dominated by the increased costs due to regulation, administration and enforcement against the expected numbers of lives and property saved per year; while for manufacturers it is the cost of production, compliance and market competitiveness.

The purpose of this research is to demonstrate whether a fire barrier inter-liner can be produced from low cost fibres which perform comparably against more expensive and established inter-liners. If successful, the low-cost barrier may make it more attractive for voluntary inclusion into furniture products by New Zealand manufacturers in light of the absence of mandatory standards.

It is by no means a 'new' invention as many inter-liner materials and composites have been patented and used for several decades but, the availability and usage of these in domestic

furnishings is still underutilized. Published data and studies on inter-liner development are difficult to find and appear to contribute a very small percentage of the total literature on domestic fire safety research.

Three likely reasons for this could be; the lack of support for the development of such materials, a shift in focus toward the improvement of the polyurethane foam compounds and the patenting of fire-blocking fabrics for commercial benefit of the inventor. There is no doubt that work has been done over the past twenty years, since the aircraft industry provided an opportunity and market for FR inter-liners in their aircraft seating.

As a cautionary comment we must point out that this work, although promoting the introduction of inter-liner materials, does not imply a complete solution to solving the combustibility problems associated with foam padded furnishings. For a more thorough approach to the problem the recommendations should incorporate an integrated fire resistance of every combustible sub-component of the furniture item i.e. upholstery, foam and frame materials.

The choice of upholstery fabric and underlying component materials has been clearly demonstrated to have pronounced effects on the burning characteristics of soft furniture composites [4, 13, 14]. Protection of the foam component does nothing to reduce the ignition susceptibility and burning of the surface material. In fact, in some cases it may increase the heat release rate contribution from the upholstery once ignition has been established, leading to greater risk of igniting nearby objects. Despite this, the greatest fire risk is from the mass bulk of polyurethane foam filling contained within the furniture.

Historically, the topic of choosing the best solution to reducing combustibility of soft furnishings has been a point of heated debate since the early 1980's [15] because of the expected costs of regulating every component material and the inevitable increased costs of production which will be passed onto the consumer. The alternative of regulating only the most combustible or greatest contributor to the fire load also raises much acrimonious debate because it singles out and disadvantages only select products and manufacturers, who see themselves as being victimized

Unlike the lack of literature on the subject it is not difficult to obtain physical samples of commonly used FR inter-liner fabrics and to ascertain their composition. The very first fire

barriers to emerge contained a high percentage of wool, blended with other fibres, which when treated with a zirconium or titanium complex (Zirpro treatment developed by the International Wool Secretariat (IWS)) obtained fire resistant capabilities above its natural FR qualities. In the years following, research and development into synthetic fibres produced FR filaments with exceptional incombustibility and heat resistance and eventually these began to replace the wool or natural fibre portion of FR materials, but at a much higher cost of production.

1.2 Objectives of this project

The objectives of this report form part of a larger FRST funded project on Functional Safe Environment. Its main aim is to develop the foundation for a low cost fire-blocking layer or inter-liner for use in New Zealand domestic furniture, by blending FR treated wool and a high temperature resistant fibre in a non-woven structure. Existing high-tech fibre fire blockers are very effective but prohibitively expensive to incorporate into furniture manufacturing. By combining low cost FR treated wool with altered proportions of different fire resistant synthetic fibres, we aim to identify the best performing fibre blend and proportion producing equivalent performance to some existing, more expensive fire blocking fabrics.

This research aims to demonstrate that:

- (i) An effective fire resisting fibrous inter-liner for domestic furniture can be simply constructed using fibre entanglement (needle-punching) instead of woven fabric.
- (ii) An effective fire-resisting inter-liner can be made using lower cost components than most similar, commercially available products.
- (iii) It is possible for a low-cost, simply constructed fire-resistant inter-liner to have comparable performance to more expensive commercially manufactured products, for a significant time exposure to flames.

1.3 Outline of report

This report examines the combustion performance of inter-liners through a combination of small and medium scale experiments. Chapters 1 and 2 introduce the topic of the research and provide a brief background of the history and involvement of fire barrier in the last 30 years.

Chapters 3 to 6 deal with thermally resistant fibres, treatments, materials and production of the experimental fabric. Chapter 3 lists the most commonly obtainable technical fibres, which were procured for the research, together with brief explanations of their relevant attributes. Chapter 4 discusses the choice of textile FR treatment for this work while Chapters 5 to 6 outline all of the materials and processes used to construct the experimental samples.

Test methods and experimental apparatus are explained in Chapter 7. Three test methods form the basis of the investigation commencing from small basic heat transfer comparisons through to more detailed measurement of performance at full scale.

Chapter 8 takes the reader through the results of the small scale experimental investigations and discusses the general outcomes from each. Analysis and results of the full scale experiment are discussed in Chapter 9 after which major conclusions are drawn and explained in Chapter 10, followed by some recommendations for further research in the final Chapter, 11. The Appendices contain a more complete graphical listing of individual sample test responses, details of test equipment and photos from full scale tests.

2.0 BACKGROUND

The introduction of inter-liners, or intermediate layers of material between the surface upholstery and the resilient polyurethane foam core of furniture has been evident since at least the 1970's and grew throughout the 1980's, when the aircraft industry began to introduce higher standards of testing and performance for aircraft seating and fixtures. During the 1970's it was recognized that the greatest fire-load contribution within the passenger cabin was exclusively from the polyurethane flexible foams used in the seating assembly [16].

Regulatory requirements were enhanced in 1986 that subsequently required the upholstery/cushion combinations to pass a severe fire resistance test, FAR 25.853(c) [16]. The easiest solution for compliance with the new regulations was to encapsulate the foam within a durable fire blocking fabric, subsequently leading to enhanced popularity and inclusion of fire-blocking inter-liners in aircraft seat design.

Research and development of fire resistant materials and composites increased during these years to cater, in part, for the increasing requirements and standards of the commercial aircraft industry.

Other fields to benefit from the new interest in FR fabrics were those such as fire-fighting, motor sport, electrical and metal production industries to name but a few. Aside from the obvious applications just mentioned the domestic market was also a prime candidate for improvement especially with consideration to the exponential growth in polyurethane foam usage and its demonstrated fire risk when ignited within an enclosed space.

For several decades now the flammability potential of modern furniture has been well demonstrated and documented both internationally and nationally. Within New Zealand work done at the Wool Research Organisation of New Zealand, (WRONZ) by Ingham et al. [5-8] in the late 1970's and early 1980's provided ample evidence of this risk while more recently, the research projects at the University of Canterbury have continued to highlight the fact that New Zealand furniture has not made any progress in terms of the fire safety issue [2, 3, 13, 17].

These concerns have been raised many times and taken to the highest political sub-committees but moves to introduce mandatory measures for improved safety have always been met with resistance and reluctance from those with commercial interests; as well as from those organizations which would inherit the responsibility of implementing and enforcing the mandatory regulations [15].

3.0 FIRE AND THERMALLY RESISTANT MATERIALS

Although the majority of textile related fibres associated with heat resistance and flame retardancy are chemically after-treated and are not originally fire resistant, about 20% by mass of textile fibres produced can be grouped into the category of synthetic, flame or heat resistant specialty fibres, Horrocks et al [18].

Their inherent high temperature characteristics can mostly be attributed, but not exclusively limited to, several mechanisms of interaction and interruption of the combustion process. Most commonly two mechanisms described by modes 2 and 3, listed in (Table 1) below, result in heightened decomposition temperature and increased char formation.

Table 1. List of different mechanisms for fire retardant action

| Modes of interruption | Example |
|---|--|
| 1 Removal of heat | High heat of fusion and/or degradation and/or dehydration. E.g in inorganic and organic phosphorus-containing agents, aluminium trihydrate or aluminium hydroxide back-coatings. |
| 2 Increased decomposition temperature | Not usually exploited by flame retardants and more usual in inherently flame and heat resistant fibres, like aramids. |
| 3 Increase in char formation and decrease in flammable volatiles | Most phosphorus and nitrogen containing flame retardants for cellulose and wool; heavy metal complexes in wool e.g. Zirpro treatment. |
| 4 Reduced access to oxygen or flame dilution | Hydrated and some char-promoting retardants release water; halogen containing retardants release water. |
| 5 Interference with flame chemistry and/or increase fuel ignition temperature | Halogen containing flame retardants, often in combination with antimony oxides. |

These qualities, pertaining to the more successful FR fibres, are significant in a handful of aromatic polymers: aromatic polyamides (also known as aramids), polyamide-imides, polybenzoxazoles, polybenzimidazoles, carbonised polyacrylonitrile and melamine based

compounds to name but a few. A good initial indication of a material's ability to resist combustion is the measure of its Limiting Oxygen Index (LOI). It is the concentration of oxygen in the test environment needed to sustain combustion of a sample of the material. Since the normal environmental oxygen concentration is approximately 21%, substances which readily burn at an LOI of 21 or less are considered to be flammable while those requiring a higher LOI index are considered to be flame resistant. Wool is often mentioned as having flame resistant qualities and the LOI of scoured (degreased) wool has a tabulated LOI value of 25 [18]. Many synthetic fibres are now available which obtain LOI indices between 30 and 40. Some exceptional fibres have LOI around 60 [18].

Most of the fibres obtained for this research fall within the categories and chemical groups just mentioned above. A brief description of each fibre type trialled in this research and their associated attributes follows below.

Kermel & Kermel Tech.

These are fibres specifically designed for high temperature applications although in different fields and conditions. Kermel is a polyamide-imide and is naturally non-flammable due to its chemical structure. It is mainly used in heat and fire protective clothing. It is thermally stable up to a temperature of 400°C, has good elasticity, abrasion resistance, chemical resistance and low thermal conductivity (~ 0.04 W/mK). Kermel has an LOI of around 32.

Kermel Tech is a polyamide-imide developed for high temperature gas filtration. It has many of the same characteristics as Kermel fibre such as thermal performance, chemical resistance and sustained mechanical performance but this fibre is designed to operate for extended periods of time between a temperature range of 160°C to 240°C [16].

P84

P84 is a polyimide fibre available from Inspec Fibres. This material provides, according to the promotional literature [20], ability to operate at high temperature, good flame retardant properties and chemical resistance. The fibre has a unique trilobal cross-section that creates air spaces between fibres to provide heightened thermal insulation at temperatures where aramids become brittle.

P84 has found a steady application in the protective clothing market especially in such items as protective hoods for fire fighters. Together with the thermal properties and flame resistance it also offers the advantage of being comfortable to wear, is durable, dexterous and offers breathability and wicking of moisture away from the skin.

It is also claimed that it has a good resistance against ultra-violet degradation which many FR fibres such as Kevlar, for example, suffer from.

This polyimide fibre is a non-melting aromatic and halogen-free compound with a LOI of 38 [21].

Basofil

Basofil is a synthetic melamine fibre developed by BASF. It is the product of a condensation reaction between melamine, a melamine derivative and formaldehyde. The resulting chemical structure inherits properties and characteristics associated with its component ingredients and their condensation reaction resins; these being a tolerance for high temperatures, low flammability and chemical resistance [21].

One advantage of Basofil is its relatively low cost compared to its competition whilst offering similar advantages and applications. Because of its low tensile strength Basofil is usually blended with aramids who naturally have superior tensile strength. Applications include protective clothing, drapery and filtration systems. Basofil or Basofil blends are soft, comfortable, durable and easy wearing.

The final structure is a three dimensional arrangement of methylene ether and methylene bridges giving the material desirable properties such as heat stability, low flammability, solvent resistance and wear resistance. It does not melt, drip or shrink when exposed to flame; it has a high LOI (~32) and low thermal conductivity. However, most of the continuous use properties are limited to a maximum use temperature of between 260° and 370°C [17].

Panox

Manufactured by SGL Carbon Group, ®Panox is a thermally stabilised, oxidized polyacrylonitrile fibre. The precursor material is polyacrylonitrile which is then slowly

baked at varying temperatures and in a controlled atmosphere. The result is a material with a very high carbon content (90 – 98) % and with a specific molecular structure. It is a specialised fibre with excellent heat resisting performance and has been widely used in protective clothing fire barriers, either on its own or in blends. It is a fibre which is very easy to process into yarns and fabrics as well as non-woven felts, although its popularity may be restricted by its permanent black colour. Panox has a LOI of around 50.

Grafil

This is also produced from carbonized polyacrylonitrile but the resulting fibre is much stiffer than Panox. The carbon content of Grafil is around 99% and the carbonizing process is taken to an extra stage than with Panox. In comparison to Panox it is a product designed for use in composite materials as opposed to fabric application. Handling of this fibre requires a degree of care as it causes skin irritation because of the extremely fine and stiff structure of the fibres. It is very stable when exposed to flames [22].

FR Viscose

Viscose is a fibre derived from cellulose, initially introduced in the 1890's. FR Viscose by Lenzing is one of a range of modernised variants with a flame retardant additive incorporated into the fibre. It is not only widely used in protective clothing for high temperature applications such as fire fighting, molten metal industries, the military and electricity supply industries but is also an established component of some existing flame barriers for upholstery. FR Viscose is often blended with other high-performance technical fibres such as those already described above. FR Viscose has a LOI of 28 [23, 24]

4.0 FLAME RETARDANT TREATMENTS FOR TEXTILES

During the combustion of any textile, several stages exist which repeat themselves in a cyclical pattern for as long as sustained combustion persists. These interactions apply themselves on the three basic components of any fire, namely the components of the fire triangle, i.e. Heat, Fuel and Oxygen.

For a flame retardant to be effective it must interrupt this mechanism. The modes of interruption can be broadly categorized into 5 groups. Retardants rarely work exclusively in one mode only and the more effective compounds function in several modes and at different stages of the flaming mechanism. Table 1 is a modified summary taken from Horrocks and Price [18] that describes these modes of flame inhibition.

Because of the high wool content chosen in the experimental materials under investigation, we require a flame retardant treatment for wool which has a high probability of success. Wool, amongst all the natural textile fibres, has a high degree of inherent non-flammability. Its qualities unite to make it such with multiple combinations of flame retardant attributes. Wool has a high ignition temperature due to high moisture regain; it has a low hydrogen content, high sulphur and nitrogen content by weight.

Wool has a high Limiting Oxygen Index (LOI) of 25 but it is also claimed that its flame temperature is only around 680°C thereby limiting the amount of decomposition or its rate. It is interesting to note that Horrocks and Price [18] state that since 1986 the flame retardant developments for wool up to 2001 have not advanced significantly. The standard flame retardant treatment for wool has been ‘Zirpro’ developed by the International Wool Secretariat (IWS) in the early to mid seventies.

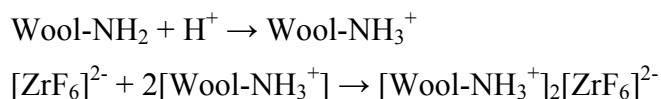
Zirpro is not the only successful FR treatment for wool available but it has withstood the test of time because of its simplicity of application via exhaustion, its reliability in fire tests, durability and compatibility with other post-treatment processing such as shrink resist, insect-resist and fabric finishes. Although not completely understood, the reason for the Zirpro treatment’s success is believed by many to be the formation of an effective intumescent char barrier.

Other flame retardant intumescent compounds, based upon ammonium-polyphosphate, such as Pekoflam TC 203, TC 303 (Clariant), NH-1197, NH-1511 (Great Lakes) and Antiblaze MC M (Albemarle® Corp.) for example, are available which can produce surprising intumescent responses from a wool substrate but, the success in intumescent char formation can conversely detract from the treatments effectiveness as a flame barrier because an over-reaction of the foaming (spumific agent) leads to a substantially large char volume with a very low density. A lowering of the char density to such extremes may lead to a very delicate and mechanically weak barrier which can be easily dislodged or decomposed by impinging flames.

4.1 FR treatment for wool

The Zirpro treatment can consistently produce an intumescent, robust char boundary layer against the penetration of flame and hot gases. The process of application of this additive to the fibre involves the exhaustion of negatively charged metal complexes of zirconium or titanium into the positively charged areas of the wool chemistry. This reaction takes place under acidic conditions ~pH 3 and relatively low temperatures of between 60°C and 70°C and in a vessel suitable for fluid circulation. The treatment recipe used for the Zirpro application for this research is included in Appendix F for completeness.

A basic representation of the Zirpro treatment reaction is shown below:



The wool fibre is exposed to an acidic aqueous solution bath where the disassociated acid components are present and able to react with the absorbing fibre. The detached positively charged hydrogen atoms are free to bond to the amino groups within the wool fibre to form protonated amino groups (-NH₃⁺). The metal fluoride ions of the treatment are then able to bond to the protonated amino groups in the absence of competing compounds, and become trapped within the chemistry of the modified fibre.

A major advantage of this FR treatment is its fastness to both wet and dry-cleaning methods. The deep penetration of the metal complex into the fibre supported by the acidic conditions, combined with the large molecular size and chemical bonding, ensure that the treatment is

effective for up to 50 commercial washes. In terms of the end-use conditions for this project it is not necessary for the treatment to have such effective fastness to washing. As a fire retardant treatment for the intermediate barrier between the foam and upholstery it has to be resistant to mechanical wear but is unlikely it will have to endure a stringent and frequent cleaning process.

Because the application of the FR chemical results in absorption into the fibre, the treatment obtains resistance against mechanical wear from rubbing without the loss of FR qualities. To this end we do not exclusively promote the use of Zirpro above other FR alternatives. Any other treatment which can demonstrate equivalent performance would be acceptable after qualification by experimental evaluation.

The reason that the Zirpro treatment was chosen for this work is the result of many years of experience and familiarity of the process at WRONZ and Canesis Network Ltd, the knowledge that it was developed as wool-specific treatment (although not limited to just wool), the relatively simple process of application and the availability of the compounds at Canesis Network Ltd.

Despite its success, the fact that heavy metals are involved in this compound leads to questions about its environmental impact. Potassium metal fluoride complexes are difficult to dissolve, resulting in unavoidable metal-containing effluent. In addition, because of the inefficient solubility of the metal complexes, there is also the issue concerning the dosage necessary to achieve an effective treatment.

The development of other intumescent treatments not reliant upon heavy metal chemistry could be a breakthrough in this area. As mentioned earlier, these are viable alternatives if equivalent performance can be demonstrated. This could be an area for further research.

5.0 MATERIALS

5.1 Fibres obtained for experimental investigation

5.1.1 Raw materials for initial bench-scale investigations

A range of synthetically produced fibres designed for specific engineering applications (hereafter referred to as ‘technical fibres’) were sourced mainly through Smith Uren Ltd - Raw Materials Traders. The requirement of the chosen fibres was a demonstrated ability to withstand flame and high temperatures. Most, if not all, of the fibres acquired have been or are currently used in protective clothing applications or applications involving high temperatures and/or flaming.

An approximate cost in NZ\$ of each raw fibre has been included in (Table 2), but these are only indicative and largely based upon prices for 2004, during which these fibres were purchased. These estimates are solely for the cost of the fibre and do not include processing costs which are assumed to be identical when blending and forming the needle-punched product.

Table 2. Fibre identification, supplier and approximate cost per kg of raw material

| Fibre | Type | Producer | Supplier | Cost NZ\$/kg |
|-------------|--|------------------|---------------|-----------------|
| Panox | PAN (oxidised) | SGL Carbon Group | Celbar | \$33 |
| Grafil | Epoxy, chopped carbon | Grafil Inc. | Grafil Inc. | \$80 |
| Basofil | Melamine formaldehyde | BASF | | \$22 |
| FR Viscose | Viscose | Lenzing | SU | \$22 |
| Kermel Tech | Aromatic polyimide-amide | Rhodia Kermel | Tex Technique | \$42 |
| Kermel | | Rhodia Kermel | Tex Technique | \$58 |
| PBO (Zylon) | Poly (p-phenylene-2,6-benzobisoxazole) | Toyobo (Japan) | SU | \$257 |
| P84 | Polyimide | Imi-Tech Fibres | SU | \$63 |
| Lambs wool | | | | \$6 |
| Zirpro wool | | | | \$9 |

The acquisition of these fibres was a difficult and time consuming exercise as suppliers and distributors were reluctant to discuss pricing or sales for relatively small quantities of fibre (quantities that are not comparable to commercial volumes for yarn or fabric production). Other fibres such as Technora and PBI could not be bought in time for the commencement of the project.

The pricing of the Zirpro wool component is an approximation based upon the lamb wool price at the end of 2004 and the treatment cost of applying an 8% w/w treatment of K_2F_6Ti (Potassium hexafluorotitanate) per kilogram of wool fibre.

5.1.2 Raw material for the developmental inter-liner

Fibre content for the developmental material consisted of a pre-oxidised polyacrylonitrile fibre (Panox) and Zirpro treated (8% K_2F_6Ti w/w) mid micron ($\sim 25\mu m$) scoured wool. The tech-fibre and proportion of each component, for this stage of the project, were selected as a result of the bench-scale assessments.

5.2 Foam

A sufficient quantity of CTU43-180, 43 kg/m^3 , polyurethane foam was readily available in the Canesis Network Ltd materials store. This foam was bought from C-Tech Comfort Technologies (NZ) with claims that it was of fire retardant quality and met the flammability requirements of BS 4735. In practice, after several experimental trials, it was found to be little better than standard polyurethane foam. A heat release rate comparison between CTU43-180 against other commonly available polyurethane foams is shown in (Figure 1) below. This comparison was conducted in the Cone Calorimeter at an irradiance level of 50 kW/m^2 and the curves are an average of three samples of each type.

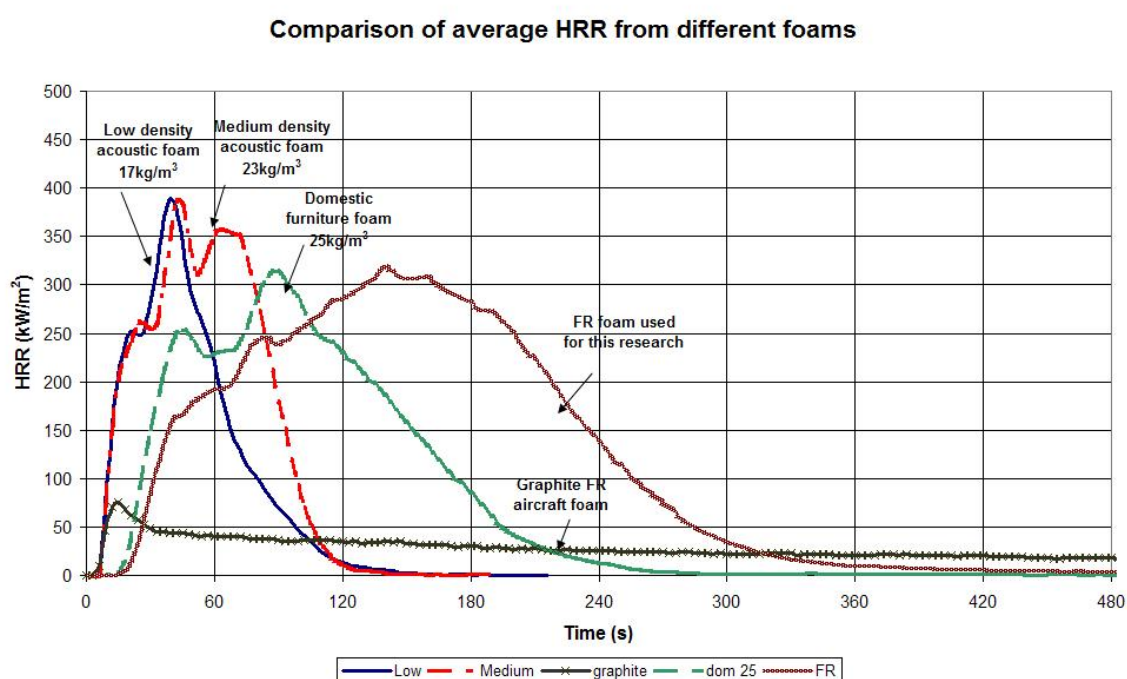


Figure 1. Heat Release Rate comparison of different polyurethane foams

The selection of polyurethane foams and suppliers is broad; such that no single foam can be considered as being the most representative of the material used in furniture construction as new formulations and variations of polyurethane foam are being continuously introduced. Despite the many variants it can easily be demonstrated that the combustion properties of these foams, excluding the highly specialised formulations like those used in aircraft, fall within a narrow band of values, especially in terms of heat release rate.

For these reasons it was decided that the foam material used during this developmental work needed only to have reasonably 'normal' combustion characteristics with respect to other furniture foams. The demonstrated combustibility of the CTU43-180 foam was sufficient to provide a basis for the performance of the inter-liner selections to be measured. It is not the purpose of this project to achieve a predetermined decrease in combustion qualities or to reach predefined targets but, to demonstrate that given the same circumstances a simple fire barrier can be produced which offers improvement in safety comparable to other accepted products.

The majority of fire retardant foams contain additives that are designed to delay the onset of ignition and for this purpose, the CTU foam does in fact demonstrate this feature to a certain degree but in comparison to some standard foams it is not overly convincing. The important characteristics to consider after ignition of domestic furnishings are the heat release rate and total energy available in the fuel package. With this in mind the chosen foam, when tested, did not exhibit any significant advantage.

Although peak heat release rate occurs about 50 seconds later in the CTU43-180 foam than in other foam types, the maximum level of heat release rate ($\sim 300 \text{ kW/m}^2$) is not significantly better than the non-treated foams which peaked in the range of 300 to 390 kW/m^2 with the highest rate being given by the lower density acoustic foams, as expected.

CTU43-180 also maintains a high heat release for a longer period than the three tested domestic foams and during this stage it is questionable whether any fire retardant quality exists in comparison. It has an average ignition time of 40 seconds when exposed to 50 kW/m^2 irradiance while the domestic untreated 25 kg/m^3 foam has an average ignition time of 38 seconds. The combustion response of 'true' fire retardant foam can be seen in the output curve of the sample labelled 'graphite' where a substantial and undeniable improvement in heat release rate is demonstrated over the entire test period.

Because of the available supply of this foam in the Canesis store and its negligible fire retardant aspect, this foam was used in all sample composites throughout the testing regimes of this project.

5.2.1 Upholstery fabric

Specifically, because of its low Limiting Oxygen Index (LOI) and high heat of combustion, ΔH_c , compared to most other popular covering materials, the worst performing upholstery in a house fire involving domestic furniture is expected to be the 100% polypropylene fabric [18, 25]. Hirschler and Shakir [5] found that the covering fabric has the greatest influence on the fire performance of the system so by including the worst expected performing covering material we aim to work with samples representing the higher end of the flammability risk spectrum for soft furnishings.

A 100% polypropylene plain weave fabric identified as Zingara was bought from Textilia Ltd and used throughout this project. The weight of this upholstery was measured as 260 g/m². Construction of the furniture composites mentioned for the Cone Calorimeter and Furniture Calorimeter tests follows a simple layout of foam inner core, a single layer of non-woven fire blocker material covered by a single layer of upholstery fabric.

6.0 PRODUCTION OF NON-WOVEN MATERIAL

For this research it was necessary to produce samples of blended non-woven material both for the bench scale and full scale experiments. The explanation below is an abbreviated summary of the non-woven production process, at Canesis Network Ltd, that produces a seamless fibrous substrate through the forced entanglement of fibres. The process is particularly useful for applications where the use of spun yarn, such as in woven or knitted fabric, would introduce an unnecessary expense.

In the production of the sample materials, Zirpro treated wool and synthetic fibre were blended and mixed together by hand in the required proportions according to mass fraction. The loose blend was then introduced to a sample card where by the action of several needled rollers spinning at differential velocities the fibres are further blended and combined to form continuous web.

The sample card is an intermediate process between hand blending and final carding. It is a reduced scale version of the Hergth card which signals the beginning of the uninterrupted commercial non-woven production process.

Needle punching of the fibres is the domain of the DILO NFZ velour punch machine. This apparatus was fitted with Regular Barb (RB) needles to produce even felting on both sides of the processed material as opposed to closed barb (CB) needles that produce a smooth felted surface on one side and a loose fibre (hairy) surface on the other.

The intention was to construct a fire blocker with smooth surfaces on either side, therefore RB needles were the preferred choice. Apart from the obvious aesthetic qualities double-sided needle-punching also implies a denser, tighter and more entangled fibre arrangement that improves both the residual strength and barrier performance qualities of the product.

Normally the non-woven production process involves the manufacture of a continuous length of material such that needling at one end occurs while raw fibre is being carded at the other end. However, because of the small quantities of raw material obtained and the size of the samples needed for the experiments, the non-woven materials were produced from rectangular shaped pieces of batting roughly 2.2 m x 1.5 m.

During the needle-punching process a reduction in width and an expansion in length occur because of the combined effect of entanglement and needle penetration. Through the experience of the operators it was possible to obtain an estimate of how much shrinkage and elongation might occur during the needlepunching process and with that information calculation of the final area of the needle-punched substrate was greatly simplified. With the likely final area established, a simple determination of the required mass to achieve the desired density was possible.

An expression relating the mass (g), density (g/m^2) and final linear dimensions of the material is given in the equation below:

$$\text{Final density} \quad \rho_f = \frac{M}{L_o \cdot W_o \cdot (1 + \alpha) \cdot (1 + \beta)} \quad (\text{g/m}^2) \quad (\text{Equation 6.1})$$

Where

| | | |
|----------|-----------------------------|-----|
| M | Mass of fibre web | (g) |
| W_f | Width of finished sample | (m) |
| W_o | Initial width | (m) |
| L_f | Length of finished sample | (m) |
| L_o | Initial length | (m) |
| α | Fractional change in length | - |
| β | Fractional change in width | - |

The length and width of the finished sample are given by

$$L_f = L_o(1 + \alpha) \quad \text{and} \\ W_f = W_o(1 + \beta) \quad \text{respectively}$$

The coefficients of fractional change of the finished non-woven product were estimated by the operators of the non-woven plant to be in the order of 0.13 and 0.10 for α and β respectively. These values were used in the process of producing samples of the required density

7.0 EXPERIMENTS

7.1 Bench scale investigations

7.1.1 Comparative heat transfer performance of pure fibre samples

In order to isolate and distinguish the best performing fibre types, non woven samples were made consisting of 100% pure fibre of a single type. Samples were made to differ in weight and the volumetric density (g/m^3) during testing was controlled by compressing the sample to a predetermined thickness by inserting the sample square into a metal template, sandwiched between a wire mesh grid and a copper disk calorimeter (Figure 2). This was done to allow assessment of the effect of fibre density on the heat transfer performance of the non-woven substrate. Although this determination was planned in the original scope of works, the effect of volumetric density was not evaluated because of time constraints. The density of samples referred to in this document is strictly the mass (g) per unit area (m^2) value at a thickness of 3 mm.

The primary form of assessment was the testing of each sample, using a modified setup of the BS EN 367, '*Method of determining heat transmission on exposure to flame*' [26], consisting of a total net heat flux of 50 kW/m^2 produced by a Meker burner flame incident on one side of the sample and a heat sensing copper disk calorimeter on the opposite side (Figure 2).

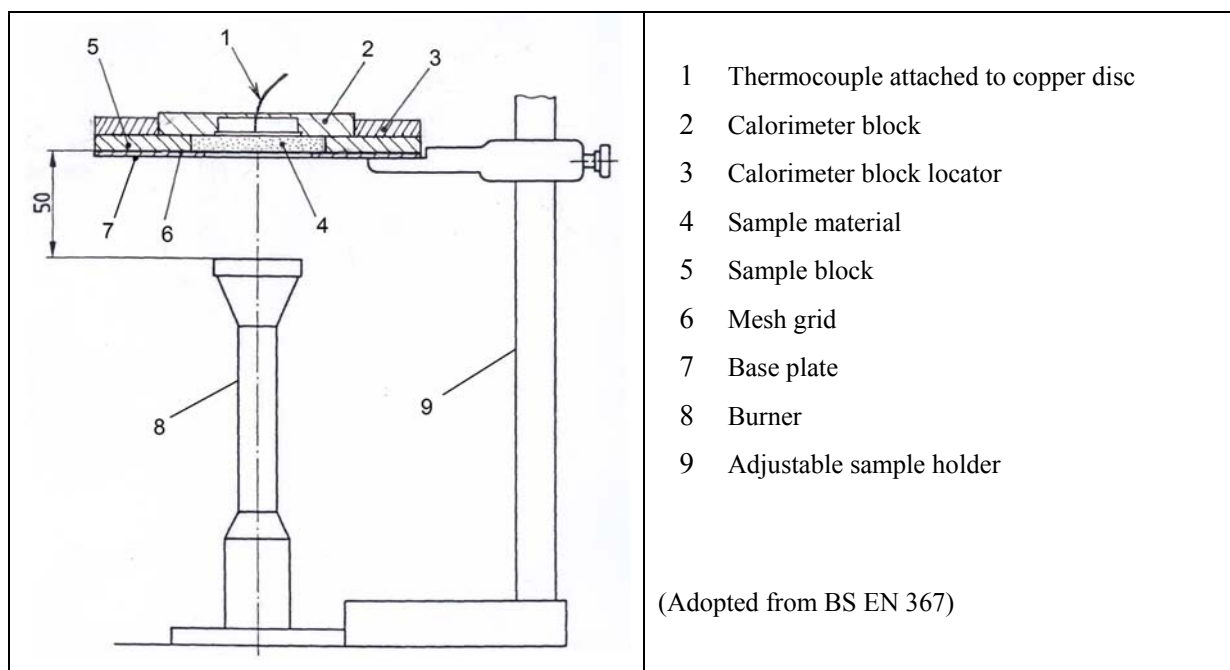


Figure 2. Schematic cross section of TPI apparatus

A parameter referred to as the Thermal Protection Index (TPI) is specifically defined for this report as: the best linear fit line to the test data of the time taken for the copper disc calorimeter to measure a temperature of 300°C, minus the TPI of the calorimeter without sample. The TPI data spans a range of densities upon which the linear fit line is imposed. The choice of 300°C follows from the approximate ignition temperature of polyurethane foam which has been shown to fall in the vicinity of 280°C [17].

By choosing the slightly higher temperature of 300°C, it allows for an easier measurement of the time interval whilst not losing significant details of any desirable performance aspects. A temperature of 20°C was obtained as the initial equilibrium temperature of the calorimeter before each test by convective cooling from a compressed air source when necessary.

Heat transfer through the sample during this set of tests would incorporate a combination of heat passage through the network of fibres and where/if the sample structure had been ruptured, split or decomposed, directly from flame to the calorimeter. This test does not distinguish between the modes of heat transfer and the physical changes of the sample during testing. Consequently it is an overall performance test for relative comparison. As a secondary form of assessment, the dimensional stability during exposure to heat and flame was also measured by estimating the intact, projected area of each sample before and after testing. Since the samples were confined in a flat space, the plane intact area was not difficult to determine.

This is an important factor when choosing a suitable fibre to combine with wool for the purpose of fire protection. It is a well established fact that wool has good ability to resist ignition when exposed to flames. It has a natural tendency to form a raised char crust which is precisely the mechanism the Zirpro treatment exploits. Despite this, wool suffers from brittleness once charred and this brittleness compromises the protection offered by the char layer of the burnt wool substrate to anything behind it.

7.2 Cone Calorimeter assessment of bench scale composites

Having identified the best performing fibres from the heat transfer tests, non-woven fabric samples were made incorporating Zirpro treated wool and one other fibre type at differing ratios. The three wool/tech-fibre ratios were selected as 95/5, 85/15 and 75/25. A nominal

density of 300 g/m² was chosen as the target density of the finished blended material. As most available fire blocking fabrics fall within the density range of 250 g/m² and 350 g/m²; the range of densities for FR aircraft seats and furniture protection. This excludes fire blankets, drop cloths and industrial barriers. The central value of 300 g/m² within this range was a convenient and realistic weight to choose as a standard for this project.

Blending was done by introducing the appropriate mass proportions of each fibre into the small sample card at Canesis Network Ltd and producing well-blended fibrous batts. The small batts of blended fibre were then laid out onto the conveyor of a needle-punch machine to an area and density which would produce a needle-punched fabric of the required weight, by using equation 6.1. Resulting non-woven fabric weights were reasonable; having a coefficient of variation of 5.4%. The major contributor of the variations is expected to be from difficulties associated with forming the final material from smaller individual pieces and the weight variations between individual batts.

These problems can be remedied or addressed more completely when working at full scale, where one continuous batting of uniform density can be produced and processed through the needle-punch machine. Table 3 shows the variants of non-woven fabrics made and the final average weight after needle-punching, with the inclusion of the two commercial fabrics (Panotex and Norfab Kevlar) for comparison.

Table 3. Sample identification and density

| Non-woven blend | Weight (g/m ²) |
|----------------------|----------------------------|
| Zirpro control | 307 |
| Zirpro/Panox 95/5 | 297 |
| Zirpro/Panox 85/15 | 295 |
| Zirpro/Panox 75/25 | 317 |
| Zirpro/Basofil 95/5 | 312 |
| Zirpro/Basofil 85/15 | 297 |
| Zirpro/Basofil 75/25 | 275 |
| Zirpro/FRV 95/5 | 327 |
| Zirpro/FRV 85/15 | 276 |
| Zirpro/FRV 75/25 | 291 |
| Zirpro/Grafil 95/5 | 289 |
| Zirpro/Grafil 85/15 | 266 |
| Average | 296 |
| Kevlar | 280 |
| Panotex | 349 |

Each of the non-woven fire blocking fabrics was incorporated into bench scale furniture composites consisting of an outer upholstery fabric, the non-woven fire blocker and polyurethane foam (Figure 3). Sizing for these specimens was a nominal (100 x 100 x 50) mm block as described in the ISO 5660 standard [27]. The foam core was cut to the standard size within a $\pm 5\%$ mass tolerance level, in keeping with many standard test protocols such as ISO Ignitability Test, ISO 5657-1986 and identical to BS 476: Part 13 [28], but with no allowance for the thickness of the covering layers, resulting in slight compression of the sample within the holder.

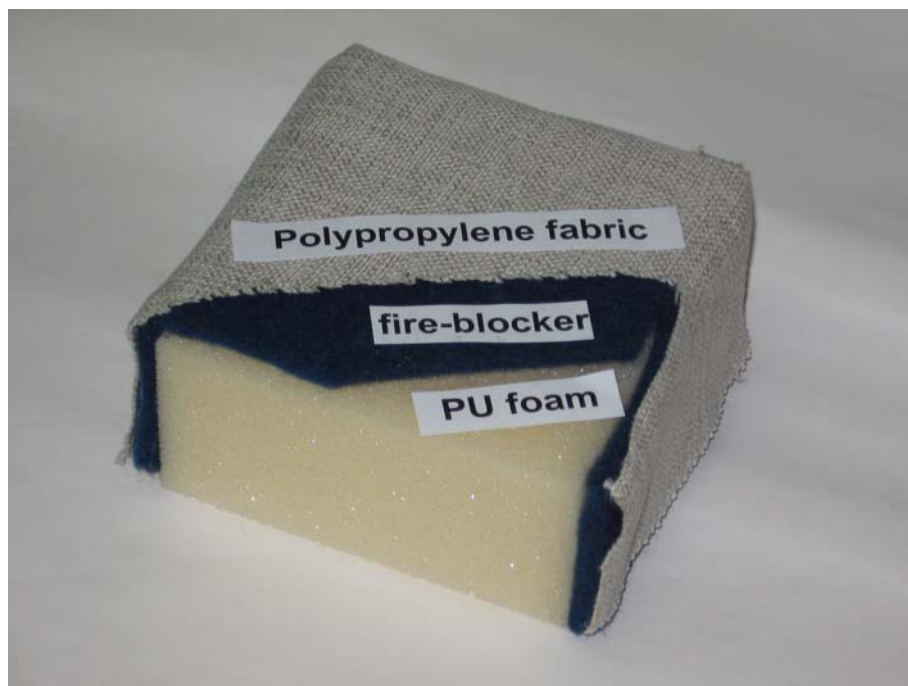


Figure 3. Representative mock-up of the Cone Calorimeter samples, showing the 3 component composition of samples used in both small and large scale tests.

Both covering layers were cut from the template shape adopted from the ISO Ignitability Test (See Figure 4 below), but adjusted to cover the surface of a block (100 x 100) mm on top with 50 mm sides, as per the standard cone calorimeter sample size. The sections below describe more fully, the procedures of forming the samples prior to testing.

▪ *Forming blocks*

Forming blocks for the construction of fabric shells were made from medium density fibreboard to dimensions of (100 x 100 x 50) mm. Two 25 mm sheets were glue together and finished to achieve the required 50 mm block thickness. All surface edges were cut straight, perpendicular to each other and smoothed.

▪ *Foam inner core*

Foam blocks of CTU43-180 were cut to dimensions of (100 x 100 x 50) mm using a band saw with foam cutting blade. The procedure followed was that of the ISO Ignitability Test [28] because this standard has an applicable sample preparation which is appropriate for the bench scale calorimetry section of this research. The test protocol allows a $\pm 5\%$ variation in foam block mass from an average of five samples. Each foam block used in the tests was selected from the basis of these criteria. Three samples were chosen from the groups of five, for testing.

▪ *Fabric coverings*

Square pieces measuring (260 x 260) mm for both inter-liner and outer upholstery fabric were cut, ensuring they were free from blemishes such as density variation or weave irregularities. The weight of these fabric pieces was recorded to verify that the uniformity was within the $\pm 5\%$ tolerance, from the average of five fabric specimens. The uniformity of the commercially produced upholstery was very consistent and all samples weighed were within 1% variation from the mean. The inter-liners used for these bench scale tests were not produced via a fully commercial process and did contain more irregularities, however the test procedure ensures that the quality of fabric used is within reasonable limits. From the original (260 x 260) mm fabric squares, the shape for the fabric shells of the test samples were transferred by tracing around a template modified from the ISO 5657 standard procedures. The template is shown in (Figure 4) below.

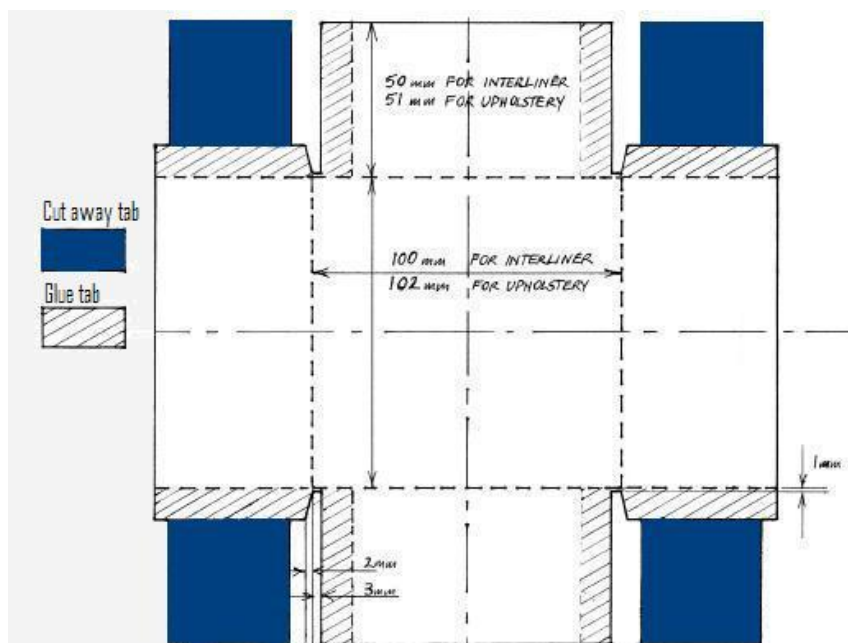


Figure 4. Fabric shell template for Cone Calorimeter samples

Two templates were used for the inter-liner and covering fabric respectively so that the upholstery shell would form a proper fit over the inter-liner and foam. The dimensions of the upholstery template were increased by 1 mm for each direction on the top and side sections, with respect to the inter-liner template, resulting in a top surface of (102 x 102) mm and sides of (51 x 102) mm.

Triplicate samples were tested in the Cone Calorimeter for each non-woven variant at an irradiance level of 50 kW/m², to measure heat release rate, smoke obscuration, ignition times and CO/CO₂ gas production. These samples were tested using the edge frame and grid to eliminate movement of the specimens off the sample holder or expansion up to the conical heater coil. Using the edge frame and grid also ensures that each specimen is exposed to the same reproducible events and conditions.

7.3 Full scale investigations (Furniture Calorimeter)

The experimental process for this stage of the project consisted of a series of furniture calorimeter tests evaluating the performance of the ‘life-size’ samples after exposure to small, steady burning ignition sources. Because of the unavailability of new and the low quantity of commercial inter-liners (Kevlar and Panotex) in stock, the number of samples tested for these could only be 1 and 2 respectively. It would have been useful to have had extra samples in order to better capture the typical range of experimental responses however, the consistent trends up to the 20 minute mark strongly indicate that any expected variation would occur after this time period for those samples just mentioned and this is enough of an indication for comparison with the developmental FB.

The chosen ignition sources were wooden cribs identified under the BS 5852 standard [9], providing approximately 16 to 17g of conditioned total mass. Use of the wooden cribs deviates from the standard ignition source used in the ASTM E 1537-99: ‘*Standard Test Method for Fire Testing of Upholstered Furniture*’, [30] in which a controlled gas burner flame impinges upon the sample for 80 seconds.

Cribs provide for the assessment of the sample with respect to a small but steadily intensifying heat source that more strongly resemble the early stages of a real fire scenario. During the early stages of a fire the behaviour of the sample assembly, whether on the surface

or involving the substrates beneath the surface, is an important consideration which is more easily observed using ignition sources such as cribs. Cleary et al. [29] recommended the use of small ignition sources in the assessment of fire hazard of upholstered furniture in conjunction with a measure of peak heat release rate and time to peak subsequent to ignition from larger sources such as the California Test Bulletin, CTB 133 gas burner.

It is true that greater reproducibility and consistency can be achieved using a burner with a metered gas supply, but usually this approach masks the initial fire resistance of a sample to a realistically increasing heat source and in many cases the immediate severity of the ignition flame is sufficiently high to guarantee combustion, regardless of the existence of moderate, passive fire resistant measures included.

A furniture calorimeter constructed to the specifications of standard ASTM E 1537-99 [30] and located at the University of Canterbury Fire Engineering laboratory was used for all large scale testing for this project. The instrument provides for a quantitative, real time measure of the heat release, mass loss and smoke production of a representative furniture sample during combustion. It operates on the oxygen consumption principle in the same way as the Cone Calorimeter (AS/NZS 3837-98, ISO 5660, ASTM 1354) [27] in order to calculate the energy dependent properties of the material under flaming combustion. For an overview of oxygen consumption calorimetry, refer to Appendix C.

Furniture cushions defining the sample were constructed to the nominal dimensions of (509 x 457 x 102) mm for the seat cushion and (635 x 457 x 51) mm for the back cushion with all dimensions having a tolerance of ± 3 mm. These dimensions were taken from the US Federal Aviation Regulations, FAR 25.853(c) [31] test procedure for aircraft seat evaluation and form a convenient and standardized method of sample seat construction. One important point to note is that the combustible portion of the test seat comprises of only the soft materials (i.e. foam, fabrics, liners and stitching) and does not include a combustible frame. Hence it is an evaluation of the soft components only and may not be comparable to other test results involving complete commercial furniture replicates.

The test rig seat frame is also from the same FAR description. See Appendix G for more detail. Testing of each specimen followed a period of conditioning in an environment of $(20 \pm 3)^\circ\text{C}$ and $(50 \pm 5)\%$ Relative Humidity for several days which in accordance with the standard is enough for constant mass equilibrium. Figure 5 on the next page shows the steel

frame positioned upon a metal tray forming the support for the cushions. The complete assembly is mounted onto a load cell which digitally records the real-time mass loss evolution during the experiments.



Figure 5. Furniture Calorimeter test set-up

After a three minute baseline period of data collection the lint on the wooden crib was wetted with 1.4 ± 0.1 ml of alcohol and ignited with a match, signifying the start of the combustion stage of the test. Combustion of the seat assembly was allowed to continue and follow its own natural progression without any external influence or interference. Data from the analyzers, thermocouples, and load cell was recorded at one second intervals until complete self-extinction of the samples was achieved.

Data reduction of the raw analyzer output was carried out using a spreadsheet programmed with the oxygen consumption calorimetry equations detailed in Appendix C. The method of calculation of the heat release rate utilized the data from all three measured gases i.e. oxygen, carbon dioxide and carbon monoxide. Calculation using the three gases is considered to be more robust and accurate [30] and this was confirmed when reduced data from simpler calculation (oxygen depletion only) was compared. Under comparison, the simpler calculation method produced data curves which appeared to be truncated and undervalued, especially at the beginning and end stages of the tests where flaming existed but was at a

reduced level. The chosen method of data reduction produced response curves which matched the observations and conditions more closely.

All tests were recorded on video-tape with still digital photographs taken intermittently over the test periods. The selection of photos for the range of samples is displayed on a timeline in Appendix L, for relative comparison. The brightness and contrast settings of the camera were not controlled; therefore the apparent contrast on each photo cannot be taken as a relative measure of the amount of smoke produced by each sample

8.0 BENCH SCALE TESTS RESULTS AND DISCUSSION

8.1 Convective heat transfer and dimensional stability of pure-fibre non-wovens

The data from the TPI tests, although showing a wide degree of scattering, demonstrates identifiable, clear linear trends between each sample type and especially between the best and worst performing samples (Figure 6). The trends become more defined and separate as the range of sample density is increased. Individual TPI graphs for each fibre type are shown in Appendix B.

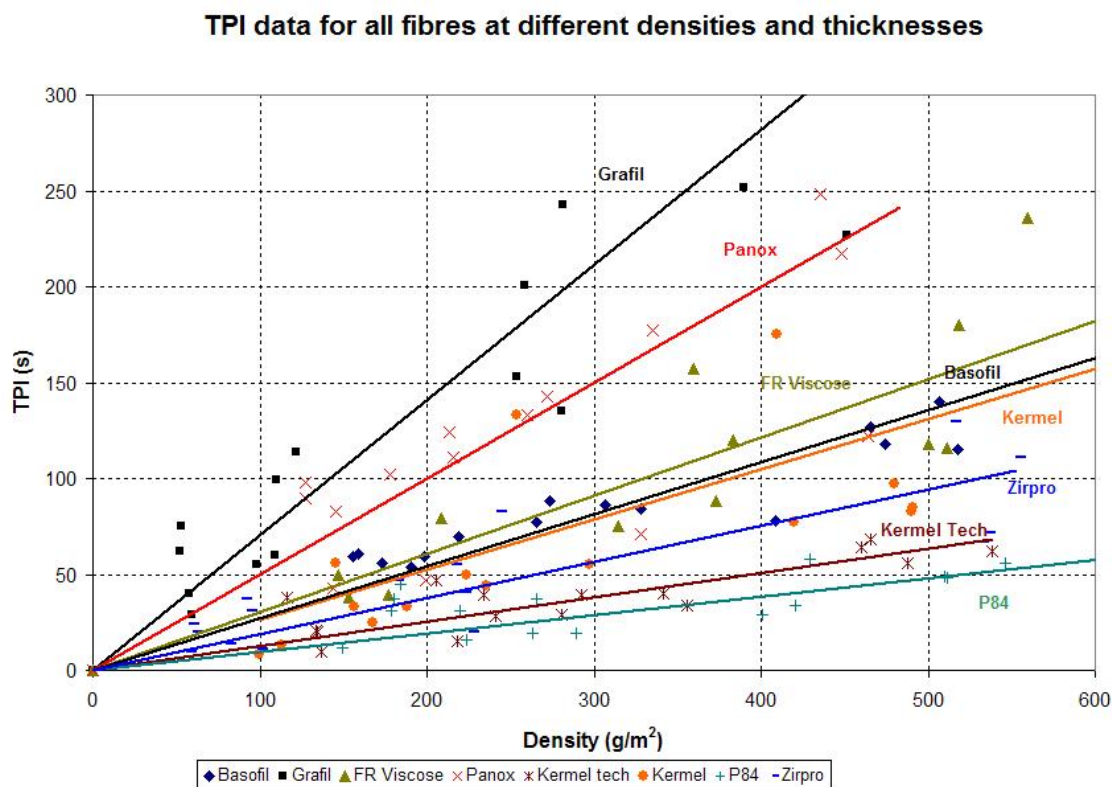


Figure 6. TPI data and trends for each pure fibre type at different densities

Heat transfer performance of a material is a good indicator for sample superiority but is not a sufficient criterion by itself. By choosing a fibre which also has a strong dimensional stability during flaming exposure, the stress on the char structure is minimized, leading to a lesser likelihood of rupture of the barrier substrate. The network of fire resistant fibres would also act as a scaffolding and support matrix upon which a continuous intumescent thermal boundary can form.

Extra samples were tested with the modified convective heat equipment and the projected, intact, surface area was calculated before and after testing to gauge the dimensional stability during high temperature thermal exposure. The relative ranking of pure fibre samples based upon TPI and dimensional stability are shown in (Table 4) below. The data in the table refers to a sample thickness of 3 mm and a density of 300 g/m² which may be taken as representing a comparative inter-liner composed entirely of a single fibre type. Dimensional change was measured separately because it was a later addition to the scope of tests. The calculated values below are an average of 10 tests.

Table 4. Ranking of pure fibre according to TPI and dimensional stability during exposure to flame

| Ranking | Fibre | Calculated TPI | Fibre | Area change % |
|---------|-------------|-------------------|-------------|------------------|
| 1 | Grafil | 210 | Grafil | 0 |
| 2 | Panox | 150 | Panox | -8 |
| 3 | Basofil | 81 | Basofil | -16 |
| 4 | FRV | 90 | FRV | -39 |
| 5 | Zipro wool | 56 | Zipro wool | -49 |
| 6 | Kermel | 79 | Kermel | -61 |
| 7 | Kermel Tech | 38 | P84 | -84 |
| 8 | P84 | 28 | Kermel Tech | -88 |
| 9 | Lamb wool | 18 ^ε | Lamb wool | n/a * |

* Could not be measured due to extensive decomposition

^ε The TPI values for lamb wool was experimentally determined at only one density and only for comparison against the FR fibres listed above.

Table 4 demonstrates a strong level of agreement for the relative performance of the sample fibres, under the convective heat transfer test, for heat transfer and dimensional stability. It can be observed from the table that the highest TPI values are given by those samples showing the least dimensional change during exposure to flame. The trend is consistent over the whole table and supports the intuitive conclusion that the best protection (i.e. higher TPI) is achieved by those samples which have fewer tendencies to shrink, crack or deform when exposed to fire. The four best performing fibres were Grafil, Panox, Basofil and FR Viscose, followed by Zipro treated wool ahead of the remaining four fibre types.

An assessment of the percentage change in area also provides a means of distinction between samples which may have very similar TPI values. The advantage of having 2 selection

criteria is that it offers a stronger base for selection that may otherwise be weakened because of the variability in the TPI results.

8.2 Cone Calorimeter tests on furniture composites

8.2.1 Heat release rate

For this series of tests the most important parameter of interest is the rate of heat release (HRR) from each sample. An effective fire barrier aims to reduce the peak heat release rate from combustion of material beneath it and/or increase the time at which this maximum heat release rate occurs. The combination of increased time to peak HRR and decrease in maximum HRR is the optimal result.

The peak HRR of interest is the peak caused by the combustion incorporating the foam core. This is not the earliest peak HRR recorded in the data and for most of the samples is also not the one of highest magnitude. Ignition of the surface upholstery is difficult to control with the use of an underlying protective barrier, although it may have a slight influence if the melting upholstery is allowed to penetrate into a porous FR barrier thereby temporarily reducing the amount of melted residue exposed to a critical heat flux. The peak HRR from the covering layer may be a maximum but is of relatively short duration compared to the remaining heat output. It is expected that in most cases the greater part of the fire load mass is incorporated within the filling (PU foam) together with the frame (wood) of soft furniture.

A lowering of the peak HRR from the covering upholstery was observed during the cone calorimeter round of tests for certain fibre types e.g. Basofil. Despite this occasional occurrence, the synthetic upholstery will produce a major HRR spike early in the combustion sequence of the samples and as expected, occurring at the same time for every sample due to the identical sample preparation and presentation to the heat source. (Figure 7) below shows the average heat release rate output over time, from the 85/15 blend of samples. Heat release rate output curves of the other two blend ratios are shown in Appendix D, but a comparison of peak heat release rates for all three blend ratios are shown in (Figure 8) followed by the time to peak comparison in (Figure 9).

From these graphs the highest heat release rate (excluding the upholstery peak) used to compare relative performance is clearly visible as having a lower magnitude and occurring at

increased time for combinations with superior fire blocking ability. These peaks are clearly distinguishable in (Figure 7) below.

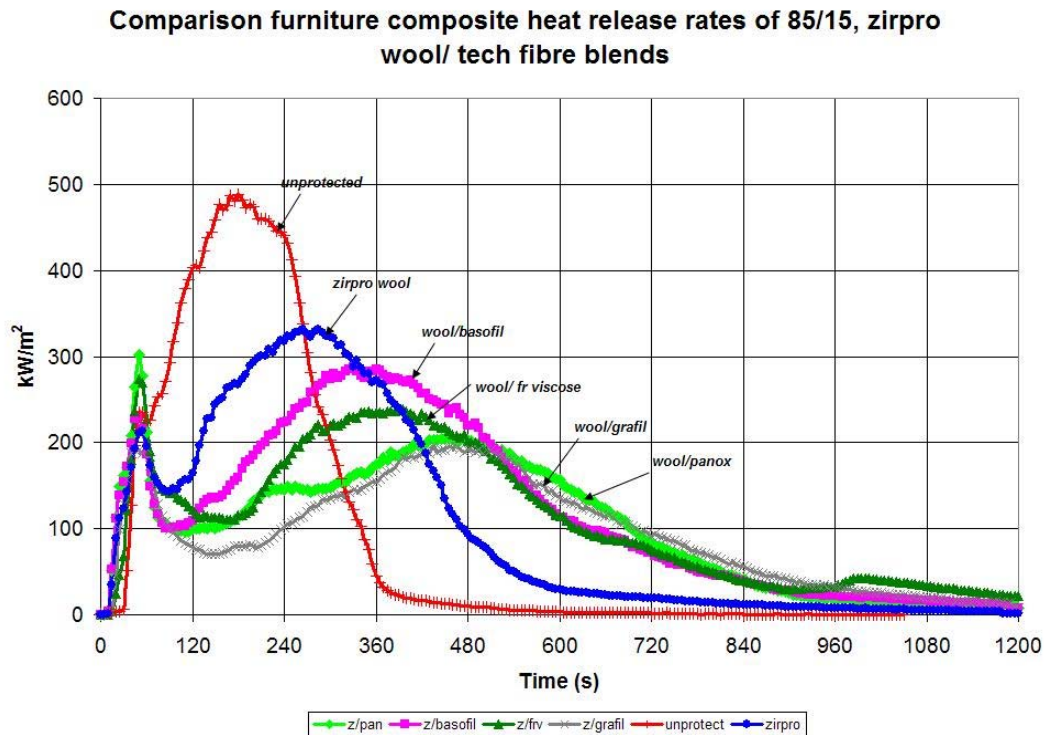


Figure 7. Comparison of heat release rates of bench scale composites with a wool/ FR fibre ratio of 85/15

The obvious trend in the graph is the decreasing downward slope from worst to best, showing that the Zirpro/Grafil and Zirpro/ Panox blends are better performers than the Zirpro/FRV and Zirpro/Basofil blends.

Data from the experiments shown in (Figure 8) below confirm the major trend and order of the best performing blends displayed but the expected trend of decreasing HRR with increasing FR fibre proportion is not conclusively clear. The density of inter-liner samples listed in (Table 4) shows there is a noticeable variation over the three blend ratios. In the case of the Basofil and FRV blends the 95/5 composition obtained a higher density than the 85/15 or 75/25 compositions and this may have contributed to the reversal in expected trend for this comparison.

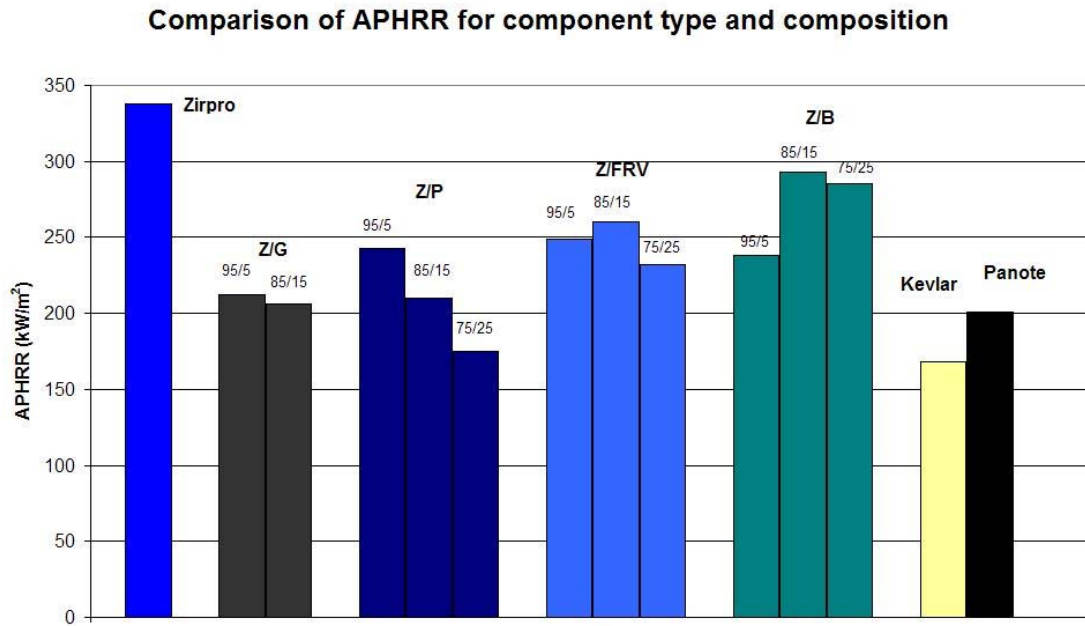


Figure 8. Average peak heat release rate for all wool/fibre samples

8.2.2 Time to peak heat release rate

Compared in similar fashion, the times to reach maximum heat release rate are displayed in (Figure 9). Conversely to the HRR results the best performing combinations are those maximizing the time to peak HRR. The same order of merit is obtained as that involving the heat release rate with the Zirpro/Grafil and Zirpro/Panox blends outperforming the Zirpro/FRV and Zirpro/Basofil blends, and also the minimum standard of plain Zirpro treated wool.

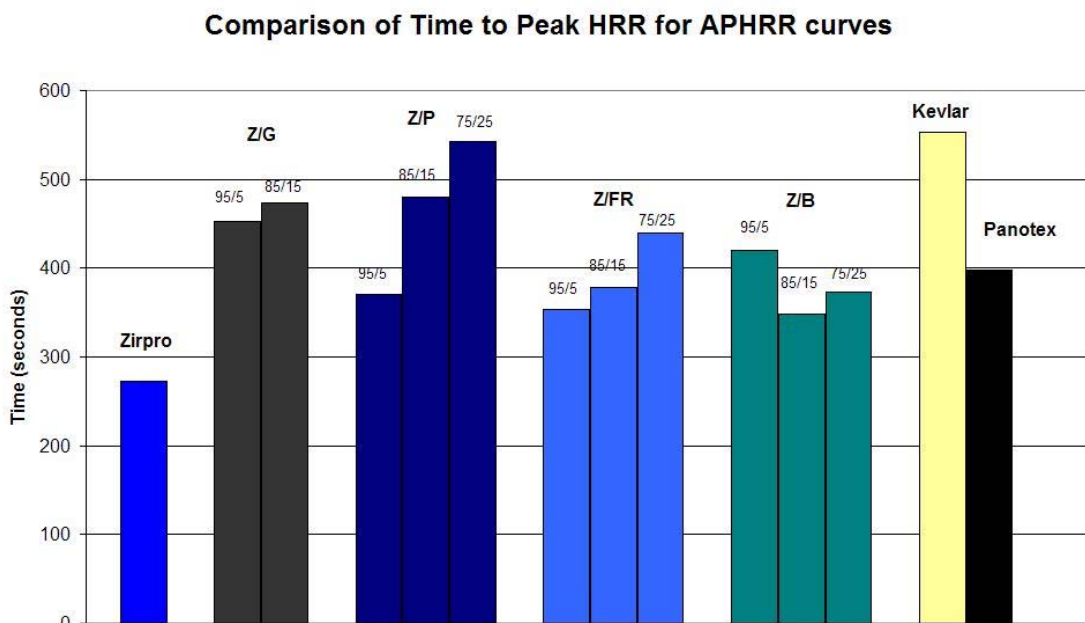


Figure 9. Average time to peak heat release rate for all sample combinations tested

The dominant trend is clear in that Zirpro/Grafil and Zirpro/Panox combinations are superior to the rest. Although, as can be observed from the displayed results, Zirpro/Grafil has a slight performance advantage over Zirpro/Panox, the former is more difficult to process and handling of the carbon fibres is not without complication. Grafil fibre is a very rigid, high carbon content (>99%) fibre and is not unlike glass fibre when in contact with human skin, causing discomfort and irritation [32].

Grafil fibre is extremely fine when individual strands are separated and can migrate almost anywhere without obvious detection until substantial accumulation renders it visible. Its ability to transport static charge also increases the undesirable side effects during carding and blending, with accumulation of fibres on rollers and cards and on some occasions causing electrical malfunctions [32]. Only two out of the three composition ratios were made containing Grafil because of the inconvenience and difficulties outlined above.

Positives of Grafil fibre are its inert quality and ability to withstand very high temperatures without physical change. It has a very slow decomposition rate and observations of heat/flame-tested samples revealed that the Grafil fibre matrix of the blends was highly intact to a superior extent when compared to the other fibre blends. Despite the success of this fibre when exposed to fire, the difficulties in processing and the very close performance of the Zirpro/Panox blend in comparison, made the Zirpro/Grafil combination less desirable and an unrealistic choice for use in furniture applications.

8.2.3 CO and CO₂ production

Data from this batch of experiments spans several more criteria for comparison than just heat release rate and time to peak heat release. Similarly to the TPI results, the use of multiple independently measured parameters goes some way to reinforce possible significant trends that may only seem suggestive from the data of a single parameter.

For carbon monoxide yield the response to increasing the technical fibre proportion is not the same for all sample types. For Z/P samples there is a clear trend that an increase in tech-fibre produces a decrease in CO yield (i.e. 0.055 to 0.035 g/g). The same is true of Z/B (0.063 to 0.043 g/g), but Z/FRV samples do not show any conclusive trend or very much difference regardless of the blend ratio. Z/G, like Z/FRV, also displays a lack of significant trend between the two component ratios tested. Z/P is clearly better than the other experimental

blends, with the exception of Z/G, because of its low CO yields.

Carbon dioxide trends are interesting because contrary to some of the other measured quantities; only Z/B displayed a decreasing trend with increasing Basofil proportion. All other samples displayed a relatively constant CO₂ yield regardless of the inter-liner composition. This may suggest that the dominant proportion of the CO₂ produced originates from complete combustion of the more flammable components (i.e. fabric and foam) and that the CO yield is more likely to be influenced by the incomplete combustion of the fire resistant layer. This is also supported, in part, by the effective heat of combustion values (refer to Table 5 below) which are likewise, relatively invariant.

8.2.4 Smoke production

The quantification of smoke is a useful tool that is often overlooked and undervalued. Considering the impact that smoke has for a person's ability to safely escape during the incident of fire, an ideal solution to improving the fire safety of our furniture should also demonstrate a measurable decrease in the amount of visible smoke.

The Zirpro/Panox blend at the 75/25 blend ratio is clearly the superior product with a specific extinction area (SEA) smoke production of 378 m²/kg which is comparable to Kevlar having a SEA of 355 m²/kg. All other samples ranged between 409 and 526 m²/kg. From the heat release rate (HRR) and time to peak HRR data the Zirpro/Panox sample was identified as the best and most practical candidate material. Other test parameters measured also supported this conclusion although the yield data should be taken with caution because it is a per unit mass value and not a total quantity measurement. Two substances may have equal yields (g/g) but may lose different amounts of mass during combustion and produce differing total quantities of by-products.

The data summary of all cone calorimeter tests is shown below in (Table 5).

Table 5. Summary of Cone Calorimeter test results

| Sample ID | | PHRR | TTP | SEA | CO | CO ₂ | EHC |
|-----------|---------|-------------------|------------|--------------------|--------------|-----------------|-------------|
| | | kW/m ² | s | m ² /kg | g/g | g/g | MJ/kg |
| Z | A | 360 | 265 | 517 | 0.066 | 1.780 | 26.7 |
| Z | B | 320 | 265 | 474 | 0.063 | 1.821 | 27.4 |
| Z | C | 333 | 290 | 515 | 0.067 | 1.976 | 29.7 |
| | | 338 | 273 | 502 | 0.065 | 1.859 | 27.9 |
| Z/P | 95/5 A | 219 | 440 | 552 | 0.055 | 2.087 | 32.5 |
| Z/P | 95/5 B | 225 | 335 | 505 | 0.058 | 1.891 | 29.7 |
| Z/P | 95/5 C | 286 | 335 | 482 | 0.052 | 2.304 | 32.0 |
| | | 243 | 370 | 513 | 0.055 | 2.094 | 31.4 |
| Z/P | 85/15 A | 199 | 475 | 427 | 0.036 | 1.940 | 29.1 |
| Z/P | 85/15 B | 201 | 525 | 423 | 0.037 | 1.966 | 30.0 |
| Z/P | 85/15 C | 230 | 440 | 457 | 0.048 | 2.004 | 31.1 |
| | | 210 | 480 | 436 | 0.040 | 1.970 | 30.1 |
| Z/P | 75/25 A | 159 | 620 | 363 | 0.029 | 2.087 | 28.5 |
| Z/P | 75/25 B | 188 | 555 | 414 | 0.038 | 2.063 | 28.4 |
| Z/P | 75/25 C | 179 | 455 | 358 | 0.039 | 2.236 | 31.0 |
| | | 175 | 543 | 378 | 0.035 | 2.129 | 29.3 |
| Z/B | 95/5 A | 232 | 440 | 422 | 0.061 | 1.942 | 28.3 |
| Z/B | 95/5 B | 238 | 415 | 427 | 0.058 | 1.999 | 28.7 |
| Z/B | 95/5 C | 243 | 405 | 605 | 0.070 | 2.086 | 29.7 |
| | | 238 | 420 | 485 | 0.063 | 2.009 | 28.9 |
| Z/B | 85/15 A | 310 | 330 | | 0.063 | 1.938 | 28.8 |
| Z/B | 85/15 B | 275 | 365 | 409 | 0.044 | 1.857 | 31.1 |
| Z/B | 85/15 C | | | | | | |
| | | 293 | 348 | 409 | 0.054 | 1.898 | 30.0 |
| Z/B | 75/25 A | 302 | 415 | 508 | 0.043 | 1.329 | 27.5 |
| Z/B | 75/25 B | 308 | 325 | 230 | 0.010 | 1.093 | 27.0 |
| Z/B | 75/25 C | 245 | 380 | 499 | 0.077 | 1.948 | 25.3 |
| | | 285 | 373 | 412 | 0.043 | 1.457 | 26.6 |
| Z/FRV | 95/5 A | 235 | 265 | 513 | 0.071 | 2.154 | 32.4 |
| Z/FRV | 95/5 B | 272 | 390 | 507 | 0.069 | 2.069 | 31.2 |
| Z/FRV | 95/5 C | 241 | 405 | 488 | 0.066 | 2.176 | 32.3 |
| | | 249 | 353 | 503 | 0.069 | 2.133 | 32.0 |
| Z/FRV | 85/15 A | 232 | 415 | 490 | 0.050 | 1.234 | 27.6 |
| Z/FRV | 85/15 B | 240 | 440 | 505 | 0.047 | 1.213 | 28.1 |
| Z/FRV | 85/15 C | 308 | 280 | 444 | 0.036 | 1.217 | 28.1 |
| | | 260 | 378 | 480 | 0.044 | 1.221 | 27.9 |
| Z/FRV | 75/25 A | 270 | 330 | 566 | 0.080 | 2.265 | 33.7 |
| Z/FRV | 75/25 B | 247 | 235 | 497 | 0.060 | 2.213 | 29.7 |
| Z/FRV | 75/25 C | 232 | 440 | 516 | 0.078 | 2.042 | 30.3 |
| | | 250 | 335 | 526 | 0.073 | 2.173 | 31.2 |
| Z/G | 95/5 A | 193 | 435 | 478 | 0.035 | 1.755 | 25.0 |
| Z/G | 95/5 B | 231 | 445 | 492 | 0.031 | 1.737 | 26.0 |
| Z/G | 95/5 C | 213 | 475 | 520 | 0.045 | 2.062 | 28.2 |
| | | 212 | 452 | 497 | 0.037 | 1.851 | 26.4 |
| Z/G | 85/15 A | 241 | 435 | 435 | 0.049 | 1.706 | 24.6 |
| Z/G | 85/15 B | 170 | 510 | 397 | 0.033 | 1.919 | 27.3 |
| Z/G | 85/15 C | | | | | | |
| | | 206 | 473 | 416 | 0.041 | 1.813 | 26.0 |
| Kevlar | A | 171 | 540 | 414 | 0.025 | 2.061 | 31.1 |
| Kevlar | B | 166 | 530 | 345 | 0.022 | 2.213 | 31.7 |
| Kevlar | C | 168 | 590 | 305 | 0.016 | 2.213 | 31.7 |
| | | 168 | 553 | 355 | 0.021 | 2.162 | 31.5 |
| Panotex | A | 217 | 310 | 539 | 0.056 | 1.932 | 32.8 |
| Panotex | B | 197 | 395 | 507 | 0.047 | 2.153 | 30.2 |
| Panotex | C | 189 | 490 | 464 | 0.043 | 2.187 | 30.5 |
| | | 201 | 398 | 503 | 0.049 | 2.091 | 31.2 |

9.0 FULL SCALE RESULTS AND DISCUSSION (FURNITURE CALORIMETER)

The identification of (75/25) Z/P as the best performed sample from the Cone Calorimeter stage, lead to the testing of this barrier in the larger scale Furniture Calorimeter. The new composition was tested in a more realistic representation of a polyurethane filled chair, alongside unprotected (upholstery and foam without interliner) control chairs, Zirpro protected and the chairs protected with the commercial inter-liner products of Kevlar and Panotex.

From the output of the Furniture Calorimeter tests, two distinctly clear patterns emerge between samples incorporating an effective protective boundary and those with non-effective protection or no protection at all.

9.1 Heat release rate of full scale samples

The data clearly shows that the control (unprotected) samples and those with an FR treated 100% wool inter-liner began to increase heat release rate at between 2 and 3 minutes following ignition of the cribs. Those samples with effective barrier protection did not show an increase in heat release rate until approximately 20 minutes after ignition of the cribs (Refer to Figure 10). The following graphs are averaged curves of each sample type.

This presents a clearer picture of the heat release rate pattern between sample types but because of the shift in response for individual tests, the average curves below do not necessarily represent the true heat release rate response in terms of shape or maximum peak. Also, the response curve of the Control A sample was not considered when the averaged curves were calculated because it was too far removed from the other two sample output curves which were quite similar. See Appendix H for the actual heat release rate curves produced by each sample.

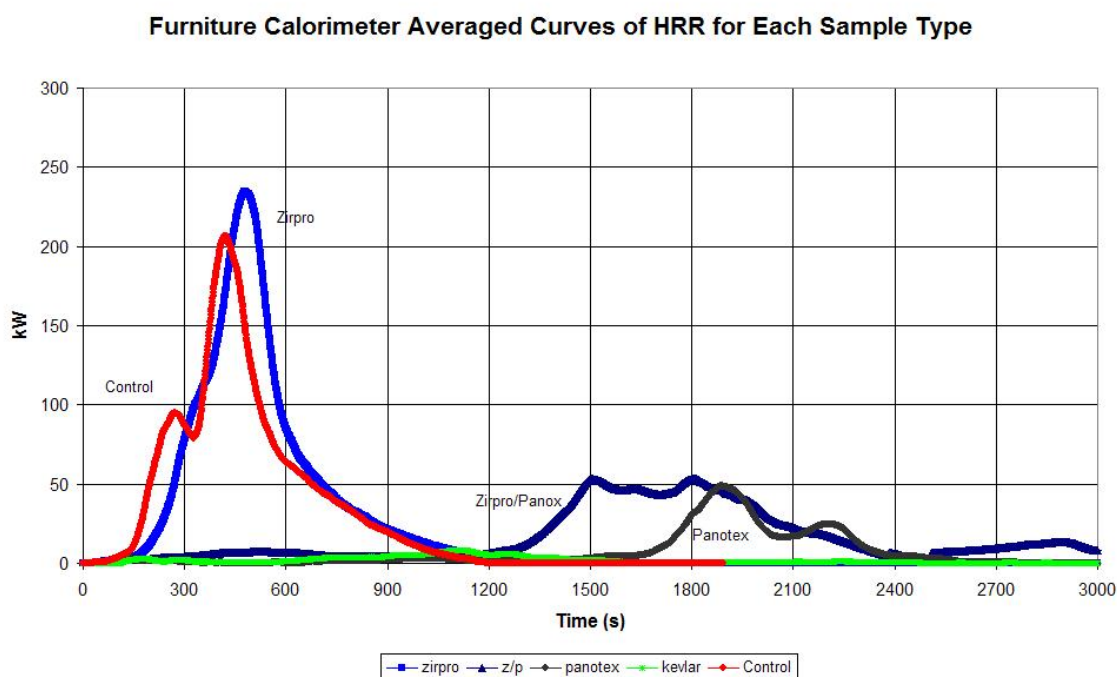


Figure 10. Averaged heat release rate of all sample types during Furniture Calorimeter testing

Not only is the time when heat release increases between the two groups a significant result, but also the magnitude of the peak heat release value between them is substantially different. Keeping in terms of the two identified groupings the best performers did not peak above 50 kW while the rest peaked at values between 210 and 240 kW. It is also encouraging to note that none of the Wool/Panox experimental blend samples obtained a peak heat release rate greater than the 100% Panox commercial product.

Results for total heat energy released are consistently better for the development barrier against the controls and Zirpro samples but are slightly higher when compared against Panotex and Kevlar (Figure 11). However, this is also due in part to the limited number of samples of the latter two combinations and the wide variation in performance during testing which in turn affects the averaged values.

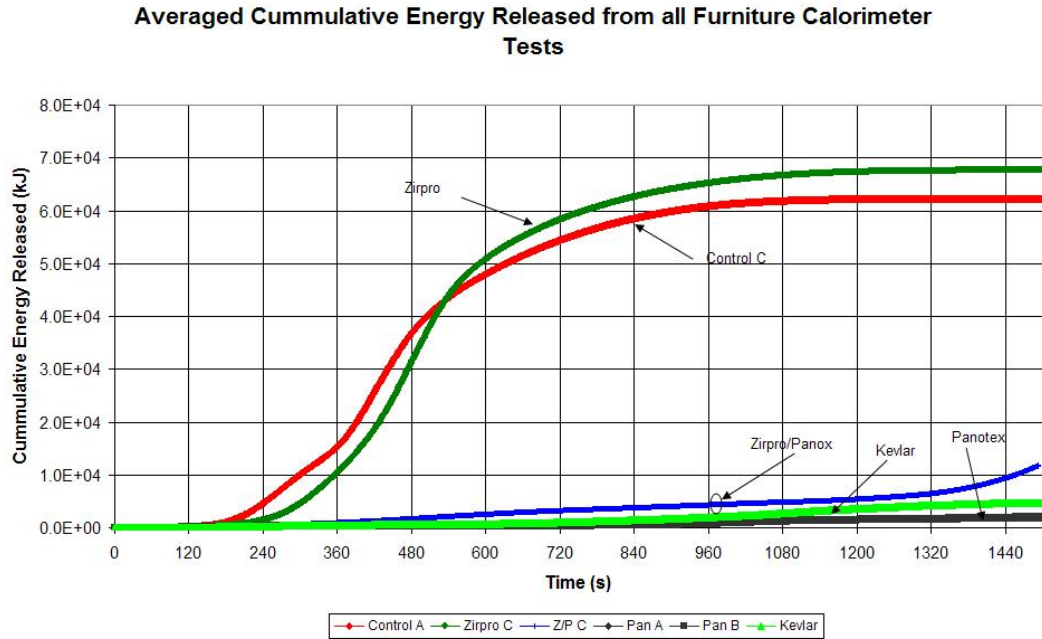


Figure 11. Averaged total energy curves for each sample type tested in the Furniture Calorimeter

9.2 Smoke production of large scale samples

Smoke production follows the similar patterns as the other measured combustion characteristics where the experimental material-lined samples are almost indistinguishable from the commercial product protected samples for approximately 1400 seconds. The smoke response of Z/P shown in Figures 12 and 13 confirms the result from the Cone Calorimeter tests in that Z/P behaves similarly to Kevlar in terms of smoke contribution for this type of application and does so for a significant amount of time.

Referring to both the averaged smoke production evolution in (Figure 12) and the cumulative smoke production in (Figure 13) confirms the closeness of the combustion characteristics between the three more successful barrier materials and in conjunction with similar trends in heat energy curves, implies that we may expect a repeat of the same trends for CO and CO₂ production between these samples.

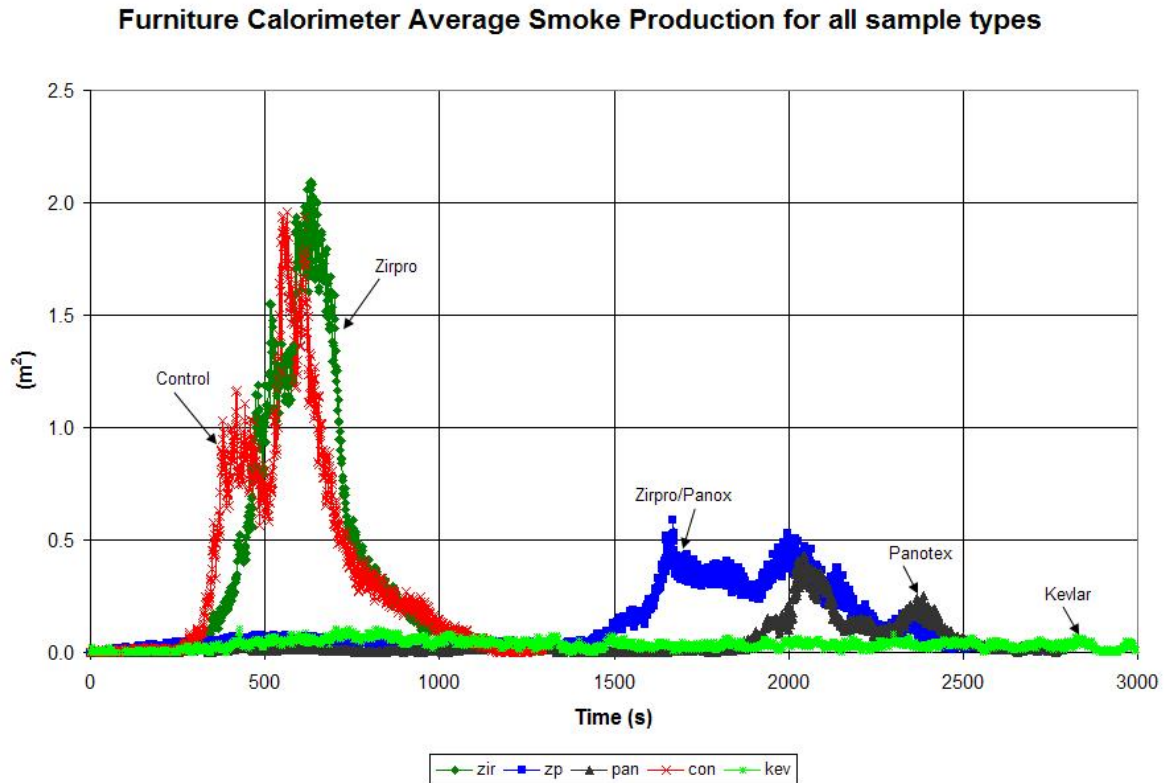


Figure 12. Averaged smoke production of each sample type during Furniture Calorimeter testing

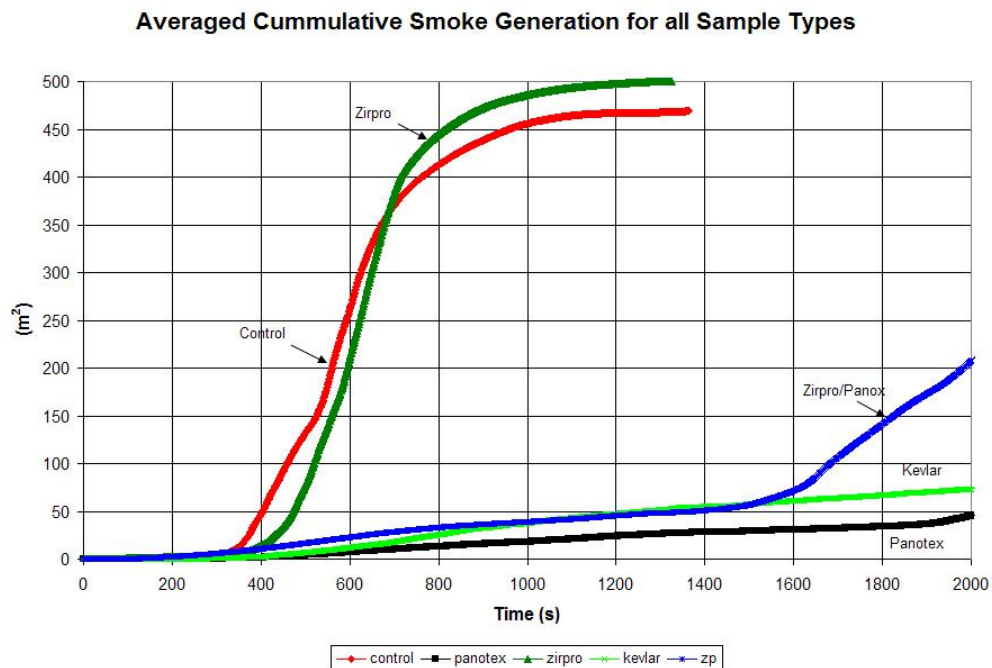


Figure 13. Averaged cumulative smoke production of all sample types tested in the Furniture Calorimeter

Another aspect which is frequently overlooked is the behaviour and stability of the samples during combustion. Between the protected and unprotected groups an obvious characteristic was observed and also recorded in the digital images (Appendix L). All unprotected samples collapsed and broke away from the frame during the burning process and continued to burn as pool fires while all protected samples remained in place whilst releasing the melted polymer at a proportionately slower rate onto the tray underneath the seat assembly. There was no substantial pool fire contribution from the protected samples although some of this could be the result of using a metal tray that may have acted as a heat sink, thereby cooling the melted residue.

An indication of the manner in which the samples were consumed, encompassing the break up of the samples and the consequent progression of combustion, can be observed in the figure below where the obvious variability of the control samples total heat curves (Figure 14) is contrasted with the more consistent curves produced by those samples incorporating an extra layer in their construction. This includes the Zirpro samples which, although did not perform any better than the controls in terms of combustion severity, did not break up or separate from the frame as early or to the same extent as the controls.

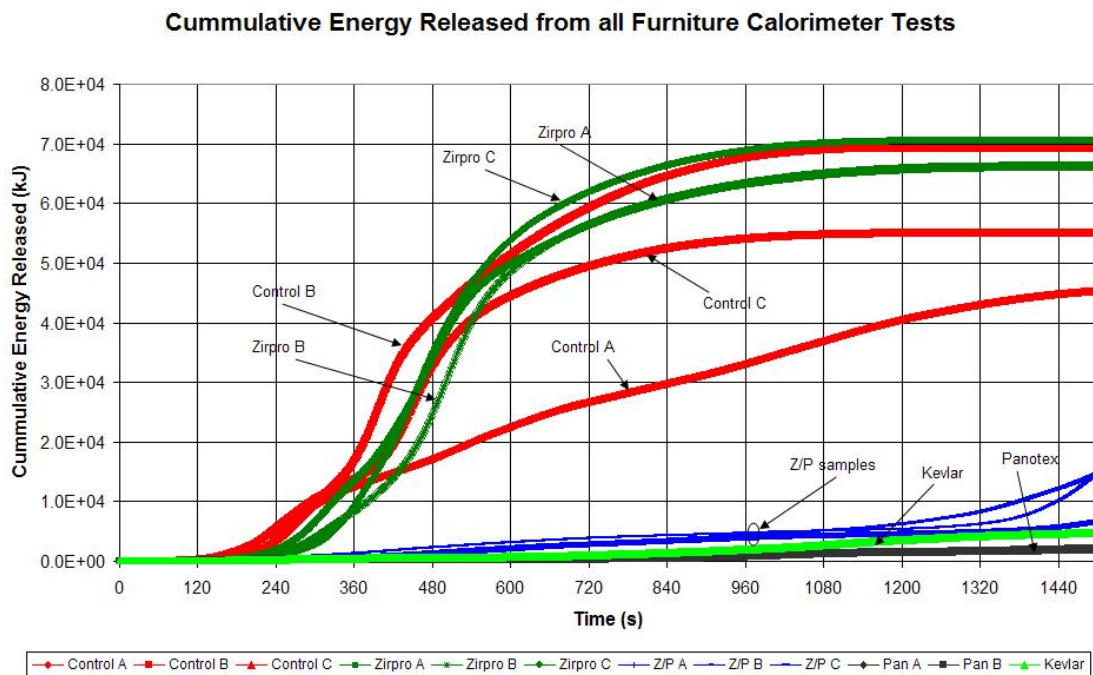


Figure 14. Cumulative heat energy curves for each separate sample tested in the Furniture Calorimeter

9.3 CO and CO₂ production

The output shown in graphs (Figure 15 and 16) is quite conclusive and supports the earlier indication that the carbon-oxide gas emissions would reflect a similar trend to the heat and smoke production between samples. Although when approaching 1500 seconds, the inter-liner developed for this project begins to deviate from the ideal response, the fact that it matched the level of performance of competing materials for at least 20 minutes is a very encouraging sign. Carbon dioxide peak levels are near to those of the competition but carbon monoxide levels are at least twice those of the expensive products. The increase in gas yield begins to occur around 1500 seconds and reaches a peak at around 2000 seconds.

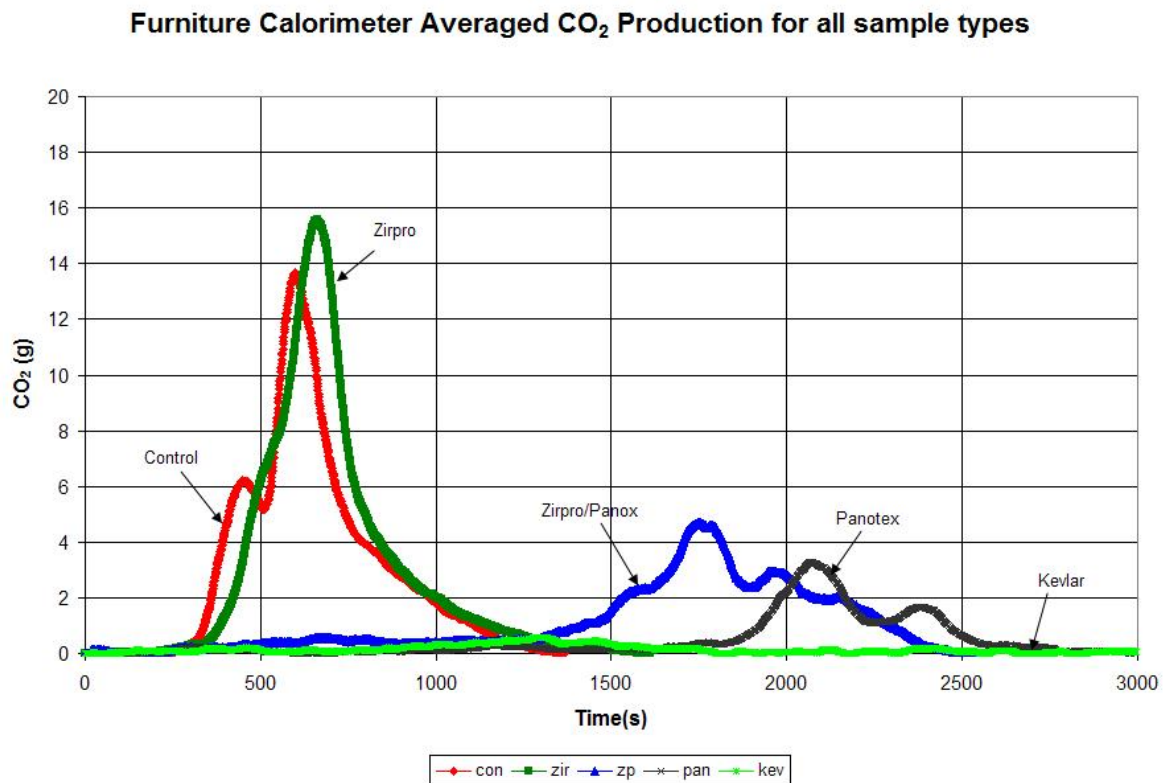


Figure 15. Averaged carbon dioxide production of each sample type during Furniture Calorimeter testing

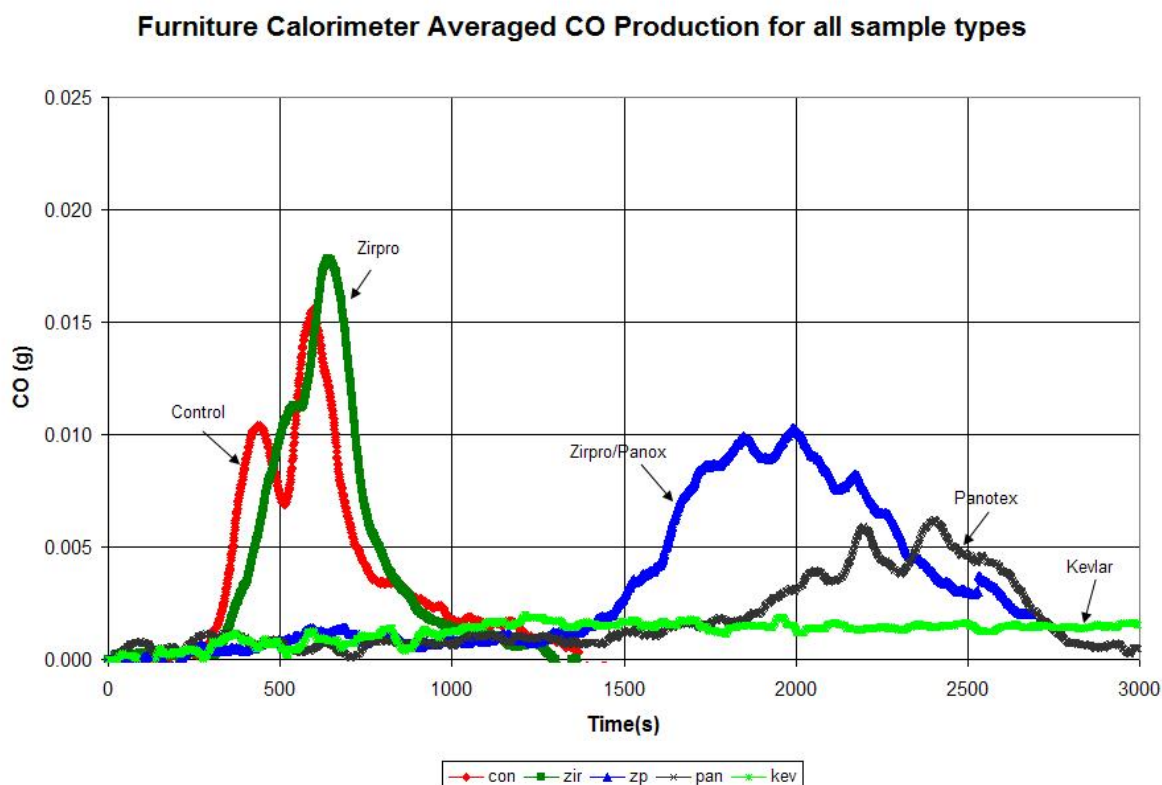


Figure 16. Averaged carbon monoxide production of each sample type during Furniture Calorimeter testing

9.4 Tabulated results at 1200 seconds and at full time

The following tables (Table 6 and 7) give a total value for each measured response during the tests. They summarise and confirm the performance of the inter-liner for the period of 20 minutes after ignition of the samples. As can be seen from Table 6, at the 20 minute mark Z/P has very a similar response to Kevlar in all measurements except CO₂. Beyond this time however, the Z/P barrier can no longer maintain its protective quality.

The next table shows the same parameters after the samples have self-extinguished and after the protection of the barrier fabric was finally overcome. The period for self extinction was around 50 to 60 minutes for the protected, slow burning samples, Figure 16 above shows that beyond 1500 seconds the Z/P samples begin to produce more CO but this occurs at a late stage in contrast to the more combustible samples which reach peak CO emissions earlier and with higher magnitude. The increased CO₂/CO production in latter stages is most likely the result of decomposition of the FR wool component to an extent where protection of combustible material is no longer possible. Flaming is then allowed to increase and react

with the high carbon content of the synthetic fibre portion of the inter-liner in addition to the more exposed flammable components, thereby producing larger carbon oxide quantities.

Table 6. Summary of Furniture Calorimeter results after 1200 seconds

| | ML kg | TE MJ | TSR m² | CO g | CO₂ g |
|-------------|------------------|------------------|------------------------------|-----------------|-----------------------------|
| Control A | 1.115 | 40.5 | 172 | 3.19 | 2279 |
| Control B | 1.630 | 69.23 | 457 | 5.40 | 4463 |
| Control C | 1.422 | 55.07 | 477 | 4.48 | 3532 |
| mean | 1.389 | 54.93 | 369 | 4.36 | 3425 |
| s.d. | 0.259 | 14.37 | 171 | 1.11 | 1096 |
| Zirpro A | 1.813 | 65.52 | 499 | 3.93 | 4360 |
| Zirpro B | 1.914 | 66.09 | 420 | 5.57 | 4165 |
| Zirpro C | 2.040 | 70.44 | 568 | 5.84 | 4576 |
| mean | 1.92 | 67.35 | 496 | 5.11 | 4367 |
| s.d. | 0.11 | 2.69 | 74 | 1.03 | 206 |
| ZP A | 0.202 | 4.66 | 0 | 0.63 | 3845 |
| ZP B | 0.320 | 5.39 | 102 | 0.79 | 2677 |
| ZP C | 0.310 | 6.22 | 34 | 1.03 | 2781 |
| mean | 0.277 | 5.42 | 45 | 0.82 | 3101 |
| s.d. | 0.065 | 0.78 | 52 | 0.20 | 646 |
| Panotex A | 1.197 | 36.04 | 228 | 1.02 | 288 |
| Panotex B | 0.201 | 4.27 | 13 | 0.68 | 320 |
| mean | 0.699 | 20.16 | 121 | 0.85 | 372 |
| s.d. | 0.704 | 22.46 | 152 | 0.24 | 23 |
| Kevlar | 0.271 | 3.57 | 47 | 0.96 | 185 |

Table 7. Summary of Furniture Calorimeter results at full time

| | ML kg | TE MJ | TSR m² | CO g | CO₂ g |
|-------------|------------------|------------------|------------------------------|-----------------|-----------------------------|
| Control A | 1.115 | 46.75 | 212 | 5.13 | 3015 |
| Control B | 1.637 | 69.23 | 457 | 7.39 | 4506 |
| Control C | 1.422 | 55.07 | 482 | 4.55 | 3493 |
| mean | 1.391 | 57.02 | 384 | 5.69 | 3671 |
| s.d. | 0.262 | 11.37 | 149 | 1.50 | 761 |
| Zirpro A | 1.813 | 65.97 | 506 | 3.94 | 4543 |
| Zirpro B | 1.914 | 66.47 | 420 | 5.86 | 4260 |
| Zirpro C | 2.040 | 70.44 | 577 | 5.95 | 4625 |
| mean | 1.92 | 67.63 | 501 | 5.25 | 4476 |
| s.d. | 0.11 | 2.45 | 79 | 1.14 | 192 |
| ZP A | 1.712 | 50.88 | 273 | 11.06 | 3845 |
| ZP B | 1.712 | 41.67 | 373 | 12.80 | 2677 |
| ZP C | 1.637 | 41.04 | 307 | 11.58 | 2781 |
| mean | 1.687 | 44.53 | 318 | 11.81 | 3101 |
| s.d. | 0.043 | 5.51 | 51 | 0.89 | 646 |
| Panotex A | 1.197 | 36.04 | 228 | 8.07 | 2404 |
| Panotex B | 0.201 | 4.27 | 13 | 2.82 | 472 |
| mean | 0.699 | 20.16 | 121 | 5.45 | 1438 |
| s.d. | 0.704 | 22.5 | 152 | 3.71 | 1366 |
| Kevlar | 0.486 | 5.7 | 109 | 4.63 | 382 |

10.0 CONCLUSIONS

- Fabric materials selected for protection against heat and flame can be compared and ranked against each other by measuring the convective heat transfer and dimensional stability performance after exposure to a high heat flux ($\sim 50 \text{ kW/m}^2$).
- It has been demonstrated that it is possible to reduce the heat release rate of soft furniture mock-ups by around 60% while concurrently increasing the time to peak heat release by a factor of 3. Both achievements are the result of incorporating a fire barrier inter-liner between the upholstery fabric and polyurethane foam filling.
- A blend ratio of (75/25), Zirpro wool/Panox fibres forming a protective barrier material has been identified which offers a comparable level of performance to more established high-end inter-liner products. This research has established an approximate bench-mark blend ratio applicable to domestic soft furniture. The blend identified has higher wool and lower tech-fibre proportion than inter-liners previously developed for aircraft seat protection against fire.
- This research may be used as an initial starting point from which further research into the fire protection of furniture could be continued.
- The aims of this project have been successfully achieved. Although there is ample scope for more research in this area, the results in this work support the theory that the fire safety of polyurethane filled furniture can be significantly improved by incorporating an inter-liner of simple construction and the correct choice of inexpensive components; thereby providing a performance based solution which may in future be voluntarily adopted by New Zealand furniture manufacturers.

11.0 RECOMMENDATIONS

- In this project the wool component of the inter-liner was Zirpro treated to enhance its fire retardant qualities. Due to the environmental impact of the heavy metal content resulting from the treatment, it would be advantageous to repeat this work using an alternative fire retardant treatment for wool.
- Only one type of foam was used throughout the experiments, therefore there is no confirmation that the reduced peak heat release rate and time to peak heat release rate would be as significant for other polyurethane foams used in furniture.
- The experimental set-up for the Furniture Calorimeter incorporated a metal tray positioned onto load cells and upon which the seat assembly was placed. The inside surface of the tray was bare metal and not insulated. Further work could be carried out to ascertain the effect of such a heat sink on pool fire formation around and under the furniture sample. Also, the effect on the burning rate of the samples and the effectiveness of the developed inter-liners.
- The ignition sources used in the Furniture Calorimeter tests were 17 g wooden cribs which deviated from the metered gas burner in the ASTM E 1537-99 standard [30]. This was done to observe the performance of the samples under small, steadily increasing flaming sources. Future work could be done using a controlled, increasing metered gas flame for improved reproducibility whilst also representing a more realistic ignition source.
- More samples need to be tested to obtain a more accurate representation of the performance characteristics and limits of the developed protection for furniture. Also a better characterization of existing commercial products would provide more reliable data for comparison.
- Only soft components of idealized furniture mock-ups were tested. There is scope for future work to be done on actual furniture models lined with the fire barrier developed in this project.

- It is recommended, that experimental fabrics in future work be should be manufactured using fully commercial processes to ensure the uniformity and density of blended fibre in the material. This would be beneficial towards reducing the variability in test results.

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APPENDICES

Appendix A: Heat Transfer Performance Test

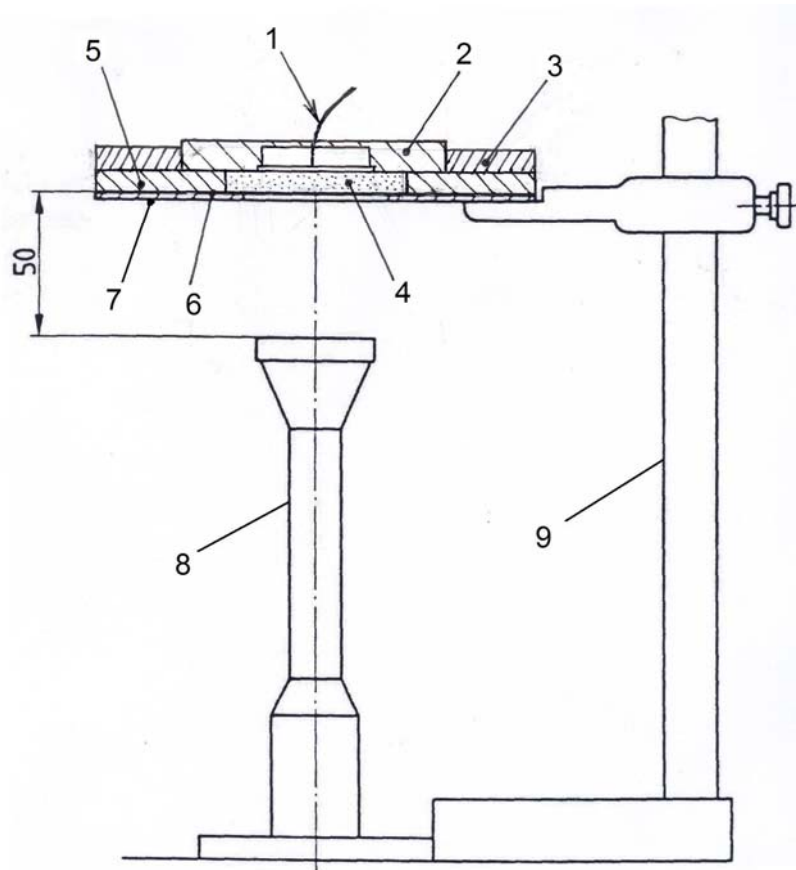


Figure A1. Modified convective heat transfer equipment

- 1 Thermocouple
- 2 Calorimeter block
- 3 Calorimeter block locator
- 4 Sample
- 5 Sample block
- 6 Mesh grid
- 7 Base plate
- 8 Burner
- 9 Adjustable sample holder stand

A schematic of the heat transfer experiment apparatus is displayed in Figure A.1 above. The main differences between this and the equipment prescribed in BS EN 367 [26] can be isolated to points (4), (5) and (6) in the figure, relating to the sample, sample holder and mesh grid above the base plate (7). Samples (4) are placed within the space provided by the sample block (5) and are compressed on the upper and lower faces by the calorimeter block (2) and mesh grid (6) respectively such that the resulting thickness is equal to the sample block plate thickness.

The heat flux from the burner flame is adjusted to give a total incident flux of 50kW/m^2 on the calorimeter placed directly on the wire mesh (without sample).

Appendix B: Thermal Protective Index (TPI) individual sample graphs

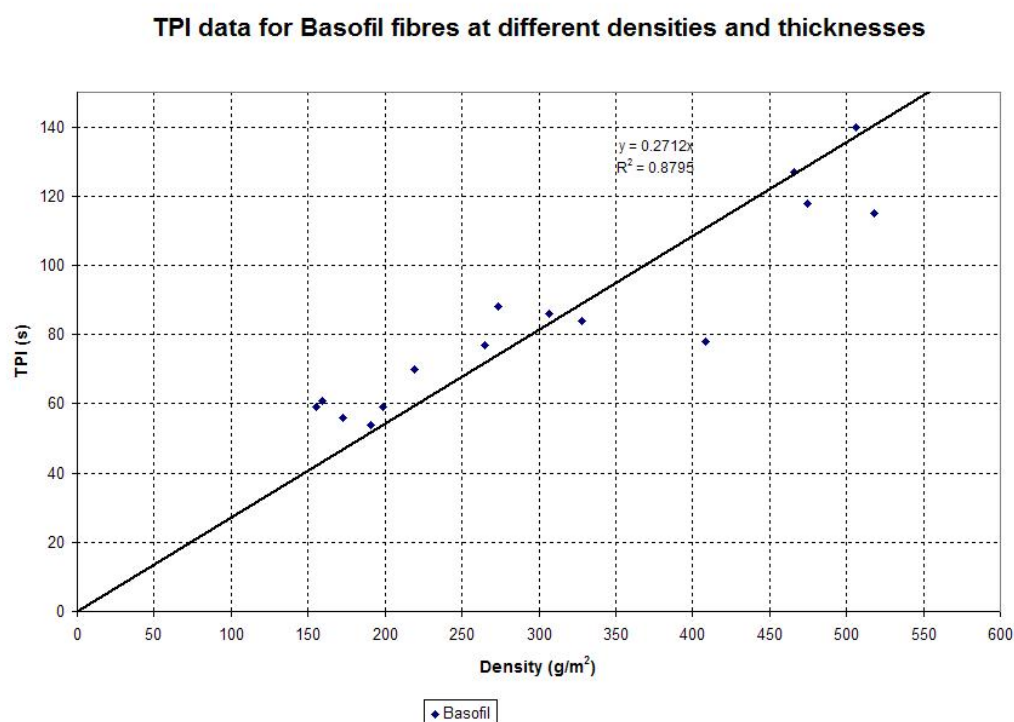


Figure B1. TPI for Basofil

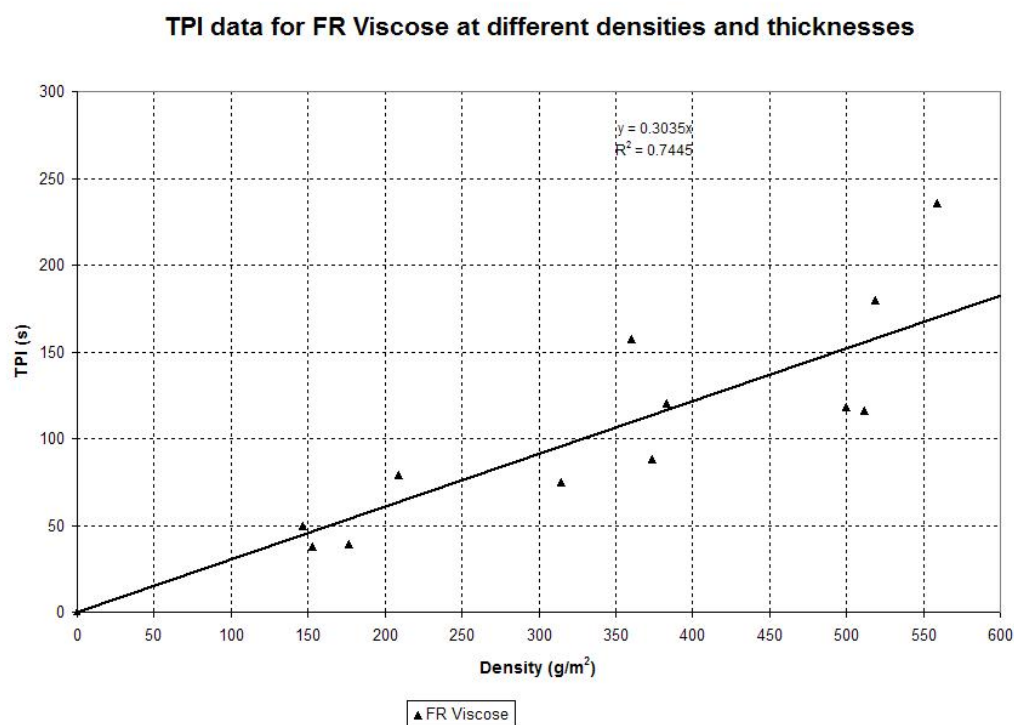


Figure B2. TPI for FR Viscose

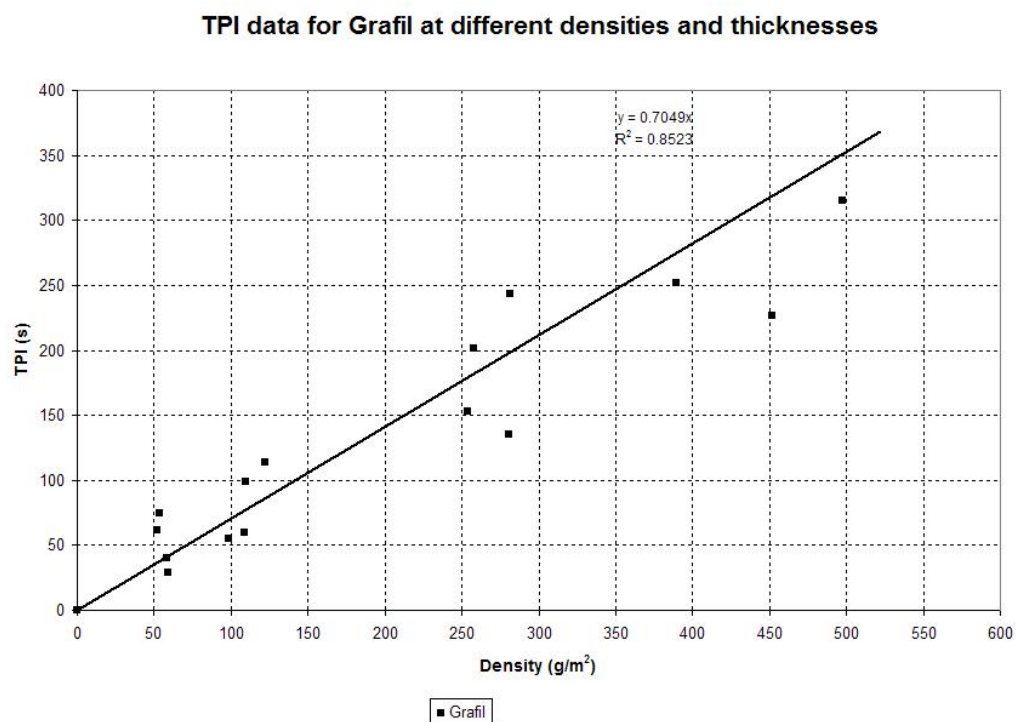


Figure B3. TPI for Grafil

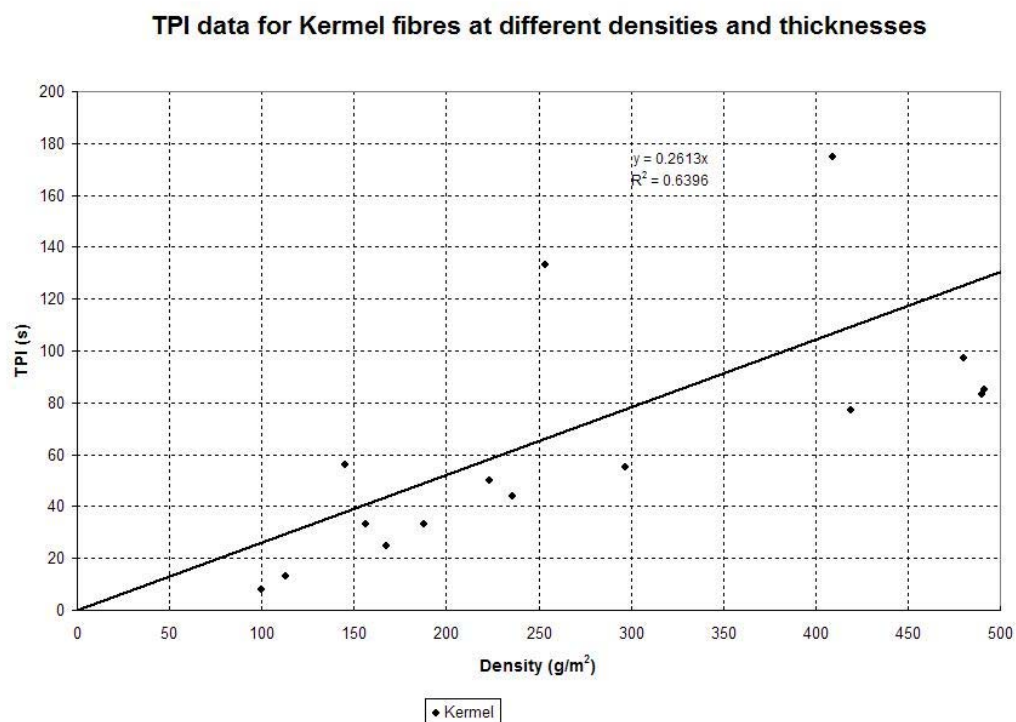


Figure B4. TPI for Kermel

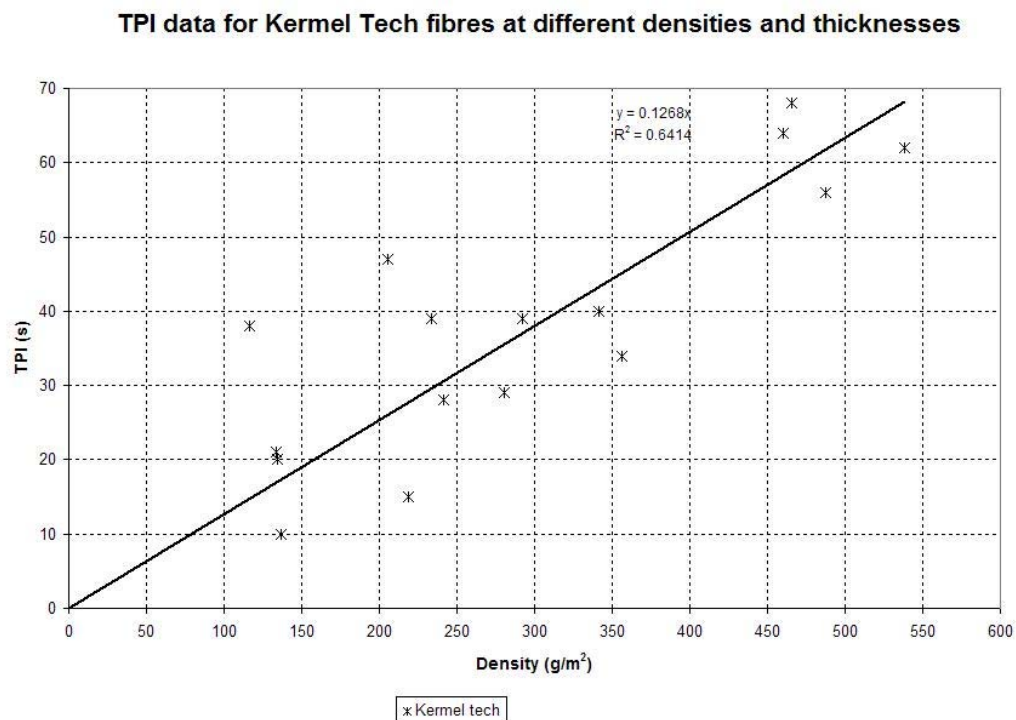


Figure B5. TPI for Kermel Tech

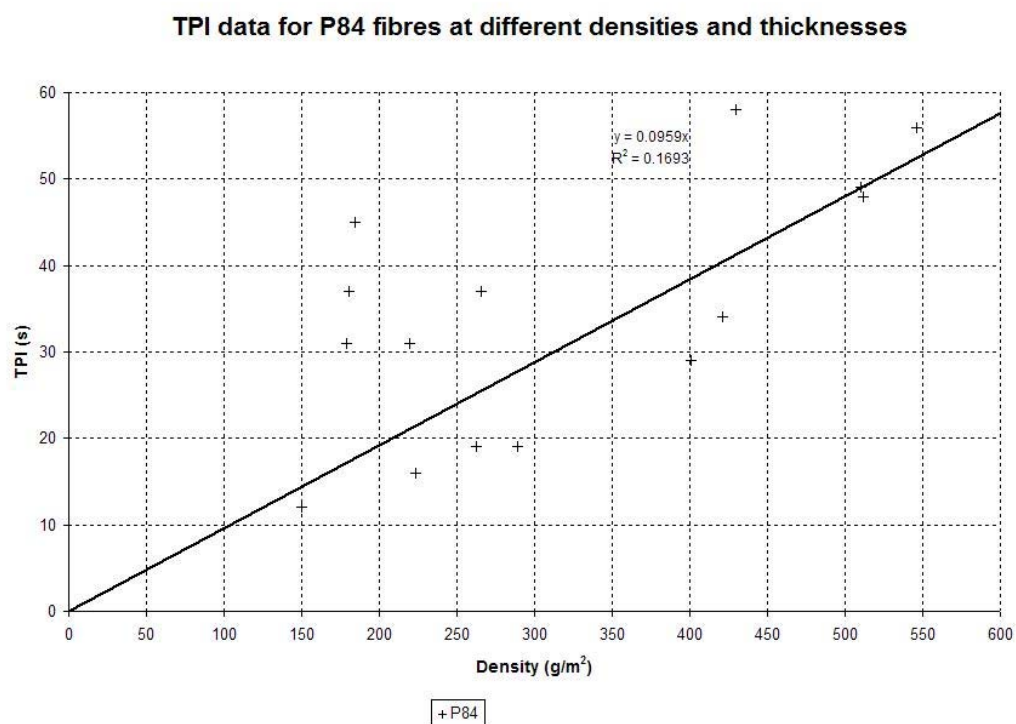


Figure B6. TPI for P84

TPI data for Panox fibres at different densities and thicknesses

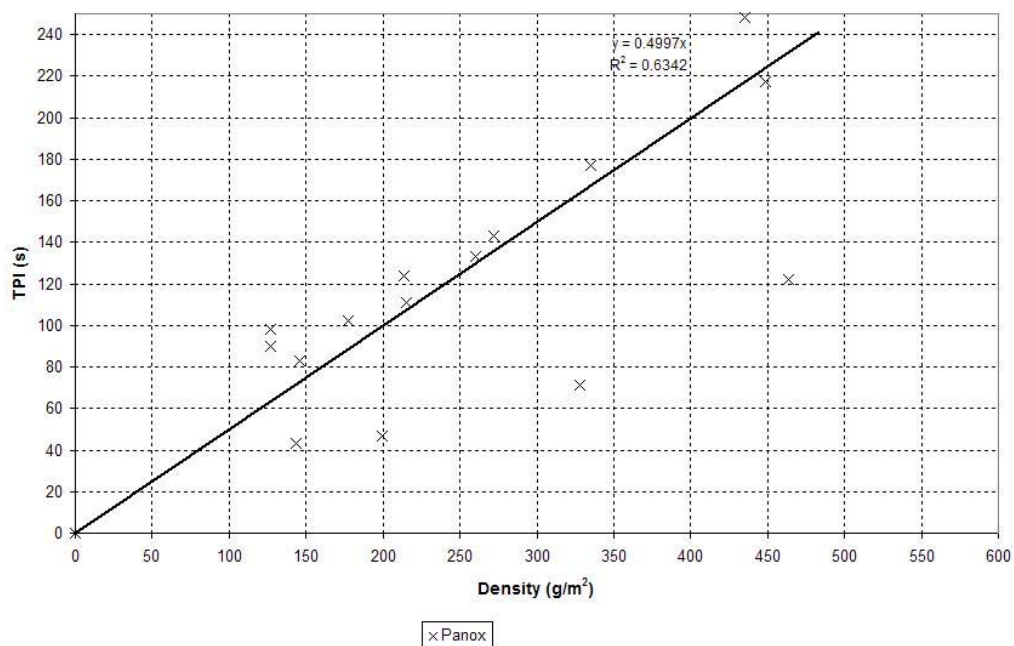


Figure B7. TPI for Panox

TPI data for Zirpro fibres at different densities and thicknesses

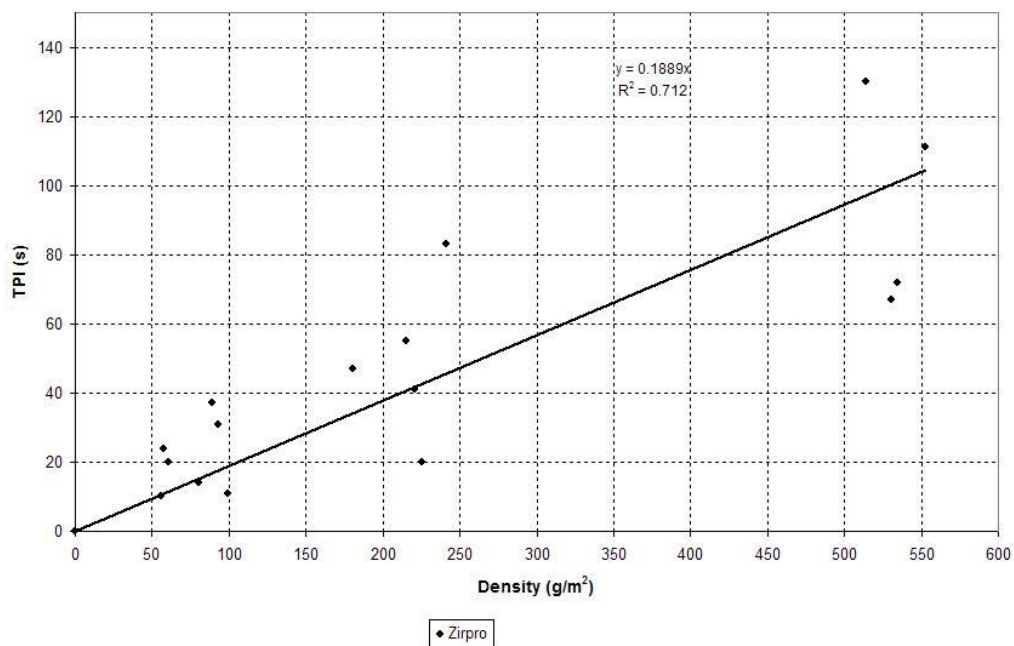


Figure B8. TPI for Zirpro

Appendix C: Oxygen Consumption Calorimetry

A simple phrase highlights the importance of the ability to measure the rate of heat release rate of materials undergoing combustion. Janssens [33] writes “Heat release rate is the primary variable that determines the contribution to compartment fire hazard from materials.”

Oxygen consumption calorimetry is one such method used for measuring rate of heat release (HRR) and has been recognized as the most practical and accurate technique for measuring HRR in both bench scale and large scale applications [25]. The underlying principle of the technique relies upon a now thoroughly substantiated principle that for a large number of organic solids, liquids and gases, a reasonably constant net amount of heat is released per unit mass of oxygen consumed for complete combustion. An average value named Huggett’s constant is used for practical applications and is taken as 13.1 MJ/kg of oxygen. It is accurate with few exceptions to within $\pm 5\%$.

According to the underlying principle, it follows that the determination of heat release is based upon an accurate measurement of the oxygen consumed during combustion of a sample. The equations developed to calculate the HRR are given below as detailed by Janssens [33]. Both the Cone Calorimeter and Furniture Calorimeter operate on exactly the same principle and the equations can be applied for the data reduction of tests from either instrument.

For this research the equations used to calculate the oxygen consumption from sample combustion incorporated expressions (C.5) and (C.8) utilizing carbon monoxide (CO) and carbon dioxide (CO₂) measurement in conjunction with the mandatory oxygen (O₂) measurement. The extra gas measurement offers a more robust calculation as it accounts for the influence of the major by-products of combustion on the overall heat energy release calculation. Smoke measurement for either test method was conducted with the use of a helium-neon laser smoke detection system and photometer cells recording the initial and transmitted intensity of the light source, from which optical density and extinction coefficient were calculated using equations (C.9) and (C.10)

Water was removed from the sample gas lines of the instruments, with the use of a desiccant water trap; therefore the production of water was not included in the data reduction and calculations; in keeping with equations (C.5) and (C.8). The test protocols followed during

the use of each instrument were taken directly from AS/NZS 3738 (or ISO 5660) [27] for the Cone Calorimeter and ASTM E 1537-99 [30].

Oxygen Consumption Calorimetry Equations

Pressure drop measurement

$$\dot{m}_e = C \times \sqrt{\left[\frac{\Delta p}{T_e} \right]} \quad [\text{C.1}]$$

Velocity measurement

$$\dot{m}_e = 26.54 \times \frac{A \times k_e}{f(\text{Re})} \times \sqrt{\left[\frac{\Delta p}{T_e} \right]} \quad [\text{C.2}]$$

Oxygen depletion factor (when only O₂ is measured)

$$\phi = \frac{X_{O_2}^{A^o} - X_{O_2}^A}{[1 - X_{O_2}^A] \times X_{O_2}^{A^o}} \quad [\text{C.3}]$$

Oxygen depletion factor (when only O₂ and CO₂ are measured)

$$\phi = \frac{X_{O_2}^{A^o} \times [1 - X_{CO_2}^A] - X_{O_2}^A \times [1 - X_{CO_2}^{A^o}]}{[1 - X_{O_2}^A - X_{CO_2}^A] \times X_{O_2}^{A^o}} \quad [\text{C.4}]$$

Oxygen depletion factor (when O₂, CO₂ and CO is measured)

$$\phi = \frac{X_{O_2}^{A^o} \times [1 - X_{CO_2}^A - X_{CO}^A] - X_{O_2}^A \times [1 - X_{CO_2}^{A^o}]}{[1 - X_{O_2}^A - X_{CO_2}^A - X_{CO}^A] \times X_{O_2}^{A^o}} \quad [\text{C.5}]$$

Rate of Heat Release Equations

When only O₂ is measured

$$\dot{q} = E \times \frac{M_{O_2}}{M_a} \times \frac{\phi}{1 + \phi \times (\alpha - 1)} \times \dot{m}_e \times X_{O_2}^{A^o} \quad [\text{C.6}]$$

α is the volumetric expansion coefficient of which the recommended average value is taken as 1.105

Equation [A3.6] reduces to

$$\dot{q} = E \times 1.10 \times C \times \sqrt{\left[\frac{\Delta p}{T_e} \right]} \times \left[\frac{(X_{O_2}^{A^o} - X_{O_2}^A)}{1.105 - 1.5 \times X_{O_2}^A} \right] \quad [\text{C.7}]$$

When O₂, CO₂ and CO is measured

$$\dot{q} = \left[E \times \phi - [E_{CO} - E] \times \frac{1 - \phi}{2} \times \frac{X_{CO}^A}{X_{O_2}^A} \right] \times \frac{M_{O_2}}{M_a} \times \frac{\dot{m}_e}{1 + \phi \times (\alpha - 1)} \times X_{O_2}^{A_o} \quad [C.8]$$

Smoke Measurement Equations

Optical Density (OD)

$$OD = \log \left[\frac{I_o}{I} \right] \quad [C.9]$$

Extinction Coefficient (*k*)

$$k = \left(\frac{1}{L_p} \right) \times \ln \left(\frac{I_o}{I} \right) \quad [C.10]$$

Volumetric flow rate

$$\dot{V}_s = \dot{V}_e \times \left(\frac{T_s}{T_e} \right) \quad [C.11]$$

Temperature adjusted air density

$$\rho = \rho_o \times \left(\frac{273.15}{T_e} \right) \quad [C.12]$$

The final equation for the volumetric flow rate can be written as

$$\dot{V}_s = \frac{\dot{m}_e}{\rho_o} \times \left(\frac{T_e}{273.15} \right) \quad [C.13]$$

Rate of smoke release (RSR) is defined by

$$RSR = \left[\dot{V}_s \times k \right] \quad [C.14]$$

Total smoke released (TSR) is defined by

$$TSR = \int RSR \cdot dt \quad [C.15]$$

Nomenclature of Oxygen Consumption Calorimetry Equations

| | | |
|-------------|--|--|
| A | Cross-sectional area of duct | (m ²) |
| C | Orifice plate coefficient | (kg ^{1/2} m ^{1/2} K ^{1/2}) |
| E | Net HR for complete combustion, per unit oxygen consumed | (13.1 MJ/kg O ₂) |
| E_{CO} | Net HR for complete combustion, per unit of oxygen consumed, for CO | (17.6 MJ/kg O ₂) |
| $f(Re)$ | Reynolds number correction | - |
| I | Light intensity for parallel light beam having traversed a length of smoky environment before reaching the photodetector. | (mV) |
| I_o | Light intensity for a parallel light beam measured in a smoke-free environment, with a detector having the same spectral sensitivity as the human eye and reaching the photodetector | (mV) |
| k | Extinction coefficient | (1/m) |
| k_c | Velocity profile shape factor | - |
| L_p | Light path length of beam | (m) |
| \dot{m}_e | Mass flow rate in exhaust duct | (kg/s) |
| M_a | Molecular weight of incoming and exhaust air | (29 kg/kmol) |
| M_{CO} | Molecular weight of carbon monoxide | (28 kg/kmol) |
| M_{CO_2} | Molecular weight of carbon dioxide | (44 kg/kmol) |
| M_{H_2O} | Molecular weight of water | (18 kg/kmol) |
| M_{N_2} | Molecular weight of nitrogen | (28 kg/kmol) |
| M_{O_2} | Molecular weight of oxygen | (32 kg/kmol) |
| OD | Optical density | - |
| Δp | Pressure drop across orifice plate or bidirectional probe | (Pa) |
| \dot{q} | Rate of heat release | (kW) |
| RSR | Rate of smoke release | (m ² /s) |
| T_e | Combustion gas temperature at orifice plate | (K) |

| | | |
|------------------|---|----------------------------|
| T_s | Combustion gas temperature near photodetector | (K) |
| TSR | Total smoke released | (m ²) |
| \dot{V}_e | Volumetric flow rate in exhaust duct | (m ³ /s) |
| \dot{V}_s | Volumetric flow rate at smoke meter | (m ³ /s) |
| X_{CO}^A | Measured mole fraction of CO in exhaust flow | - |
| $X_{CO_2}^A$ | Measured mole fraction of CO ₂ in exhaust flow | - |
| $X_{CO_2}^{A^o}$ | Measured mole fraction of CO ₂ in incoming air | - |
| $X_{O_2}^A$ | Measured mole fraction of O ₂ in exhaust flow | - |
| $X_{O_2}^{A^2}$ | Measured mole fraction of O ₂ in incoming air | - |
| α | Combustion expansion factor (normally 1.105) | - |
| ρ | Density of air at temperature in exhaust duct | (kg/m ³) |
| ρ_o | Density of air at 273.15 K | (1.293 kg/m ³) |
| ϕ | Oxygen depletion factor | - |

Appendix D: Cone Calorimeter-Averaged Heat Release Rate graphs

Comparison furniture composite heat release rates of 95/5, Zirpro wool/tech fibre blends

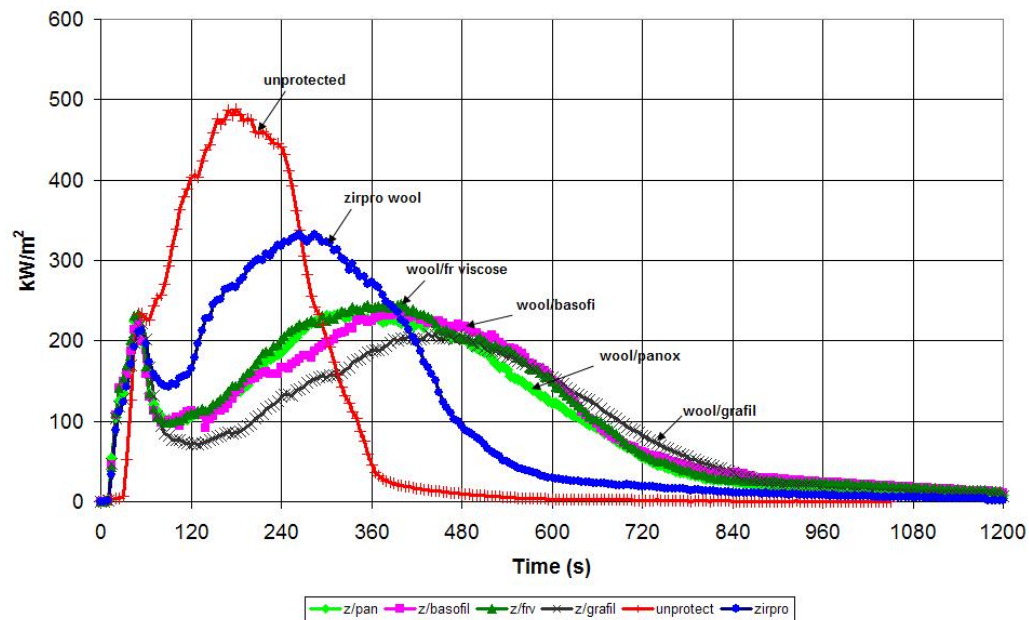


Figure D1. HRR of 95/5 composite ratio samples

Comparison furniture composite heat release rates of 85/15, zirpro wool/ tech fibre blends

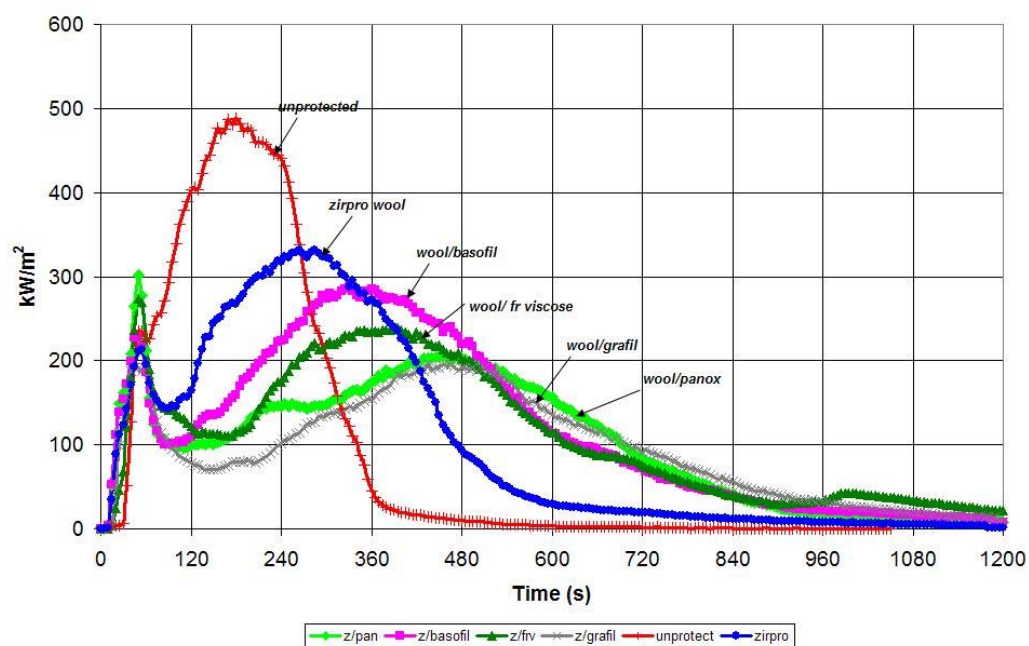


Figure D2. HRR of 85/15 composite ratio samples

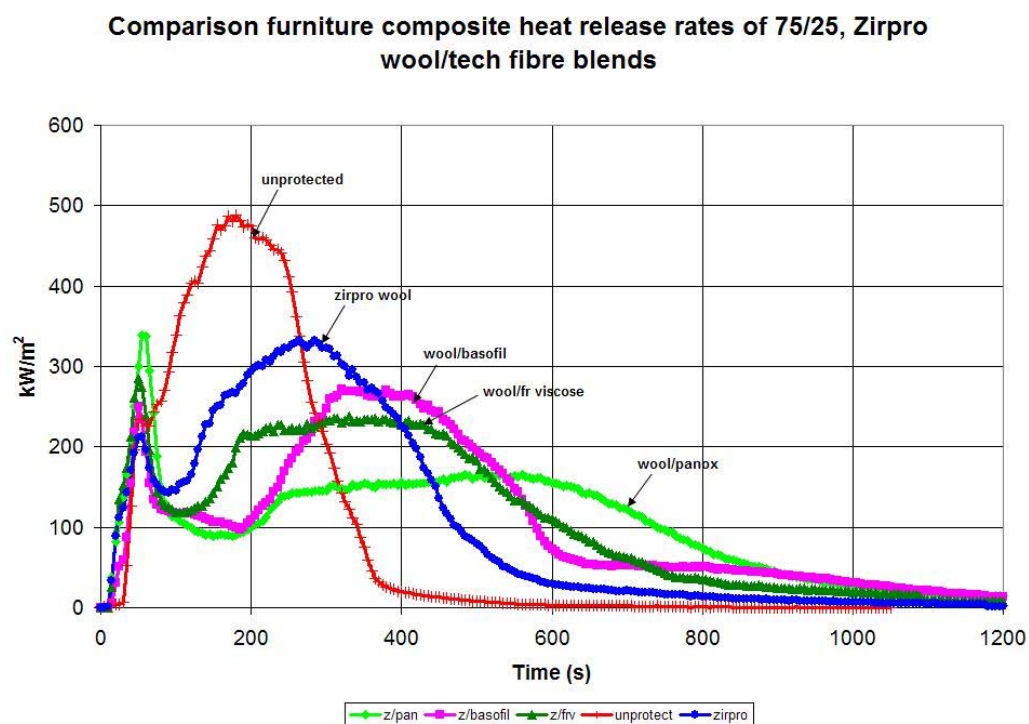


Figure D3. HRR of 75/25 composite ratio samples

Appendix E: Cone Calorimeter-Heat Release Rate graphs

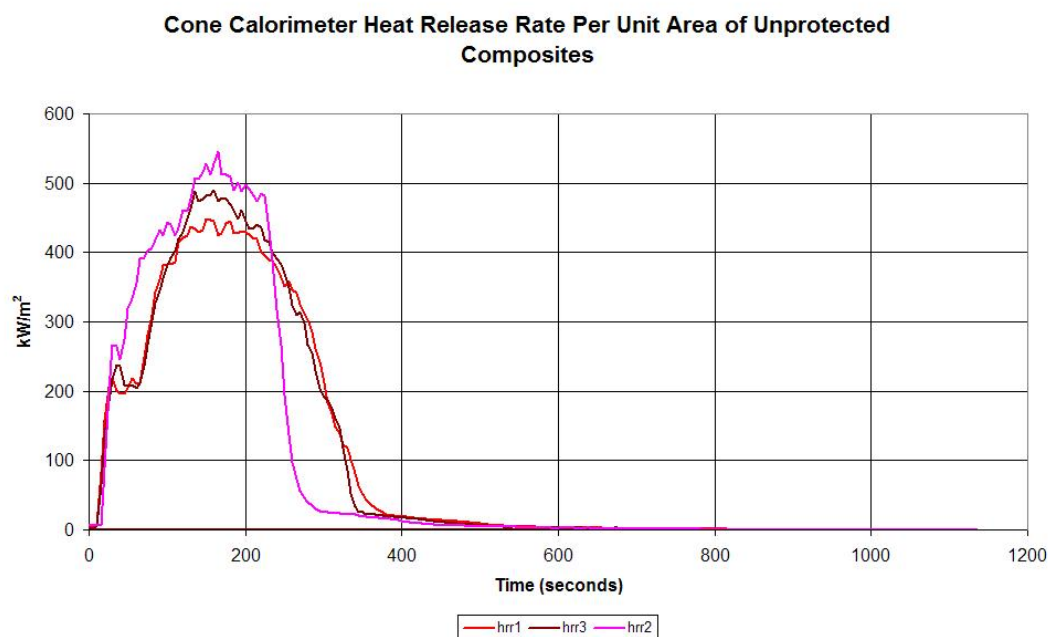


Figure E1. HRR of unprotected individual composite samples

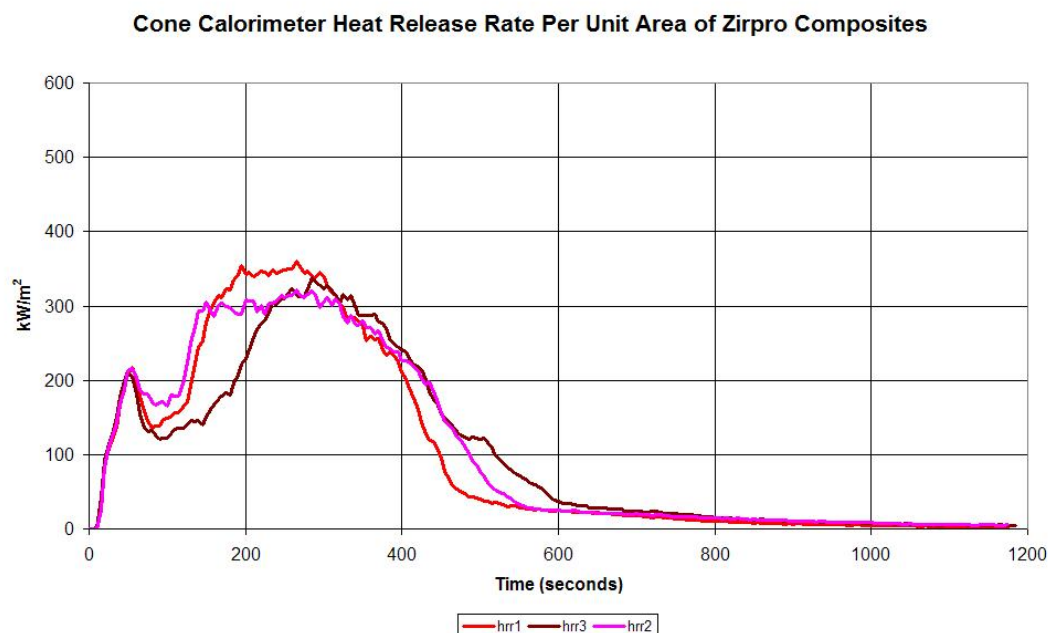


Figure E2. HRR of Zirpro individual composite samples

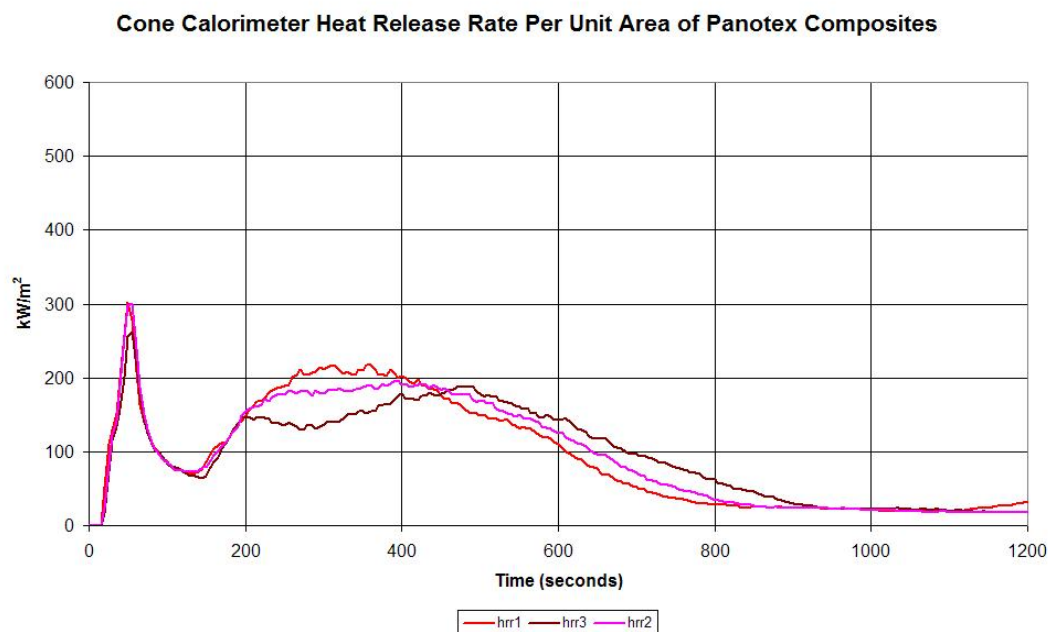


Figure E3. HRR of Panotex individual composite samples

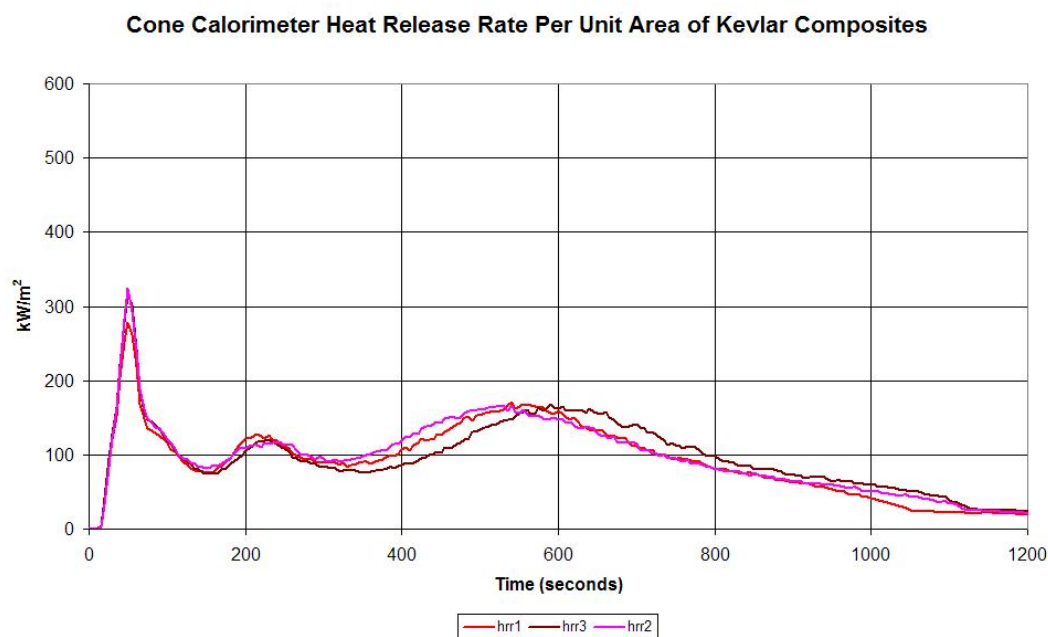


Figure E4. HRR of Kevlar individual composite samples

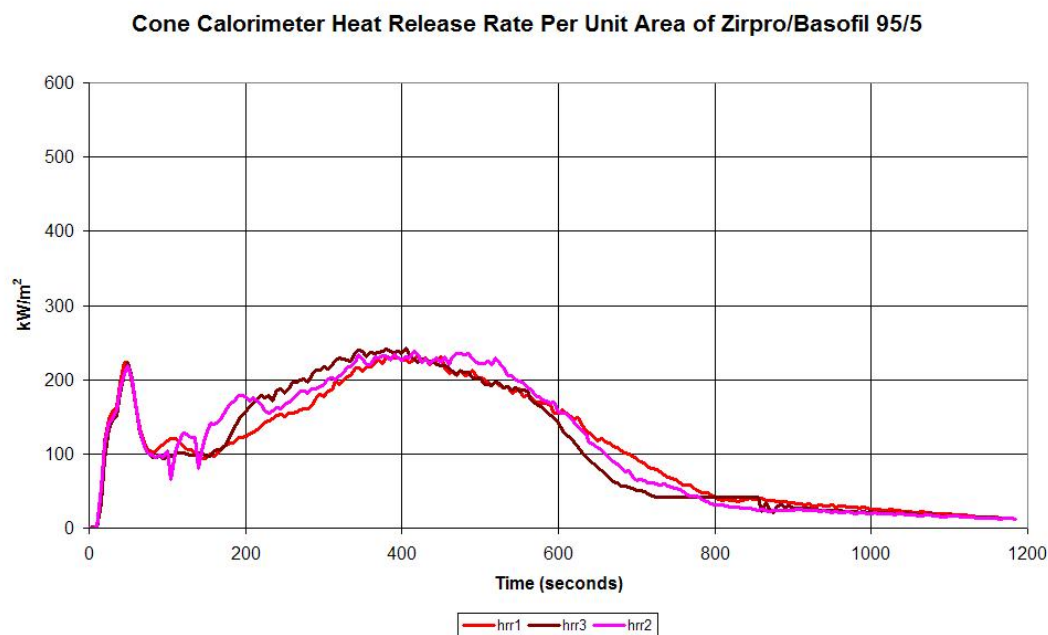


Figure E5. HRR of Z/B 95/5 individual composite samples

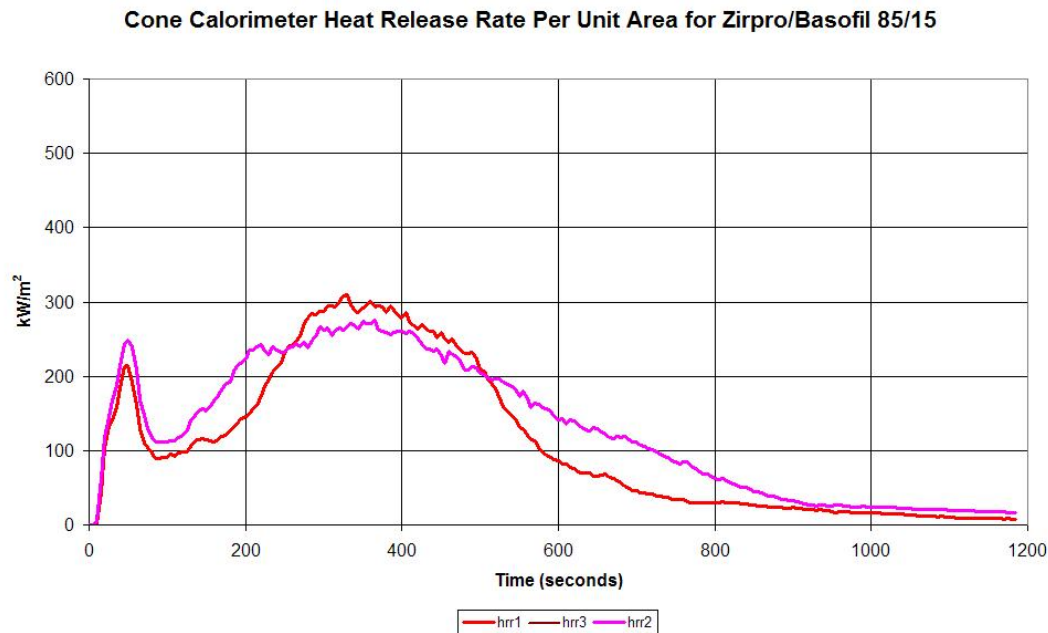


Figure E6. HRR of Z/B 85/15 individual composite samples

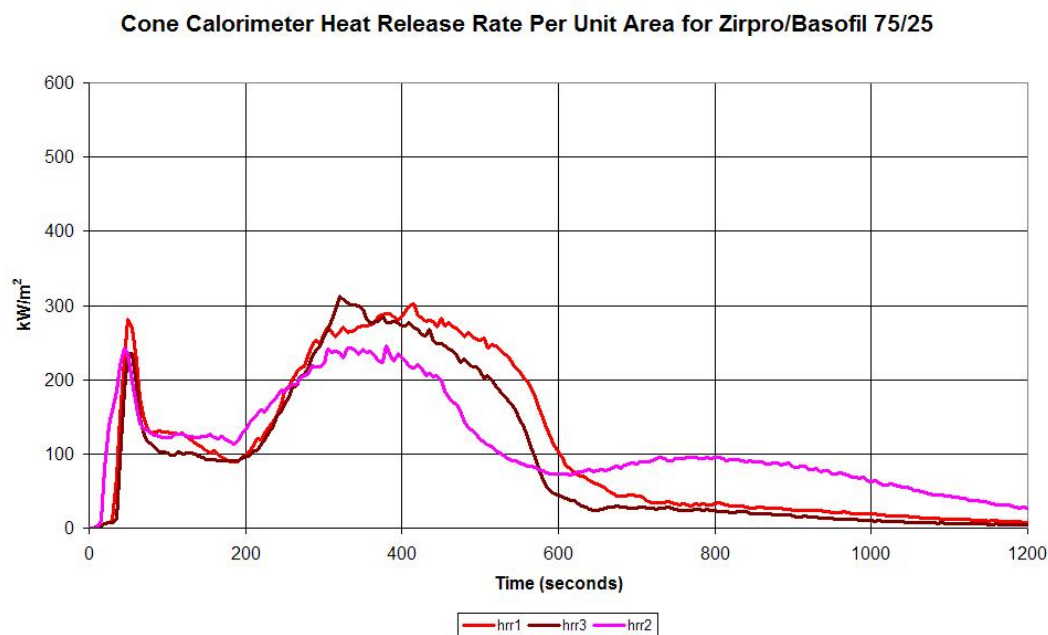


Figure E7. HRR of Z/B 75/25 individual composite samples

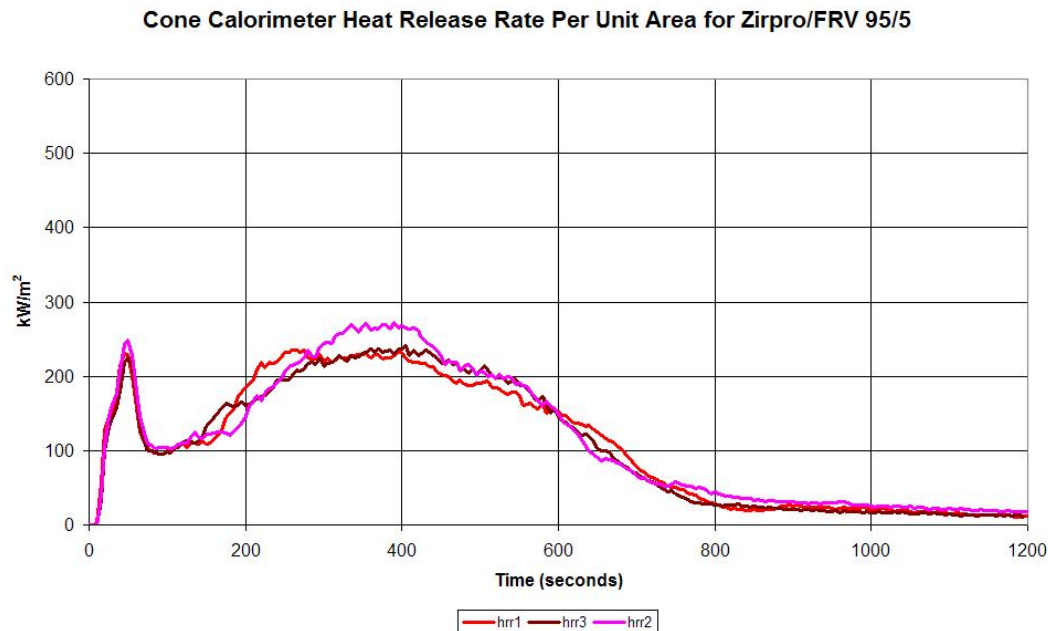


Figure E8. HRR of Z/FRV 95/5 individual composite samples

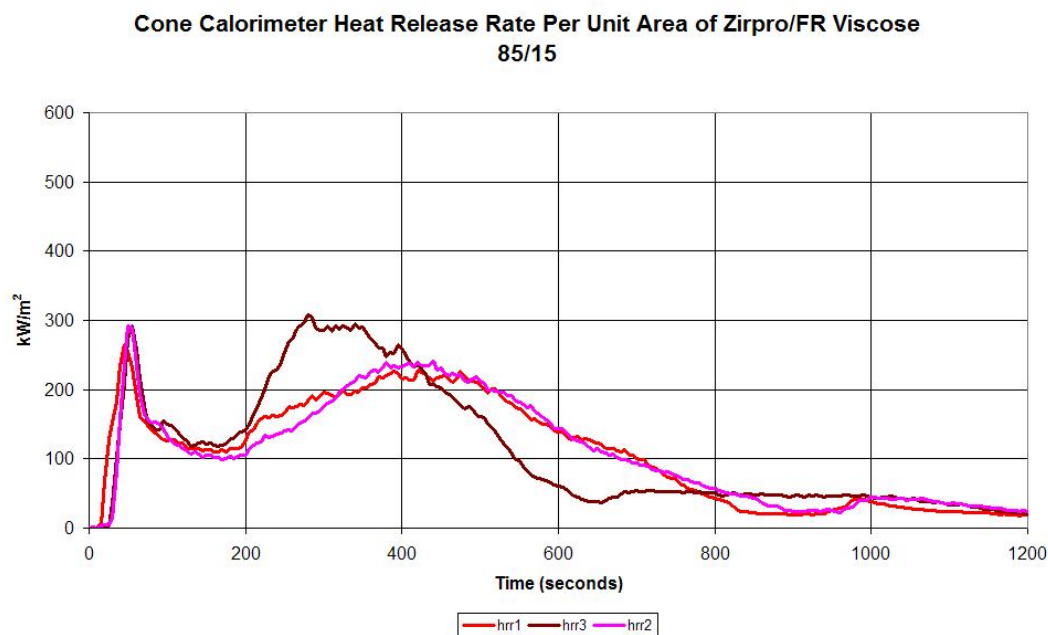


Figure E9. HRR of Z/FRV 85/15 individual composite samples

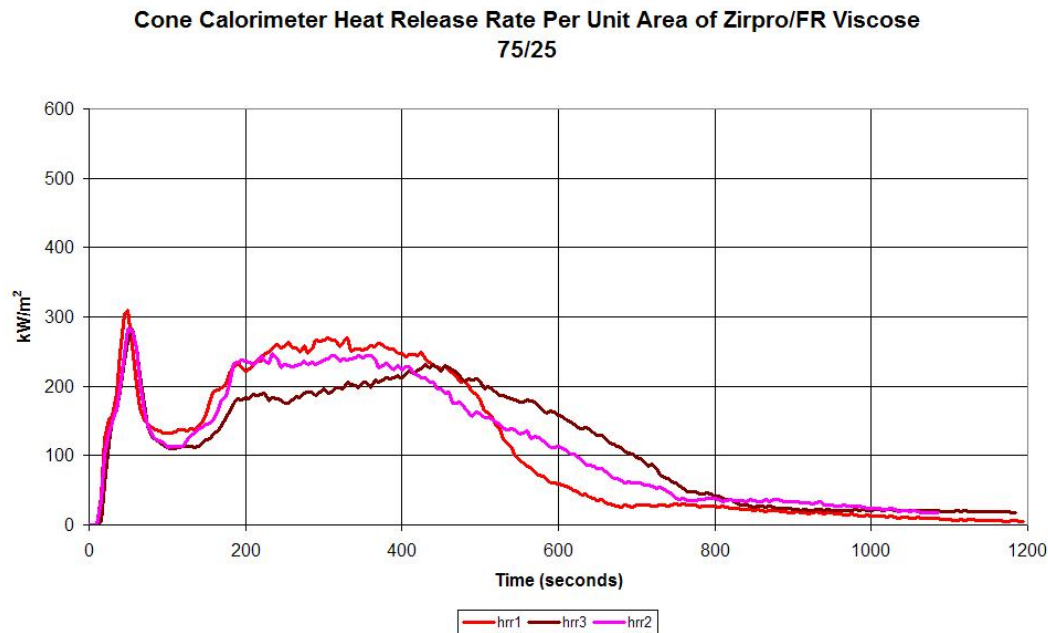


Figure E10. HRR of Z/FRV 75/25 individual composite samples

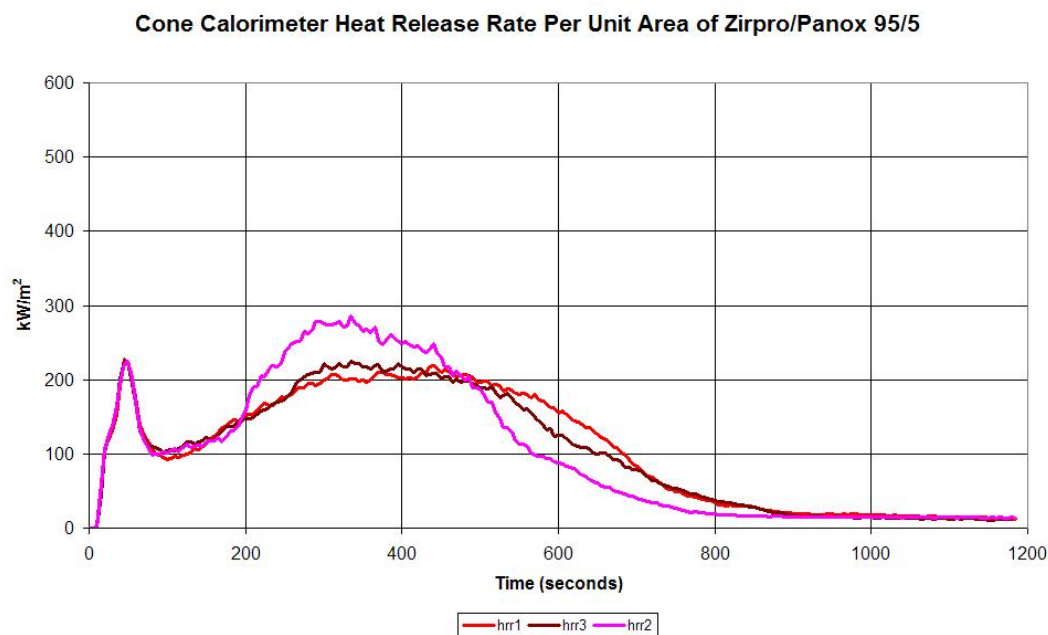


Figure E11. HRR of Z/P 95/5 individual composite samples

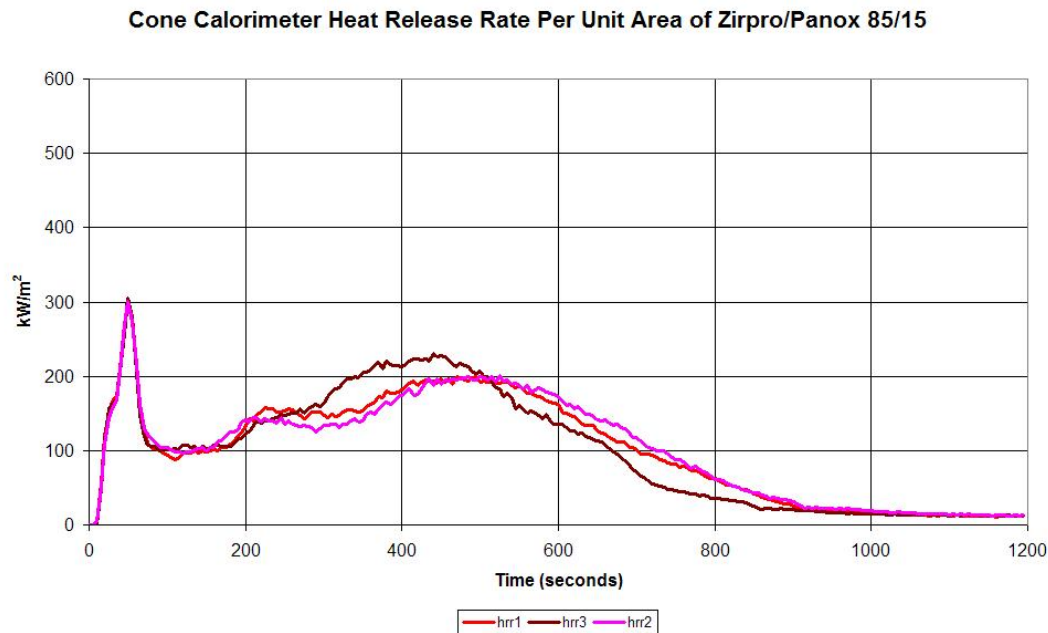


Figure E12. HRR of Z/P 85/15 individual composite samples

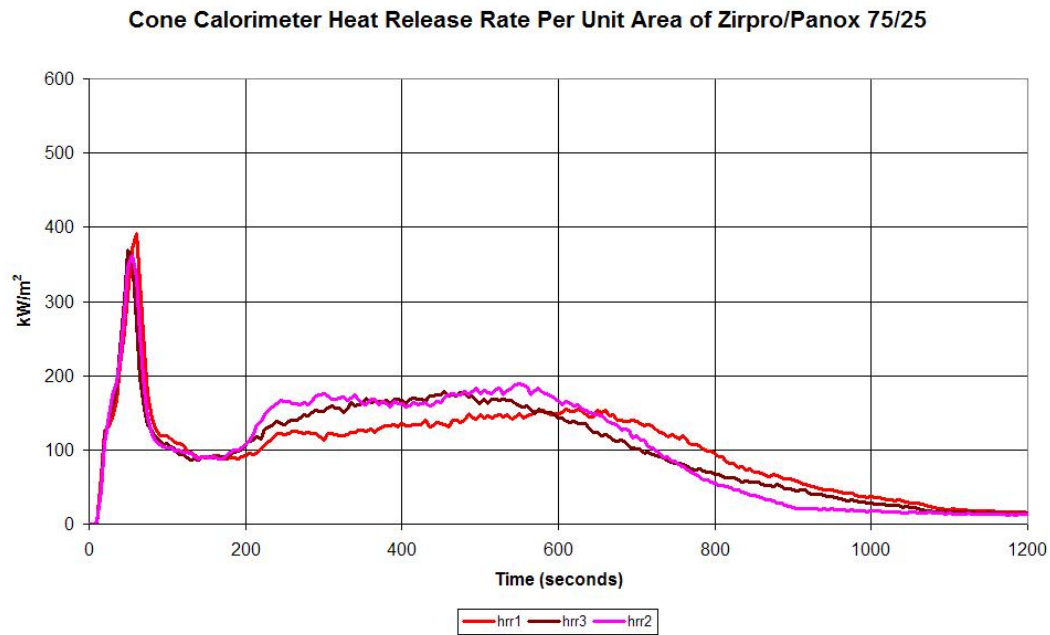


Figure E13. HRR of Z/P 75/25 individual composite samples

Appendix F: Zirpro Flame Retardant Treatment for Wool

Zirpro Flame retardant treatment recipe

Using a closed vessel with water circulation, containing the wool and water at the required liquor ratio

Start at 20°C

Add 0.1ml/l non-ionic wetting agent (Teric GN9)

Run fabric for 5 minutes.

Add 14% Hydrochloric acid (33%)

Add 4% Citric acid (dissolved)

Run 10 minutes

Add 8% Potassium Hexafluorozirconate (well dissolved in hot water)

Run 5 minutes

Add 15% Apex 1694 MOD (diluted in cold water)

Run 5 minutes

Raise to 70-75°C at 1.5°C/min or longer.

Run 30 minutes.

Cool to 40°C

Rinse cold twice.

Appendix G: FAR 25.853(c) Test Frame and Cushion Dimensions

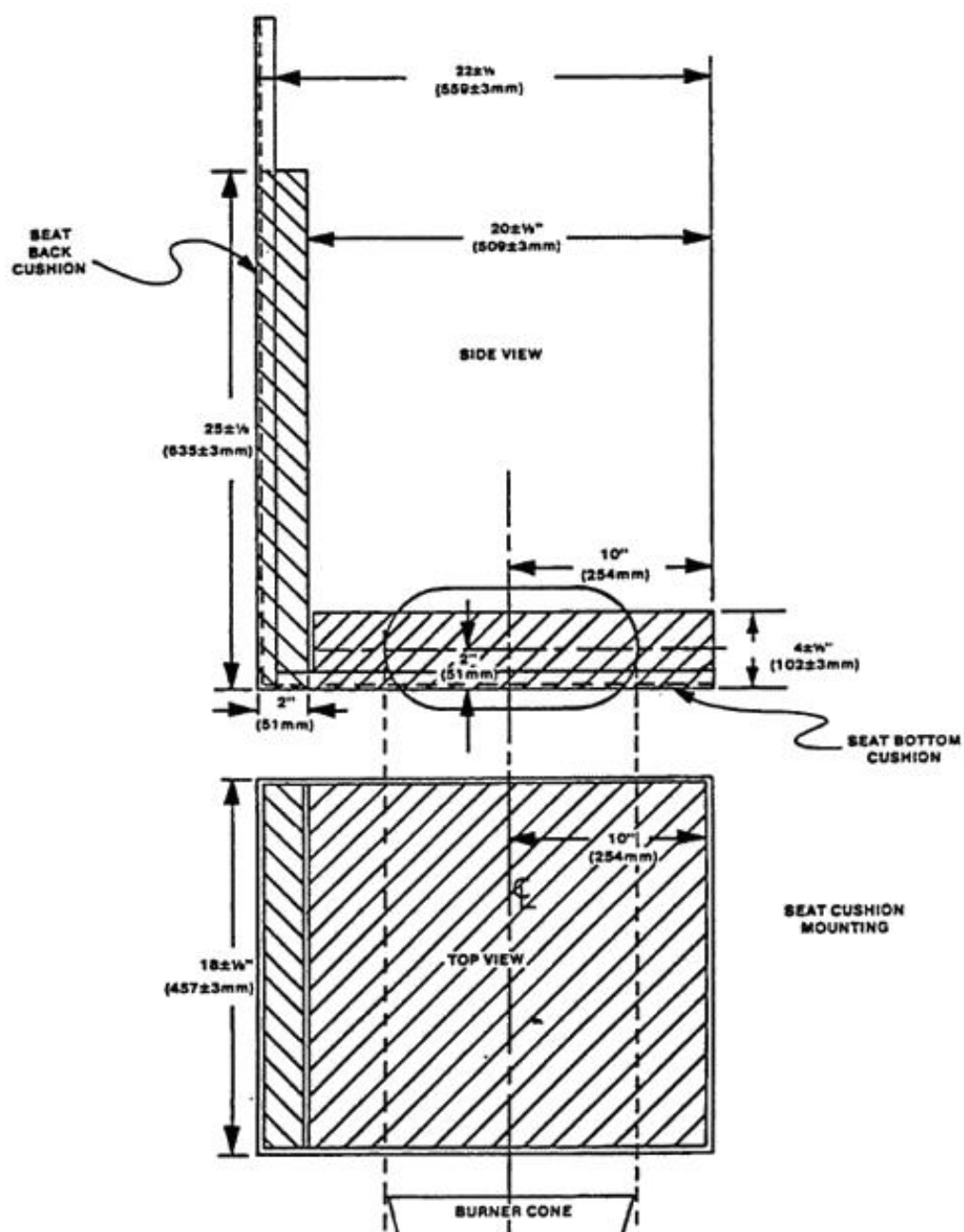


Figure G1. Dimensions of the FAR 25.853(c) seat frame

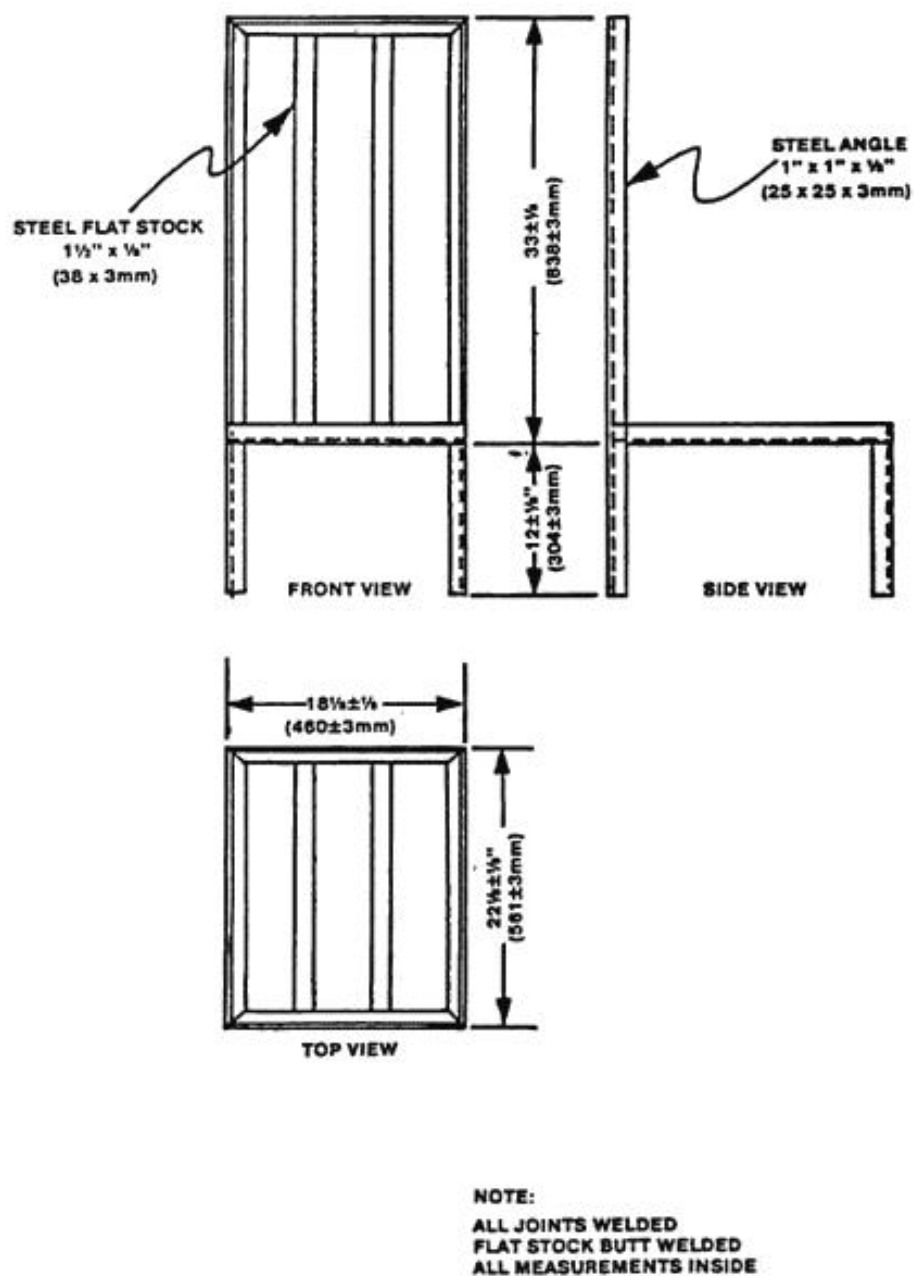


Figure G2. Dimensions of the FAR 25.853(c) seat frame

Appendix H: Furniture Calorimeter-Heat Release Rate Graphs

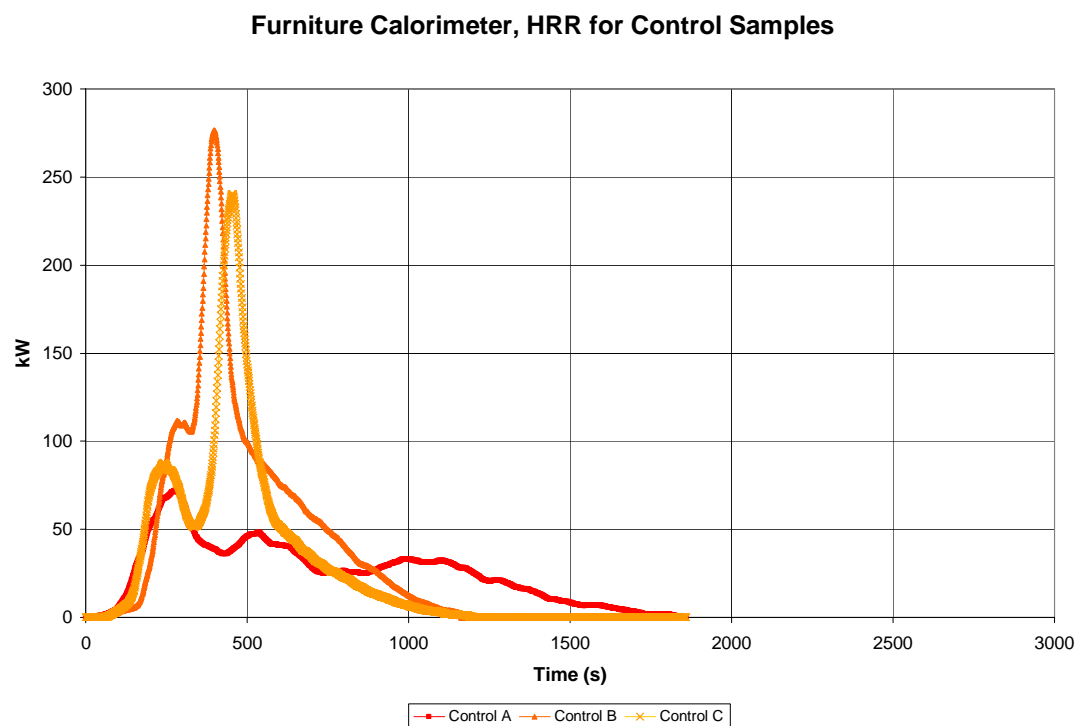


Figure H1. HRR of Control samples in the Furniture Calorimeter

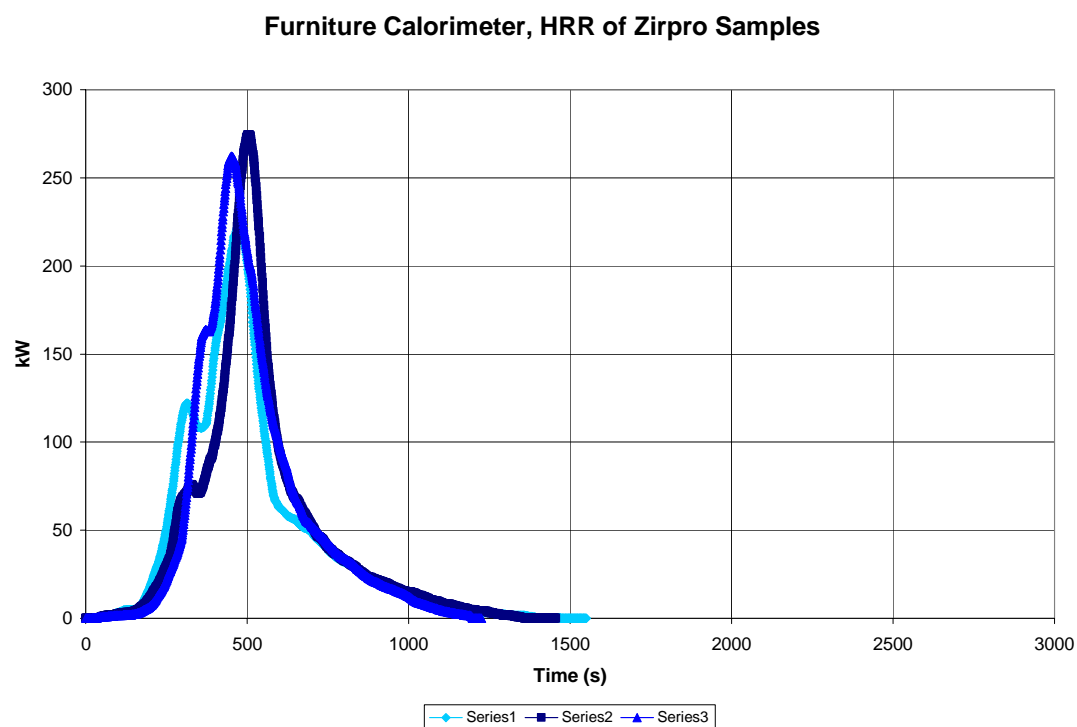


Figure H2. HRR of Zirpro samples in the Furniture Calorimeter

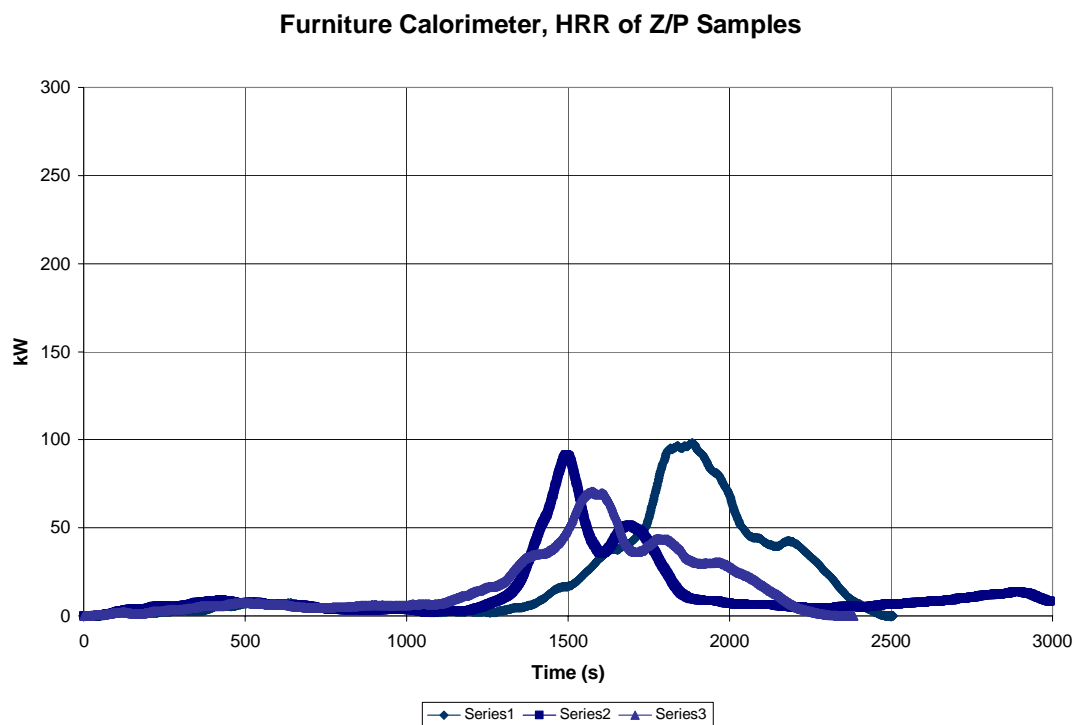


Figure H3. HRR of Z/P samples in the Furniture Calorimeter

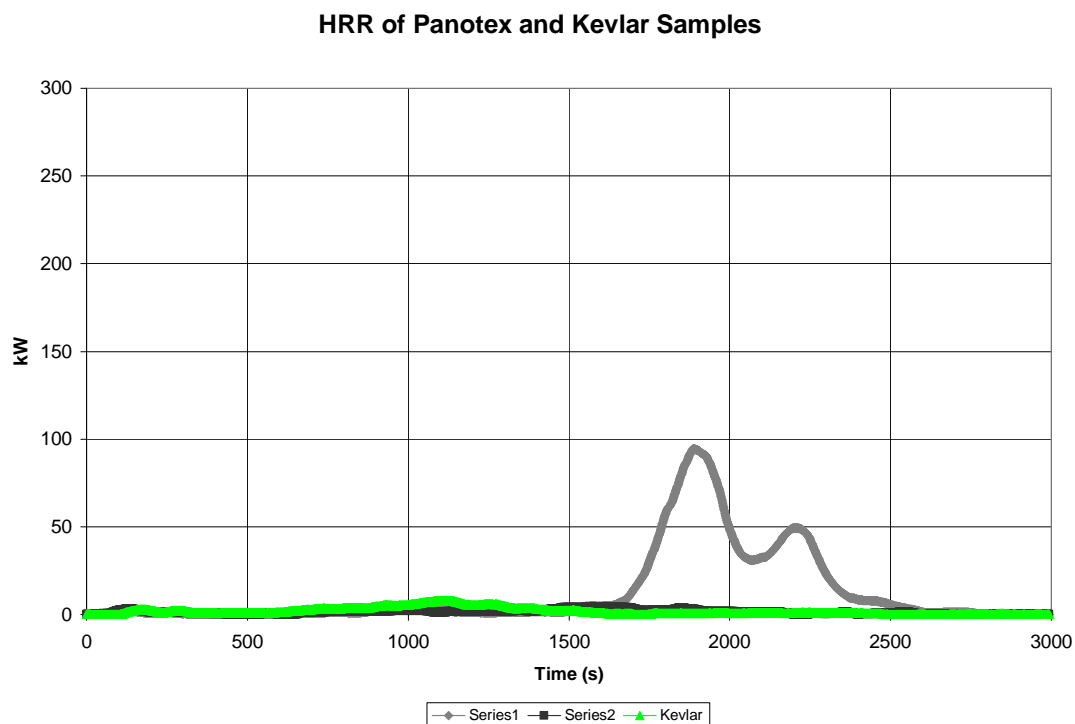


Figure H4. HRR of Panotex and Kevlar samples in the Furniture Calorimeter

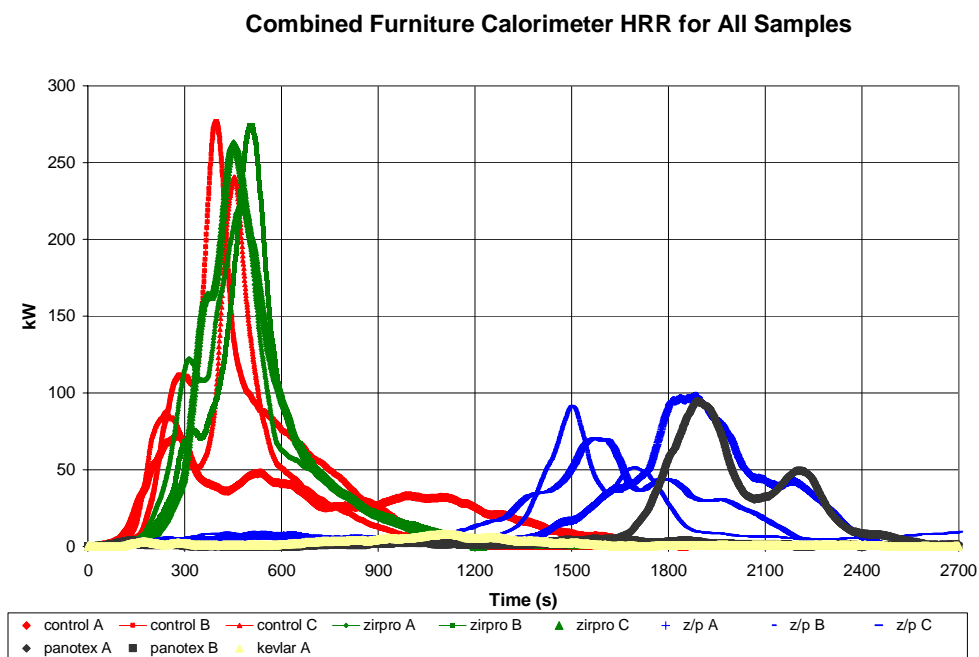


Figure H5. HRR of all samples in the Furniture Calorimeter

Appendix I: Furniture Calorimeter Smoke Production Graphs

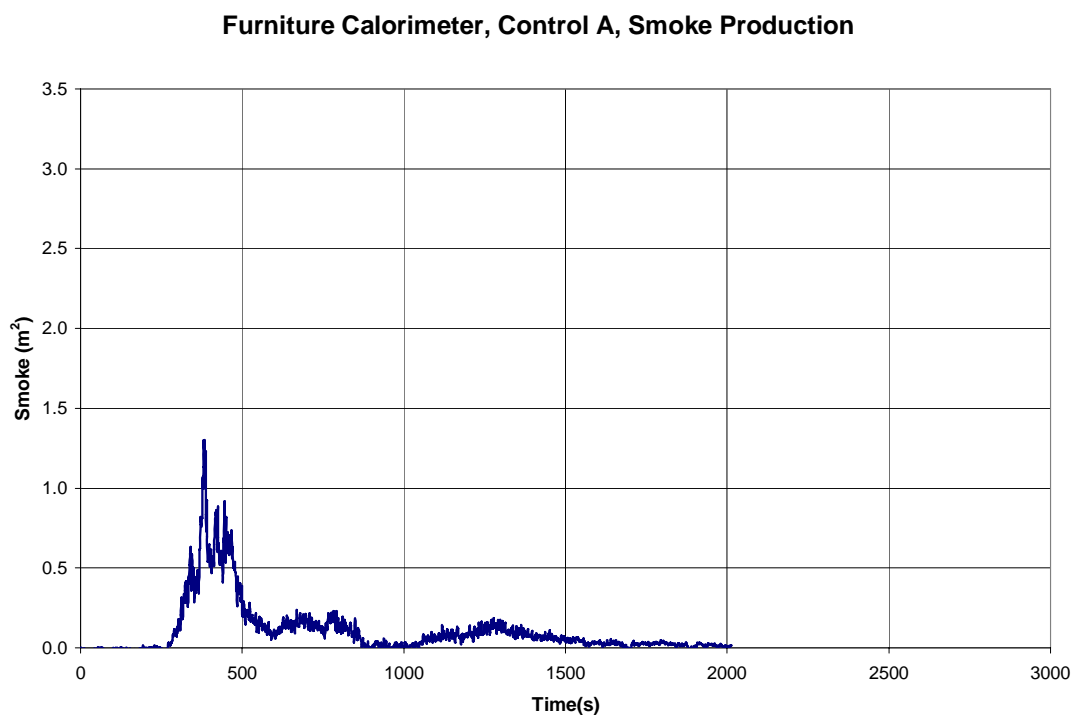


Figure I1. Smoke Production of Control A sample in the Furniture Calorimeter

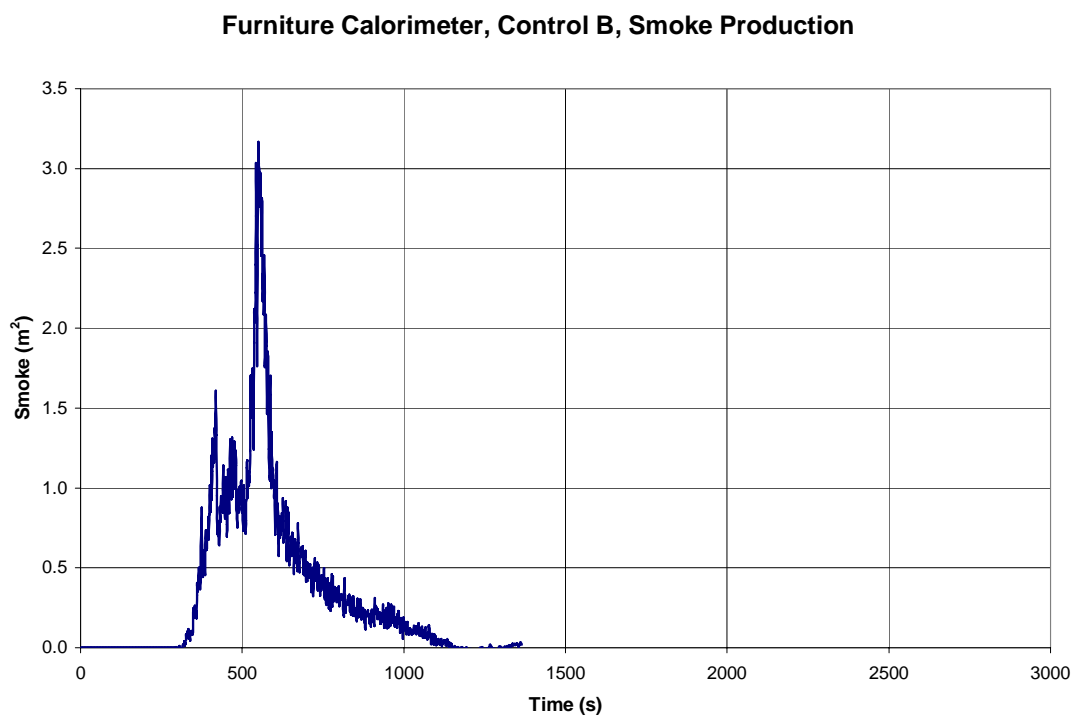


Figure I2. Smoke Production of Control B sample in the Furniture Calorimeter

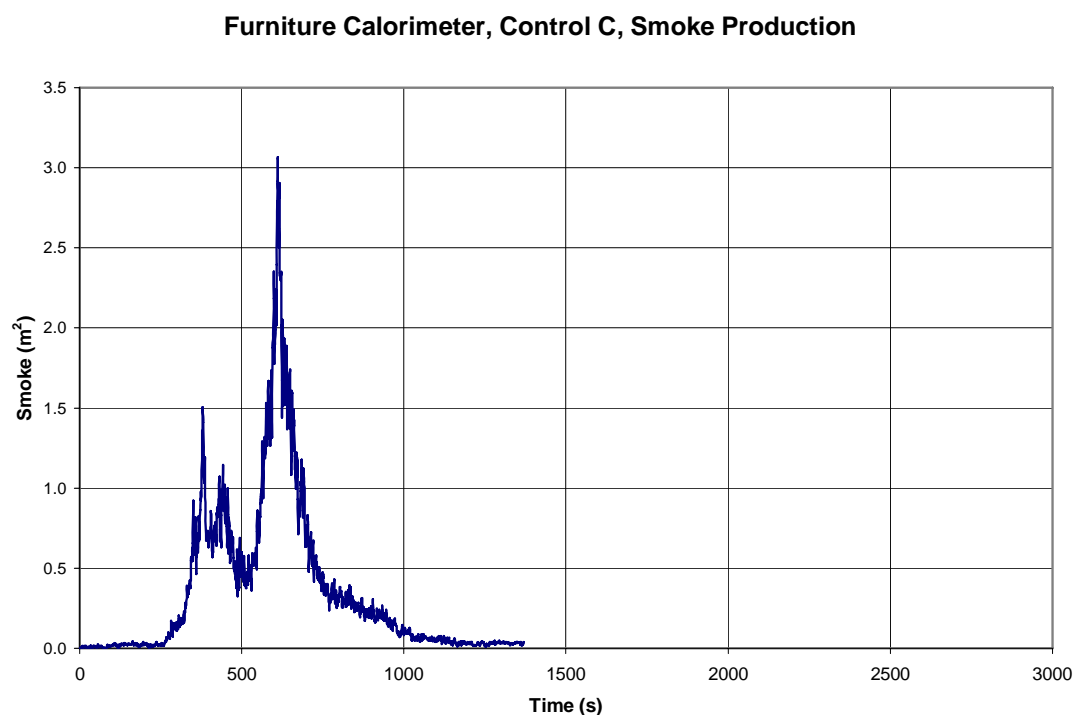


Figure I3. Smoke Production of Control C sample in the Furniture Calorimeter

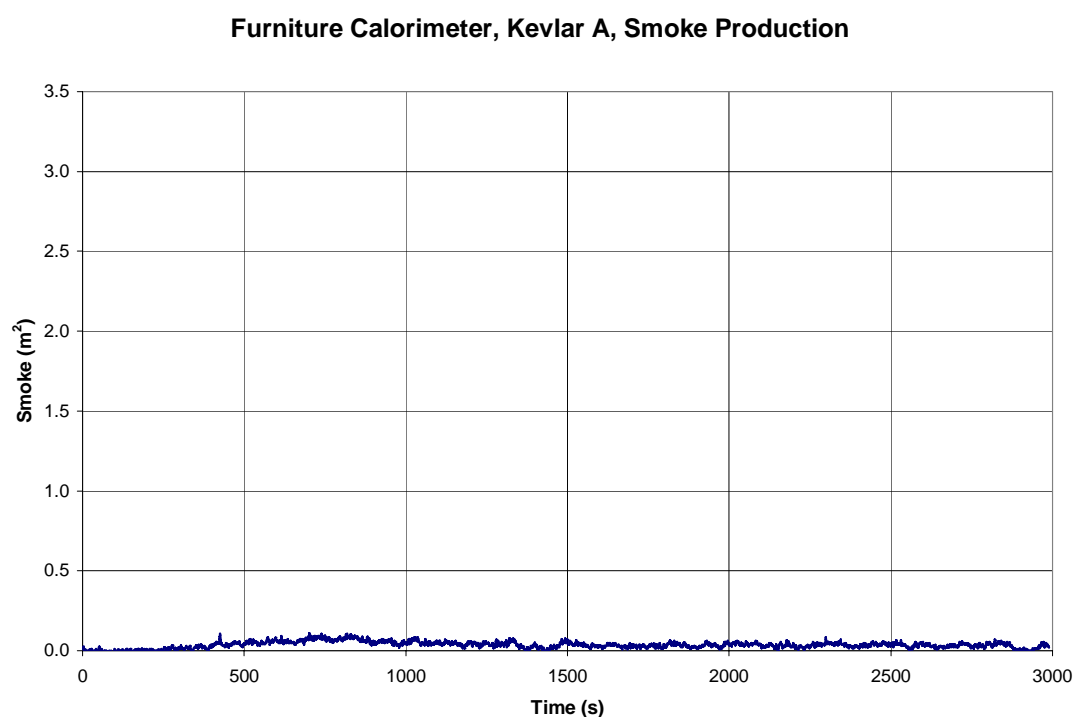


Figure I4. Smoke Production of Kevlar sample in the Furniture Calorimeter

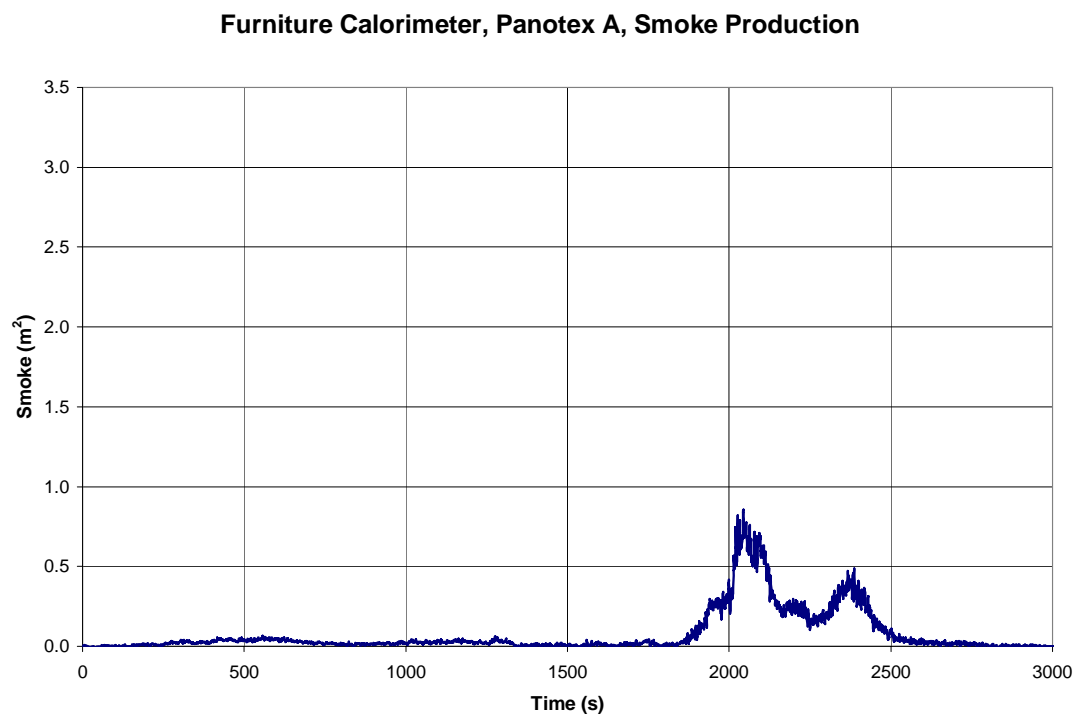


Figure I5. Smoke Production of Panotex A sample in the Furniture Calorimeter

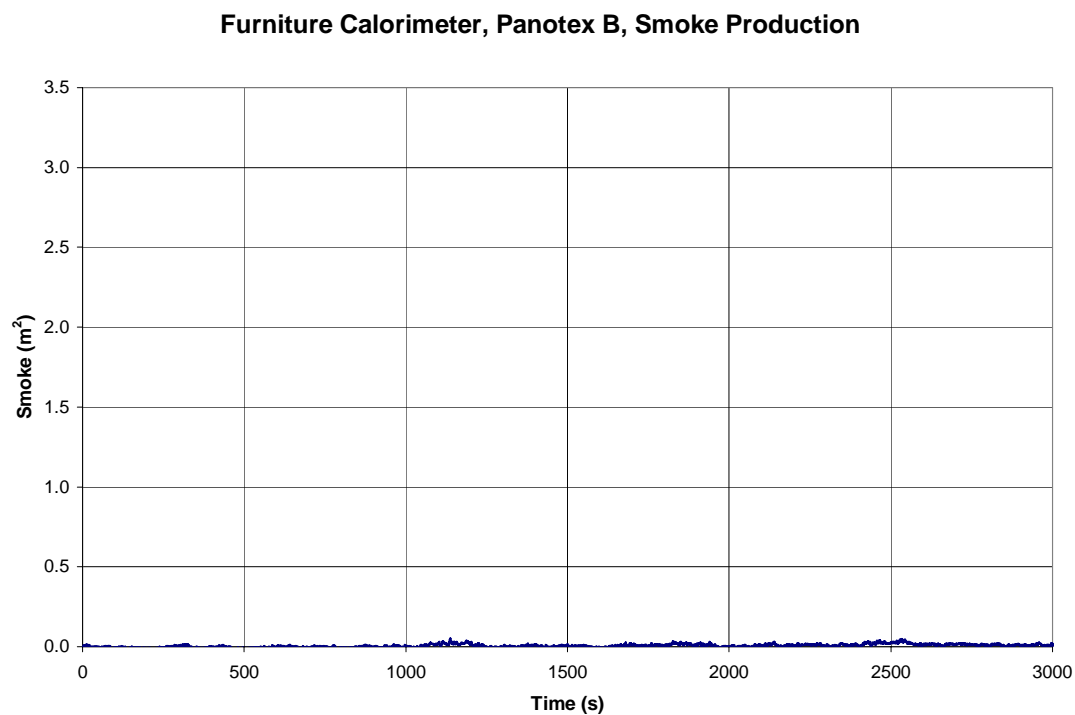


Figure I6. Smoke Production of Panotex B sample in the Furniture Calorimeter

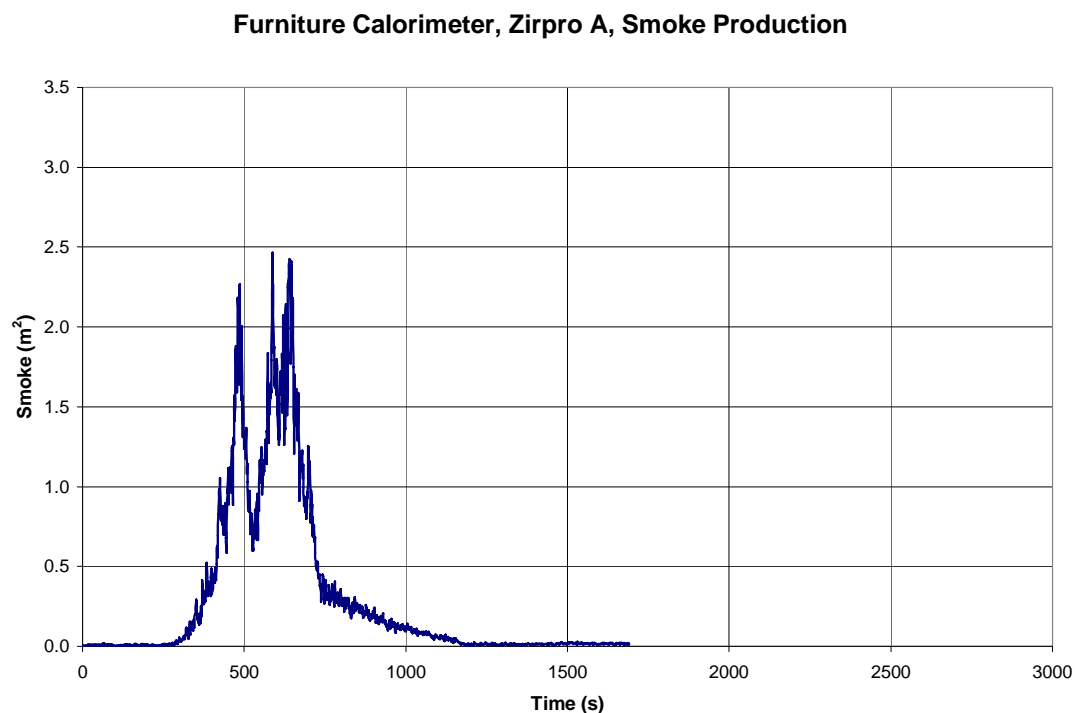


Figure I7. Smoke Production of Zirpro A sample in the Furniture Calorimeter

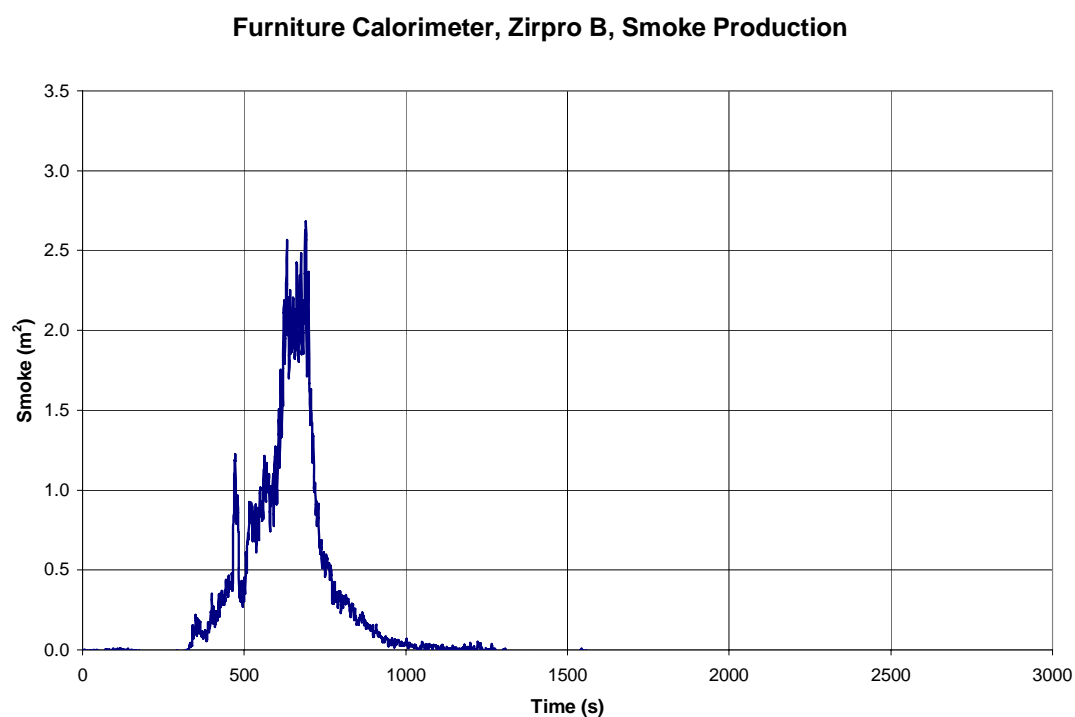


Figure I8. Smoke Production of Zirpro B sample in the Furniture Calorimeter

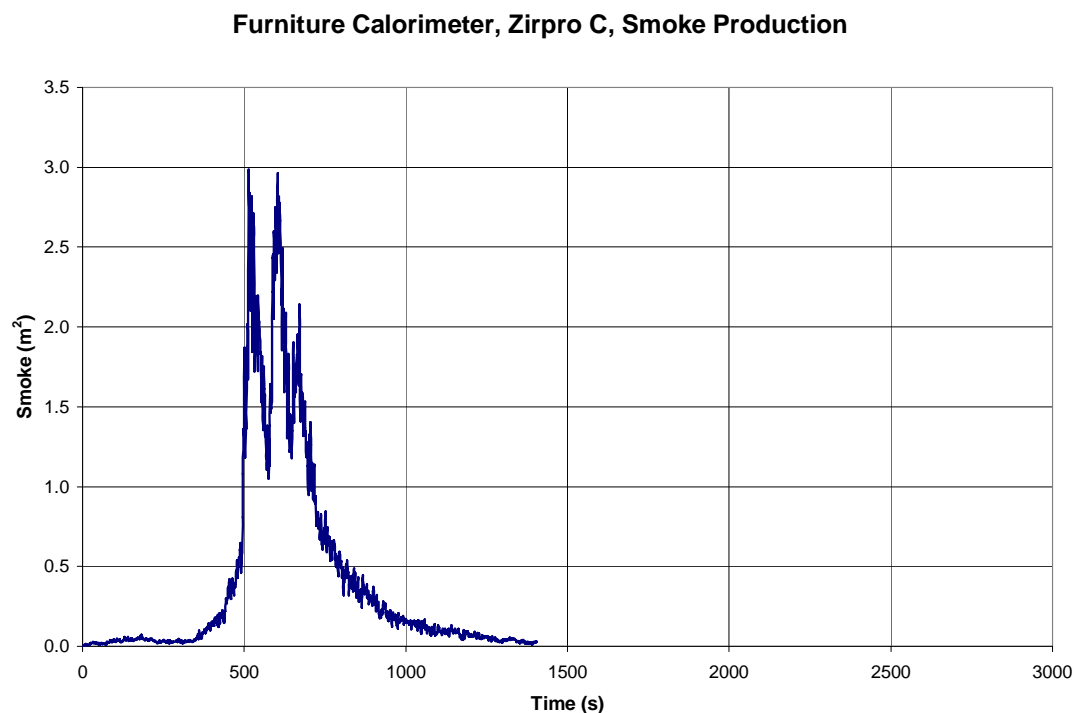


Figure I9. Smoke Production of Zirpro C sample in the Furniture Calorimeter

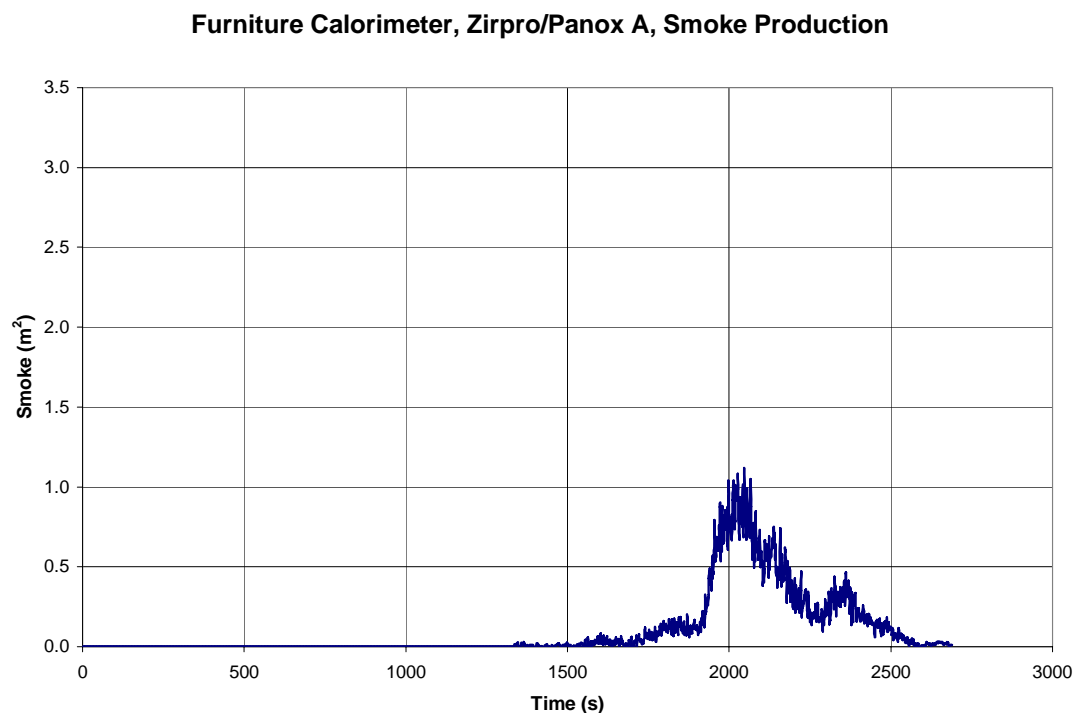


Figure I10. Smoke Production of Z/P A sample in the Furniture Calorimeter

Furniture Calorimeter, Zirpro/Panox B, Smoke Production

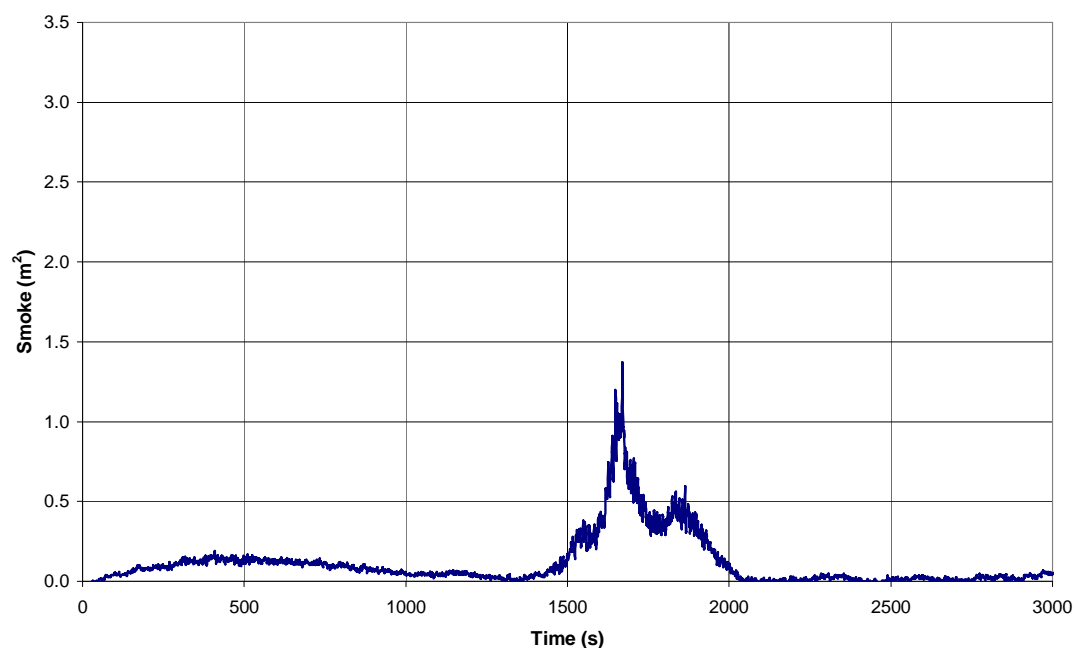


Figure I11. Smoke Production of Z/P B sample in the Furniture Calorimeter

Furniture Calorimeter, Zirpro/Panox C, Smoke Production

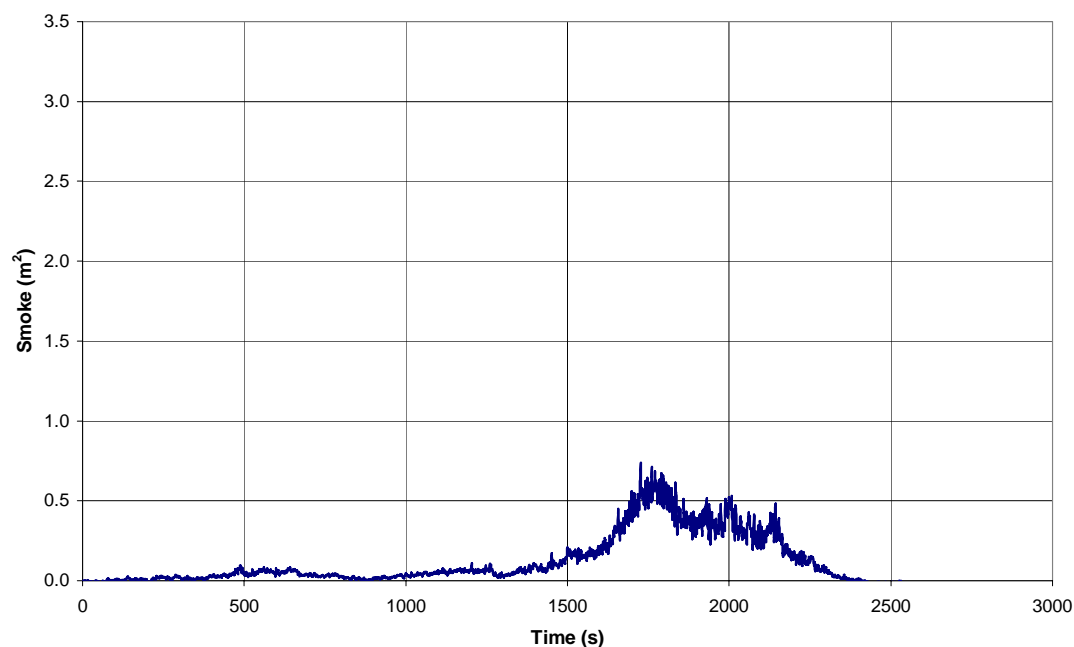


Figure I12. Smoke Production of Z/P C sample in the Furniture Calorimeter

Appendix J: Furniture Calorimeter Carbon Dioxide Production Graphs

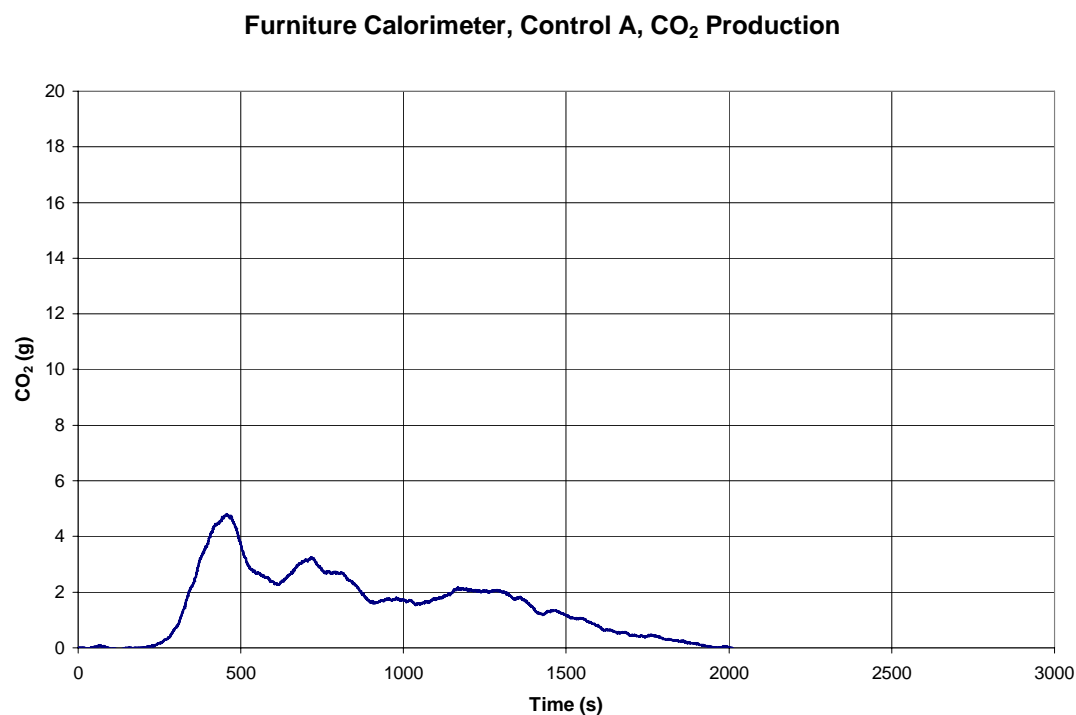


Figure J1. CO₂ Production of Control A sample in the Furniture Calorimeter

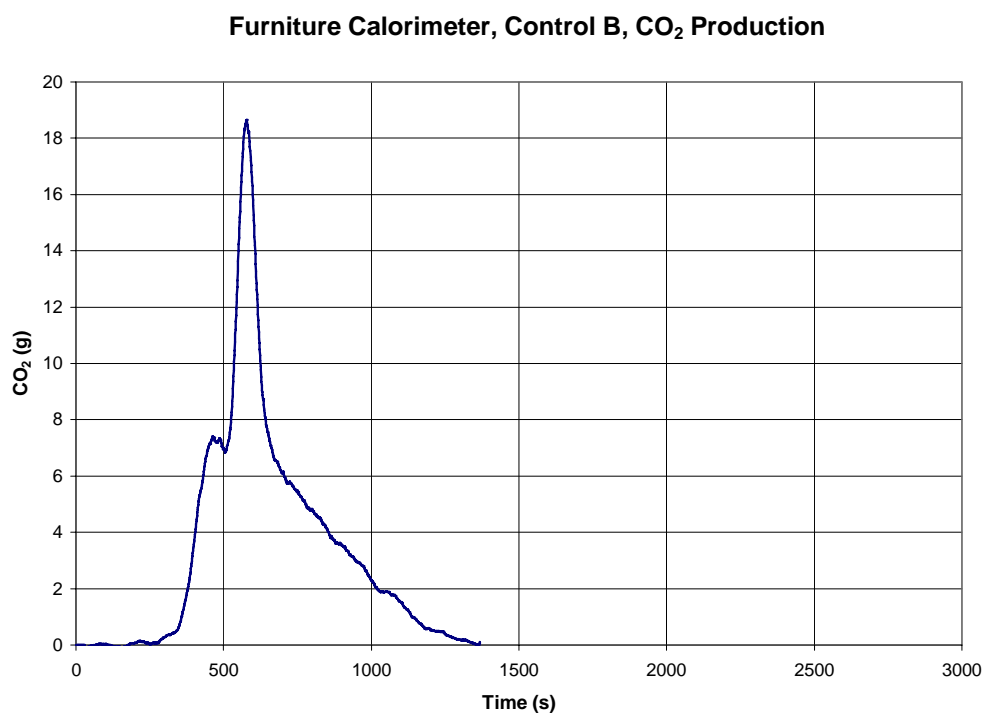


Figure J2. CO₂ Production of Control B sample in the Furniture Calorimeter

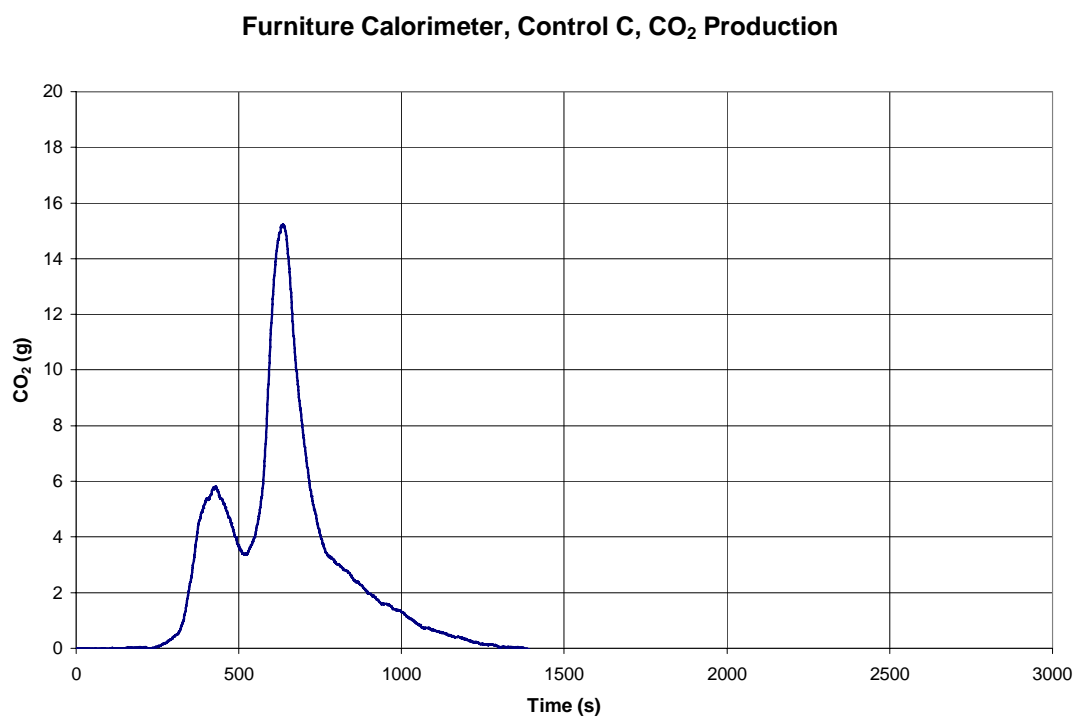


Figure J3. CO₂ Production of Control C sample in the Furniture Calorimeter

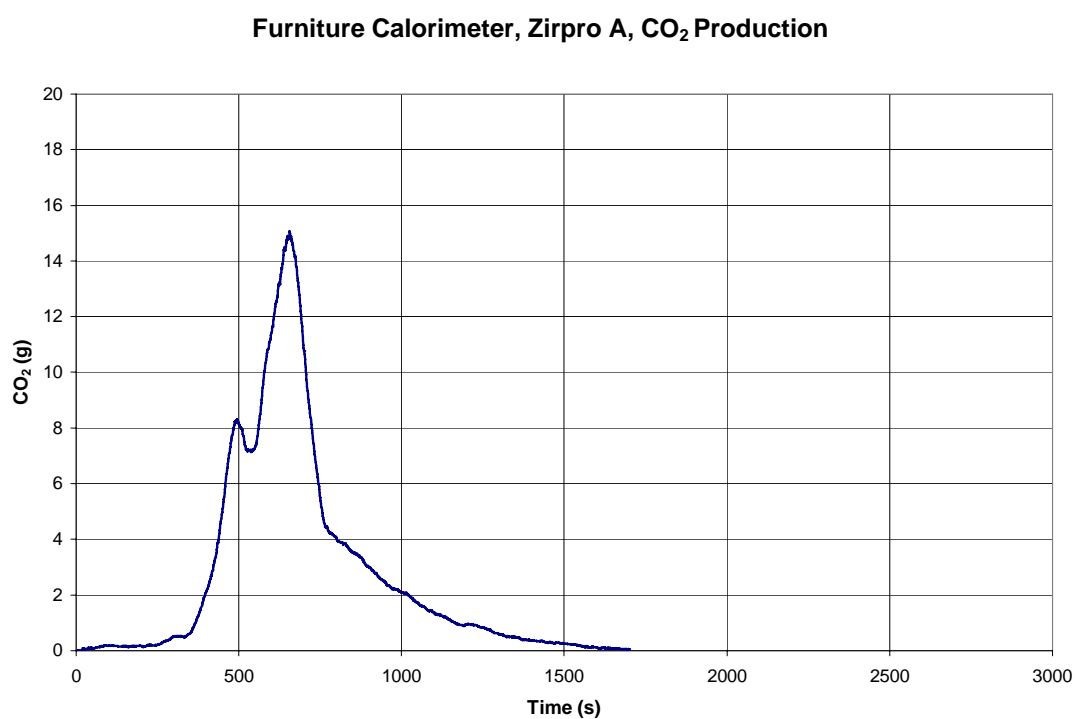


Figure J4. CO₂ Production of Zirpro A sample in the Furniture Calorimeter

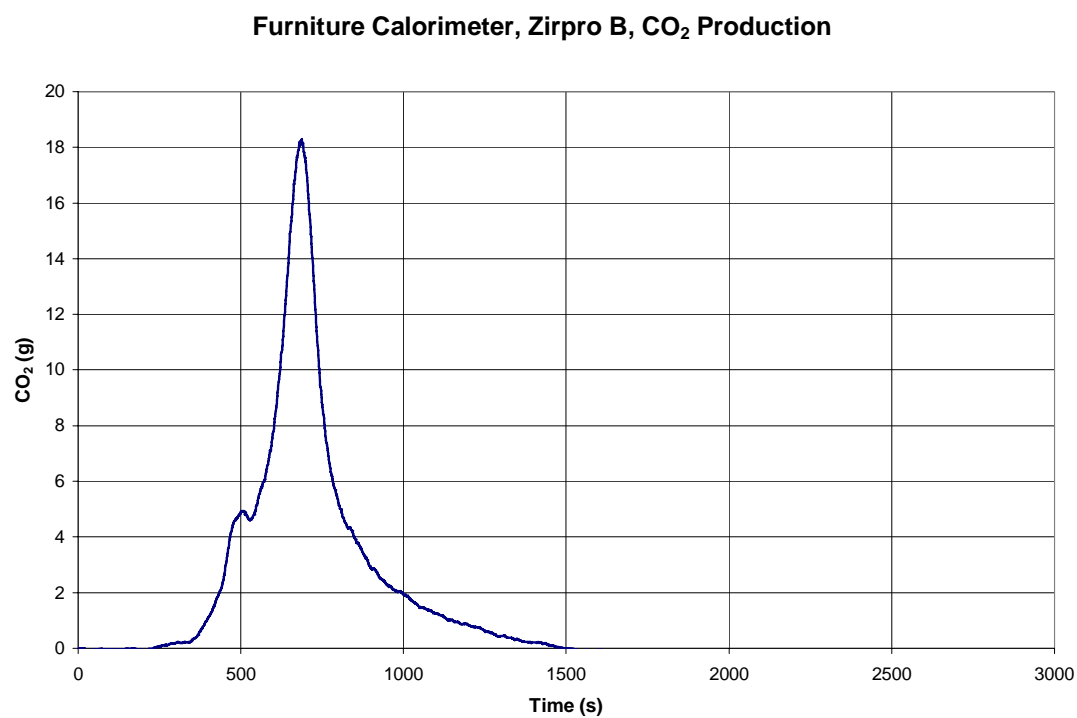


Figure J5. CO₂ Production of Zirpro B sample in the Furniture Calorimeter

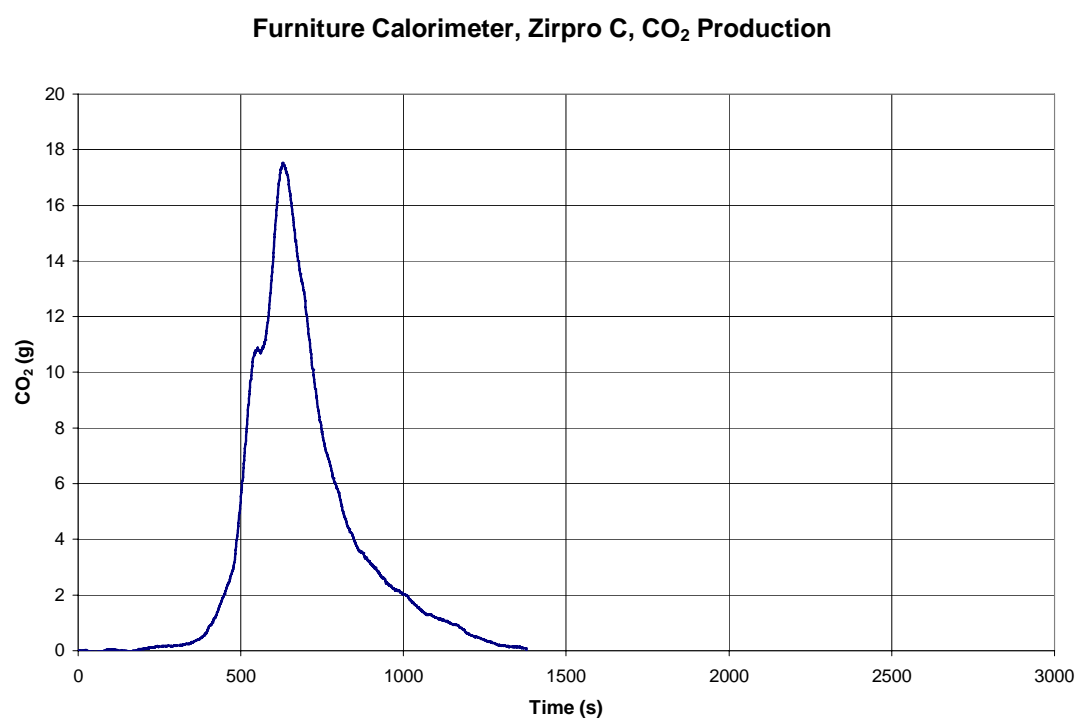


Figure J6. CO₂ Production of Zirpro C sample in the Furniture Calorimeter

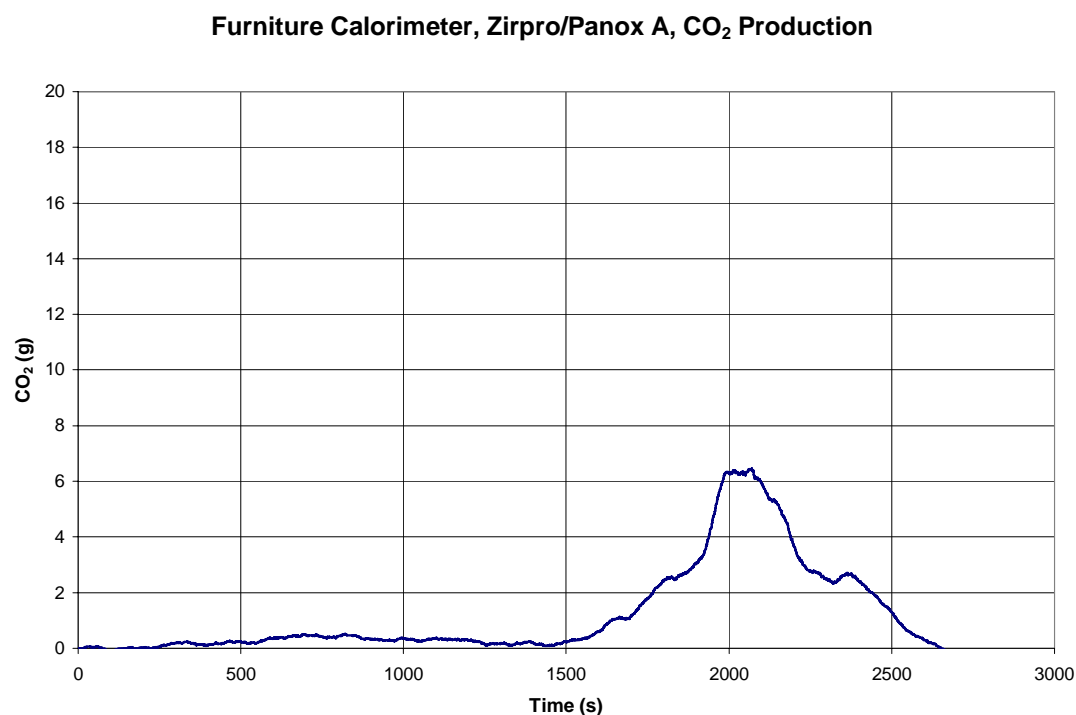


Figure J7. CO₂ Production of Z/P A sample in the Furniture Calorimeter

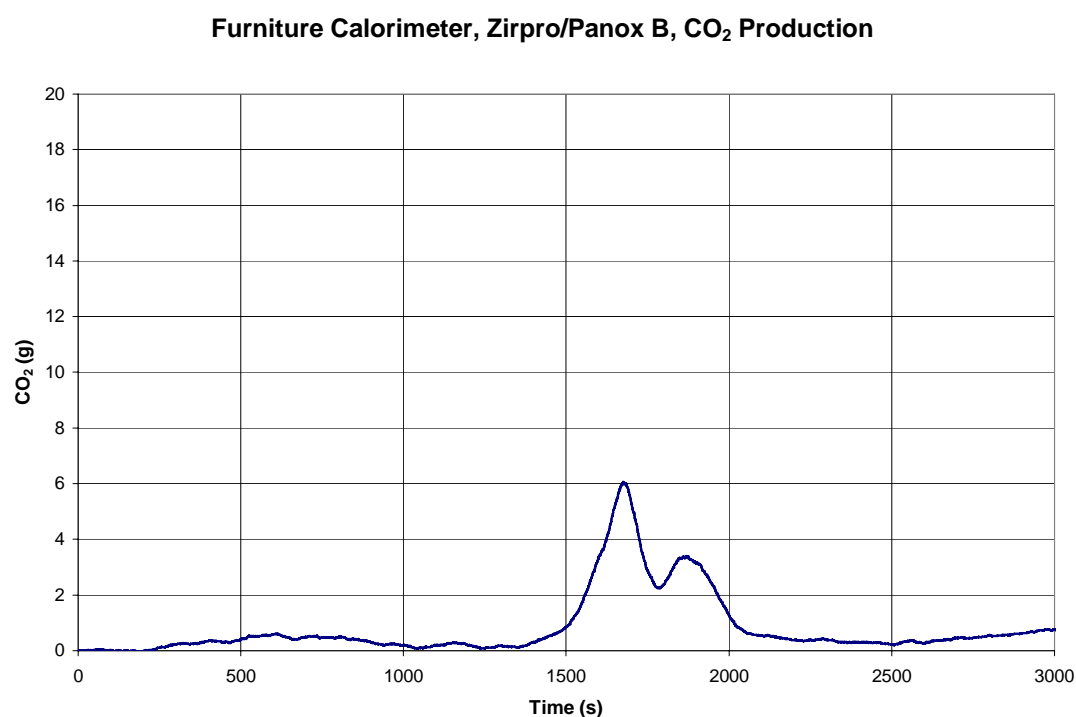
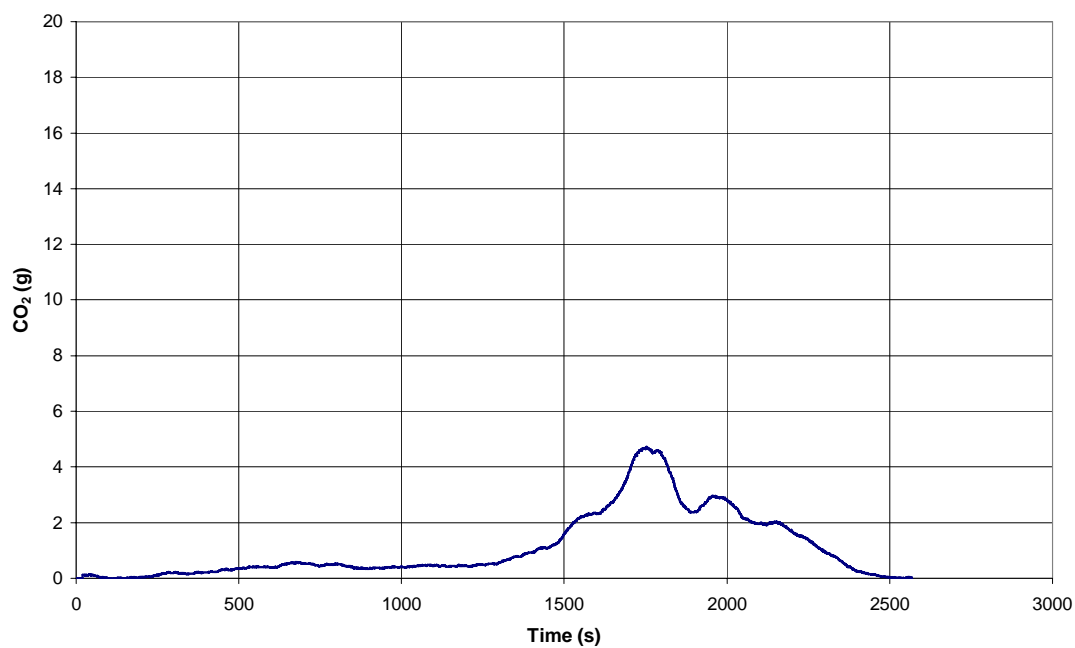
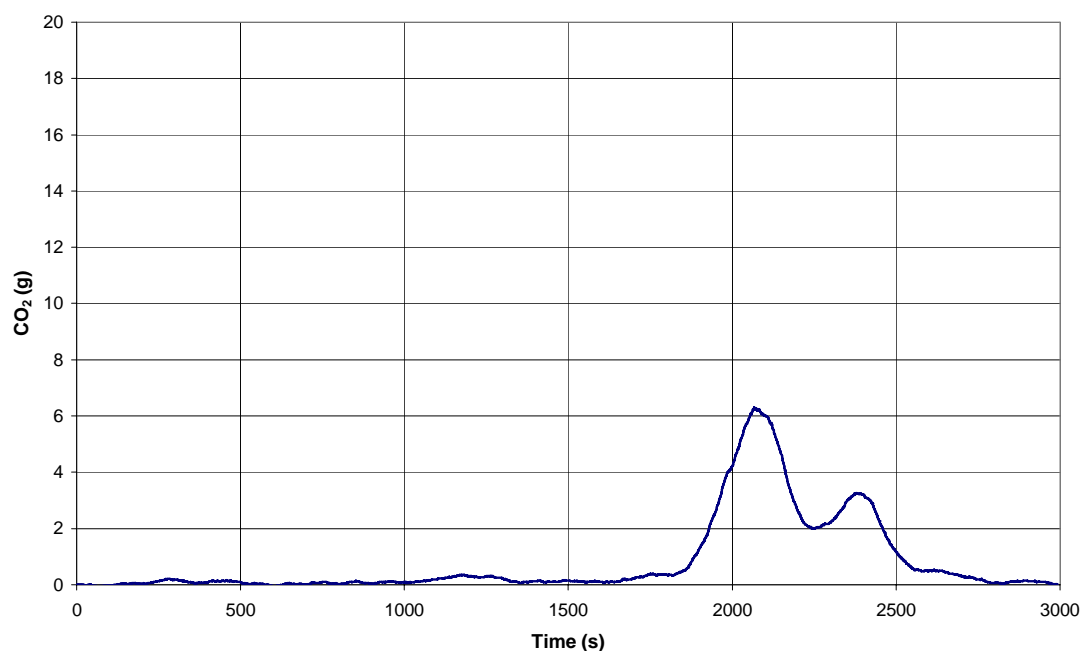


Figure J8. CO₂ Production of Z/P B sample in the Furniture Calorimeter

Furniture Calorimeter, Zirpro/Panox C, CO₂ Production**Figure J9. CO₂ Production of Z/P C sample in the Furniture Calorimeter****Furniture Calorimeter, Panotex A, CO₂ Production****Figure J10. CO₂ Production of Panotex A sample in the Furniture Calorimeter**

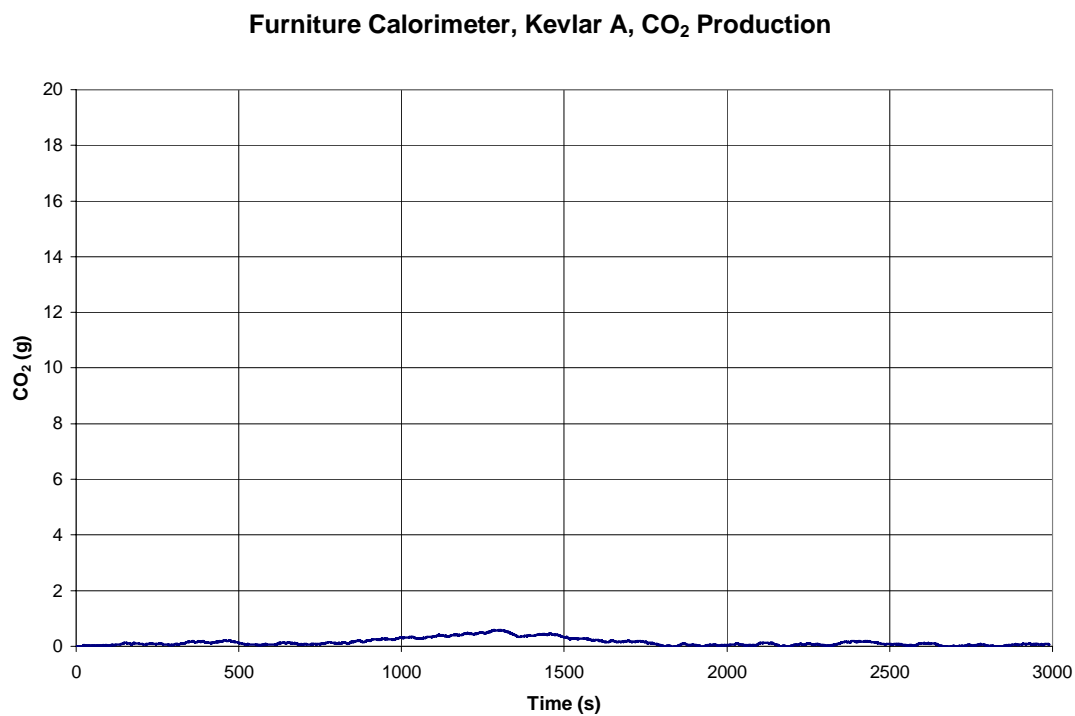


Figure J11. CO₂ Production of Kevlar A sample in the Furniture Calorimeter

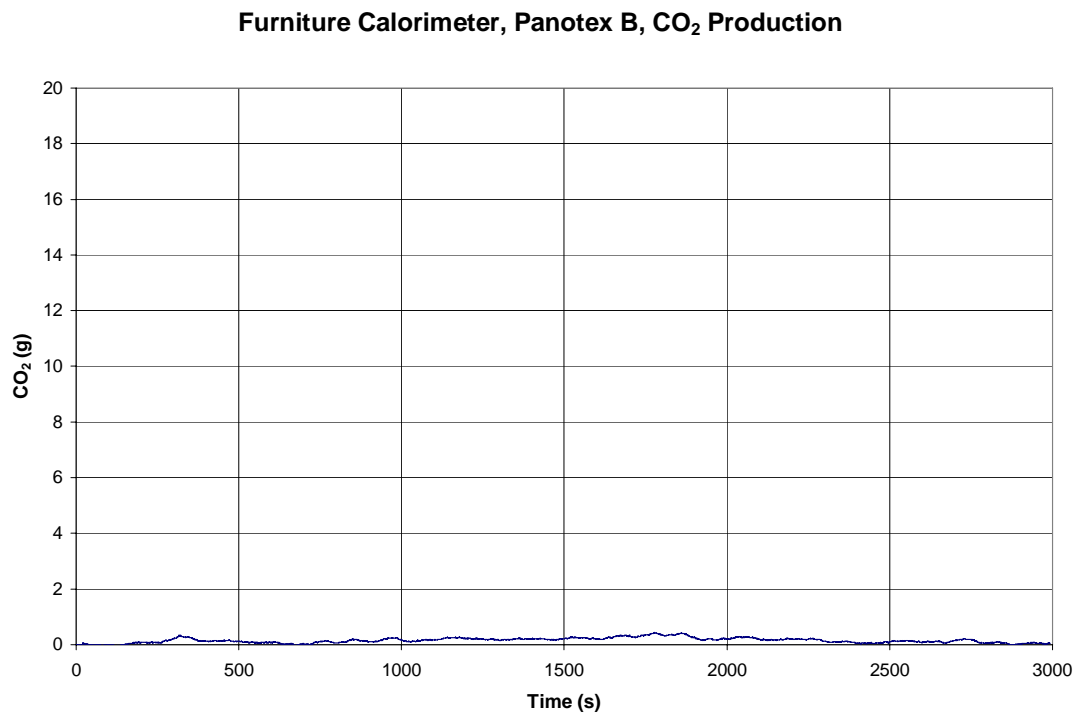


Figure J12. CO₂ Production of Panotex B sample in the Furniture Calorimeter

Appendix K: Furniture Calorimeter Carbon Monoxide Production Graphs

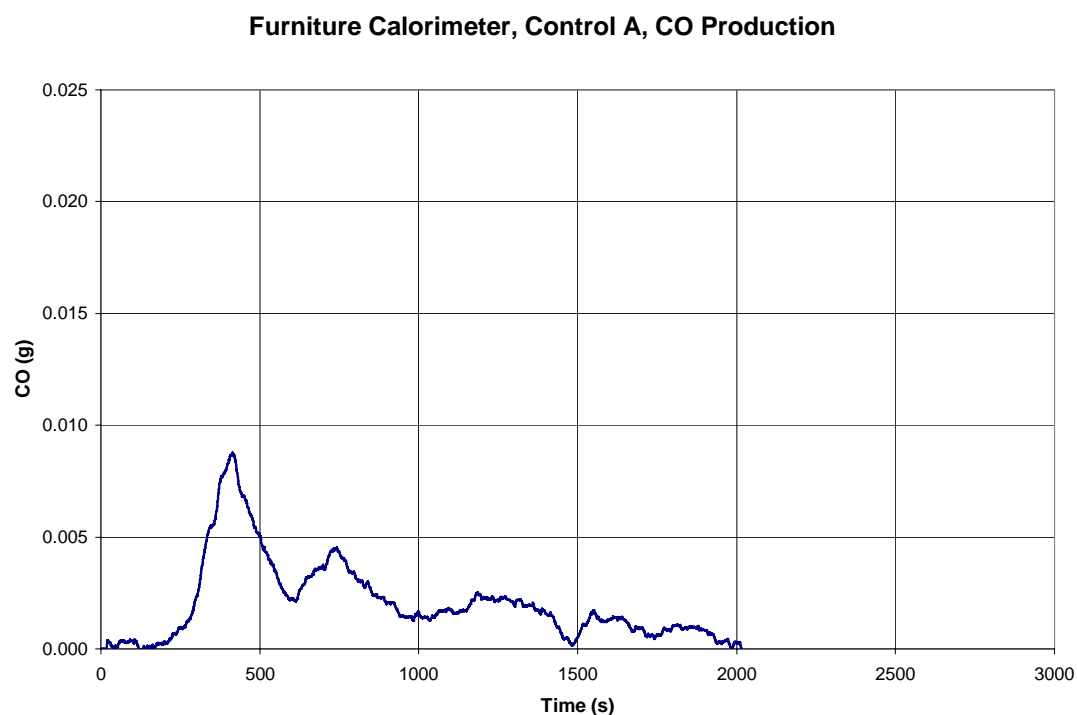


Figure K1. CO Production of Control A sample in the Furniture Calorimeter

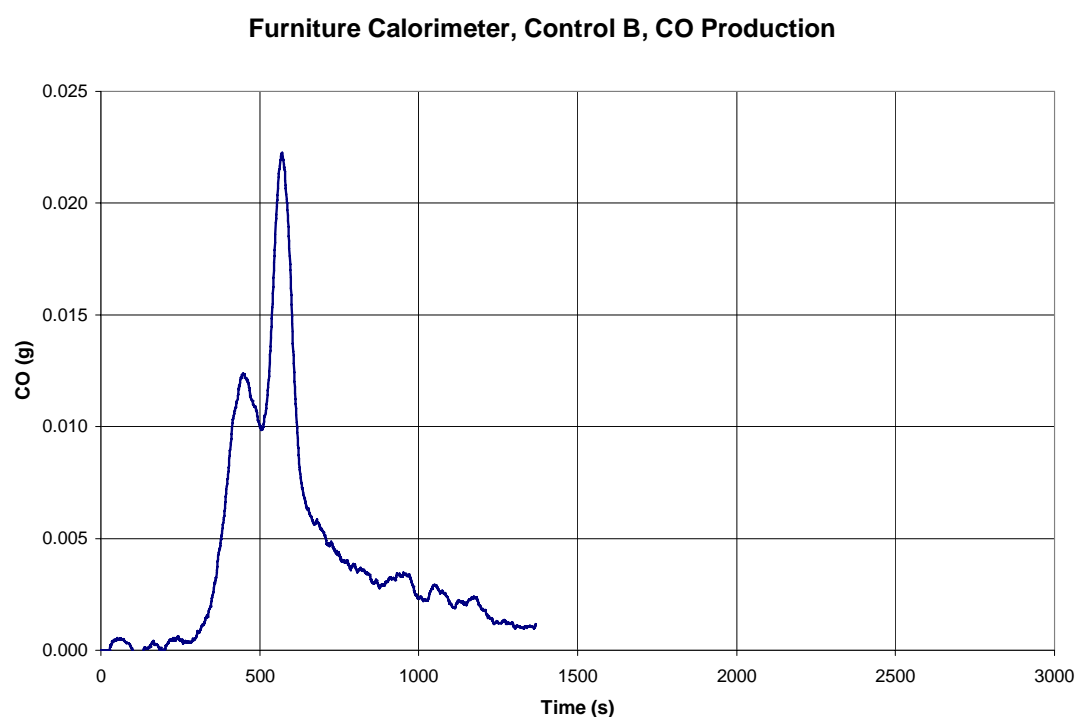


Figure K2. CO Production of Control B sample in the Furniture Calorimeter

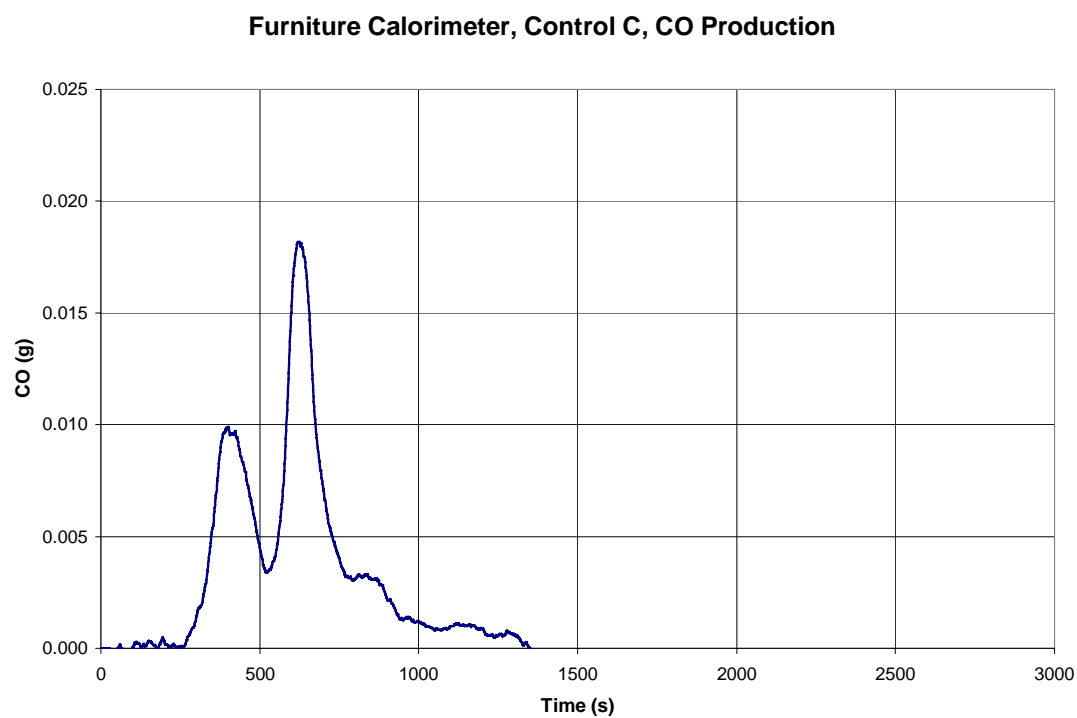


Figure K3. CO Production of Control C sample in the Furniture Calorimeter

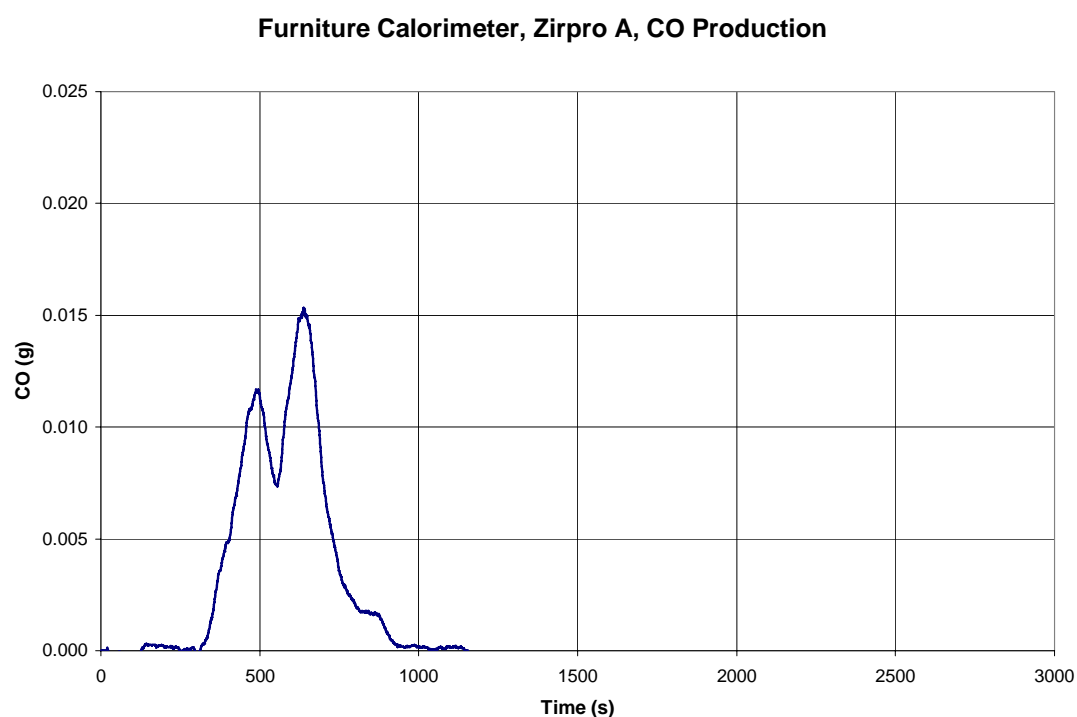


Figure K4. CO Production of Zirpro A sample in the Furniture Calorimeter

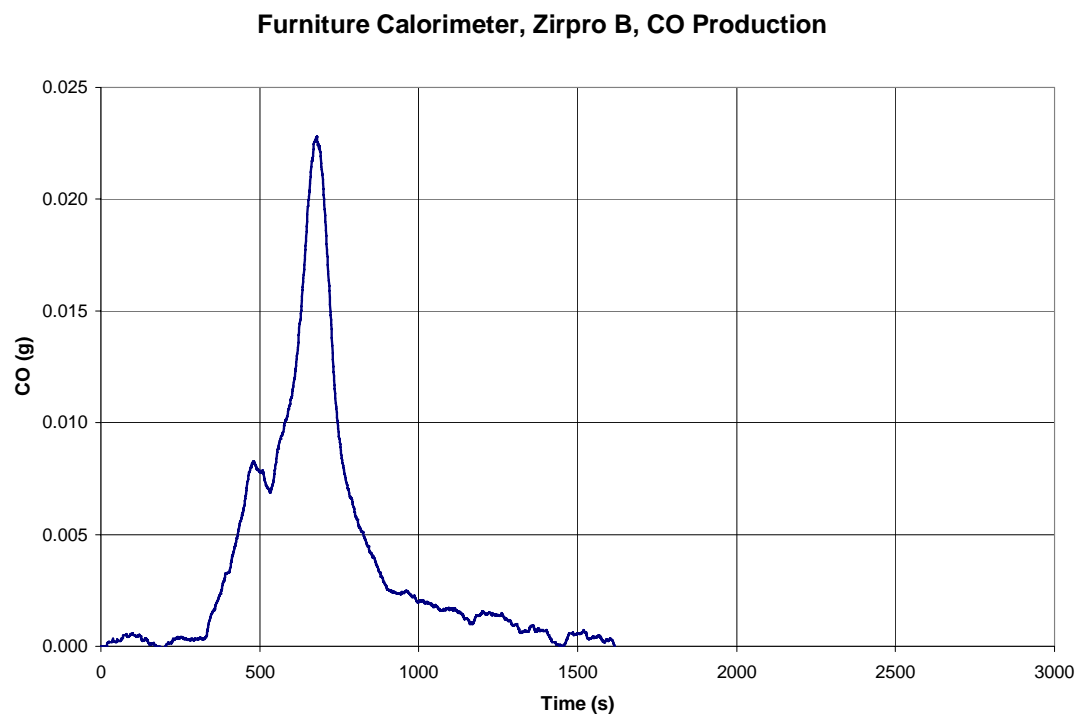


Figure K5. CO Production of Zirpro B sample in the Furniture Calorimeter

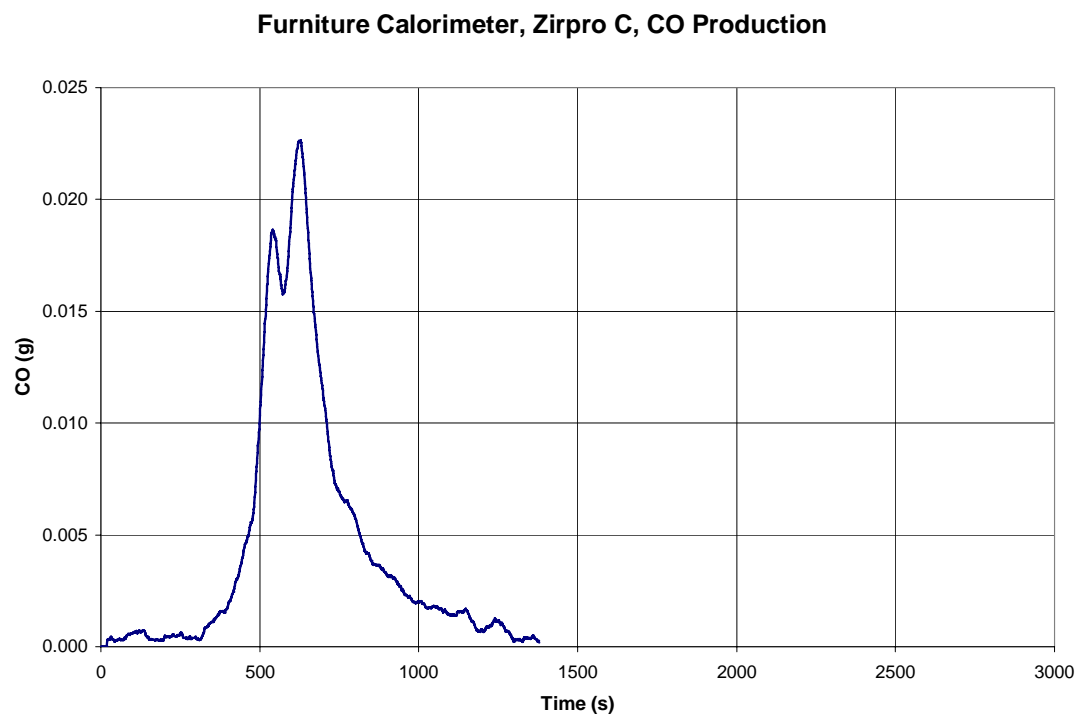


Figure K6. CO Production of Zirpro C sample in the Furniture Calorimeter

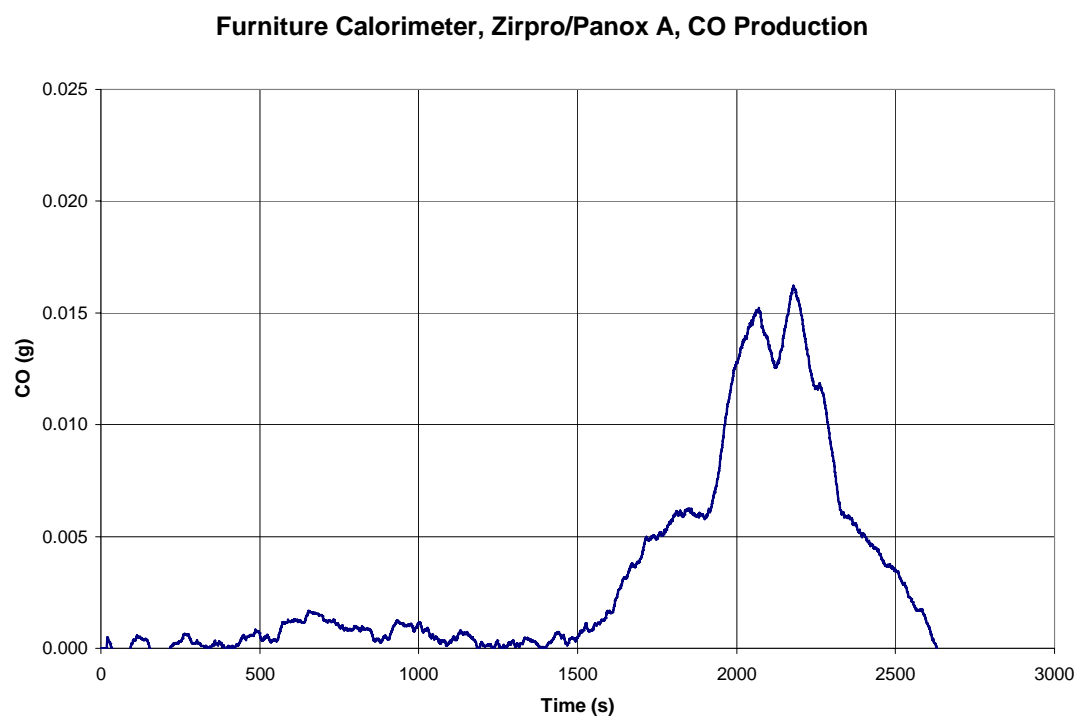


Figure K7. CO Production of Z/P A sample in the Furniture Calorimeter

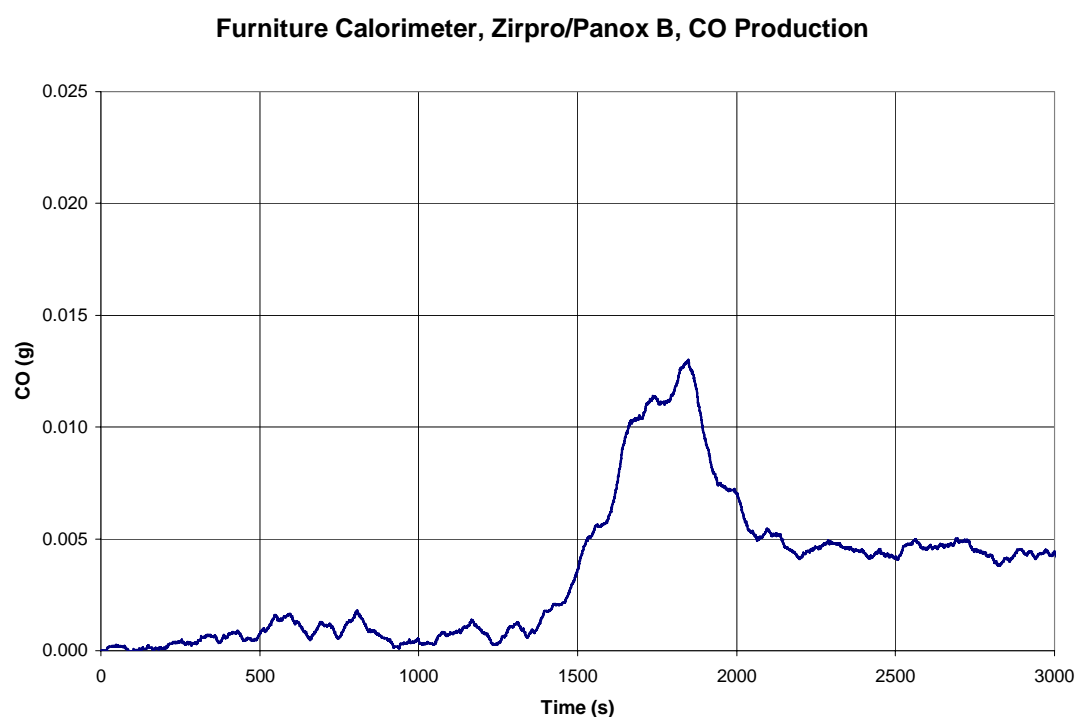


Figure K8. CO Production of Z/P B sample in the Furniture Calorimeter

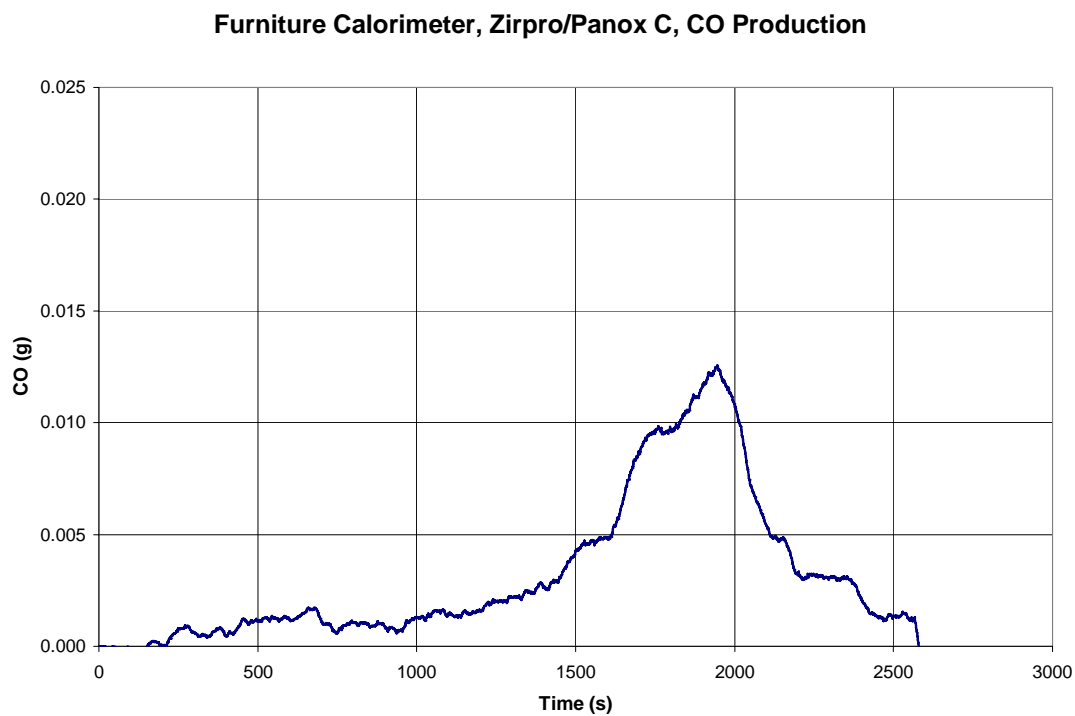


Figure K9. CO Production of Z/P C sample in the Furniture Calorimeter

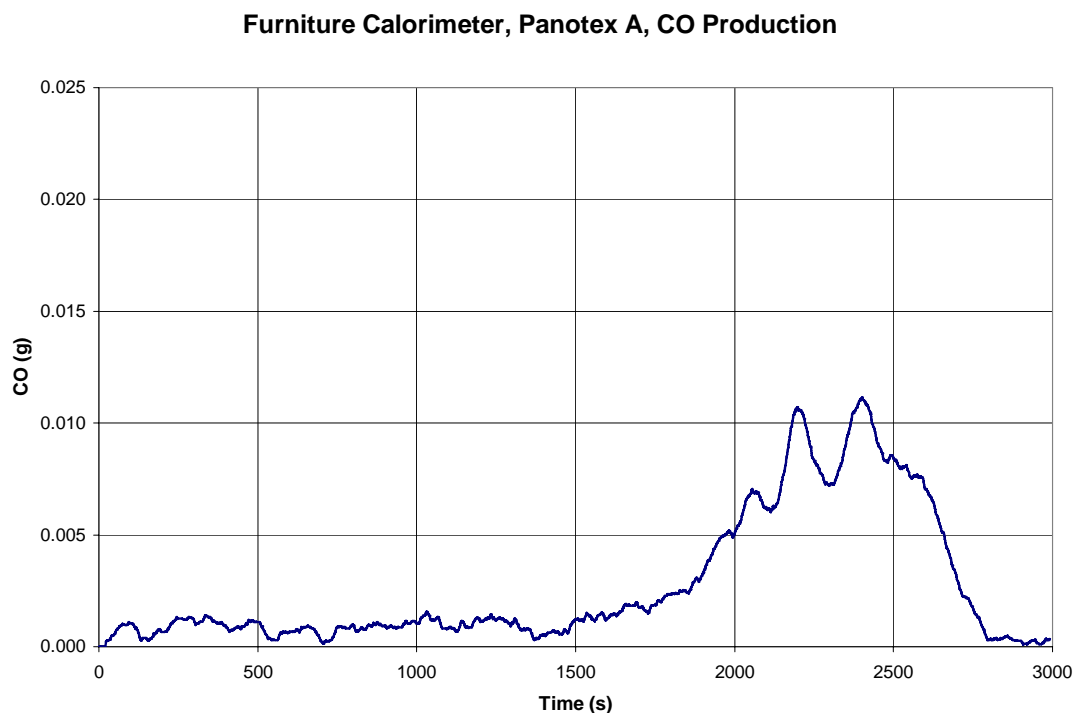


Figure K10. CO Production of Panotex A sample in the Furniture Calorimeter

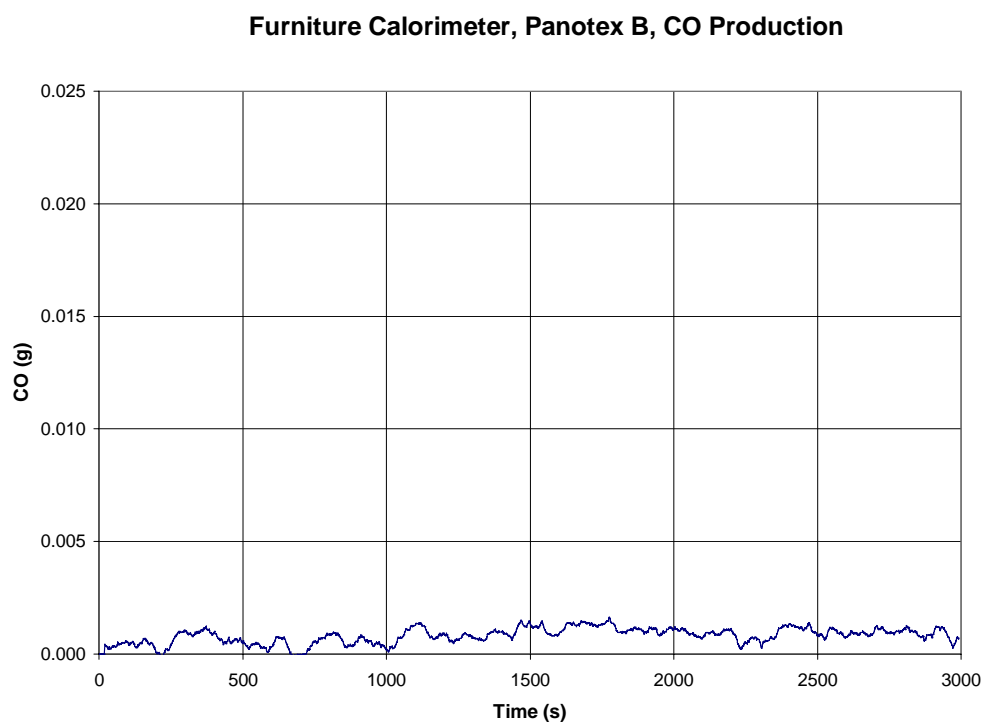


Figure K11. CO Production of Panotex B sample in the Furniture Calorimeter

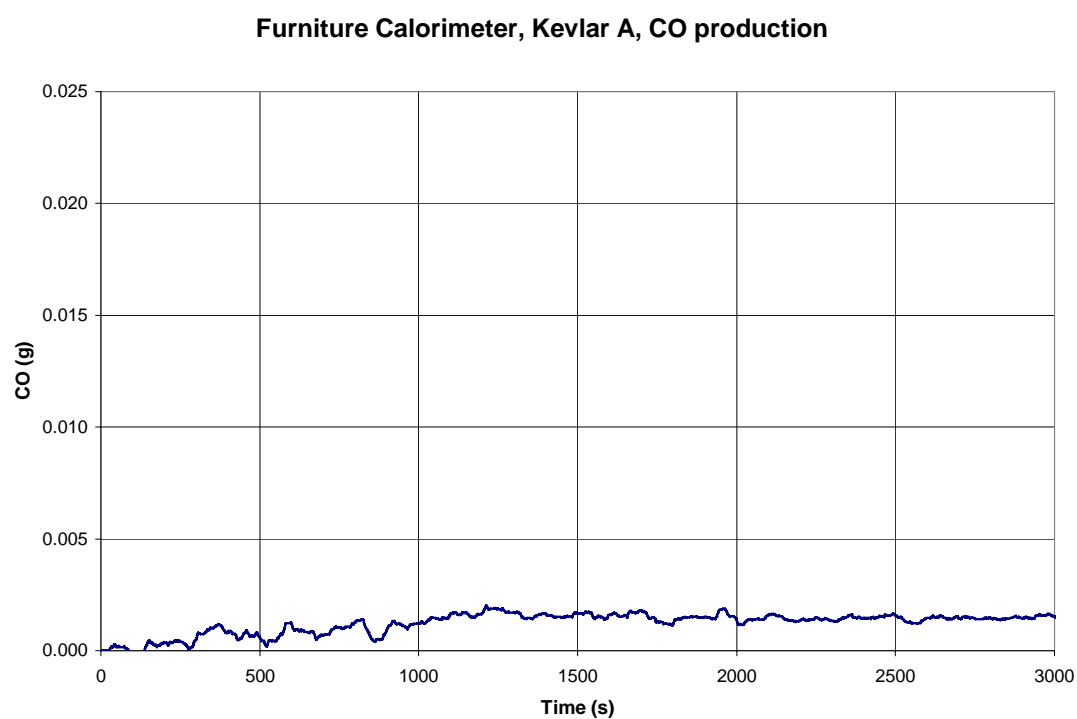












Figure K12. CO Production of Kevlar A sample in the Furniture Calorimeter

Appendix L: Furniture Calorimeter Tests Photo Sequence Record







Zirpro wool





| | | | | | | | | | |
|---|---|---|----|----|----|----|----|----|----|
| |  |  | | | | | | | |
| 3 | 6 zir a | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |





| | | | | | | | | | |
|---|---|---|----|----|----|----|---|----|----|
| |  |  | | | | |  | | |
| 3 | 6 zir b | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

| | | | | | | | | | |
|---|---|---|--|----|----|---|----|----|----|
|  |  |  |  | | |  | | | |
| 3 | 6 zir c | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |







75/25 Zirpro/Panox

| | | | | | | | | | |
|---|---|---|----|----|----|---|---|----|---|
|  |  |  | | | |  |  | |  |
| 3 | 6 z/p a | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |





| | | | | | | | | | |
|---|---------|---|---|----|----|---|---|----|---|
| | | |  | | |  |  | |  |
| 3 | 6 z/p b | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

| | | | | | | | | | |
|---|---|---|----|----|----|----|---|----|---|
| |  |  | | | | |  | |  |
| 3 | 6 z/p c | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |







Control




| | | | | | | | | | |
|---|---|---|--|----|----|---|----|----|---|
|  |  |  |  | | |  | | |  |
| 3 control a | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |





| | | | | | | | | | |
|---|---|---|--|----|----|---|----|----|----|
|  |  |  |  | | |  | | | |
| 3 control b | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

| | | | | | | | | | |
|---|---|---|----|--|----|----|----|----|----|
|  |  |  | |  | | | | | |
| 3 control c | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

Panotex

| | | | | | | | | | |
|---|---|---|----|--|---|---|----|----|---|
|  | |  | |  |  |  | | |  |
| 3 panotex a | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

| | | | | | | | | | |
|-------------|---|---|---|--|----|----|---|----|----|
| |  | |  |  | | |  | | |
| 3 panotex b | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |

| | | | | | | | | | |
|----------|---|---|----|--|----|----|---|----|----|
| |  |  | |  | | |  | | |
| 3 kevlar | 6 | 9 | 12 | 15 | 18 | 21 | 24 | 27 | 30 |