Evaluation of Fire Safety Characteristics of Laminated Wood Panels

by

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Abstract

The goal of this study is to assess the fire performance of laminated wall panels comprised of medium density fibreboard (MDF) core sandwiched between two outer layers of a thin sheet Arborite laminates. Both fire retarded (FR) and non-fire-retarded (NFR) versions of each material were tested by themselves and also in various laminated combinations. In this research, the hypothesis is that the fire performance of each individual material will be mirrored layer by layer in the properties of the overall assembly. Important questions then included, how many of the layers need to contain fire retardant additives to achieve a target performance for the panel assembly? In addition, the effect of the glue used in the construction of the panel was unknown, but it was hypothesized that due to the flammability of most glues, the adhesives have a significant impact on the requirement for FR additives in each layer.

The main apparatus used in the investigation is a Cone Calorimeter. Testing followed the ASTM E-1345 protocol, so the time to ignition, mass loss rates, heat release rates (HRR) during open flaming periods, peak heat release rates and time to reach peak heat release rate were measured. These parameters were used to assess the relative fire performance of each base material and assembly, thus deducing the efficacy of the fire retardant additives in each combination.

The panel assembly selected for the present study is typical of laminated MDF panels used as elevator cab lining materials. All materials were obtained from Elevator Cab Renovations (ECR), the industrial partner for much of this work. Both front and backer materials were made by Arborite and both regular NFR and FR versions of each were used. Similarly NFR and FR core MDF specimens were used in custom assembled test panels glued together using Permagrip PG107, a common glue in the industry.

In total seven different individual materials, eight unglued panel assemblies and eight fully assembled and glued laminated panels were tested for this research. In most cases, three repeat tests were run for each specimen to determine repeatability and, where necessary, allowing averaging to reduce overall variability in the results.

Key performance indicators were determined using the results from each test and the relationships between various combinations of samples were examined. A recommendation is presented that FR additives should be used in the front and core sections of the panel assembly. This is based on the results across all tests and the observations made regarding the effectiveness of FR additives to each individual material, as well as to the panel assembly. It was also concluded that there is no strong evidence to demonstrate that the use of NFR backer materials significantly reduces the fire performance characteristics of the panel assembly when FR additives are used in the other two layers. Finally, there

is strong evidence that the glue in a laminated assembly does lead to increased values of measured HRR, and also has a discernible effect on the rate of Carbon Monoxide (CO) production from the assembly.

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Nomenclature

Abbreviations

$ANSI$	American National Standards Institute.
$ASTM$	American Society for Testing and Materials.
ECR	Elevator Cab Renovations.
FAA	Federal Aviation Administration.
FR	Fire rated.
FSI	Flame Spread Index.
FTT	Fire Testing Technology.
HRR	Heat release rate.
ICC	International Code Council.
LOI	Limiting Oxygen Index.
MDF	Medium density fibreboard.
$NBCC$	National Building Code of Canada.
$NFPA$	National Fire Protection Association.
NFR	Non-fire rated.
OBC	Ontario Building Code.
$PCFC$	Pyrolysis Combustion Flow Calorimeter.
PF	Phenol-formaldehyde.
UL	United Laboratories.
$USDAFPL$	United States Forest Service, Forest Products Laboratory.
$UWFRG$	University of Waterloo Fire Research Group.

Greek Symbols

α	Volumetric expansion factor, [].
ϕ	Oxygen consumption factor, [].

Roman Symbols

Δp	Pressure differential across the stack orifice plate, [Pa].
$\dot{m}_e$	Mass flow rate of gases through the stack, [kg/s].
A_s	Exposed specimen surface area, [m^2].
C	Orifice plate coefficient, [].
E_{O_2}	Heat release per mass of oxygen consumed, [kJ/kg_{O_2}].
$m_s\,(t)$	Specimen mass at time t, [s].
M_{air}	Molecular weight of dry air, [kg/kmol].
M°_{air}	Molecular weight of ambient air, [kg/kmol].
M_{H_2O}	Molecular weight of water vapour, [kg/kmol].
M_{O_2}	Molecular weight of oxygen, [kg/kmol].
$ML\,(t)$	Specimen mass loss at time t, [s].
ML_b	Specimen mass loss over the burning period, [kg].
p°_{air}	Barometric pressure of ambient air, [Pa].
$p_{s,air}$	Saturation pressure of water vapour in ambient air, [Pa].
$q\,(t)$	Rate of heat release at time t, [kW].
$q''\,(t)$	Rate of heat release per exposed specimen area at time t, [kW/m^2].
RH°_{air}	Relative humidity of ambient air, [%].
t	Time elapsed from the start of a test, [s].
T_e	Temperature of gases in the stack, [K].
t_{ig}	Time to ignition, [s].
t_{out}	Time to flame out, [s].
$t_{q_{peak_{ig}}}$	Time to peak HRR after ignition, [s].
t_{sust}	Sustained flaming period, [s].
X_{CO_2}	Volume fraction of carbon dioxide in the sample gas, [%].
$X^{\circ}_{CO_2}$	Volume fraction of carbon dioxide in ambient air, [%].

X_{CO}	Volume fraction of carbon monoxide in the sample gas, [%].
X°_{CO}	Volume fraction of carbon monoxide in ambient air, [%].
$X^{\circ}_{H_2O}$	Volume fraction of water vapour in ambient air, [%].
X_{O_2}	Volume fraction of oxygen in the sample gas, [%].
$X^{\circ}_{O_2}$	Volume fraction of oxygen in ambient air, [%].
m''	Mass loss rate, [kg/s].
M_{Total}	Total mass loss, [kg].

Chapter 1

Introduction

Current building code requirements and regulations are ever increasing in their demand for the use of fire rated (FR) materials that can withstand a number of different fire loads in a range of design scenarios. In the elevator business, flammable materials such as laminated panels comprised of medium density fibreboard (MDF) core sandwiched between various sheeting materials are used as a finishing product inside elevator cabs. In order to meet certain fire safety regulations required by many building codes in North America, fire rated materials have historically been used for all layers of these laminated panels by both elevator manufacturers and those fabricating similar finishing panels for indoor applications. In most cases, the manufacturer of the panel chooses a given layered structure and designs the final composite panel such that it is fire rated, or partially fire rated, as needed to meet code requirements.

A laminated MDF panel typically consists of a thin plastic laminate sheet on the front, with an MDF core and another thin plastic backer material. While each individual material has been tailored in different ways to improve its fire retardant capabilities, there have not been many studies which have examined the panels as a whole system and evaluated the combined fire performance characteristics. Due to the complexity of tailoring fire retardant additives, coupled with the large variety of materials and fire retardant chemicals used in the industry, there is limited understanding of how fire retardant additives might have been optimized to meet performance requirements for each material which comprises the assembly. In addition, there is limited understanding of the behaviour of each material as the fire penetrates between and through the layers in the composite assembly. As such, it is difficult to assess the trade-offs between the cost of adding fire retardants to each layer, as is currently the practice, and any change in overall fire performance of an MDF laminated panel that is comprised of, for example, only one or two fire rated layers.

The objective of the present research is to assess the fire performance of laminated

wall panels comprised of MDF core sandwiched between two layers of thin outer sheet material. For this, it is important to demonstrate how a given FR additive impacts the fire performance of an individual material within a front-core-backer laminate assembly as well as how these individual components influence the performance of the fully laminated MDF panel assembly. This objective is of importance to the industry since there is currently limited understanding on which to develop a strategy that can be used to aid in fine-tuning the fire retardant properties of the various composite layers. Knowing the effectiveness of the fire retardant additives in each component on a individual basis, as well as how the various layers interact as a whole panel should lead to the determination of the most cost and weight effective constructions for satisfying local construction and building codes.

The scope of this study is limited to those laminated MDF panels that are comprised of fire retarded (FR) and non-fire-retarded (NFR) Arborite brand front and backer panels. The composition of the MDF core and associated FR additives are unknown to the author, making it difficult to generalize the results of the thesis to materials other than those used in the tests. While these are very common and widely used components for laminated paneling, the specific findings on the fire performance of these materials are limited to the present sub-group of materials. On the other hand, the findings are of particular relevance to the industrial partner, Elevator Cab Renovations (ECR), as they develop multiple product lines from this combination of base materials. Furthermore, the findings are of value to the fire safety engineering community as they do add to the present general understanding of the impact of FR additives in fully laminated MDF paneling.

Cone calorimetry testing has proven to provide reliable and repeatable results that can aid in comparison and ranking of a range of materials at a fraction of the cost of large scale testing and with a much higher turn around rate. In this work, a systematic parametric study into the fire safety characteristics of FR and NFR laminated panel materials was conducted. Using the cone calorimeter as the main testing apparatus, the first step is to test each individual layer in the laminated MDF panel. Following this, the full laminated samples are tested without glue and, as a final stage, the fire performance of a set of fully glued laminated samples are examined. Results were collected across a large sample population and the results were used to make direct sample to sample comparisons, as well as to draw correlations between the fire performance of various layer combinations in assembled panel systems.

Chapter 2

Background

2.1 Elevator Panel Assembly

A traditional elevator consists of a cab (also referred as a car), a hoist-way (the enclosing space) and the elevating mechanism (motor, pulleys, counterweights, etc.). The riders occupy the inside of the elevator cab where different types of wall lining materials, panel assemblies and connections are used to finish the inside of the cab. A typical layout of a cab is shown in Figure 2.1 which shows some of the different materials that are used. These include laminated wood panels, steel handles, and flooring to list a few. Depending on the location (and thus the jurisdiction) where the elevator is to be installed, some or all of these materials must meet certain fire safety requirements based on standards such as those from the American Society for Testing and Materials (ASTM) E-84 [3] and E-1354 [2]. The specific tests that materials used inside an elevator cab must pass, will be discussed in a later section.

In Figure 2.1, it can be seen that the largest quantity of material inside an elevator cab is the paneling material. Each layer of the laminated panel is specifically designed for certain purposes. The front sheet is the layer that is intended to provide most of the resistance to fire and moisture. It is also used as added structural support for the MDF core. If a fire were to occur inside an elevator the front sheet would be the first material exposed to convection and radiation from the fire and hot gas plume. Furthermore, the front sheet is subject to wear and tear during use of the elevator. The MDF core of the laminated panel is the main structural member of the finished assembly. The core is also intended to provide sound-proofing for the inside of the cab. Finally, the backer material is intended to further enhance the structural rigidity of the MDF core, and thus of the panel, by providing a stiff back to the sandwiched assembly.



Figure 2.1: Elevator Cab Renovations Ashbury model [19].

With that brief introduction to elevator panels, the next several sections of this chapter summarize the key concerns and work completed to date related to fire performance of the materials and assemblies which are typically found in North American elevators.

2.2 State of The Art Research Review

Recently, there have been fire safety concerns related to the increasing use of wood-based composite panels in buildings and as interior finishing materials [40]. Such wood-based composites are used in both non-structural and structural applications, in product lines ranging from panels for interior wall covering, to furniture and other support structures in buildings [48]. Wood and its derivative products are combustible and have led the fire safety community to conduct extensive research into the properties of various wood products and their behaviour under fire.

The United States Department of Agriculture Forest Products Laboratory (USDAFPL) defines the term wood composite as being any wood-based material bonded together [48]. As such, both MDF and laminated paper sheets would classify as wood composites. In addition, a typical multi-layer wood-based laminated panel consists of up to 94% by mass

of a wood-based material in the core [48] sandwiched between various thin front and backer materials. In most typical panels today, the core is comprised of MDF sheets produced by mechanically reducing raw wood into small particles, applying adhesive binders to the particles, and consolidating a loose mat of particles with heat and pressure into a panel product [48]. The mechanical characteristics of MDF, as well as tolerance limits and health and safety concerns with formaldehyde and other chemicals in the panel, are governed by American National Standard Institute (ANSI) standards [1, 51]. The front and backer sheets are Arborite, themselves wood-based, thermoplastic composites manufactured using a melamine resin layer pressed over a Kraft paper core that is impregnated with phenol resin and set under high pressure [57]. Fire rated Arborite is often used in finished multi-layer assemblies [7, 5, 6].

In general, multi-layer, laminated panel assemblies are optimized for structural performance, as well as water and tear resistance and fire performance. The fire performance characteristics of interest for use in elevators are the time that the material take to ignite under an open flame (time to ignition); the amount of carbon monoxide (CO) and carbon dioxide (CO_2) produced as well as the amount of energy given off by the material under combustion (heat release rate). In general better fire performance is measured by using materials with lower overall values in their time to ignition, production of CO and CO_2 and lower peak heat release rate (HRR) as well as the time it takes to reach these values. For this reason, the individual components can be combined in many ways into the finished product and, as a result, there has been very little research related to the fire safety performance of laminated MDF panels as an assembly. It has rather been focused towards the performance of the individual materials most commonly used to make these products. Thus, it is of interest to understand the current state of the art in fire performance of each component of an MDF laminated panel, including the MDF sheet, the plastic front and backer materials and the adhesives, resins and fire retardant agents used in commercial panels. The subsequent sections therefore summarize research that has been conducted to investigate the fire properties of the materials used in the panels of interest in this work. In particular, fire retardant strategies and previous small scale fire performance testing of each component material is outlined, with some discussion on research projects that have been undertaken with regard to large scale testing as well.

2.2.1 Medium Density Fiberboard

Medium density fiberboard forms the core of the present panel assembly. It is manufactured using fine wood particles mixed with binders and an adhesive and then pressed together and dried [50]. Since MDF is a wood-based product, it requires treatment with an appropriate

fire retardant in order to meet the fire performance criteria specified for most applications. One of three strategies is usually employed to fire retard a finished particle board:

1. Powdered fire retardant additives are mixed in with the wood particles or the matrix of the material.
2. The wood product is impregnated with water-based fire retardant chemicals before being formed into a panel.
3. Fire retardant surface coating is applied to the finished wood product.

Early work by Syska from the USDAFPL [49] explored the efficacy of using each of these three strategies, with 15 different powdered and water based fire retardant chemicals, to fire retard particle board made with 2 types of wood particles and 3 different binders. The finished fiberboard panels were tested using an 8 foot tunnel and the ASTM E-84 [3] standard test method for determination of flame spread and smoke obscuration parameters [49]. It was found that certain borates, AWPA Type C and Type D fire retardants, and monoammonium phosphate showed the most promise in terms of optimizing fire performance characteristics such as flame spread and smoke production, while maintaining the strength and stability of the board itself. In particular boric acid-disodium octaborate, a type of salt, was one of the most effective fire retardant additives. Mixing the fire retardant salt solutions with the base wood particles before the panels were formed appeared to provide better results than were obtained using dry fire-retardant salts. Syska concluded that the application of the fire retardant into the matrix before the drying process was most effective in improving the fire retardant characteristics of the finished product; however, those additives impacted the bonding characteristics of the adhesive used in the material assembly. Therefore, an appropriate balance between fire performance and other material characteristics had to be optimized in the finished product.

Within the three strategies outlined above for fire retarding wood based products, many different categories of fire retardant chemicals can be employed to treat MDF, wood and its derivatives. Rowel explains that these generally fall into one of six classes [46]:

- chemicals that promote the formation of increased char at a lower temperature than that at which untreated wood degrades;
- chemicals which act as free-radical traps in the flame;
- chemicals used to form a coating on the wood surface;
- chemicals that increase the thermal conductivity of wood;
- chemicals that dilute the combustible gases coming from the wood with non-combustible gases; and

– chemicals that reduce the heat content of the volatile gases.

Further, Rowell explains "that in most cases a given fire retardant operates by several of these mechanisms" [46], hence there is usually room for optimization of the formulation for a particular end goal. The usage of different inorganic compounds to enhance the fire retardant capabilities of wood has been studied in detail by authors such as Pedieu [44]. Other recent work has been focused toward maintaining fire performance while reducing formaldehyde emission from MDF board in response to ongoing concerns about indoor air quality in the industry and by governmental organizations [13, 43]. Related work by Wang [52] suggests the use of recycled wood as a main component in MDF and studies the fire safety characteristics of those materials.

Unfortunately, the fire retardant chemicals that were added to the MDF used in the present research, and thus the strategy that was implemented to tailor its fire performance, are proprietary to the manufacturer of the MDF and unknown even to our industrial partner in this research. Thus, a first step in this work is to study the fire performance of the NFR and the FR versions of the as-supplied MDF using a cone calorimetry to determine the baseline performance of the NFR material and thereby assess the comparative effectiveness of the fire retardant used in the board as well.

2.2.2 Laminate Paneling

The front and backers of laminated panels typically used in elevator cabs are Arborite sheet material. As can be seen in Figure 2.2, Arborite plastic laminate sheets are also composites made of layers of plastic and wood based materials. Arborite decorative laminates, such as those used here, consist of multiple layers of Kraft paper impregnated with phenolic resins that have excellent fire performance characteristics. For wear resistance, this core is then covered by a melamine impregnated surface layer, where melamine and melamine salts are again known to be used as fire retardant additives in paints, papers, and urea formaldehyde based or other similar resins. In the final step, the layered composite is manufactured into the final solid, thermoset, front or backer sheet in a high temperature and high pressure process [6].

Again, for the Arborite front and backer materials, samples of both the NFR and FR versions were tested to assess the comparative effectiveness of the fire retardant used in the FR version of the material of interest for use in elevator panels.

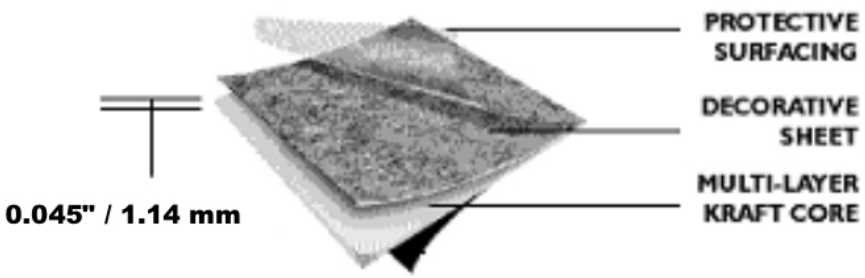


Figure 2.2: Arborite's laminate panel breakdown [6].

2.2.3 Resins and Adhesives

There are many types of laminating resins and glues that are used for different purposes in wood laminates, particleboard and multi-layer panel assemblies. As a result, there is also a large amount of research being conducted into the fire performance of adhesives and epoxy resins. The intended end of use of a laminated MDF panel, however may limit a manufacturer to use adhesives with other properties specific to a particular application. For example, the adhesive chosen may have to maintain certain mechanical properties, while also being moisture-resistant and low in emissions of formaldehyde and other volatile organic compounds (VOCs). These limitations, coupled with the fact that the addition of inorganic fire retardant additives impact the bonding characteristics of most glues and adhesives [49, 34, 15], have presented a complex challenge into which much research continues. Since the design of the FR additives used in the present panel materials and glues is not the subject of the present work, these are not reviewed in detail here. Instead only a few particularly important aspects are highlighted below. Otherwise, the interested reader is referred, for example, to Gerard et al. [29] for a thorough review of some of the work being conducted in the fire retardation of epoxies and to Bourbigot and Duquesne [12] for a detailed overview of developments of fire retardants in polymers. It should finally be noted that due to the similarity in the chemical composition of the resins used to create laminate sheeting such as Arborite and the adhesives employed in manufacture of multi-layer laminated MDF panels [50], in many respects research between laminate resins and adhesives overlaps.

Specific to the present work are the family of urea melamine formaldehyde polymers that form the base resins used in both MDF and Arborite. These polymers can be used for a wide range of purposes, notably as adhesive agents, catalysts, strengthening agents,

and additives for combined fire and moisture resistance [50]. In terms of fire resistance, particular formulations provide an intumescent protective coating to the material when exposed fire or may include phosphorus-based flame retardants which promote char formation, inhibit the action of free-radicals key to sustaining combustion and/or form strong surface layers that separate the base material from the outside air (oxygen) and insulate the material from heat transfer back from the flame [50, 58]. The mechanisms of phosphorous flame inhibition and its effectiveness in fire safety have been studied in great detail as reviewed by Weil [53].

An alternative binder for MDF and another prominent component in Arborite laminate sheets are the phenol-formaldehyde (PF) resins. These resins are again typically used in the manufacture of sheet materials, construction plywood and oriented strand-board where exposure to moisture is important since they enhance the water resistance properties of the finished product [50]. They are sometimes again combined with additional fire retardant additives to further enhance their inherent fire resistance. Again due to the trade-offs between improved fire performance and other desired properties of the finished material, research continues towards optimized formulations for particular applications.

More recent research into alternative resins, binders and adhesives for wood composite products has been driven by the growing recognition that indoor air quality may be negatively impacted through use of finishing products and wood laminates that contain VOCs. These negative impacts have been linked to products containing both urea melamine formaldehyde polymers and phenol-formaldehyde (PF) resins [50, 13, 43]. While work thus far focuses mainly on quantifying the emission of these chemicals under typical indoor ambient conditions (not in a combustion or fire situation), the increasing concern over VOC generation is driving new research into improving the fire retardant characteristics of plastic laminates. Some of the alternatives are discussed in recent work by Chapple et al. [14] which examines the effectiveness of natural fiber-reinforced laminates in fire retardation and similar work by Gallo et al. [28] which focuses on analyzing the effectiveness of using a multi-component laminated composite material that contains biodegradable components in the assembly.

2.3 Test Methods for Fire Performance of Laminated Wood Panels

Current building codes in North America may be broadly separated into those used in the United States and those applied in Canada. The US requirements are based on the model building code produced by the International Code Council (ICC) [36]. The National Fire

Protection Association (NFPA) Life Safety Code [41] provides a further set of guidelines for life safety from fire in buildings and structures . The provisions in these documents "become statutory requirements when adopted by local or state authorities having jurisdiction" [54]. In Canada, the National Building Code of Canada (NBCC) is applied[30], along with additional codes such as the National Fire Code (NFC) [31] and provincial variations such as those contained in the Ontario Building Code (OBC) [39]. Together these stipulate the fire safety performance criteria that given materials have to meet in order to be allowed for use in certain applications. Generally, such requirements are based on the results from fire performance tests with given ranking criteria, as set out by a recognized standard setting organization [54]. Therefore, organizations such as United Laboratories (UL) and ASTM International have developed test methods, but it is still up to the local or state authorities to specify benchmarks acceptable for their jurisdictions.

The OBC provides specific fire safety stipulations for both the construction and materials that can be used in elevators. These specifications deal with all aspects of the elevator that would be affected during a fire. Of most pertinence to the present research, the OBC specifies that any wall lining material must meet a maximum flame spread index (FSI) of 75 and a maximum smoke developed classification of 450 under ASTM E-84 standard testing [39].

The ASTM E-84 standard test is one of the most widely used testing standards in the construction industry, and is generally applied to determine fire performance rankings for finishing materials [35]. This test requires the use of a 2' [0.68 m] wide by 24' [7.35 m] long specimen* mounted in a specialized testing apparatus, instrumented only to provide the pass fail criteria specified in the method itself. Due to the size of sample required, dearth of flexibility in instrumentation and cost of testing the wide range of materials to be investigated in this research, it was not practical to consider a full set of ASTM E-84 tests. Instead, substitute ways were sought by which to gain preliminary understanding of the fire safety characteristics of the individual materials and the panel assemblies, at smaller scale and with the option of adding additional instrumentation as required.

In this respect, there has been a considerable amount of work on scaling of test results from bench scale test methods to large scale tests, including work done by Wickstrom [56] and Petrella [45]. In these studies, small scale tests such as the ASTM E-1354 [2] cone calorimeter have been shown to provide useful results. Other comparative studies have been made through ongoing efforts at the Federal Aviation Administration (FAA) to develop fire-safe polymers and polymer composites for commercial aircraft under their Fire Resistant Materials Program [23]. This program leads research into next generation polymer composites and adhesives with advanced fire safety properties. For this, several

*Non SI units are used here because the sample size is specified as such in the ASTM E-84 standard

criteria for assessing the fire safety characteristics of these materials were defined [58]:

- ease of ignition - how readily a material ignites;
- flame spread - how rapidly fire spreads across a surface;
- fire endurance - how rapidly fire penetrates a wall or barrier;
- rate heat release rate - how much heat is released and how quickly;
- ease of extinction - how rapidly or how easily the flame chemistry leads to extinction; and
- smoke evolution - amount, evolution rate and composition of smoke released during various stages of a fire.

To determine these various parameters, the FAA uses a combination of small- and larger-scale standard tests, such as the very small-scale limiting oxygen index (LOI), the small-scale cone calorimeter and the large-scale Steiner Tunnel, along with their newly developed pyrolysis-combustion flow calorimeter (PCFC) [58]. Using a combination of different tests, an extensive study was conducted into the fire safety characteristics of many polymer and polymer composites used in airplane cabins, including materials similar to the phenol resins and adhesives of interest here. While the work done by the FAA does not specifically address plastic laminates, some aspects of the methodology and certainly the use of the cone calorimeter for testing is adopted in the present research. As such, the following section outlines the cone calorimeter and the related ASTM E-1354 standard test in further detail.

2.3.1 Cone Calorimeter

The cone calorimeter is a bench-scale test method that is known to provide consistent and repeatable fire performance rankings for a wide variety of materials [9, 8, 11]. A schematic of the main components of the system is shown in Figure 2.3. The test was originally developed at the National Institute of Standards and Technology in 1982 [8] and is commonly used to determine the time to ignition, heat release rates, mass loss rates, effective heat of combustion, and visible smoke development of materials and products [2].

Cone calorimeter tests are done by exposing a material with nominal dimensions and varying thickness to a uniform radiative surface heat flux generated by a conical heat source. The behaviour of the material is monitored as it decomposes and burns. During a test, the sample, measuring nominally 100mm by 100mm in surface area and with a known thickness, is mounted in a special steel holder, covered by a steel edge frame, and loaded onto a calibrated load cell. When the test commences, the protective shutters are opened, exposing the sample to the preset value of radiant heat flux, and the electric spark

igniter is activated. As the sample is exposed to the incident flux, it heats and begins to vaporize. The vapours mix with air and, if flammable, may be ignited by the radiant source (non-piloted) or by a spark igniter (piloted ignition) as specified in a particular test method. Figure 2.4a shows a laminated sample mounted in the cone calorimeter and off-gassing shortly after the beginning of a test, while Figure 2.4b shows a similar sample burning under the cone calorimeter.

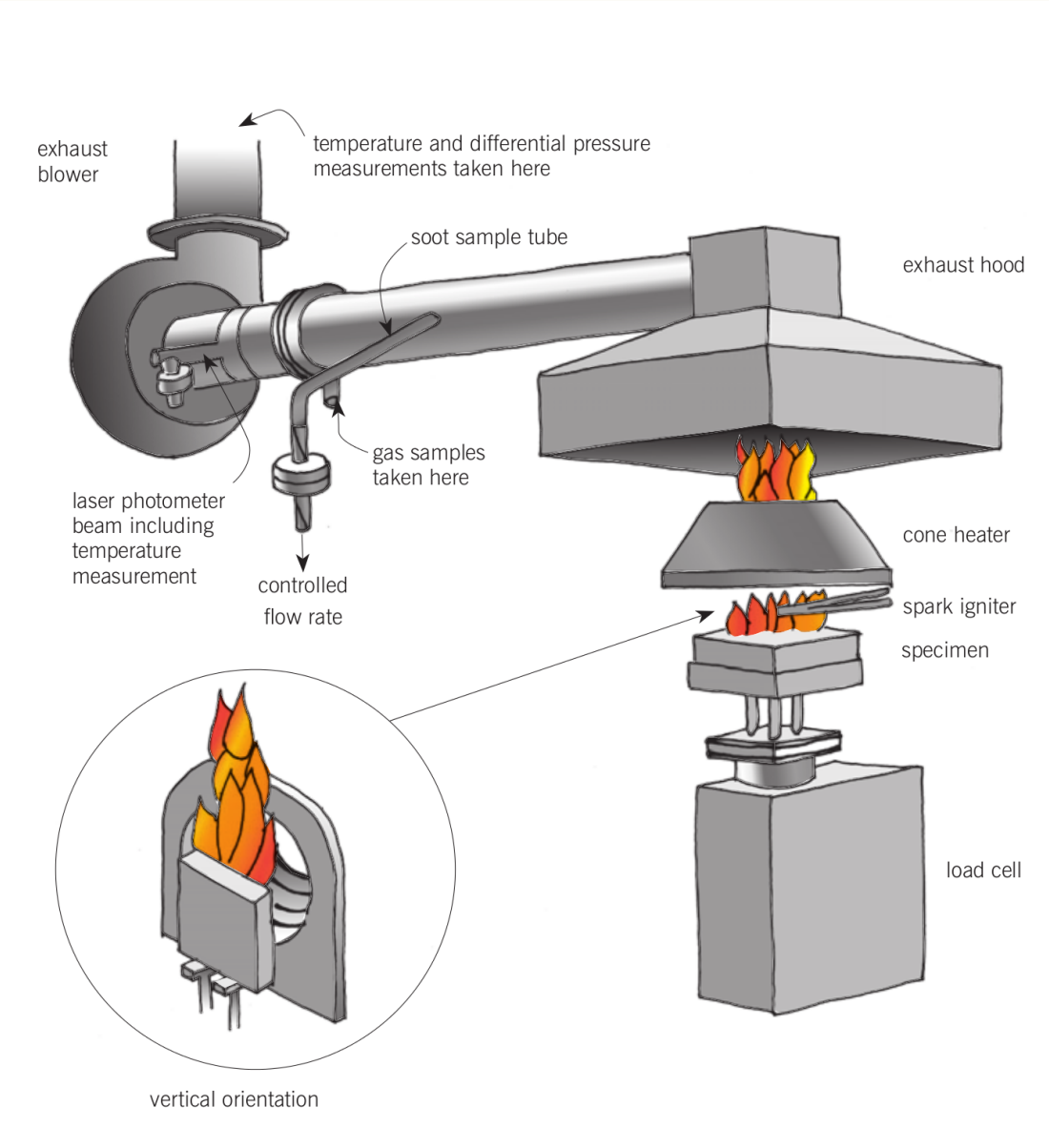
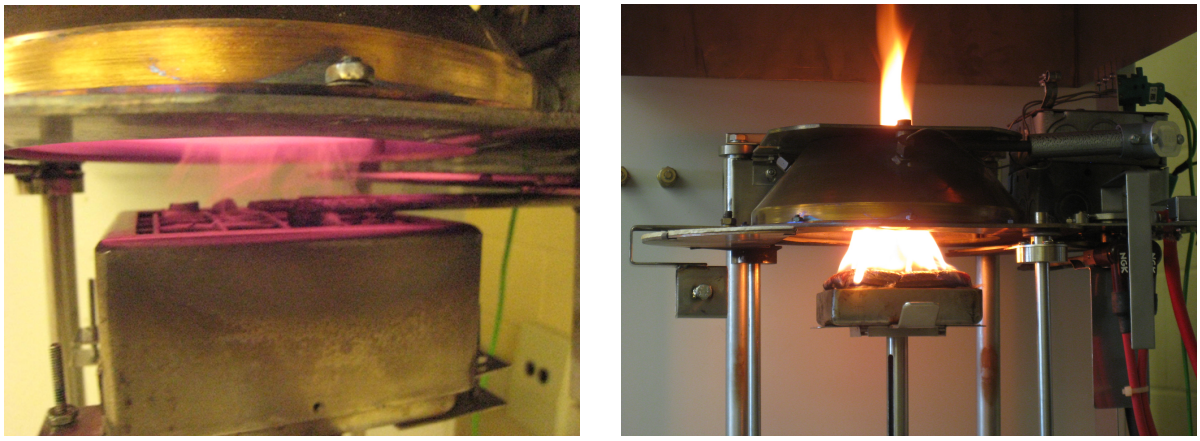


Figure 2.3: Cone calorimeter schematic [16].



(a) (b)

Figure 2.4: Cone calorimeter testing evolution, (2.4a) off-gassing period and (2.4b) flaming period.

The time it takes from the moment the shutters are opened to when the sample ignites is noted as the time to ignition. As the samples burns, the load cell monitors the rate of mass loss of material. The decomposition and combustion gases are extracted by a fan, located in the exhaust duct. Representative gas samples are withdrawn from this duct and sent to the gas analysis system for determination of volume fractions of oxygen depleted, as well as of carbon dioxide and carbon monoxide generated in burning the sample. Pressure differential and temperature sensors in the exhaust duct are used to approximate the flow rate of gases in the stack. Lastly, a laser mounted after the gas sampling ring, measures the smoke obscuration percentage based on an integrated measurement of light intensity across the duct where 100% is the intensity of a non-attenuated laser beam and 0% is that for a fully obscured laser beam.

During the time of testing, the specimen may go through several different burning states (pyrolysis, ignition, fully developed and smouldering flame) that are observed and analyzed to further understand the fire performance characteristics of that sample. Such observations are particularly useful for cases in which fire retarded materials or multi-layer samples are being tested [55, 26]. Under ASTM E-1354 specifications, the test may end under different criteria; a drop in the measured values of heat release, the absence of flame zones (flame out) for more than 4 seconds or a drop below a critical value of the mass of the specimen [2].

Heat Release Rate

From a fire safety perspective, one of the most important measurements that can be extracted from cone calorimeter data are the measured values of heat release rate (HRR) as a function of time [11]. Babrauskas argues that heat release rate measurement is the "most important variable in characterizing the 'flammability' of products and their consequent fire hazards" [11]. Using various large scale and small scale fire scenarios, with different testing apparatus, Babrauskas demonstrated that heat release rate can be directly linked to the severity of a fire. Consequently, ASTM E-1354 uses the heat release rate measurements as one of its main indicators for the fire performance of a material.

In general, the heat release rate per exposed specimen area, $q"(t)$, can be calculated using the concept of oxygen consumption calorimetry. This method is derived from the understanding of equation 2.1 and the principle of oxygen-consumption during combustion. The definition of all the terms used in this equation and hereafter, can be found in the nomenclature section of this study.

$$\Delta h_{c,eff} = \frac{q"}{m"} \tag{2.1}$$

The principle of calorimetry states that for most hydrocarbon based combustibles an amount of heat equal to 13.1 MJ/kg is released for each kilogram of oxygen consumed from the air stream during combustion of the material [2]. This estimate is accurate to $\pm 5\%$, particularly when corrections are made for the amounts of CO_2 and CO produced. The cone calorimeter approximates the heat release rate of a given specimen by measuring the change in the mass of the sample under test, as well as the percentage of oxygen, CO_2 and CO in the combustion gases. Equation 6.1 [37] shows the application of this principle to provide a measurement for heat release rate.

$$q''(t) = E_{O_2}\left(\frac{\phi}{1+\phi(\alpha-1)}\right)\dot{m}_e\frac{M_{O_2}}{M^{\circ}_{air}}\left(1 - X^{\circ}_{H_2O} - X^{\circ}_{CO_2}\right)X^{\circ}_{O_2} \tag{2.2}$$

To apply the above equation, it is necessary to determine the flow rate of gases through the exhaust stack as well. This is calculated using equation 2.3, knowing the orifice plate coefficient, C, the temperature and the pressure change [2] over time during a test.

$$\dot{m}_e = C\sqrt{\frac{\Delta p}{T_e}} \tag{2.3}$$

The oxygen consumption factor, ϕ, is found using equation 2.4.

$$\phi = \frac{X_{O_2}^{\circ}\left(1 - X_{CO_2} - X_{CO}\right) - X_{O_2}\left(1 - X_{CO_2}^{\circ}\right)}{\left(1 - X_{O_2} - X_{CO_2} \cdot X_{CO}\right) X_{O_2}^{\circ}} \tag{2.4}$$

The mole fraction of water vapour in the incoming air is calculated using psychometrics and the ambient temperature, pressure and relative humidity values measured in the lab. The molecular weight of the air is found using the molecular weight relationship shown in equation 2.5.

$$M_{air}^{\circ} = M_{air}\left(1 - X_{H_2O}^{\circ}\right) + M_{H_2O} \cdot X_{H_2O}^{\circ} \tag{2.5}$$

Using equation 6.1, the instantaneous heat release rate per unit area, in units of kW/m^2, is calculated and plotted as a function of time to characterize the burning characteristics of the specimen during testing (see Appendix A for a test report sample). The measured value of peak heat release rate, q_{peak}, as well as time to peak HRR, $t_{q_{peak}}$, provide additional indicators of potential intensity and speed of development of a fire involving the material under test. In general a better fire performance would exhibit lower values of overall peak HRR as well as longer times to peak HRR. Another way to look at the peak to HRR is to use the time to peak HRR after ignition, $t_{q_{peak_{ig}}}$ which is defined as the time it takes the sample to reach its peak HRR after ignition has occurred. Because cone calorimeter specimens are usually tested with an edge frame (see Figure 2.4a), the total exposed specimen area is constant. For a standard edge frame, this area will be approximately 88.4 m^2. Multiplying the area by the heat release rate per unit area provides the total rate of energy release from the specimen, q_t, where a lower overall value indicates better fire performance.

Carbon Dioxide and Carbon Monoxide

The combustion of a hydrocarbon fuel produces carbon dioxide (CO_2), carbon monoxide (CO) and water (H_2O) as three of the major by-products [18]. In addition to the heat release rate measurements above, the cone calorimeter system provides measurements of the concentrations of both CO_2 and CO over time. Complete combustion of a sample could be assessed by determining the ratio of CO_2 to O_2 [8], but in reality, even under the well ventilated conditions in the cone calorimeter, CO is also produced in amounts which increase as more incomplete combustion takes place. In the case of fire retarded samples, higher quantities of CO are produced when the fire retardant chemicals further inhibit combustion. This relationship has been used to quantify the effectiveness of different fire retardants in MDF [32]. In general higher values of CO are indicative of better fire performance whereas higher values CO_2 is indicative of poor fire performance.

Mass Loss

The cone calorimeter is equipped with a load cell of high accuracy and repeatability that is used to measure the total mass loss, M_{Total}, and the mass loss rate, m', of each test sample. The mass loss rate data can be interpreted to provide an indicator of the different stages of pyrolysis of a sample, as well as how fast the material burns once ignited. This is explained by Fateh [22] in their work on modeling the thermal decomposition of FR plywood. In their work, the data obtained from the time evolution of total mass loss and mass loss rate is used to determine the different states of pyrolysis of a given plywood specimen and hence to determine the effectiveness of FR used in the different materials tested, where generally a lower mass loss rate signifies a material with better fire performa

Time to Ignition and Flame Out

The first measurement that is recorded in a cone calorimeter test is the time to ignition, t_{ig}. ASTM E-1354 defines the term ignitability as the propensity for ignition, as measured by the time to sustained flaming at a specified heating flux [2, 4]. Either piloted or non-piloted ignition can be used in a cone calorimeter test. Piloted ignition occurs when a body is ignited by an external heat source such as sparks, flames or a hot surface [47]; in the case of the cone calorimeter this is achieved through use of a continuous spark ignitor positioned over the center of the sample under test. Non-piloted ignition in its simplest definition is known as "ignition in the absence of a pilot source" [38]. For this ignition mode, the spark igniter on the cone calorimeter can be disabled such that the sample ignites due only to the incident heat flux on its surface. The time to ignition under either mode of operation is important for understanding fire performance since it provides a benchmark for how fast a material would ignite under a given heat flux. Further, Babrauskas explains that while the time to ignition may not be important as a deterministic measure in terms of the time taken for the first item to ignite for a given fire situation, it is certainly important in probability based models or to determine when additional items might become involved in a given fire scenario [8]. Because testing conditions in the cone calorimeter are tightly controlled, with known heat flux, environmental conditions and sample characteristics, the measured time to ignition is often used as a parametric factor in ranking the flammability and ignition propensity of a given material.

There is a considerable amount of work aimed at modeling piloted ignition. Shi and Lin provide a summary of the work done on the development of numerical models for ignition [47]. They explain that there are two general approaches to the development of these models: formula deduction and empirical formulation through experimental data. In the case of data derived from cone calorimeter testing of different configurations; however,

the time to ignition is measured directly and no modeling is required. On the other hand, empirical equations that relate the density of the sample to an externally applied heat flux for piloted ignition in a cone calorimeter do exist [10]. Such equations can be used to check measured data, particularly with respect to assessment of the effectiveness of fire retardant additives [10].

The time to flame out, t_{out}, is the last measurement recorded during an ASTM E-1354 standard test. This event marks one measure of the end of a cone calorimeter test as discussed above. It is also used to denote the total duration of burning for the HRR calculations included in the ASTM E-1354 report. The time to flame out is defined in ASTM E-1354 as the event when a flame ceases to exist on or over most of the specimen surface for periods of at least 4 seconds [2]. It should be noted that in the fire safety community there has not been much research done related to application of this parameter in lieu of other end of test parameters, particularly for samples of some wood products which may smoulder for long periods of time. The flame out time is therefore presented in this work to indicate the end of a test and then to determine the sustained flaming period, t_{sust}, which is the time between ignition and flame-out. This period can then be used as another comparative parameter to distinguish fire performance characteristics of the different samples tested.

Having looked into the current and past research related to the fire performance of the different components of multi-layered laminated MDF panels and the different testing techniques used to quantify the fire performance characteristics of such materials, the following chapter outlines the testing methodologies used in the present research. In that chapter an outline of the specific apparatus used for testing, as well as the preparation, conditioning and types of specimens tested during this work is presented.

Chapter 3

Experimental Methodology

The experiments undertaken in this research are aimed towards characterizing the behaviour of each of the components used in the laminated wood panels described in previous sections. Typical fire-rated and non-fire-rated backer, MDF core, front panel materials and glue were first tested individually using the cone calorimeter to assess key parameters related to their overall fire performance. Following this, the tested components were assembled into laminated wood panels in various combinations, with and without the use of glue, and the full panels were tested again. This chapter outlines the experimental methods used to study the fire performance of the individual materials, the glues and the final panel assemblies.

3.1 Cone Calorimeter Testing

The cone calorimeter used in this research is a modern cone calorimeter apparatus that is manufactured by Fire Testing Technology (FTT) and housed in the laboratories of the University of Waterloo Fire Research Group (UWFRG).The system is shown in Figures 3.1 and 3.2 and further details can be found in Appendix B.

The unit is configured for, and testing is conducted according to, the ASTM E-1354 specifications [2]. A series of preliminary tests were carried out to gather initial information on the fire characteristics of the various samples, as well as to optimize the cone calorimeter settings and procedure to be used in the present research. This initial work was aimed toward determining an optimal value of heat flux for the tests, as well as an appropriate separation distance between the samples and the heating element and an appropriate mode of ignition (piloted or un-piloted ignition). A summary of these test results is included in Appendix C. Although some of the preliminary tests ran for extended periods, it was

determined that both the individual components and the laminated assemblies should be tested using piloted ignition, under exposure to a heat flux of $50\,\mathrm{kW/m^2}$, and using a standard element to sample spacing of 25 mm [2]. Further, because many of the samples did not lose much mass and/or smouldered for long periods of time during a test, the end of test was consistently set as the time when the flame had extinguished for more than 4 seconds.

FTT supplies the software, Conecalc 5 [24], that is used to control the tests and to analyze the results. Eight key measurements are logged as raw data during each test:

- specimen mass, m_s [kg] ;
- time to ignition, t_{ig} [s];
- time to flame out, t_{out} [s];
- oxygen volume fraction, X_{O_2} [%];
- carbon dioxide volume fraction, X_{CO_2} [%];
- carbon oxide volume fraction, X_{CO} [%];
- exhaust stack temperature, T_e [K]; and
- pressure change in stack, Δp [Pa].

The software uses the laboratory ambient conditions, physical properties of the sample and the raw data to calculate the parameters outlined in Section 3.1. From this data the software produces a reduced excel file and a test report with key testing information. The report also includes operator input for the test start and end times, as well as any visually observed events noted during the test (e.g. flash ignition, change in flame colour, etc).

Appendix A shows an example of a ConeCalc test report for a MDF core specimen. This report provides a summary of all of the key numerical data, such as the time to ignition and time to flame out, as well as graphical results for heat release rate, carbon dioxide production rate, carbon monoxide production rate and mass loss rate as functions of time. These are used in analysis and interpretation of all test results in the remainder of this thesis.

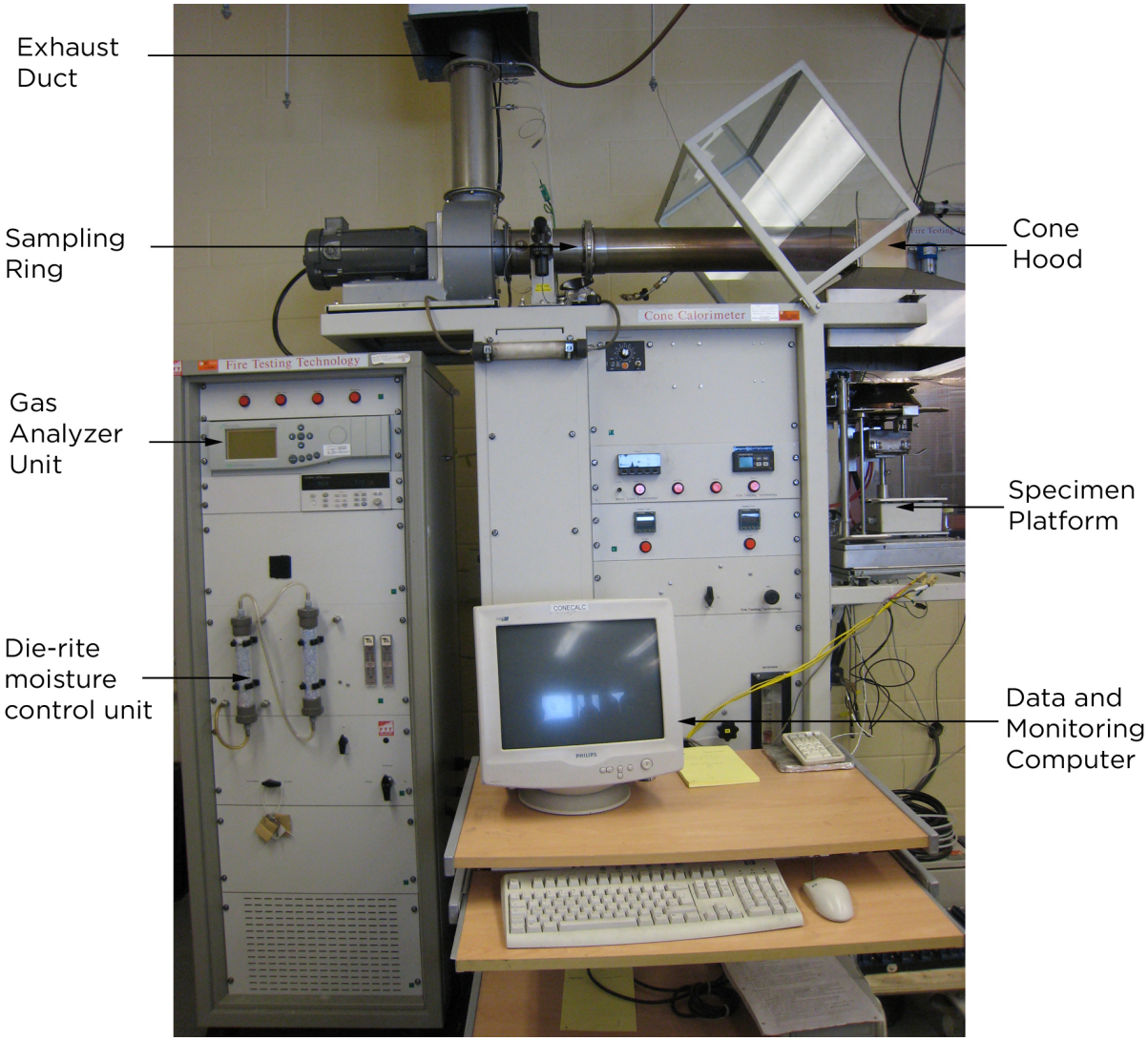


Figure 3.1: UWFRG's cone calorimeter detail.

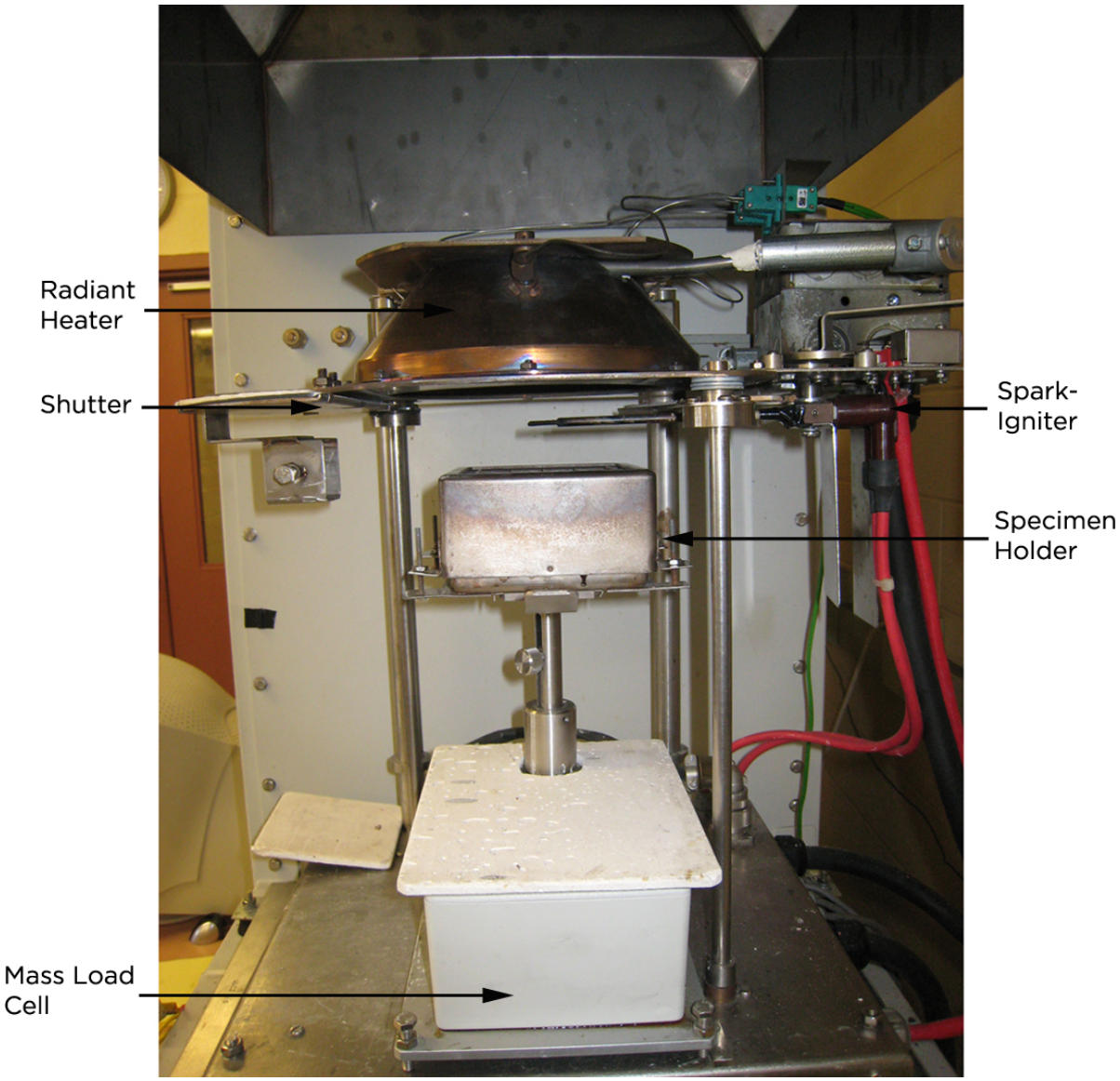


Figure 3.2: UWFRG's cone calorimeter specimen platform details.

3.2 Sample Details

Cone calorimeter testing is conducted on all of the individual component materials typically used in laminated panels, as well as on the panel assemblies themselves. In general, a laminated panel is made using a 'sandwich' technique in which the top and bottom (or front and back) plastic laminated sheets are bonded to the MDF core. This technique adds structural strength to the MDF core. As well, it allows for the customization of each panel for other attributes such fire performance, humidity or wear resistance. With respect to fire performance, individual components in each panel may or may not contain fire retardant additives. Figure 3.3 illustrates a typical laminated MDF panel.

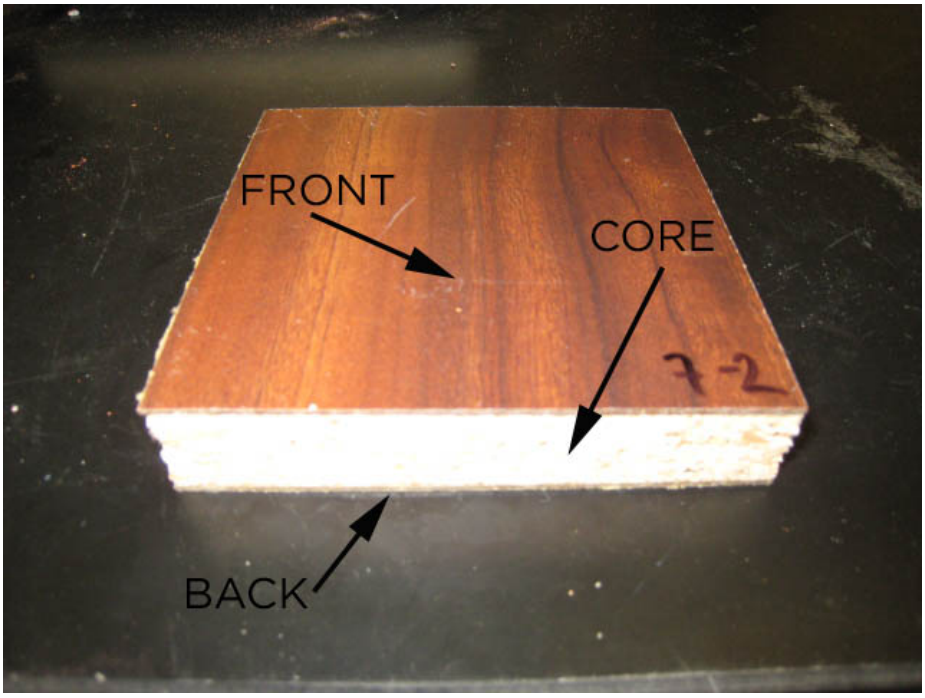


Figure 3.3: Typical laminated MDF panel.

ECR [20] supplies all of the samples used in the present research. The front and backer plastic laminates consist of FR and NFR materials chosen from the Arborite line of products in order to ensure similarity of the base samples used in this investigation. For the laminate core, both FR and NFR versions of comparable MDF panels are obtained from a local supplier; the precise fire retardant chemical additives and glue in the various components are confidential. To construct the laminated panel samples, the above individual materials are either press-fit into a sandwich configuration using a modified sample holder or glued together in different combinations using Permagrip PG107 adhesive.

Seven different materials were used in the course of the present testing. Three of these materials have both FR and NFR variants. Table 3.1 summarizes the individual samples tested, their types, manufacturer and specific product numbers. Wherever possible, the specification sheets for these materials are provided in Appendix D.

Table 3.1: Individual laminated MDF materials testing matrix.

Type	Name	Samples	Manufacturer	Manufacturer Part #
Front FR Laminate	Front-FR	3	Aborite	GPPL
Front NFR Laminate	Front-NFR	3	Arborite	A5
Core FR MDF	Core-FR	3	NIL	NIL
Core NFR MDF	Core-NFR	3	NIL	NIL
Back FR Laminate	Front-FR	3	Arborite	33PL
Back NFR Laminate	Front-NFR	3	Arborite	LB45
Adhesive	Glue	4	Henkel	PermaGrip PG107

Based on the individual components listed above, there are a large number of samples and sample combinations possible for the glued and un-glued laminated panel assemblies. Therefore, the following naming convention was used to clearly differentiate the various samples and their combinations:

$$LaminatedPanelAssembly = \underbrace{NFR}_{\text{front}} - \underbrace{FR}_{\text{core}} - \underbrace{NFR}_{\text{back}}$$

Where:

- FR = fire rated material; and
- NFR = non-fire rated material.

Table 3.2 summarizes the material combinations tested for both un-glued and glued composite assemblies presented in this work. In total, more than 25 tests were carried out with a least three tests conducted for each sample and all but the NFR-FR-NFR laminated panel configuration.

Table 3.2: Laminated MDF panel assemblies: un-glued and glued.

Laminated MDF Panel Assembly (Un-Glued)		
Specimen #	Specimen Name	Samples Tested
1	NFR-NFR-NFR	3
2	FR-NFR-NFR	3
3	NFR-NFR-FR	3
4	FR-FR-FR	3
5	NFR-FR-FR	3
6	FR-NFR-FR	3
7	NFR-FR-NFR	2
8	FR-FR-NFR	3
Laminated MDF Panel Assembly (Glued)		
Specimen #	Specimen Name	Samples Tested
1	NFR-NFR-NFR	3
2	FR-NFR-NFR	3
3	NFR-NFR-FR	3
4	FR-FR-FR	3
5	NFR-FR-FR	3
6	FR-NFR-FR	3
7	NFR-FR-NFR	3
8	FR-FR-NFR	3

3.2.1 Sample Preparation

Most of the cutting and sample preparation was done by ECR in Ottawa and the finished samples were supplied to the University of Waterloo Fire Research Group (UWFRG). Samples of each individual component material were cut to dimensions of 101 mm x 101 mm as required by the ASTM E-1354 test specifications. Laminated combinations were constructed from the individual component samples as required. Through the initial testing discussed in Section 3.1 above, it was found that the laminated samples could swell up and explode under heating, so for the remainder of testing, the laminated samples were mounted on a sample holder with both an edge protection and wire mesh cover to protect the cone calorimeter from damage. Figure 3.4 shows a sample mounted in the final sample holder before a test.

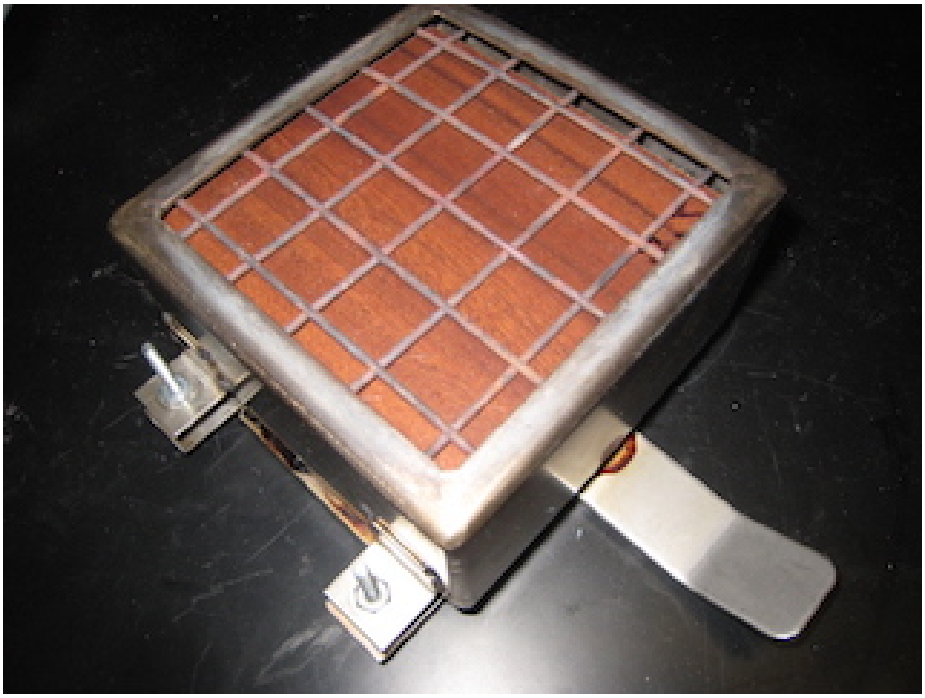


Figure 3.4: Specimen holder with guard mesh.

Before testing, the cone calorimeter to sample spacing was carefully adjusted since the thickness of the samples is found to vary depending on whether they contain fire retardant additives. All samples that are fire rated (FR) are heavier than their non-fire rated (NFR) variants. Sample dimensions, weight and volume are provided in Section 3.1.

After the materials were chosen and the samples prepared, each of the component materials was first tested individually in order to quantify and analyze the fire performance of that material alone. They were then assembled into laminated samples according to the matrix given in Table 3.2 and each laminated sample was tested and the results compared to those of the individual materials making that sample. Finally, to assess potential variations in the fire performance of a glued panel assembly due to the glue, the laminated panel assemblies were then tested with and without glue between the layers. The results for the individual materials are contained in Chapter 4, followed by those for the glued and un-glued laminated samples in Chapter 5. Finally, the sources of errors are discussed in Chapter 6 followed by Conclusions and Recommendations in Chapter 7.

Chapter 4

Individual Material Testing Results

This section deals with the cone calorimeter test results that were obtained during testing of the individual materials shown in Table 4.1. Since it was not possible to obtain data and fire performance test specifications for the FR and NFR variants of each material from the open literature, or even to obtain information about the fire retardant additives used, it was necessary to test samples of each individual material to independently determine its fire performance characteristics. In addition, it was necessary to characterize the fire performance of the glue used in laminating a panel since glue has been shown to influence fire characteristics of other glued wood products [27]. This section, includes the test results for each individual material, as well as a comparison of the overall fire performance of the FR and NFR variants of the individual materials, specifically the Arborite front and backer layers and the MDF wood core, as well as the Permagrip PG107 glue.

4.1 Front NFR and FR Arborite Laminate

The front section of a laminated MDF panel is the layer that is generally targeted to provide the panel with most of the resistance to fire and moisture, as well as being used as added structural support for the MDF core. If a fire were to occur inside an elevator the front laminate would be the first material exposed to convection and radiation from the fire and hot gas plume. Furthermore, the front laminate is subject to wear and tear during use of the elevator. The dimensional and physical characteristics of the front laminate samples used in this study are provided below, with further specifications and manufacturer information included in Appendix C.

Table 4.1 summarizes measured values for the mass, thickness and volume of each of the Arborite samples used in the present testing. Property data for other samples used

are consistent with these since all of the specimens are cut from 3' [0.91 m] by 8' [2.44 m] sheets from the same batches of material.

Table 4.1: Front NFR and FR laminate sample specifications.

Non Fire Rated Front			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Front NFR 1	16.2	1.1	11.2
Front NFR 2	16.2	1.1	11.2
Front NFR 3	16.2	1.1	11.2
Fire Rated Front			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Front FR 1	19.4	1.2	12.4
Front FR 2	19.5	1.2	12.4
Front FR 3	19.4	1.2	12.4

From the Table 4.1 it can be seen that within each set of three samples of the same material, the sample thickness is extremely consistent and there is less than 1% variation in density across the individual test samples. This suggests that data from samples within a given set should not be affected by factors such as moisture content, the in-homogeneity of the binder or FR additive distribution, or other inherent manufacturing imperfection. Further, it is clear that the FR front Arborite panel samples are thicker, and around 8-9% denser, than the NFR front panel samples. Such differences would be expected and are consistent with differences in the visual characteristics and finish of the surface of the FR material as well.

4.1.1 Time to Ignition, Time to Flame Out and Sustained Flame

Time to ignition, time to flame out and the sustained flame period for each of the front panel samples are shown in Table 4.2. Times to ignition are fairly consistent (within 11%) for a given material but there is a clear distinction between the time to ignition for the NFR versus the FR samples. As expected, the FR front panel samples took considerably longer, 2.5 to 3 times longer, to ignite in comparison to the NFR front panel materials.

Once the front panel samples ignited, there was significant variability in the burn time from sample to sample across samples of the same material - 17% variation for NFR and 25% for FR samples - resulting in overall times to flame-out that do not appear to be significantly different between the two sets of materials. Thus, it would seem that the FR

added to the front panel works by delaying the onset of ignition, but once ignited, the FR does not have an appreciable effect on the total time for which the material sustains a flame.

Table 4.2: Front NFR and FR time to ignition, flame out and time to sustained flame.

Non Fire Rated Front			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Front NFR 1	43	300	257
Front NFR 2	34	210	176
Front NFR 3	46	249	203
Fire Rated Front			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Front FR 1	110	285	175
Front FR 2	125	290	165
Front FR 3	123	364	241

The above observations merit further investigation to gain a better understanding of the differences in burning characteristics between the NFR and FR panel materials, as well as the potential implications in relation to the overall fire performance of the two materials. Additional analysis of visual observations, together with examination of the other fire performance parameters measured during testing was undertaken for this purpose. The results are described in the sections below.

4.1.2 Visual Observations

As the tests began, the front panel materials started to heat up and cracking noises were heard as the top surface of a sample fractured. The material then started to off-gas, and after a period of time it ignited. For the case of NFR samples, the flame grew quickly after ignition and leveled off to a more steady-state burning regime for a period of time until it decreased in intensity as the material was consumed. The FR samples also cracked and began to off-gas, and after a longer period of time, the samples ignited and burned for about the same length of time as the NFR samples, but the flame does not appear to be as large. Differences in the overall evolution of burning is further explained using the heat release rate, mass loss and species concentration data presented in the following sections.

4.1.3 Heat Release Rates

Figure 4.1 shows the heat release measurements over time for all three samples of NFR and FR front panel material across the duration of the tests. Table 4.3 summarizes the peak HRR, time to peak HRR and time to peak HRR after ignition measurements. It can be seen that there is fairly good sample to sample repeatability in both the magnitudes and trends in evolution of the heat release rates across samples of the same material.

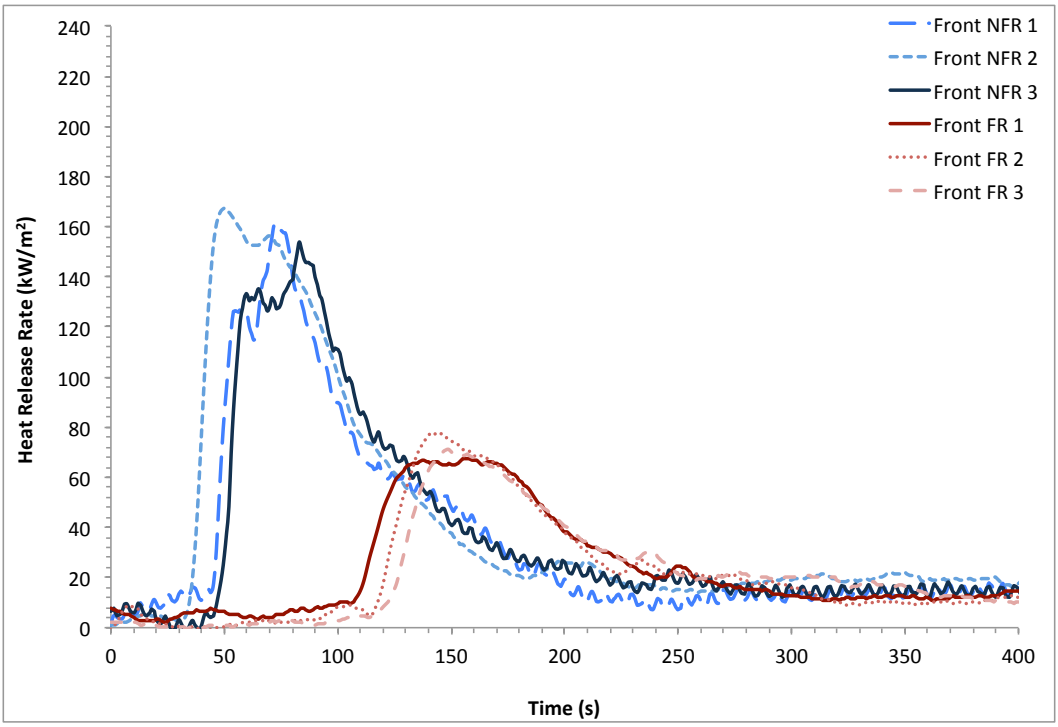


Figure 4.1: Front NFR and FR HRR over time.

As expected based on ignition time and visual observation of the tests, there was a clear difference in the evolution of measured HRR over time between the different types of samples. The time to peak heat release, $t_{q_{peak}}$, is significantly different, with the front NFR samples reaching their peak values at 68 seconds on average, versus the FR samples at an average of 148 seconds. However the times to peak HRR after ignition, $t_{q_{peak}}$, for both samples are similar with an average value of 27 seconds for the front NFR samples and 29 seconds for the front FR samples. Further, the average values of peak HRR, q_{peak}, are substantially different between the two materials: 160 kW/m^2 and 72 kW/m^2 for the front NFR and FR samples respectively. Based on the results, not only is ignition delayed, but it is clear that the total energy released from the FR samples is substantially less than from the NFR samples over the course of this test. This is supported by observations of mass loss and gas concentrations as discussed below.

Table 4.3: Front NFR and FR peak HRR, time to peak HRR and time to peak HRR after ignition.

Non Fire Rated Front			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Front NFR 1	161	72	29
Front NFR 2	167	50	16
Front NFR 3	153	83	37
Average	161	68	27
Fire Rated Front			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Front FR 1	68	156	46
Front FR 2	77	141	16
Front FR 3	71	148	25
Average	72	148	29

4.1.4 Mass Loss Rate and Total Mass Loss

Figure 4.2 shows the mass loss rate of each variant of front panel material over time. Comparison of the two plots further highlights the difference in behaviour between the NFR and FR samples. For the first 30-50 seconds after exposure to the radiant heat flux, the mass of all samples remained constant, after which it began to decrease but at different rates for the NFR versus the FR samples. In the case of the NFR samples, upon ignition the sample mass began to decrease significantly as it is consumed by the fire, and continues to decrease at about the same rate through the steady-state burning period. Following this, the sample mass decreased again until flame out at the end of the test. In contrast, the FR sample mass began to decrease well before ignition of the sample, but at a rate less than that of the burning NFR sample. This indicates that there is significant off-gassing and pyrolysis of the FR material as the sample heats early in the test. Upon ignition of the FR samples, there is only a slight change in the rate of decrease of sample mass which never reaches the high mass loss rates seen for the NFR samples consistent with the notion of lower total energy release from these samples during burning. As is the case for the NFR samples, approximately the same rate of mass loss continues through steady burning and then it decays as the sample flames out. Examination of these plots supports differences in both the visual observation of the burning samples, as well as the HRR plots in the previous section, and suggest that more of the NFR sample is consumed during each test in comparison to the FR sample. This is substantiated through examination

of the total mass loss over the sustained flame period for the NFR and FR samples as presented in Table 4.4. Between 61-65% of the mass of the NFR front panel samples are consumed, while only 25 - 31% of the FR sample mass is lost during the test. Based on the cone calorimeter data above, the FR front panel samples clearly exhibit improved fire performance over the NFR, from the point of view of delayed ignition, as well as lower peak and total heat release in the case where the material ignites during a fire.

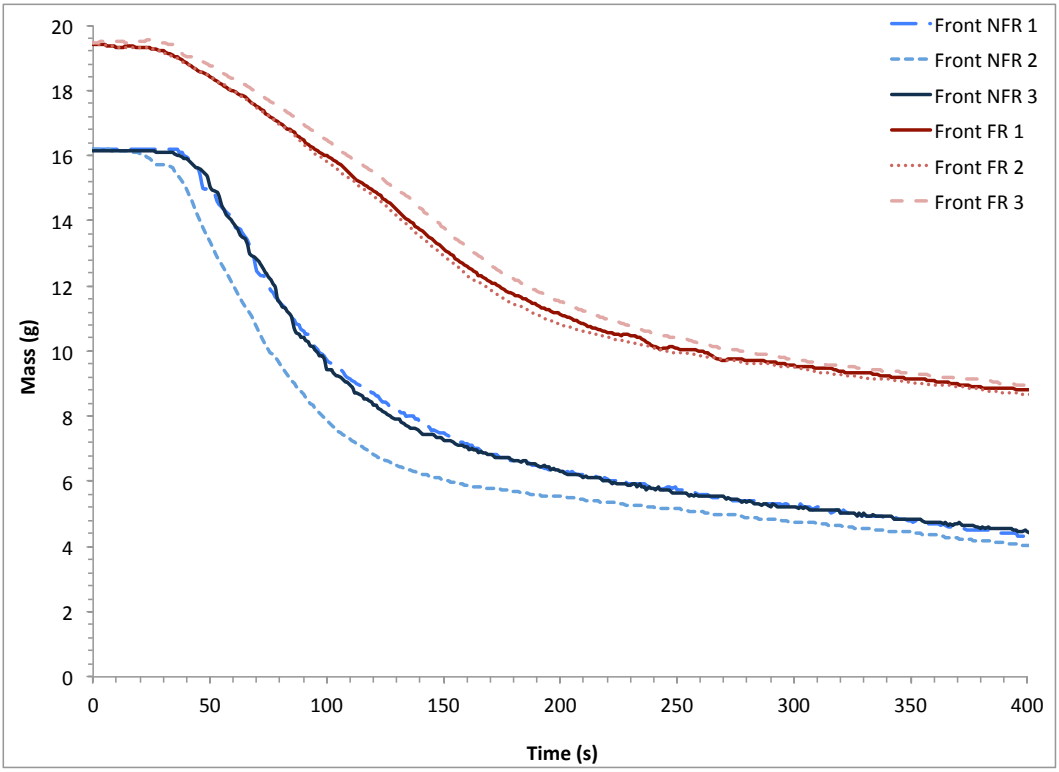


Figure 4.2: Front NFR and FR mass loss over time.

Table 4.4: Front NFR and NFR laminates total mass loss results.

Non Fire Rated Front			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Front NFR 1	16.2	10.5	65
Front NFR 2	16.2	10.2	63
Front NFR 3	16.2	19.9	61
Fire Rated Front			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Front FR 1	19.4	5.7	29
Front FR 2	19.5	4.9	25
Front FR 3	19.4	6.2	31

4.1.5 Carbon Monoxide and Carbon Dioxide Rates

An additional indicator of the impact of FR additives on the fire performance of the front panel materials can be deduced through examination of the amounts of CO_2 and CO evolved over time during each test. The relative presence of CO_2 and CO during combustion of the samples can be a further gauge that the fire retardant additives are inhibiting combustion, leading to pyrolysis and/or incomplete combustion of the sample. Figure 4.3 shows the CO_2 (%Vol) and Figure 4.4 shows the CO production rates over time for both the front NFR and FR laminates.

As pointed out in the background section of this work (Chapter 2.3.1), the presence of CO_2 is an indicator of more complete combustion, so the evolution of CO_2 with time should follow the time evolution of heat release rate very closely. Comparison of Figure 4.1 and Figure 4.3 illustrates that this is indeed the case in the present tests for NFR samples. For the FR samples, the peak in CO_2 concentration over time is very broad, extending from a period before ignition to a time after flame out. Since the sample appeared to be pyrolyzing before ignition and smouldered after flame out, the extended period of CO_2 production may suggest secondary oxidation reactions are occurring, even though open flaming combustion cannot be sustained. This is consistent with expected modes of action of fire retardant additives that might also be used in laminated front panel materials.

In contrast, however, differences in behaviour between the NFR and FR samples can be observed through examination of Figure 4.4.

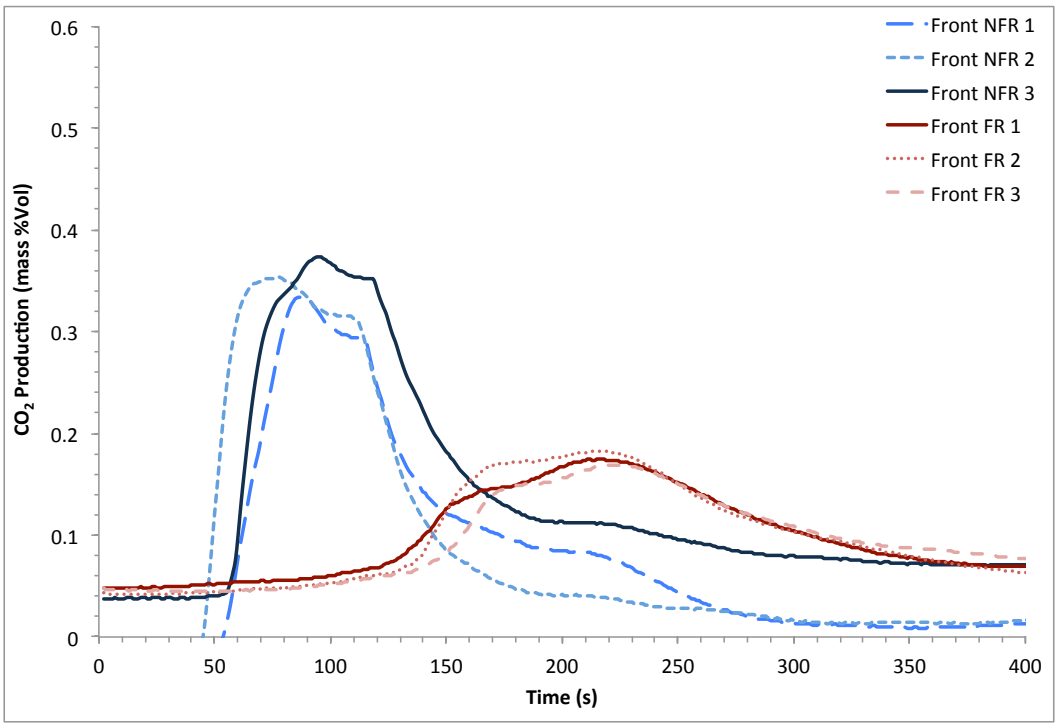


Figure 4.3: Front NFR and FR CO_2 production over time.

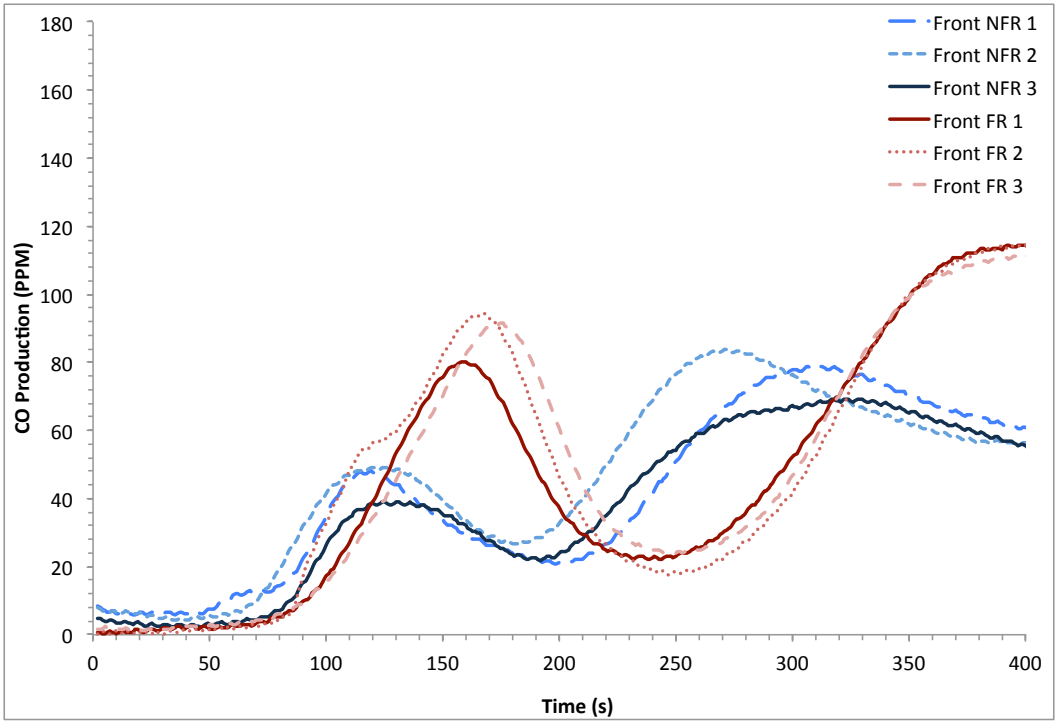


Figure 4.4: Front NFR and FR CO production over time.

For the NFR sample, CO concentrations follow trends in HRR and CO_2 over time through the growth and steady burning of the sample. As the sample flamed out and the tail of the HRR curve is approached, however, the CO concentrations increased again, gradually tailing off through the remainder of the test. Since at this time there is still more than 25% of the sample mass remaining, the production of CO aligns with observations that the samples continue to smoulder after flame out and until the test is ended.

In contrast, but consistent with observations of mass loss above, CO concentrations for the FR samples began to increase at times well before ignition of the sample. As the sample ignited and burned, they peaked to values of around 80 - 95 ppm, higher than those seen in the case of the NFR samples during the steady burning period. Following this, they decreased again as the sample flames out. As with the NFR sample, since there is still over half of the sample left at flame out, the CO concentrations increased significantly again as the sample continues to smoulder until the end of test. There is a clear difference in the amount of CO produced by the NFR and FR front panel samples; the FR samples begin to produce CO at about the same time and rate as the NFR samples, but peak to higher values during both steady burning and post flame smouldering of the samples. This evolution of CO over time is entirely consistent with the observation that the fire retardant additives act, in large part, to inhibit ignition and combustion in the FR front panel material. While these results clearly point toward potential differences in gas production from the NFR versus FR samples, it is impossible to deduce the impact of these differences on the overall fire environment since it is entirely outside the scope of the present study to examine the quantity or detailed nature of pyrolysis gases generated before ignition, or the smoke generation and smoke toxicity evolved during burning, of the samples.

4.2 Core NFR and FR MDF

The core of a laminated panel consists of medium density fibreboard, MDF, or a similar material. This is the component with the largest mass and thus the highest potential to contribute the most energy in a given fire situation. The MDF panel serves as the member to which the anchoring system is attached and, in concert with the front and back panels, gives the overall assembly its structural strength.

The dimensional and physical characteristics of the MDF core samples used in this study are provided below, with further specifications and manufacturer information included in Appendix C.

Table 4.5 summarizes measured values for the mass, thickness and volume of each of the MDF laminate core samples used in the present testing. Property data for other samples

used are homogeneous since all of the specimens were cut from 3' [0.91 m] by 8' [2.44 m] sheets taken from the same batches of material. As with the front panel of the laminate, the thickness and weight of the MDF core samples were very consistent, with only small variations in sample volume due to cutting and preparation. This suggests that data from samples within a given set should not be affected by factors such as variations in sample size, moisture content, in-homogeneity of binder or FR additive distribution, or other inherent manufacturing imperfections. Further, it is clear that the FR core panel samples are thinner but around 8-9% denser, than the NFR core panel samples. Any sample-to-sample differences are well in range with what can be accepted for sample variability.

Table 4.5: MDF core NFR and FR sample specifications.

Non Fire Rated Core			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Core NFR 1	127.0	18.8	192.3
Core NFR 2	128.0	18.8	192.2
Core NFR 3	126.8	18.8	192.2
Fire Rated Core			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Core FR 1	142.9	17.3	176.5
Core FR 2	142.3	17.3	176.5
Core FR 3	142.0	17.3	176.5

4.2.1 Time to Ignition, Time to Flame Out and Sustained Flame

Table 4.6 summarizes measured values for the time to ignition, time to flame out and sustained flaming period.

Table 4.6: MDF core NFR and FR time to ignition, flame out and time to sustained flame.

Non Fire Rated Core			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Core NFR 1	55	1818	1762
Core NFR 2	50	1734	1682
Core NFR 3	53	1943	1890
Fire Rated Core			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Core FR 1	75	1016	941
Core FR 2	79	945	866
Core FR 3	80	875	795

From Table 4.6 it can be seen that the time to ignition is consistent (within 10%) for the NFR MDF core and the FR core samples. Only small differences in time to ignition (about 25 seconds on average) were measured between the two materials. The measured time to flame out within samples of the same material was more consistent (within 12% for the NFR and 17% for the FR samples respectively) than observed for the front laminates. When the time of sustained flaming for the two sample populations was compared, it is clear that the FR MDF core does not flame for as long as its NFR variant. Furthermore, a green flame is observed during ignition which is indicative of the presence of FR additives within the structure of the MDF and readily available to the combusting zones[17].

4.2.2 Heat Release Rates

Figure 4.5 shows the heat release measurements for both the NFR and FR core samples over time throughout the duration of the tests. Table 4.7 summarizes the peak HRR, time to peak HRR and the time to peak HRR after ignition. There are clearly large differences in the evolution of heat release rate with time between the two types of core specimens.

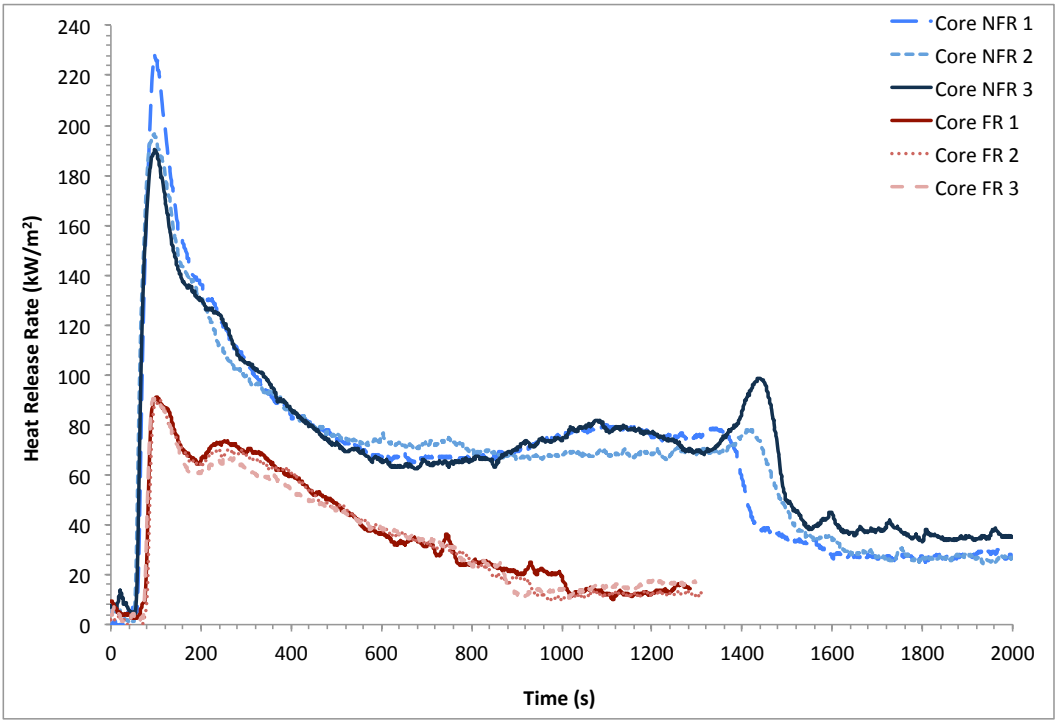


Figure 4.5: MDF core NFR and FR HRR over time.

Table 4.7: MDF core NFR and FR peak HRR, time to peak HRR and time to peak HRR after ignition.

Non Fire Rated Core			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Core NFR 1	227	98	42
Core NFR 2	196	95	45
Core NFR 3	190	97	44
Average	205	97	44
Fire Rated Core			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Core FR 1	91	101	26
Core FR 2	90	108	29
Core FR 3	90	103	23
Average	91	104	26

After ignition, the heat release rate from both samples initially increased quickly,

reaching peak HRR($t_{q_{peak}}$) values at 44 seconds after ignition for the NFR and 28 seconds for the FR sample respectively. The values of peak HRR are very different however, being 205 kW/m^2 for the NFR and much lower, 91 kW/m^2, for the FR samples. After reaching the peak value, the HRR from the FR sample gradually decreased to zero, while that of the NFR sample initially decreased but then leveled off to a constant value for about 13 minutes until the sample burned out. Clearly the fire retardant additives significantly reduce the value of peak HRR in this case, as well as reducing the duration of burning and the amount of energy released by the FR MDF core samples as they ignite and burn.

4.2.3 Mass Loss Rate and Total Mass Loss

The differences discussed above with respect to time of sustained flame and heat release rate of the NFR and FR core samples are further substantiated through examination of the mass loss rate over time curves plotted in Figure 4.6. The slopes of the respective curves are similar but actually suggest that after ignition, the FR samples burned at a slightly faster rate than the NFR specimens over their entire period to flame out. Because the FR specimens burned for a relatively short time, however, only about 50% of the original mass of the specimen burns during the test, as presented in Table 4.8. In contrast, about 79% of the original mass of the NFR samples was consumed during the test period.

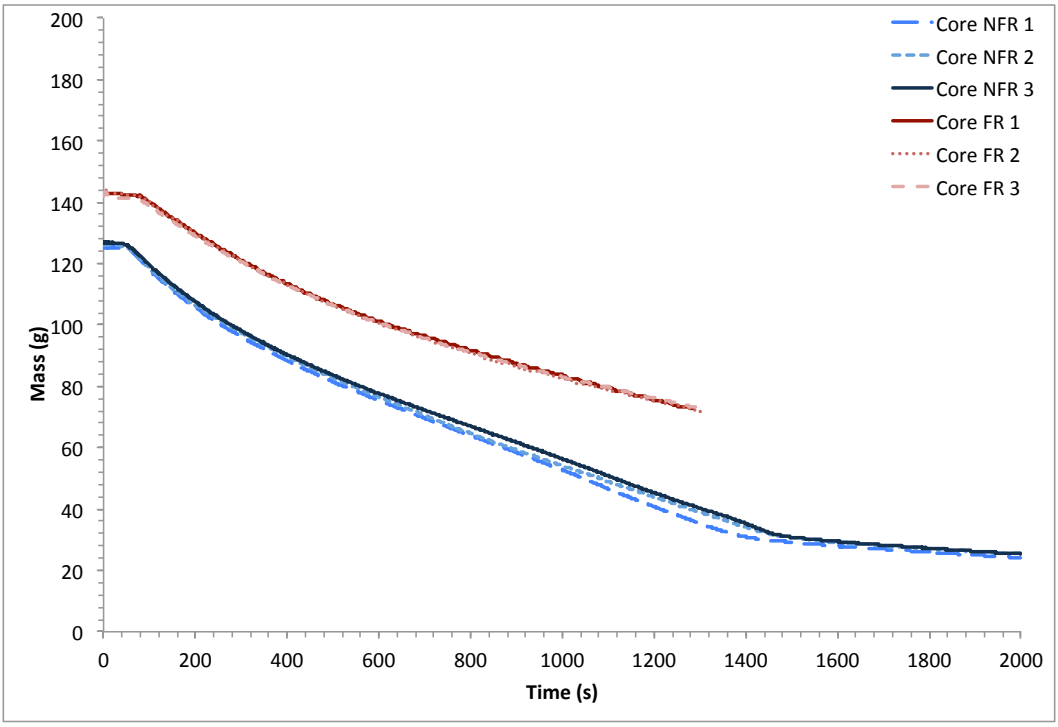


Figure 4.6: MDF core NFR and FR mass loss over time.

Table 4.8: MDF core NFR and FR laminates total mass loss results.

Non Fire Rated Core			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Core NFR 1	127.0	99.2	78
Core NFR 2	128.0	99.1	77
Core NFR 3	126.8	100.5	79
Fire Rated Core			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Core FR 1	142.9	68.8	48
Core FR 2	142.3	70.1	49
Core FR 3	142.0	67.5	47

4.2.4 Carbon Monoxide and Carbon Dioxide Rates

The HRR graphs and the time to ignition measurements show that the fire retardant additives have a large effect on the fire performance of the FR MDF core in comparison to the NFR MDF. An additional indicator of the impact of FR additives on the fire performance of the MDF core materials is deduced through examination of the evolution of amounts of CO_2 and CO over time during each test. The evolution of these product gases are plotted in Figure 4.7 and Figure 4.8, respectively. The relative presence of CO_2 versus CO is also of interest as it provides a further indication of the impact of fire retardant additives on combustion processes, as well as on production of pyrolysis gases and smoke.

As explained in the section on the front panel materials, trends in the CO_2 concentration over time, as plotted in Figure 4.7, follow similar trends as shown for the HRR of the samples in Figure 4.5. This is expected as production of CO_2 is a direct indicator of combustion of, and heat release from, the samples.

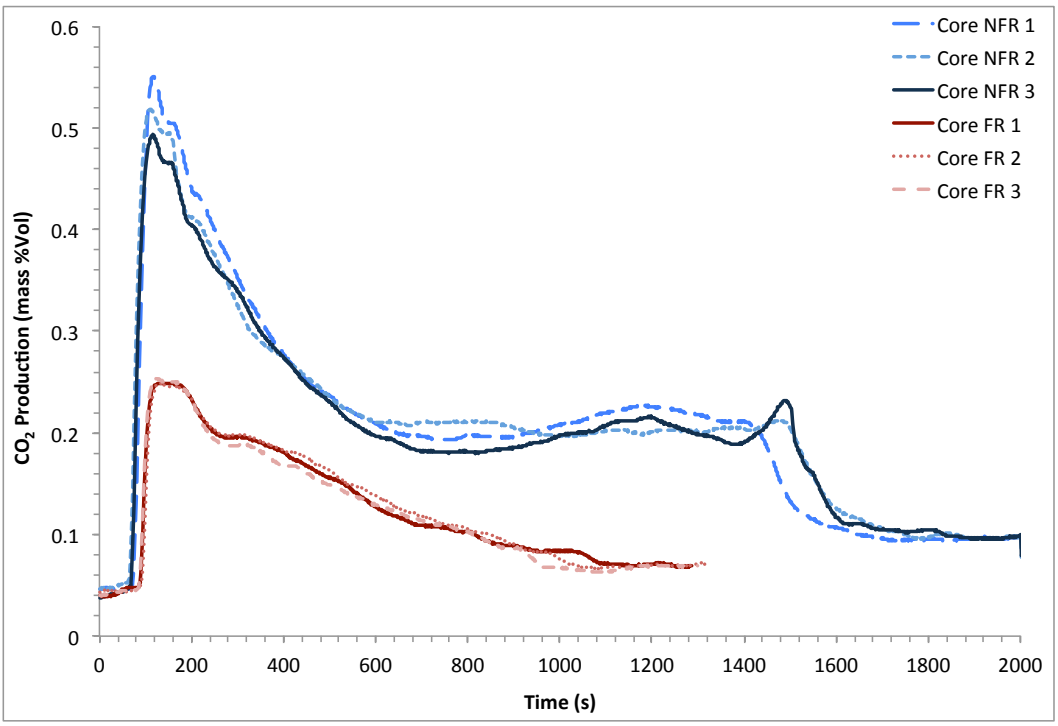


Figure 4.7: MDF core NFR and FR CO_2 production over time.

Figure 4.8 shows the differences in CO production between the core NFR and FR samples. As the HRR decreased from its peak value the CO production from the core FR samples increased significantly while the CO_2 production continued to decrease. In contrast, the production of CO from the NFR sample decreased and then leveled out, such that the ratio of CO to CO_2 production remained nearly constant during the entire open flaming period. Near the end of the test, as the sample burned out, it began to smoulder in a fashion similar to that for the FR MDF core sample and the CO production from the NFR sample increased. It reached only about 90 ppm, significantly less than the peak of 120 PPM reached during testing of the FR samples. Consistent with this are visual observations that the FR MDF core samples produced more smoke than the NFR core samples throughout the open flaming burning period. Commensurate with the increase in CO production at the end of the test, all MDF core samples smouldered for an extended period after the sustained flame died down.

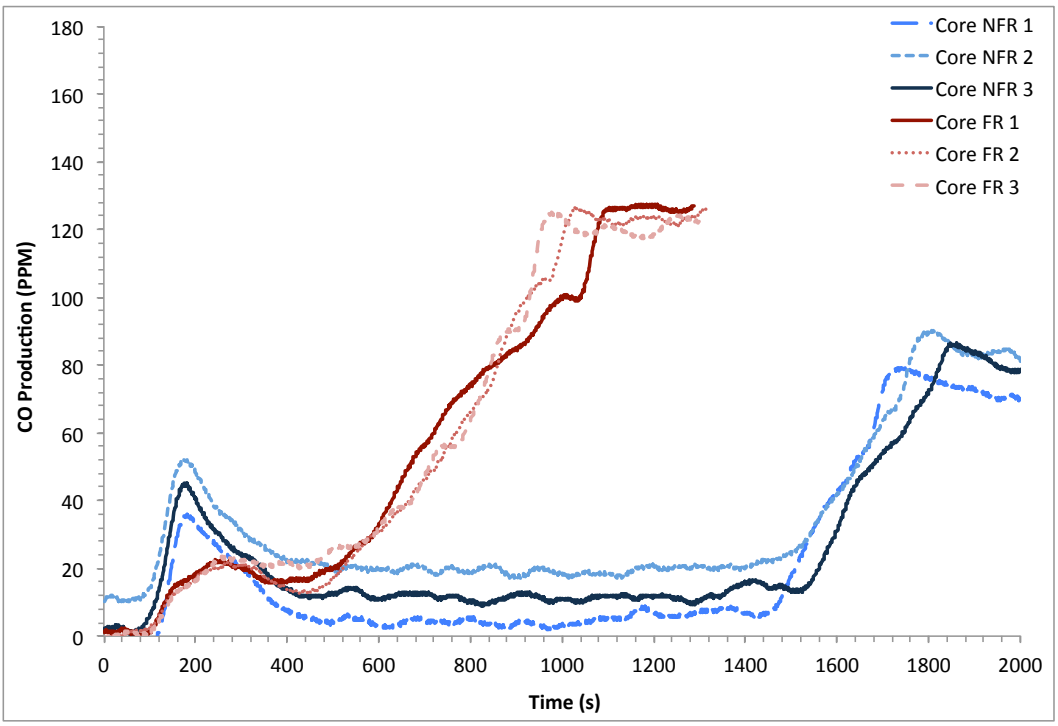


Figure 4.8: MDF core NFR and FR CO production over time.

Based on the results discussed in this section, the fire retardant additives in the MDF core material resulted in a relatively short delay in the time to ignition, but once the FR MDF core material was ignited, the FR had a significant effect on the peak and total HRR, as well as the total time for which the MDF core sustained a flame. These reductions were accompanied, however, with the production of higher levels of smoke and CO than what was measured during testing of the NFR MDF core material. Considering that these panels are intended for use as elevator paneling, the higher production of CO in such a confined space may pose an additional threat to occupants. These results point to the need for further consideration as to whether, should a fire occur, there are conditions under which adding FR to the MDF core may contribute to a more dangerous situation than having used an NFR core panel with an FR front material.

4.3 Back NFR and FR Arborite Panels

The backing component of a laminated MDF elevator panel is meant to provide further structural support to the composite assembly. The dimensional and physical characteristics of the laminate backer samples used in this study are provided below, with further specifications and manufacturer information included in Appendix C.

Table 4.9 summarizes measured values for the mass, thickness and volume of each of the Arborite samples used in the present testing. Property data for any other samples are consistent with these since all of the specimens are cut from 3' [0.91 m] by 8' [2.44 m] sheets from the same batches of material.

Table 4.9: Back NFR and FR laminates sample specifications.

Non Fire Rated Back			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Back NFR 1	9.1	0.6	6.5
Back NFR 2	8.8	0.6	6.3
Back NFR 3	8.9	0.6	6.4
Fire Rated Back			
Specimen Name	Mass (g)	Thickness (mm)	Volume (cm^3)
Back FR 1	16.9	1.2	12.1
Back FR 2	17.0	1.2	12.2
Back FR 3	17.0	1.2	12.2

From Table 4.9, it can be seen that within each set of three samples of the same backing material, there are only minor variations in thickness, and there was again less than 1% variation in density across the samples. The FR back Arborite panels are clearly thicker than the NFR variant, but in this case, and unlike the front panel samples, they are of approximately the same density, as the NFR back panels. Otherwise, since the backer samples are also from the Arborite line of products, it was expected that they would demonstrate similar fire performance as that of the front panels. Indeed, as the samples began to heat up, cracking noises are heard and these specimens began to off-gas and burn in similar fashion to that observed and discussed in Section 4.1.

4.3.1 Time to Ignition, Time to Flame Out and Sustained Flame

Time to ignition, time to flame out and the sustained flaming period for all of the samples can be found in Table 4.10. The times to ignition are fairly consistent (within 6%) across samples of the FR material, as well as between samples 1 and 2 of the NFR material. There is again a clear distinction between the time to ignition for the NFR versus the FR samples, with the FR backer samples taking over twice as long to ignite in comparison to the NFR backer panel materials except in the case of the third NFR sample which has a significantly longer time to ignition than the other NFR samples. This is most likely an

out-lier within the population sample. Once the backer panel samples did ignite, the burn time from sample to sample across samples of the same material varies 2-3% for NFR and around 20% for FR samples. Within the scatter of the data, the FR again does not appear to have an appreciable effect on the total time for which a back panel specimen sustains a flame.

Table 4.10: Back NFR and FR time to ignition, flame out and time to sustained flame.

Non Fire Rated Back			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Back NFR 1	26	127	101
Back NFR 2	29	130	91
Back NFR 3	50	149	99
Fire Rated Back			
Specimen Name	t_{ig} (s)	t_{out} (s)	t_{sust} (s)
Back FR 1	68	165	97
Back FR 2	67	154	87
Back FR 3	64	181	117

4.3.2 Heat Release Rates

Figure 4.9 shows the heat release measurements over time and Table 4.11 summarizes the peak HRR, time to peak HRR and time to peak HRR after ignition values recorded for the backer materials.

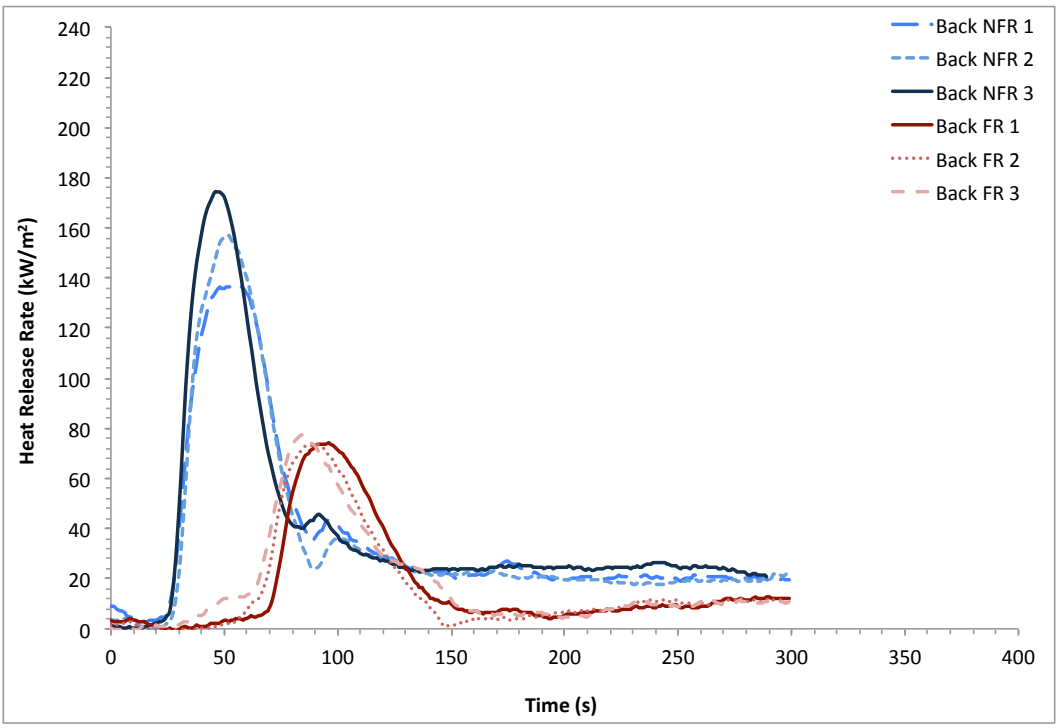


Figure 4.9: Back NFR and FR HRR over time.

Table 4.11: Back NFR and FR peak HRR, time to peak HRR and time to peak HRR after ignition.

Non Fire Rated Back			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Back NFR 1	138	56	30
Back NFR 2	152	49	20
Back NFR 3	174	47	20
Average	155	51	23
Fire Rated Back			
Specimen Name	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	$t_{q_{peak_{ig}}}$ (s)
Back FR 1	74	96	28
Back FR 2	74	91	24
Back FR 3	78	84	20
Average	75	90	24

It can be seen that the fire retardant additives again have a distinct effect on energy release from the sample over the duration of the test. Although both sets of samples reach a peak in HRR at around 24 seconds after ignition, the average peak HRR for the NFR backing material is 154kW/m^2, in contrast to only 75kW/m^2 for the FR samples. Closer examination of the HRR versus time curves for the FR back panel samples demonstrate that for several of the samples there is some energy release from the sample 10 to 20 seconds before ignition. This indicates that the sample is pyrolyzing, and that the pyrolysis gases are undergoing some oxidation during this time as well. After reaching the peak HRR, the HRR from the NFR sample decreases quickly again, but then levels off to about 25kW/m^2 for the duration of the test, though these latter values may be suspect due to a inaccuracy later found with the load cell of the cone calorimeter (see Section 4.3.3). The HRR from the FR sample, on the other hand, decreases to extremely low levels after reaching the peak value indicating that the sample smoulders until flame out occurs.

Comparison of Figure 4.9 and Figure 4.1 illustrates the shorter times to ignition for both NFR and FR backing materials in comparison to their front counterparts. The average values of peak HRR for front and back panel samples are similar, however, with a peak of 154kW/m^2 for the NFR back and 160kW/m^2 for the NFR front, in contrast to 75W/m^2 for the FR back panel samples and 72kW/m^2 for the front. This corresponds to very similar initial burning behaviour between front and back panel materials. In general, the width of the HRR peaks for the backing material are narrower than those for the front panel samples. This is consistent with the differences in density between the two materials.

Once again for these samples, not only is ignition delayed, but the total energy released from the FR samples is substantially less than that released from the NFR samples. This observation is supported by mass loss and gas concentration data discussed below.

4.3.3 Mass Loss Rate and Total Mass Loss

Figure 4.10 shows the mass loss over time plots measured for each of the back NFR and FR samples. For samples NFR 2 and 3, an apparatus error occurred at 125 seconds into the test, thus results past this time are invalid. Further information on the cause of this problem is provided in Chapter 6.

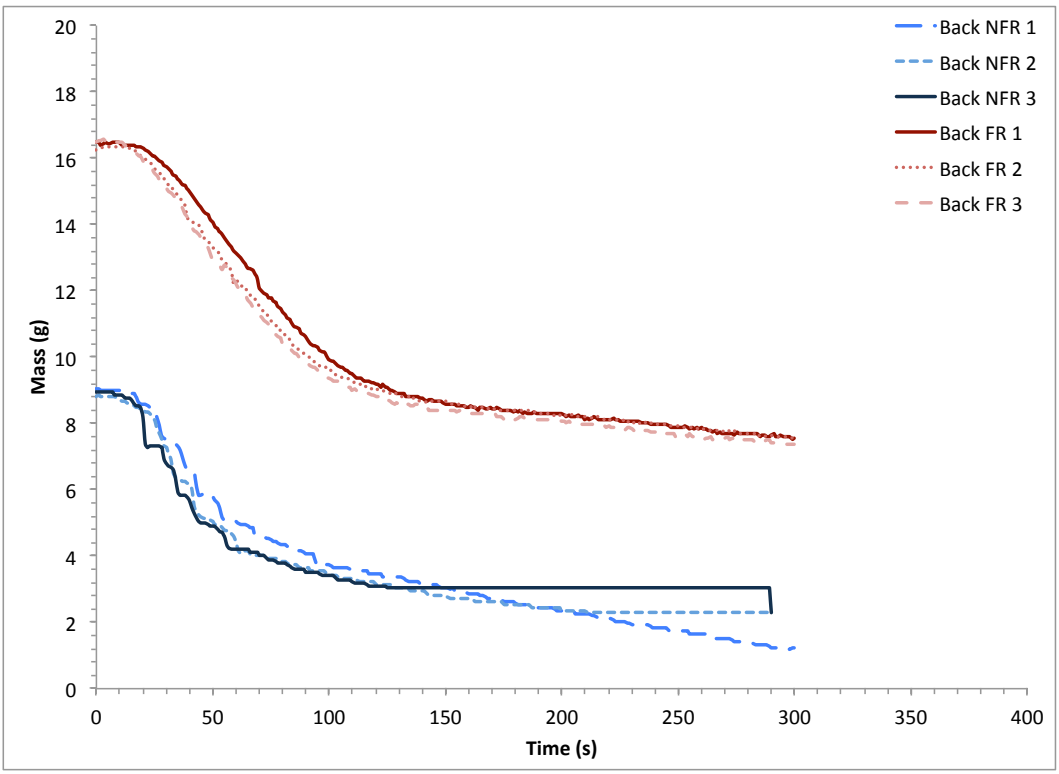


Figure 4.10: Back NFR and FR mass loss over time.

Comparison of the plots in Figure 4.10 indicates that for the first 20 seconds after exposure to the radiant heat flux, the mass of all samples changed very little, after which both NFR and FR samples decreased in mass at relatively similar rates during peak burning periods, before tailing off as the flames died down. The FR sample mass began to decrease due to off-gassing and pyrolysis before ignition of the sample, but trends in the plots of sample mass over time support differences in visual characteristics of the burning samples. Combined with the HRR plots in the previous section, it indicates that more of the NFR sample is consumed during a test than the FR sample. This is confirmed through the data in Table 4.12 which indicates that the NFR back panel samples lose up to 67% of their total mass during a test versus only 28% loss of the total mass for the FR back samples.

Table 4.12: Back NFR and FR laminates total mass loss results.

Non Fire Rated Back			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Back NFR 1	9.1	6.0	66
Back NFR 2	8.8	5.9	67
Back NFR 3	8.9	5.5	61
Fire Rated Back			
Specimen Name	Mass (g)	M_{Total} (g)	Difference (%)
Back FR 1	16.9	4.6	28
Back FR 2	17.0	3.9	23
Back FR 3	17.0	4.5	26

4.3.4 Carbon Monoxide and Carbon Dioxide Rates

Figure 4.11 and Figure 4.12 show the CO_2 and CO production rates as functions of time, respectively, for both the NFR and FR backing panels of the laminate. Trends in the CO_2 concentration over time are similar to those seen for the front panel materials and again follow those plotted in Figure 4.9 as expected. For the backing materials it does not appear that significant CO_2 is produced before ignition for either the NFR or FR samples. The overall trends in CO production are also similar to those seen during testing of the front panel materials. Notably, similar to results for CO_2 generation above, it appears that there is little CO produced by the backing materials before ignition, particularly for the FR samples.

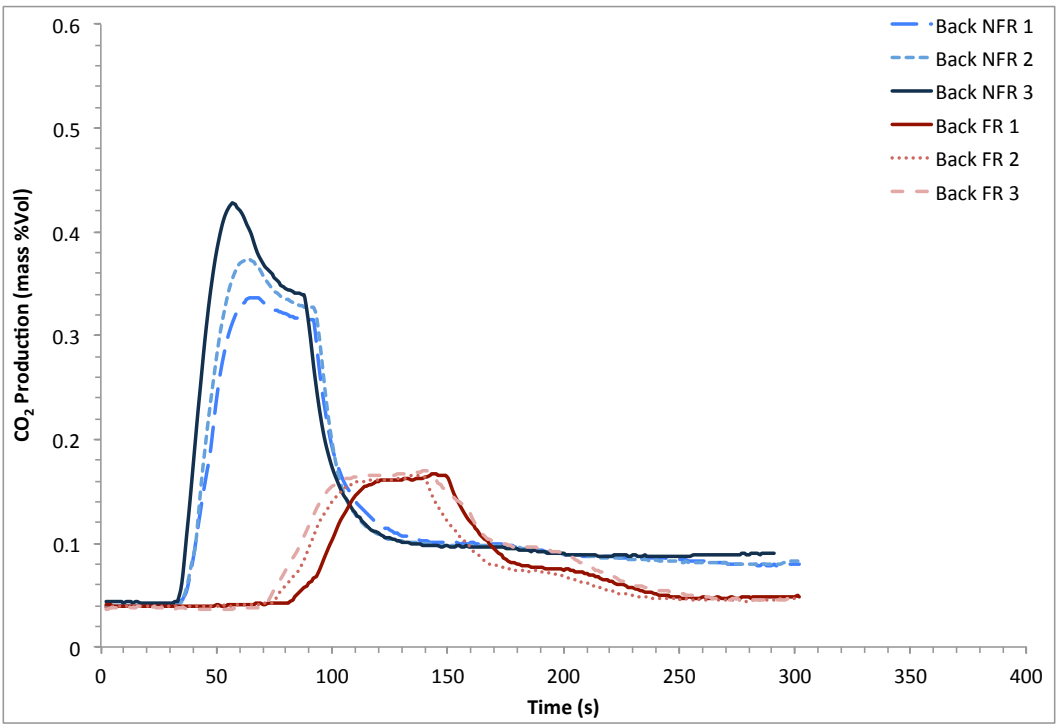


Figure 4.11: Back NFR and FR CO_2 production over time.

As the samples ignited and burned, and the HRR decreased from its peak value, CO production for the FR back panel samples increased significantly while the CO_2 production appears to level off. In contrast, the production of CO for the NFR samples dips and then began to increase again as the sample started to smoulder. Overall, the CO production rates for the back FR samples are higher than those for the NFR samples both during and after the flaming period, reaching peak values of 80 - 95 ppm during burning. Consistent with this are visual observations that the FR back panel samples produced more smoke than the NFR core samples throughout the open flaming burning period. Commensurate with the increase in CO production at the end of the test, all back panel samples smouldered for an extended period after the sustained flame died down.

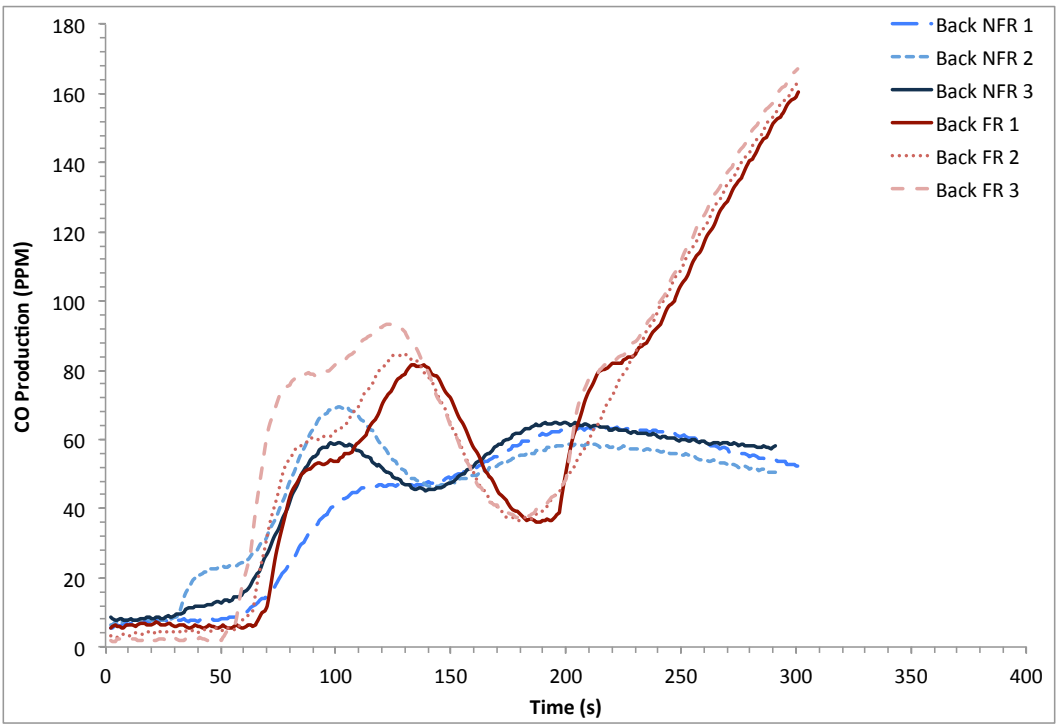


Figure 4.12: Back NFR and FR CO production over time.

Based on the results discussed in this section, it appears that the fire retardant additives in the back panel materials resulted in a short delay in the time to ignition, but once the FR backing material was ignited, the FR had a significant effect on the peak and total HRR, as well as the total time for which the material sustained a flame. These reductions were accompanied, however, with the production of higher levels of smoke and CO than were measured during testing of the NFR back panel material.

4.4 Permagrip PG107

The final individual component in a laminated elevator panel assembly is the adhesive that is used to attach the front and back panel materials to the MDF core. In the present study the adhesive used is Permagrip PG107 which is listed as a flammable material by the manufacturer [33].

While it was understood that the Cone Calorimeter is not a testing apparatus intended for this use [3], a preliminary round of testing was conducted using the cone calorimeter to expose samples of the adhesive to a known, constant incident heat flux in order to gain some understanding of the fire performance characteristics of this component. For this,

the Permagrip PG107 adhesive was sprayed in a thin layer onto a sheet of stainless steel measuring 100mm by 100mm as shown in Figure 4.13 and exposed to an incident flux of 50 kW/m^2. A typical image of the glue under test is shown in Figure 4.15.

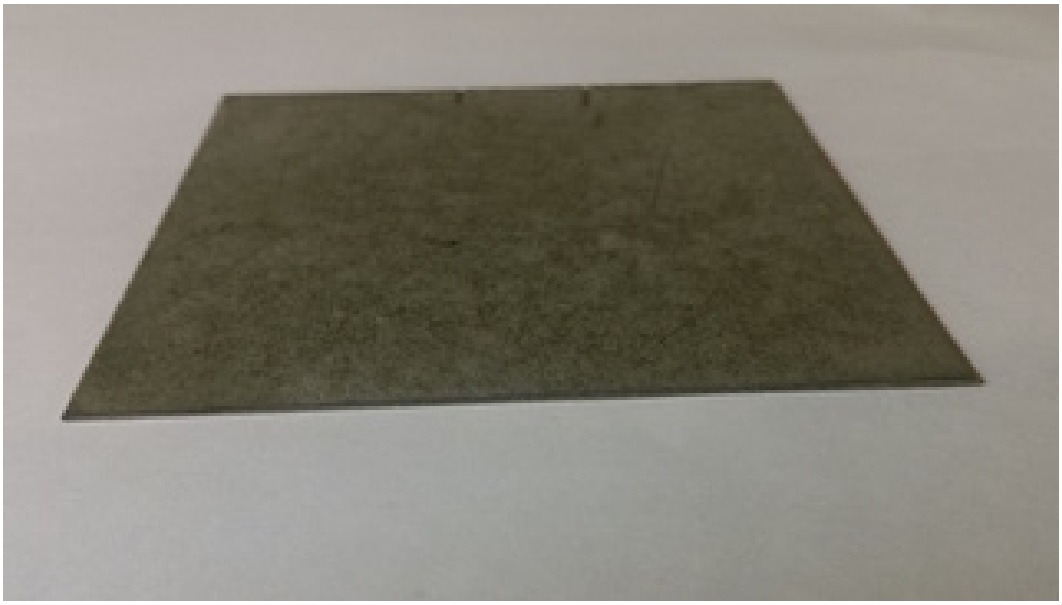


Figure 4.13: Permagrip PG107 sprayed on a stainless steel sheet.

During testing, it proved difficult to control the amount of glue sprayed onto each sheet which meant that the quantity of glue used in each test could not be determined. Nonetheless, the results from four repeated tests do highlight some important characteristics of the glue which are summarized in Table 4.13 and Figure 4.14.

It can be seen from Table 4.13 that in three of the four samples tested, the glue ignited in between 60 and 75 seconds after exposure and burns out approximately 25 seconds after ignition. Both Table 4.13 and Figure 4.14 indicate that the time to peak HRR is approximately 15 seconds after ignition, but measured values of peak HRR vary significantly from sample to sample, ranging from 39 kW/m^2 to 61 kW/m^2. These differences are most likely due to differing amounts of glue being used in the test, as well as variations in the heat losses through conduction and radiation to the metal substrate. As such, while an indicator of the energy that could be released by a layer of glue, these samples are subject to significantly higher heat loss.

Table 4.13: Key cone calorimeter testing results for Permagrip PG107 glue.

Permagrip PG107					
Specimen Name	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Flare (s)
Glue 1	N/A	N/A	N/A	N/A	96, 99, 101, 102, 104
Glue 2	75	103	38.84	90	72
Glue 3	62	100	49.27	78	N/A
Glue 4	57	82	60.65	72	N/A

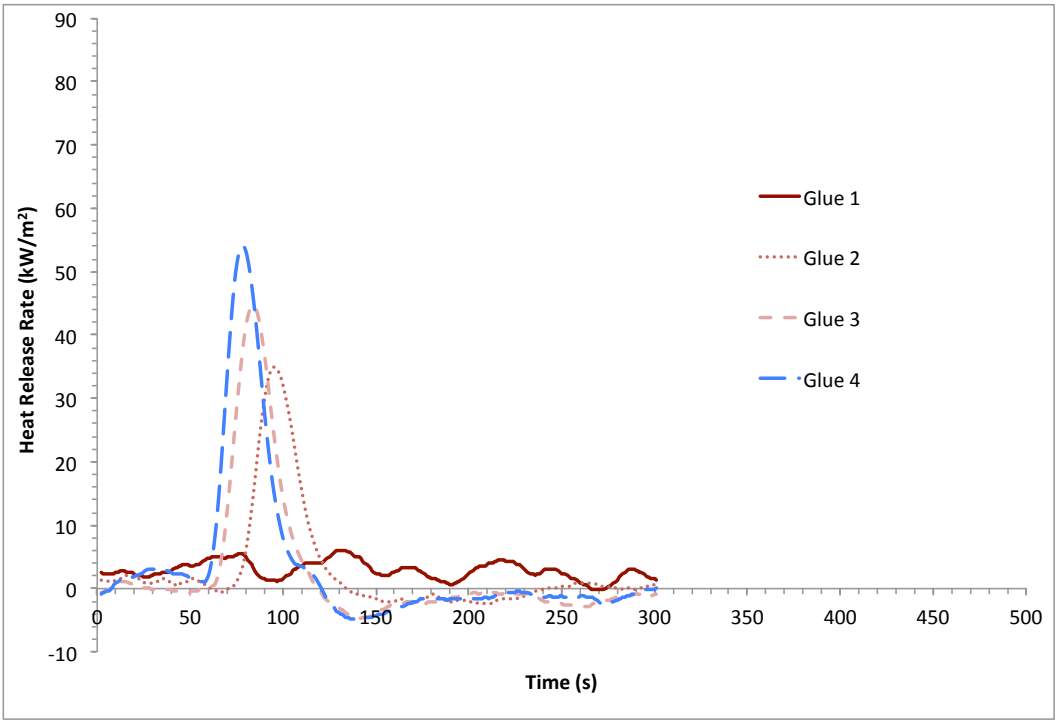


Figure 4.14: Permagrip PG107 HRR over time.



Figure 4.15: Permagrip PG107 igniting under the cone calorimeter.

At this stage in the research, each of the components in a typical laminated elevator panel, in both NFR and FR variants, had been tested individually using the cone calorimeter to investigate key aspects of their fire performance. The next stage in the research was to test these components layered together with or without glue. First, the components were layered without glue in order to study the fire performance of an un-glued assembly when heat is applied to the front panel material and transferred through to the MDF core, and then to the backing material. For this, the matrix of combinations of NFR and FR components outlined in Table 3.2 were used to construct the assembly. Finally, this matrix of tests was repeated for the same components constructed into fully glued assemblies. The results of these test series are presented and discussed in the following chapters.

Chapter 5

Laminated MDF Panel Testing Results

5.1 Laminated MDF Panel (Un-glued)

Research outlined in the previous chapter was aimed towards investigation of the impacts of FR additives on the fire performance of each component of a laminated MDF core panel. The results form the basis for this section, in which the FR and NFR variants of each panel material are combined into eight different assemblies as shown in Figure 5.1. While there is research on the performance of many individual materials under exposure to radiative flux in a cone calorimeter, more research is required into how a multi-layered MDF core assembly responds under similar conditions during testing. This section deals with layered panel assemblies that are not glued together; the examination is extended in the next section to similar glued assemblies.

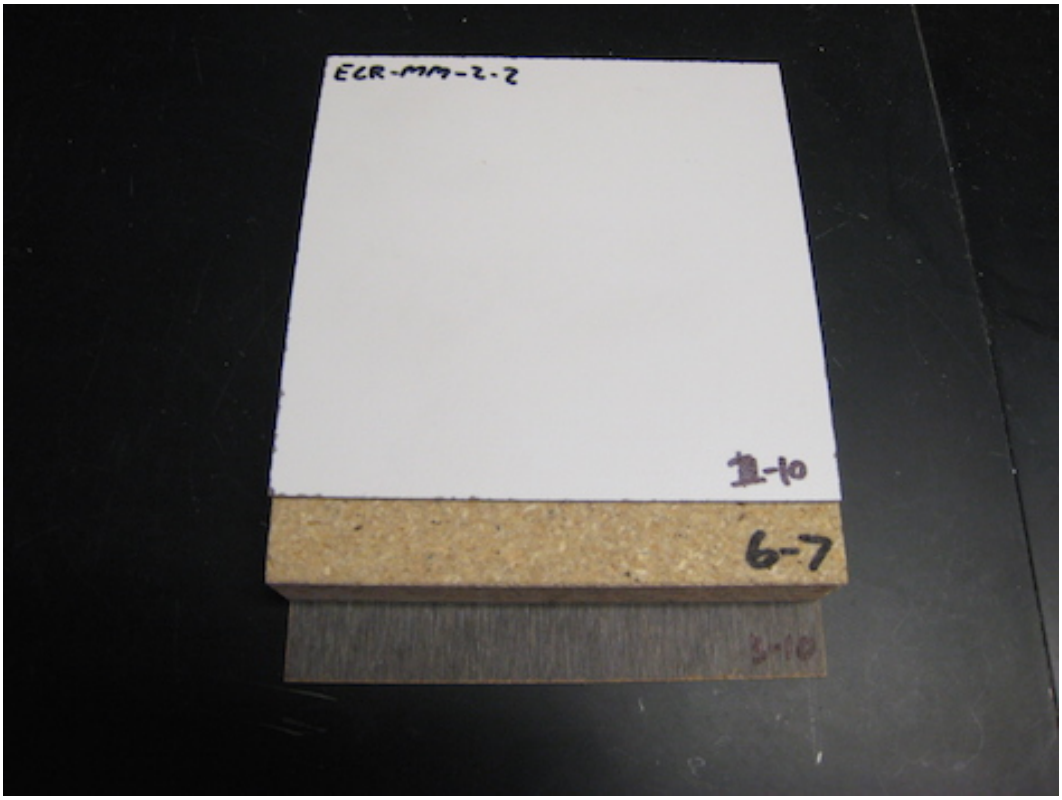


Figure 5.1: Laminated panel assembly (un-glued).

Eight different assemblies were constructed using different combinations of FR and NFR front, core and backing layers. The various assembly specimens were labeled according to the nature of the front-core-backing layers. For example an FR-NFR-NFR assembly consisted of an FR front layer, an NFR MDF core material and an NFR backing layer, respectively. In the results presented here, three specimens of each of the combinations were tested, except for the case of NFR-FR-NFR assembly for which only two specimens were available. Table 5.1 shows results for the time to ignition, time to flame out, peak HRR, time to peak HRR and percent mass loss for each sample, as well as the average values for each assembly. In the table, the data are split into two groups according to whether or not the front panel material contained a fire retardant additive. Each group is further subdivided for changes in the backing and core materials.

Table 5.1: Laminated MDF assembly testing results (un-glued).

Non Fire Retarded Front Panel Samples						
Specimen Type	Test #	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-NFR-NFR	Test-1	42	2184	157.2	57	82
	Test-2	45	2446	146.7	68	77
	Test-3	45	2636	147.2	57	78
	Average	**44**	**2422**	**150.4**	**61**	**79**
NFR-NFR-FR	Test-1	53	2170	156.2	84	75
	Test-2	56	2151	169.3	75	75
	Test-3	47	2131	155.0	61	74
	Average	**52**	**2141**	**162.2**	**68**	**75**
NFR-FR-FR	Test-1	69	2702	131.8	92	63
	Test-2	56	2691	127.4	65	63
	Test-3	53	2613	136.7	69	62
	Average	**59**	**2669**	**132**	**75**	**63**
NFR-FR-NFR	Test-1	60	2873	116.2	78	65
	Test-2	46	3035	164.5	60	70
	Average	**53**	**2954**	**140.2**	**69**	**68**
Fire Retarded Front Panel Samples						
Specimen Type	Test #	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
FR-FR-FR	Test-1	123	3100*	92.1	288	62
	Test-2	105	3100*	71.3	313	62
	Test-3	96	3100*	98.9	275	61
	Average	**108**	**3100***	**87.5**	**292**	**62**
*Samples did not flame out, test ended manually						
FR-NFR-NFR	Test-1	101	2770	155.3	280	76
	Test-2	115	2783	177.8	295	75
	Test-3	74	2527	176.7	333	75
	Average	**97**	**2693**	**169.9**	**302**	**75**
FR-NFR-FR	Test-1	120	2660	138.1	235	71
	Test-2	112	2697	136.7	259	71
	Test-3	98	2650	137.5	246	71
	Average	**110**	**2669**	**137.4**	**246**	**71**
FR-FR-NFR	Test-1	90	2963	69.4	261	65
	Test-2	80	2947	82.3	448	65
	Test-3	56	2833	71.5	420	65
	Average	**75**	**2914**	**74.4**	**376**	**65**

Comparison of the upper and lower halves of Table 5.1 illustrates that there are distinct differences in fire behaviour between assemblies that are fully non-fire retarded (NFR-NFR-NFR) versus fully fire retarded (FR-FR-FR). All samples assembled with NFR front panels demonstrated noticeable differences in time to ignition and several of the other key indicators of fire performance over their FR equivalents. In general, results are consistent with the observations for the individual materials discussed in Chapter 4, where the FR components demonstrated better fire performance characteristics than the NFR versions. A more detailed analysis of these differences is provided in the sections below.

5.1.1 FR-FR-FR vs NFR-NFR-NFR (Un-glued)

Comparison of the data presented in the top row of each section of Table 5.1 and plotted in Figure 5.2 shows the distinct differences in behaviour between the full NFR and FR assembly specimens. First, the FR assembly took on average 108 seconds, or more than twice as long, to ignite than the full NFR assembly which took 44 seconds on average. Furthermore, the average peak heat release rate for the NFR assembly was 150.4kW/m^2 and occurred at only 17 seconds after ignition of the sample. In contrast, the average peak HRR for the FR assembly was 87.5kW/m^2 and occurred at a significantly longer time, 184 seconds after ignition of the sample.

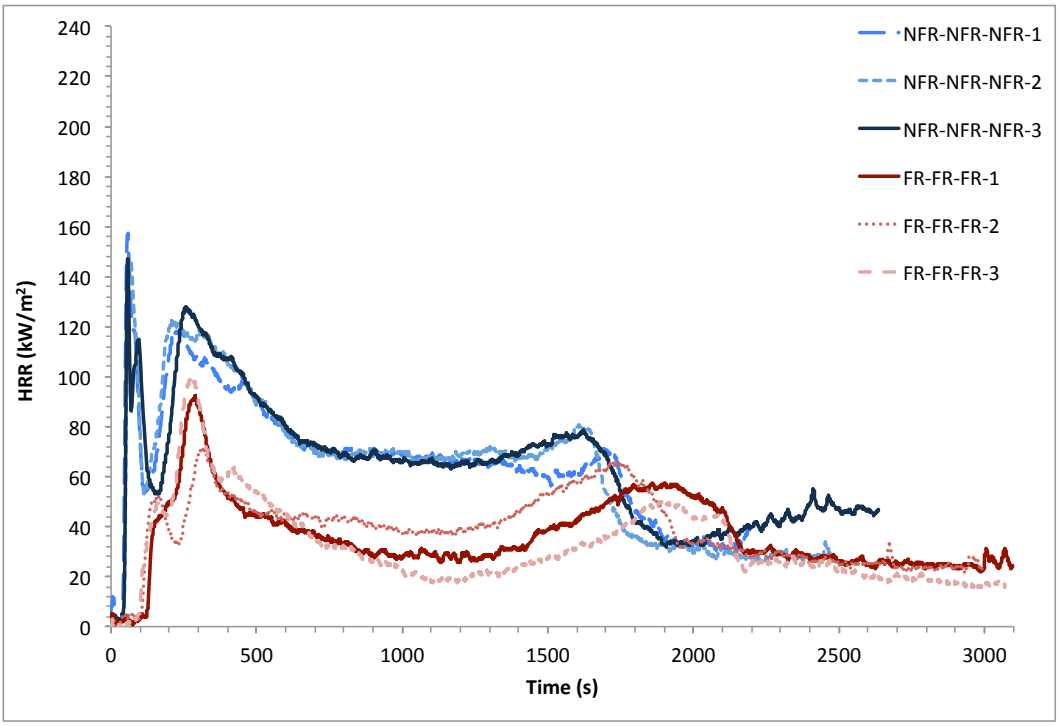


Figure 5.2: Full NFR and FR panel assemblies (un-glued) HRR over time.

The plots of HRR versus time contained in Figure 5.2 provide a more detailed explanation of the burning behaviour of the two assemblies. As can be seen from the figure, the NFR assembly exhibited a pronounced double-peak in HRR in the early stages of the test, followed by a long period of relatively steady HRR, ending with a slight shoulder before the sample flames out and a final smouldering phase begins. The observed time history of HRR is indicative of the assembly burning layer by layer. The initial peak value of HRR, 150kW/m^2, aligns well with values measured for peak HRR of NFR front panel materials (Section 4.1), suggesting the mode and intensity of burning of this layer is comparable in both sets of tests. The second peak in HRR, along with its subsequent steady burning period, is very similar to the behaviour seen during cone calorimeter testing of the NFR MDF core samples. Peak values of HRR for the NFR core in the assembly (125 kW/m^2) are lower than those seen for the same material tested individually (292 kW/m^2). This is most likely a result of changes in heat transfer and reduced availability of air when the core burns as part of a three-layer assembly. It is worth noting that there was no marked transition between the burning of the NFR core and the backing material so there is no notable increase in HRR when the backer begins to burn. Rather, the HRR passes through a shoulder and decreases in the final stage of the test.

In contrast, two peaks in HRR were not seen in two of the three full FR assembly tests. Instead, initially there was a marked shoulder on the HRR versus time plot, followed by a peak that was not only lower than the peak seen for the NFR assembly, but this peak also occurred at a much later time after ignition when compared to initial peak in HRR for the NFR laminate. Following this, the burning behaviour was quite similar to that of the NFR assembly, with the long steady burning phase and shoulder just before flame out. The peak HRR in these tests more likely corresponded to the initial stages of burning of the FR MDF core material than that of the FR front sheet. This is also supported by the comparable values observed in the assembly tests here and the peaks seen in Figure 4.5 for tests on each individual material. After the initial peak in HRR for the FR samples, green flames were observed, indicating the presence of the FR additives. These additives clearly affected the combustion process since the HRR of the FR sample quickly decreased from its peak value, after which it burns less intensely than the NFR assembly for an extended period of time. In fact, although the NFR assemblies flamed out in between 2100 and 2600 seconds, the tests for all FR assemblies are manually ended after 3100 seconds because the flames do not completely disappeared and the Drierite filter on the cone calorimeter could have became saturated with water.

The rate of mass loss is plotted as a function of time in Figure 5.3 for both the fully NFR and fully FR assemblies. The mass loss rate curves support the observations that the assemblies burned from the front panel through to the backing layer fairly consistently, with no evidence of unexpected behaviour. The several small changes in the slope of

the mass loss rate graphs align with the times at which the assembly ignited and burned through the front panel, followed by the long, fairly steady combustion phase as the core MDF material burned, and finally changing again as the final MDF and backing material burned through. Flame out then occurred and there was a transition to smouldering until the end of the test.

From the last column in Table 5.1, it is clear that the total percent mass loss was more for the fully NFR sample than for the FR assembly, with 79% mass lost for the NFR assembly and 62% for the FR equivalent. For the NFR sample, this value was very similar to what was previously determined to be the total mass loss for the MDF core material alone (both the front and back panels showed lower overall mass loss in Chapter 4). For the FR assembly, the total mass loss during the assembly tests was slightly higher than the values previously seen for any of the individual materials (25-30% for front and back panel materials and 50% for the MDF core, respectively.) This again suggests that the burning behaviour of a laminated assembly can be affected by the local heat losses and ventilation conditions affecting each layer as it burns.

Comparison across all values in Table 5.1 indicates that, as expected on a mass averaged basis, it is generally the nature of the MDF core which governs the overall mass loss of the assembly. For the NFR core samples, the average mass loss is 75% while for the FR MDF core samples it was around 63%, with up to 40 percent of the mass of the original sample left behind as char.

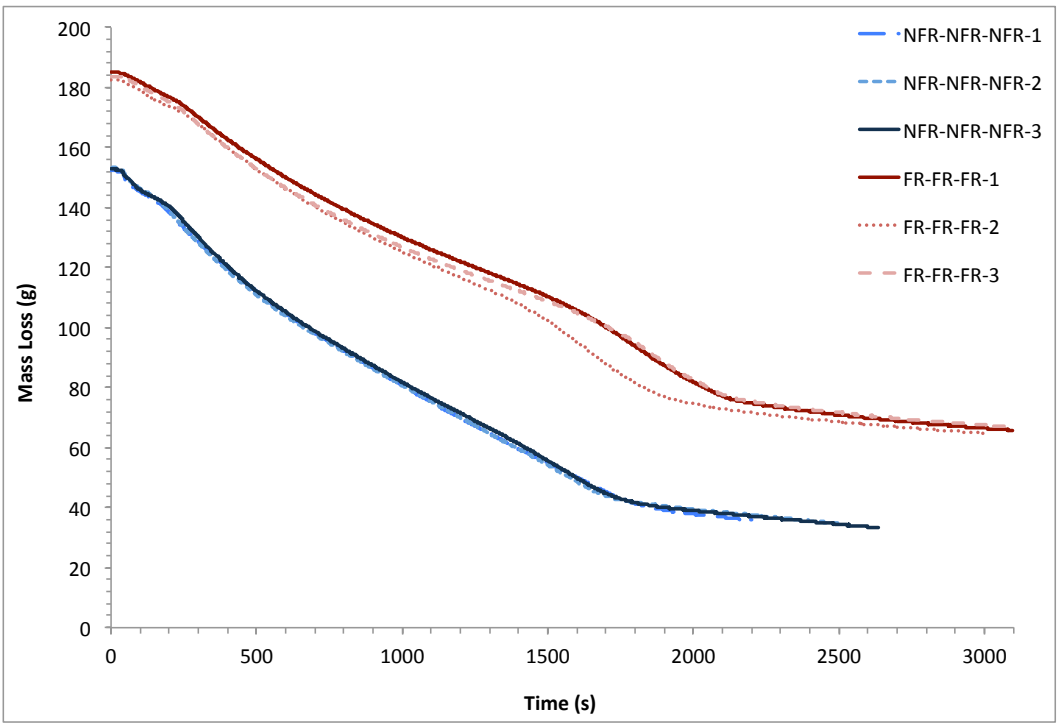


Figure 5.3: Full NFR and FR panel assemblies (un-glued) mass loss rate over time.

The amount of CO produced during testing of both the NFR and the FR assemblies was consistent with the differences in HRR discussed above. This is illustrated in Figure 5.4. Considerably more CO was produced for the FR samples than was measured for the NFR assembly during the initial period leading to their respective peak HRRs, with significantly higher amounts of CO produced for the FR samples throughout the extended burning phase. As is observed during testing of the individual MDF core samples, after the somewhat steady burning period, there was a final sharp increase in CO being produced as the samples began to smoulder towards the end of the test.

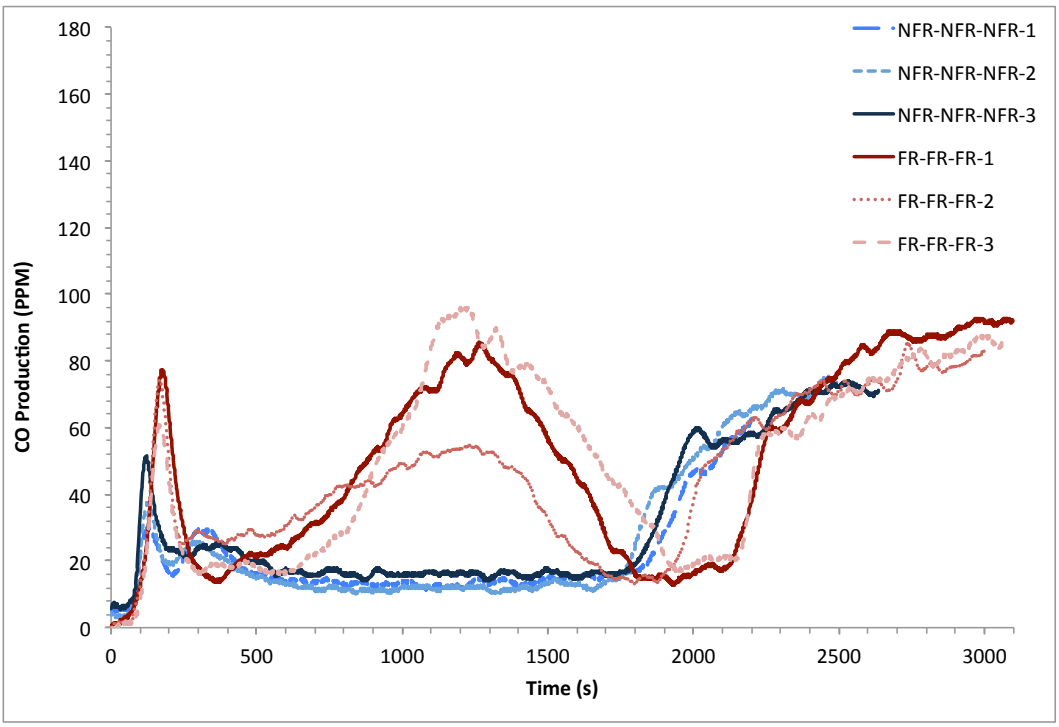


Figure 5.4: Full NFR and FR panel assemblies (un-glued) CO production over time.

While the above discussion points out distinct variations in behaviour between fully NFR and fully FR laminated assemblies, it is also of interest to understand the importance of using FR variants in different combinations within the same assembly. To gain this insight, the impact of FR addition on each layer of such assemblies is discussed in the following sections.

5.1.2 The Effect of Front Panel Type on Fire Performance (Un-glued)

This section pertains to the performance of assemblies that are constructed using a FR front panel in comparison to those with no fire retardant in the front panel. To understand this investigation, a comparison is made between assemblies with different front variants (FR vs NFR), while keeping the core and back materials constant. The time to ignition, time to flame out, peak HRR, time to peak HRR and mass loss for testing of the comparative assemblies are contained in the upper and lower sections of Table 5.1 respectively and repeated in Table 5.2

Table 5.2: Comparison of NFR vs FR front effect on laminated panel assembly (un-glued).

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-NFR-NFR	44	2422	150.4	61	79
NFR-FR-FR	59	2696	132	75	63
FR-NFR-NFR	97	2693	169.9	302	75
FR-FR-FR	108	3100	87.5	292	62

As can be seen from Table 5.1, all samples with an NFR front panel exhibited low times to ignition; on average 44 and 59 seconds for the two sets of samples. In contrast, assemblies with FR front panels took much longer to ignite - between 96 and 108 seconds on average. The difference is further demonstrated in the HRR versus time plot for the two extreme combinations, NFR-FR-FR and FR-NFR-NFR, shown in Figure 5.5*. Evident from Figure 5.5, regardless of the core and back material, the time to ignition is longer for samples with an FR front panel. Both assemblies with an NFR front panel exhibit the characteristic peaks in HRR seen previously for samples with NFR front panel materials, although the value of the peak HRR is around 12% lower for the NFR-FR-FR assembly than that for the fully NFR laminate. Similar HRR peaks were not seen for either of the assemblies with FR front panel materials, for which the peak HRR occurred as the core materials began to burn.

Other differences in behaviour were seen depending on the nature of the core material in the assembly as well. In the case where an NFR front panel was over an NFR core, a double peak in HRR was seen as described in Section 5.1.1 above. When the same NFR front panel is over a FR core, the expected peak in HRR due to the NFR front material was observed, but this was followed by much lower values of HRR due to subsequent combustion of the FR core and backer materials. In contrast, while a fully FR assembly was characterized by very low HRR throughout the test, if an FR front panel is coupled to an NFR core, after ignition of the front panel, the HRR grew steadily and the peak value appeared to be typical of those seen during testing of an NFR core alone.

*For clarity, the average of the HRR measurements is used in this plot and the x-axis is scaled to show only the first 1000 seconds of the test

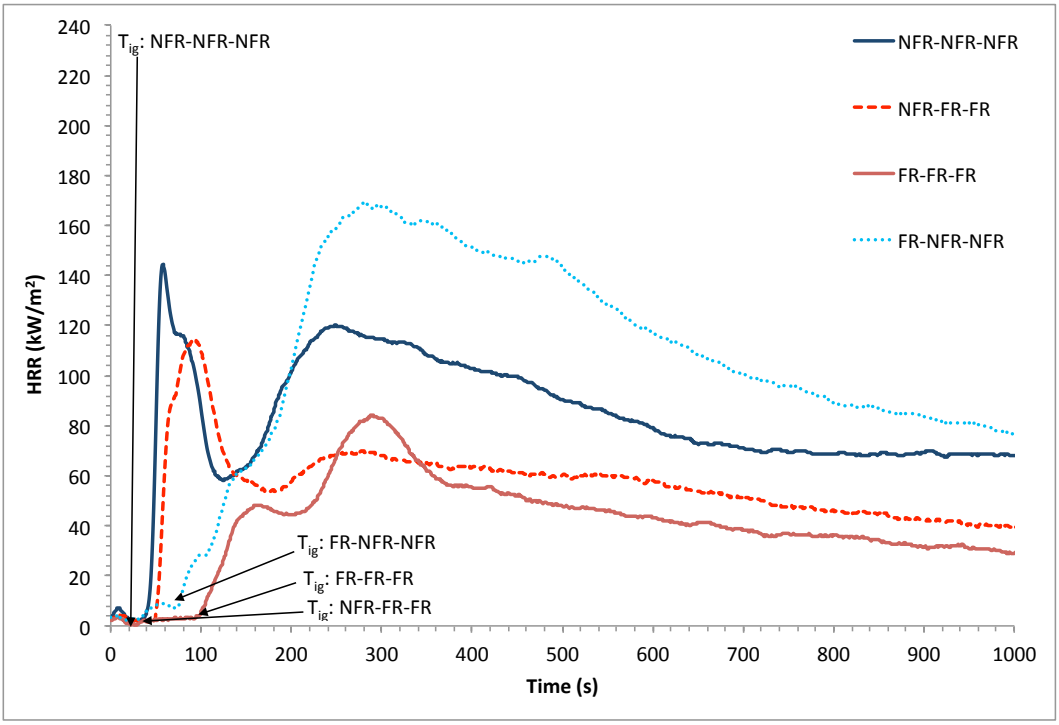


Figure 5.5: Effect of NFR and FR front on time to ignition within the panel assembly (un-glued).

In general, these results indicate that for assemblies with an NFR front panel, the peak HRR arose from combustion of that panel, whereas, when an FR front panel is used, the peak HRR resulted from combustion of the core. Evolution of mass loss and CO production, shown in Figure 5.6, are consistent with the trends in HRR as well.

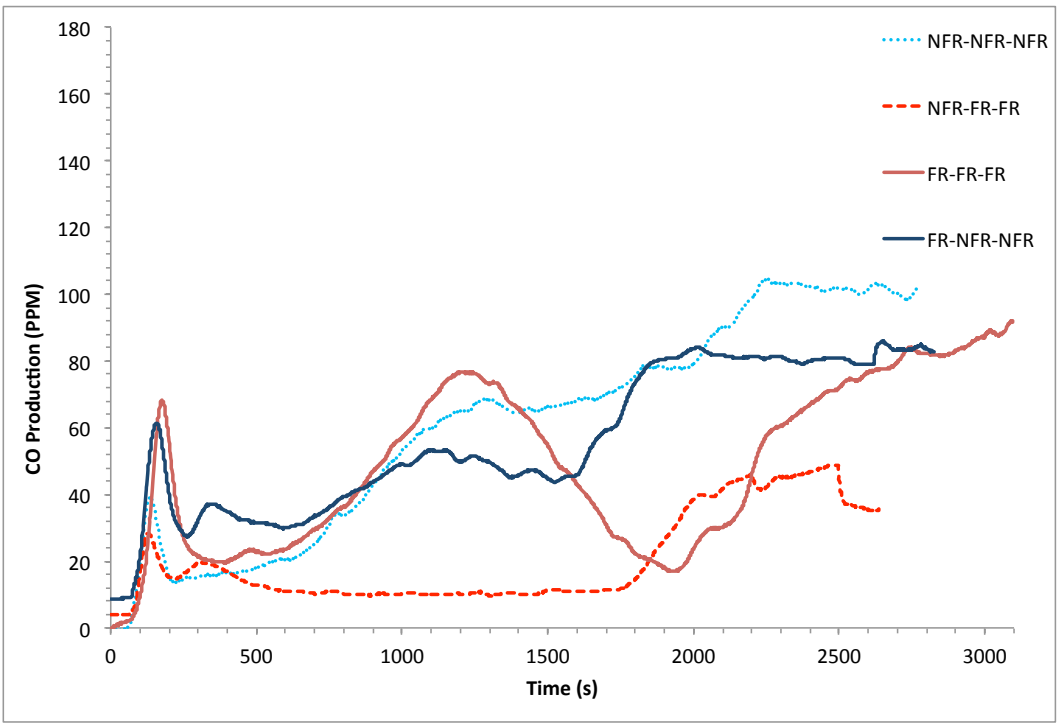


Figure 5.6: Effect of NFR and FR front on CO production within panel assembly (unglued).

5.1.3 The Effect of Core Panel Type on Fire Performance (Unglued)

The type of core used in the assembly has been demonstrated above to exert a noticeable impact on the overall fire performance of the laminated panel assemblies. To investigate this further, the results from fully NFR assemblies (NFR-NFR-NFR) were compared to those with NFR front and back panels, but with a FR core layer. Similarly the fire performance of fully FR (FR-FR-FR) panel assemblies was contrasted with that of assemblies having FR front and back panels with NFR core material (FR-NFR-FR). Results for average values of time to ignition and related parameters are contained in Table 5.3, while the evolution of HRR over time for the four assemblies is plotted in Figure 5.8.

Table 5.3: Comparison of NFR vs FR core effect on laminated panel assembly (un-glued).

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-FR-NFR	58	1181	137.9	87	60
NFR-NFR-NFR	44	2422	150.4	61	79
FR-FR-FR	108	3100	87.5	292	62
FR-NFR-FR	110	2669	137.4	246	71

From Table 5.3 and Figure 5.8 it is clear that there was only a very small delay in ignition between a fully NFR panel and an NFR panel with an FR core. For the FR panels with NFR versus FR core layers, on the other hand, there was no discernible difference in the time to ignition indicating that the FR front layer is the determining factor in ignition for those assemblies. The differences between the two situations is more evident upon examination of the HRR results plotted in Figure 5.7.

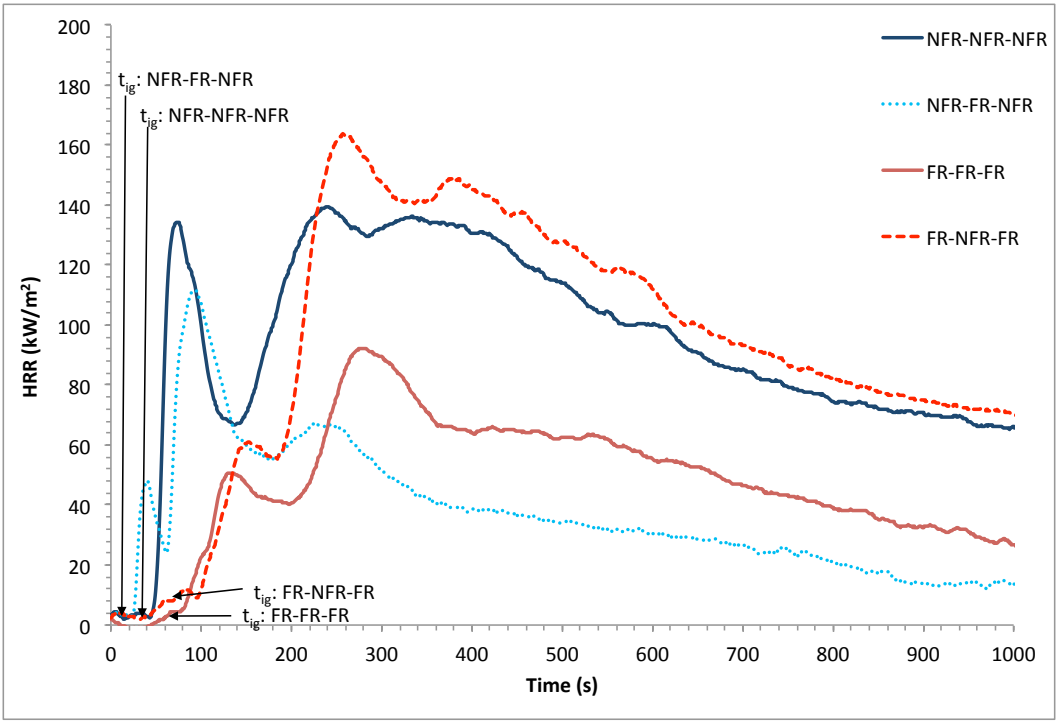


Figure 5.7: Effect of NFR and FR core on time to ignition within the panel assembly (un-glued).

As anticipated from the discussion in Section 5.1.2 above, in both cases when an NFR front panel was used there was a double peak in the HRR-time curve, the first shortly after

ignition of the front panel and the second at a later time aligned with ignition of the MDF core material. From the Figure 5.7, it can be seen that, in addition to the slight delay in ignition noted above, there was also a difference in the slopes of the early HRR curves between the NFR assemblies with NFR versus FR core materials. This led to the panel with the FR core to take longer time to reach its peak HRR. Further and consistent with previous observations, the value of both the initial and secondary peak HRRs, as well as the HRR during steady burning, is lower for the sample with an FR core in comparison to samples with NFR front panel materials.

Conversely when a FR front panel was used in the assembly, there is no initial peak in HRR and instead the peak HRR occurs at a much later time after ignition as the MDF core begins to burn. The type of core then determined the HRR after the peak, with the FR core demonstrating consistently lower values of HRR than the NFR core throughout the remainder of the test.

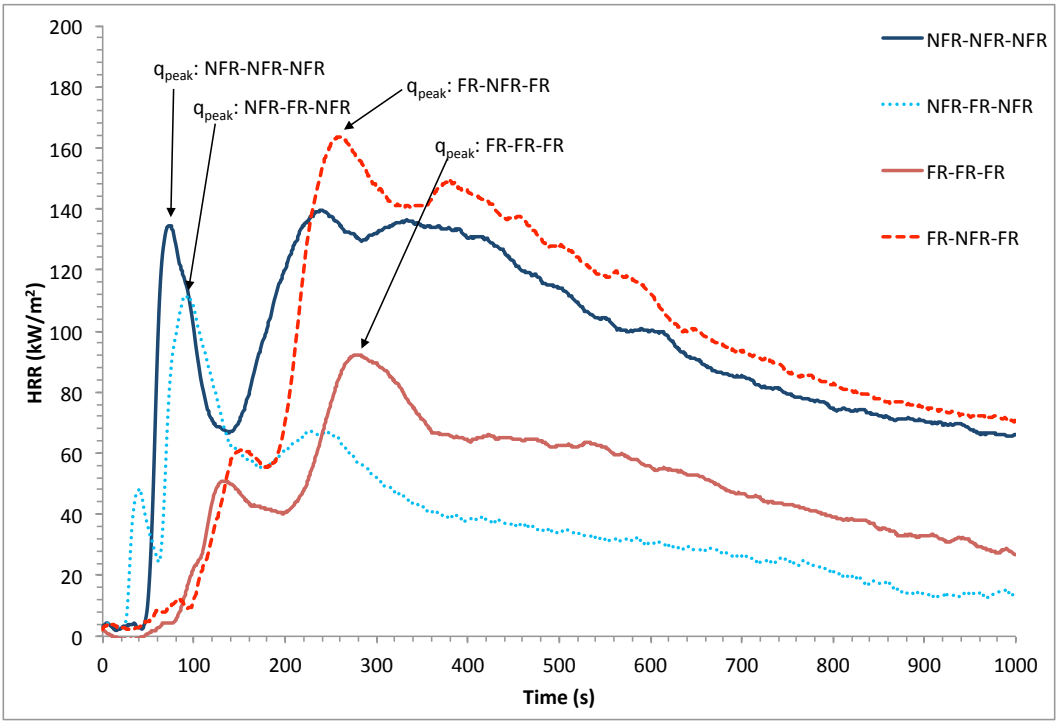


Figure 5.8: Effect of NFR and FR core on peak HRR within the panel assembly (un-glued).

The effect of FR additives in each layer used in the laminated assembly can also be seen in the measured values of CO from the samples as tested under the cone calorimeter and plotted in Figure 5.9. During testing of the individual materials, FR samples produced more CO than their NFR variants. For the four assemblies discussed in this section, the initial peaks and valleys in CO production with time aligned with the type of front

panel and further, the type of core can be identified by observing the CO measurements taken during the period of sustained combustion. There was a clear and consistent difference between samples with FR and NFR panel and MDF core materials consistent with observations in Section 5.1.2 above.

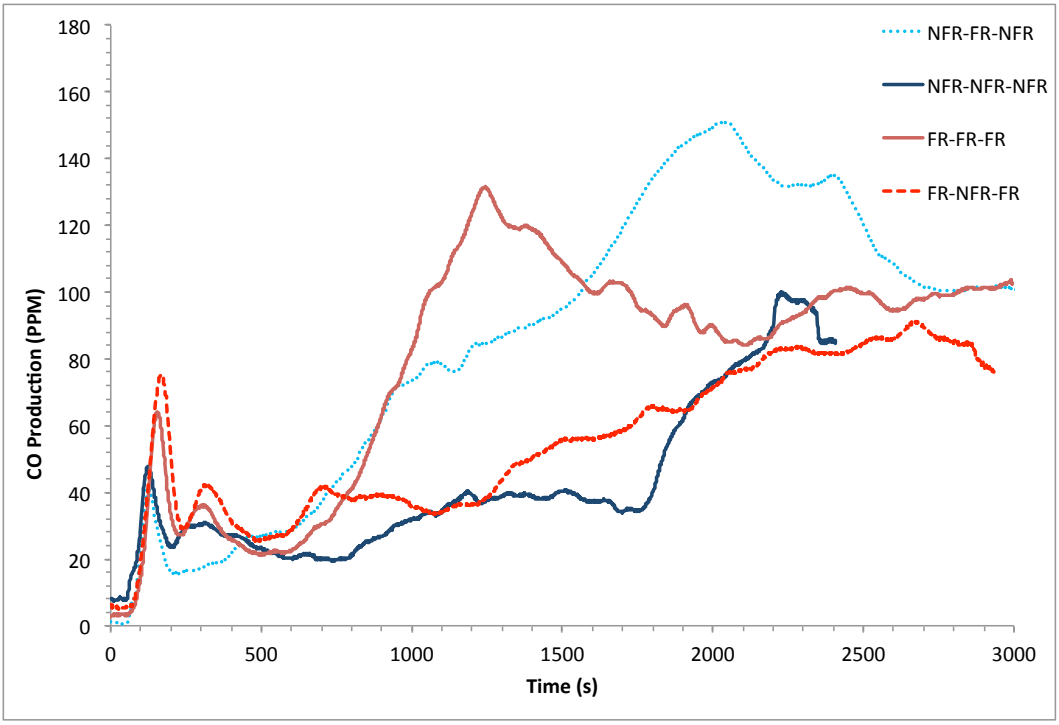


Figure 5.9: Effect of NFR and FR core on CO production within the panel assembly (un-glued).

5.1.4 The Effect of Backing Panel Type on Fire Performance (Un-glued)

It has been demonstrated that the front and core materials have a noticeable effect on the fire performance of a laminated panel. Using the same methodology that was used to study the effect of front and core materials on fire behaviour, the effect of NFR versus FR back panel materials was determined by comparing the NFR-NFR-NFR and NFR-NFR-FR average test results, as well as the FR-FR-FR and FR-FR-NFR data. These are summarized in Table 5.4, with the evolution of HRR over time plotted in Figure 5.10.

Table 5.4: Comparison of NFR vs FR back effect on the laminated panel assembly (un-glued).

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-NFR-NFR	44	2422	150.4	61	79
NFR-NFR-FR	51	2141	162.2	68	75
FR-FR-FR	108	3100	87.5	292	62
FR-FR-NFR	75	2914	74.4	376	65

From the data presented, there is little evidence of the effect of using a different backing material on the fire performance of the laminated panel assembly. The time to ignition, sustained flame period and smouldering/flame out phases are very similar, as are the time evolution of HRR and CO generation, suggesting the nature of the backing material has little influence on the overall burning behaviour of the assembly. This is because the backing is the bottom material in the laminated assembly in the current test set up, and the mass of the core material is much larger than that of the back material. As a result, any effect of including a FR in the backing material cannot be discerned.

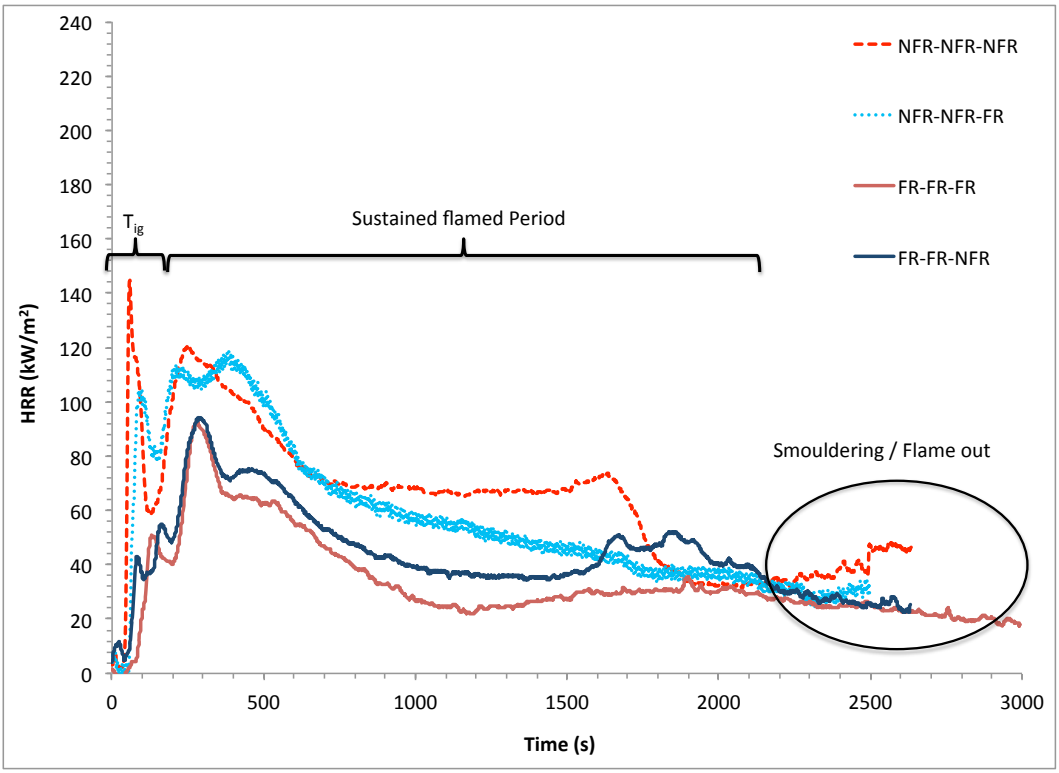


Figure 5.10: Effect of NFR and FR back on HRR within the panel assembly (un-glued).

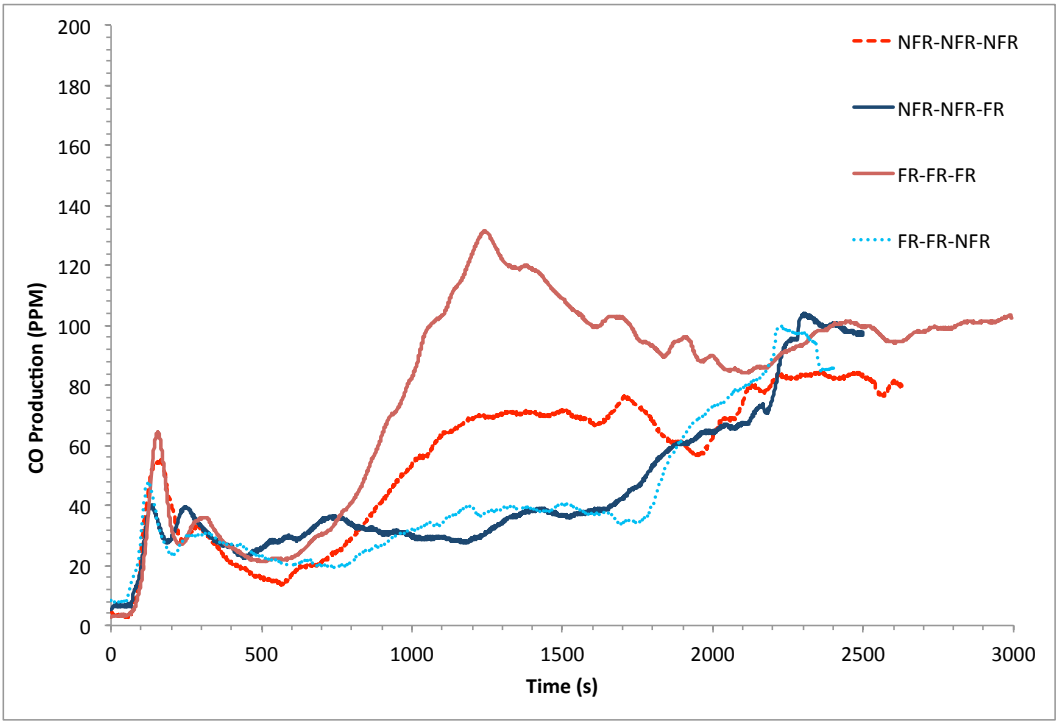


Figure 5.11: Effect of NFR and FR back on CO production within the panel assembly (un-glued).

5.2 Laminated MDF Panel (Glued)

The previous section deals with the fire performance of laminated panel assemblies without glue between the layers. It was demonstrated that there is a clear effect of using FR materials on the burning behaviour of the assembly as a whole. The importance of the front and core materials in affecting time to ignition, peak HRR and time to peak HRR is also discussed. This section deals with the analysis of results of a similar test series that is conducted on laminated assemblies with glue. These are more realistic assemblies in terms of what is most commonly used in indoor panels and building furnishings, as well as elevators. Figure 5.12 shows a typical glued laminated panel (NFR-NFR-NFR) with the same physical configuration as all of the other samples discussed in this section. Given that a considerable amount of evidence has already been presented for the effect of FR additives on the fire performance of the individual materials as well as in assemblies without glue between the layers, this section seeks to confirm previous conclusions where applicable and extend them as necessary based on data from cone calorimeter testing of fully glued, laminated samples.

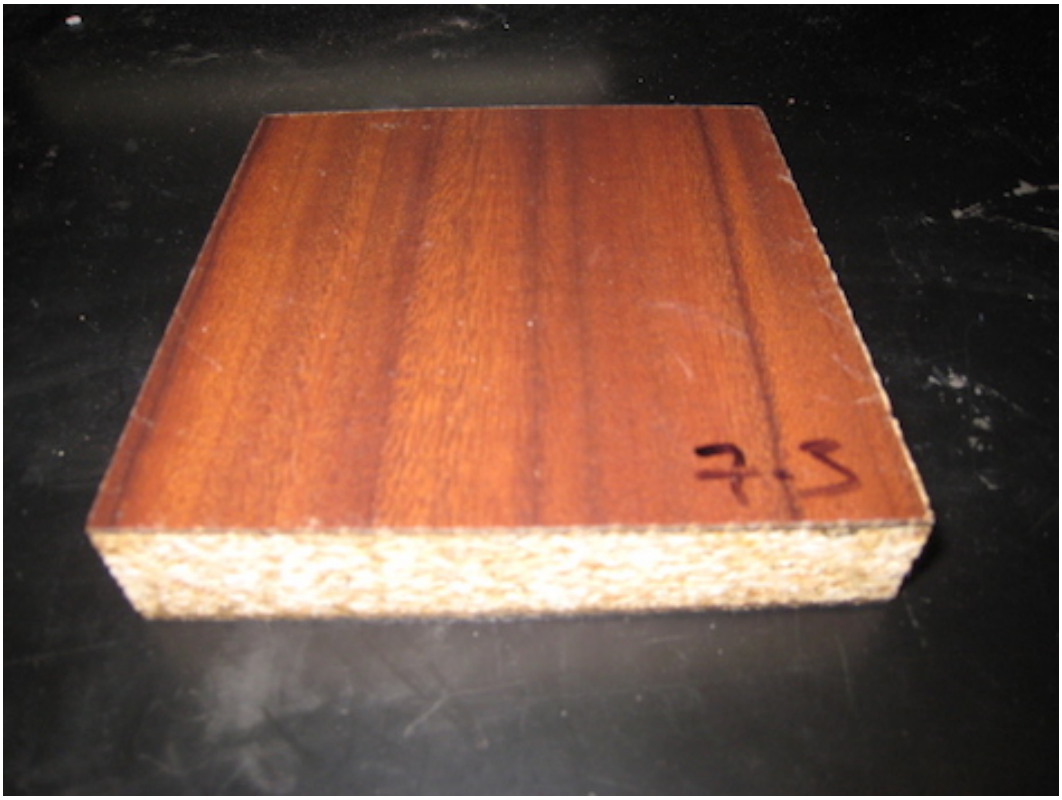


Figure 5.12: Laminated panel assembly (glued).

Table 5.5 presents the individual results for time to ignition, time to flame out, peak HRR, time to peak HRR and mass loss as well as the averaged data for each set of glued laminated panels. The naming convention is consistent with the convention used in the previous section.

Table 5.5: Laminated MDF assembly testing results (glued).

Non Fire Retarded Front Panel Samples						
Specimen Type	Test #	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-NFR-NFR	Test-1	55	2415	149.2	256	79
	Test-2	50	2174	171.3	76	78
	Test-3	47	2310	149.7	64	79
	Average	**51**	**2300**	**156.7**	**132**	**79**
NFR-NFR-FR	Test-1	53	2409	122.9	415	75
	Test-2	56	2168	124.4	385	73
	Test-3	68	2276	117.6	210	74
	Average	**59**	**2284**	**121.7**	**337**	**74**
NFR-FR-FR	Test-1	70	1346	129.1	83	35
	Test-2	71	1136	108.2	84	30
	Test-3	64	1147	130.4	86	31
	Average	**68**	**1210**	**122.6**	**84**	**32**
NFR-FR-NFR	Test-1	62	1229	137.4	94	57
	Test-2	54	1134	138.6	80	57
	Test-3	60	1370	139.0	88	56
	Average	**59**	**1244**	**138.3**	**87**	**57**
Fire Retarded Front Panel Samples						
Specimen Type	Test #	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
FR-FR-FR	Test-1	104	3100*	100.8	267	63
	Test-2	109	3100*	88.9	282	61
	Test-3	81	3100*	93.4	312	62
	Average	**98**	**3100***	**94.3**	**287**	**62**
*Samples did not flame out, test ended manually						
FR-NFR-NFR	Test-1	80	2639	152.4	244	75
	Test-2	64	2449	162.8	258	75
	Test-3	54	2527	168.0	266	76
	Average	**66**	**2538**	**161.1**	**256**	**75**
FR-NFR-FR	Test-1	129	2800	160.8	248	77
	Test-2	95	2918	156.4	252	77
	Test-3	116	2738	177.5	262	75
	Average	**113**	**2819**	**164.9**	**254**	**76**
FR-FR-NFR	Test-1	56	2431	99.3	259	65
	Test-2	70	2577	100.4	274	65
	Test-3	141	2438	100.0	310	62
	Average	**63**	**2504**	**99.8**	**266**	**64**

The results presented in Table 5.5 are consistent with what is observed when the individual materials and laminated panel assemblies without glue were tested. When results from the top and bottom sections of Table 5.5 are compared, it is clear that there is a consistent difference in the time to ignition between the NFR and FR versions of the glued samples tested. Comparing the time to ignition for the glued NFR-NFR-NFR laminated panel versus the FR-FR-FR samples, it can be seen that the full NFR samples ignited at about 51 seconds whereas the full FR samples ignited at a later time, about 98 seconds on average. This difference in time to ignition is consistent with the values that are presented for the laminated assemblies without glue that are constructed of the same material types. Comparing the times to ignition of the glued NFR-NFR-NFR samples in Table 5.5 to those for the unglued specimens in Table 5.1, the difference in time to ignition was only about 7 seconds on average with the unglued samples igniting slightly earlier than the glued. Comparing the glued and un-glued FR-FR-FR samples, the difference in time to ignition between the two specimens was about 10 seconds, again with the un-glued samples igniting earlier.

The consistency in results between glued and un-glued assemblies is also clearly seen in the measured values for several of the other fire safety parameters in Table 5.5. The average peak HRR for the glued NFR samples was 149.2kW/m^2 and for the glued FR samples was 100.8kW/m^2, in contrast to measured values of HRR for the unglued samples which range from 150.4kW/m^2 for the fully NFR samples to 87.5kW/m^2 for the fully FR samples. The time after ignition at which the glued NFR-NFR-NFR samples reached their peak HRR is 82 seconds and for the glued FR-FR-FR specimens, it is 189 seconds. This recorded average value for the glued FR-FR-FR specimen is similar with what was measured for the equivalent un-glued samples, which exhibited a time to peak HRR after ignition of 184 seconds (Table 5.1). The recorded times to peak HRR for the glued, fully NFR assemblies are not similar to their unglued counterparts however, so it is certainly of interest to further examine the specific behaviour of the various glued assemblies as discussed in the following sections.

Comparison of the upper and lower sections of Table 5.5 illustrates that there are distinct differences in fire behaviour between the fully non-fire retarded (NFR-NFR-NFR) versus the fully fire retarded (FR-FR-FR) glued assemblies. All samples assembled with NFR front panels demonstrated noticeable differences in key indicators of fire performance over those assembled with FR front panels, as illustrated in Table 5.5. In general, results were again consistent with what was observed for the individual materials discussed in Section 5.1, where the FR components demonstrated better fire performance characteristics than the NFR versions as measured through cone calorimeter testing.

5.2.1 FR-FR-FR vs NFR-NFR-NFR (Glued)

As discussed briefly in Section 5.1, the differences in values presented for the time to ignition, peak HRR, time to peak HRR after ignition and mass loss for the fully NFR versus fully FR glued samples were consistent with those observed for the equivalent unglued samples. Looking at the results presented in Table 5.5 and the plots presented in Figure 5.13, Figure 5.14 and Figure 5.15, the following observations can again be made:

- there was good sample to sample correlation of data which demonstrates the repeatability of results across glued panel assembly tests;
- fully FR samples were characterized by longer times to ignition, as well as lower peak and overall values of HRR than NFR samples;
- the FR panel materials produced considerably more CO than the NFR samples, strengthening the argument that FR additives disrupt the combustion mechanism; and
- the mass loss rates for the FR samples were less than those for NFR samples indicating that the NFR samples burn more quickly and completely across the duration of the test.

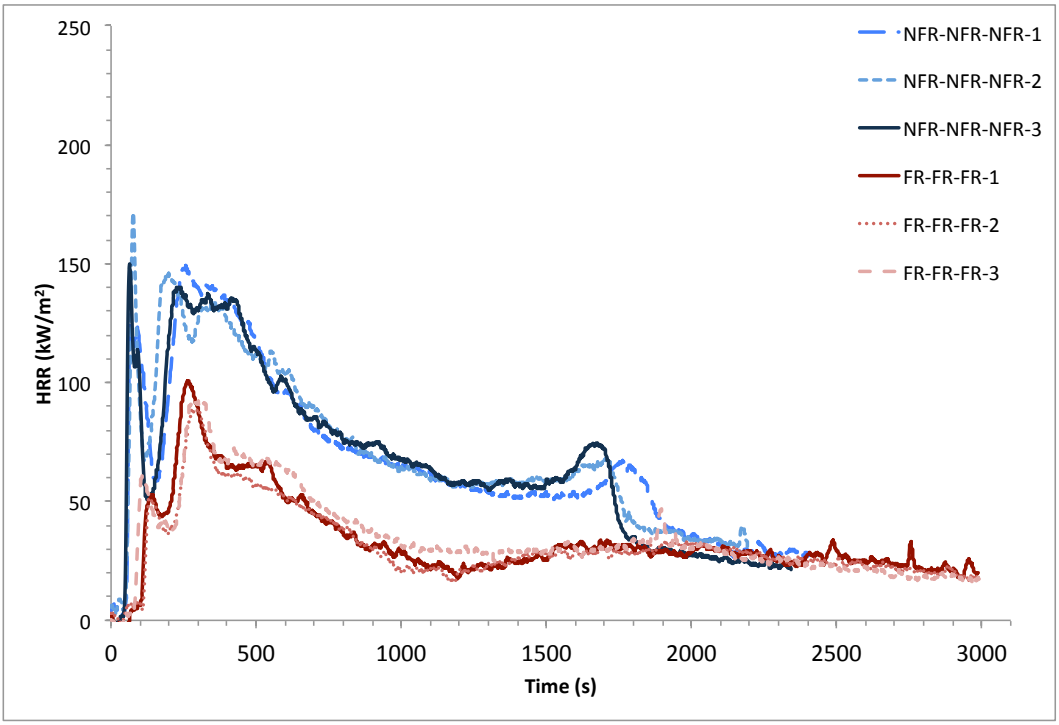


Figure 5.13: Full NFR and FR panel assemblies (glued) HRR over time.

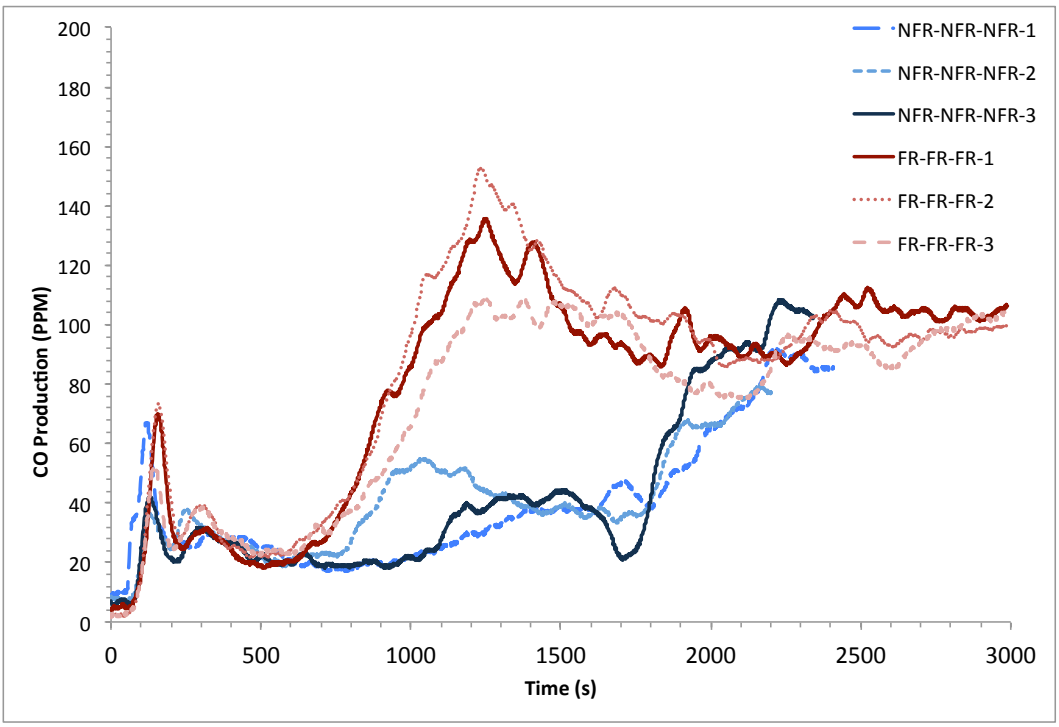


Figure 5.14: Full NFR and FR panel assemblies (glued) CO production over time.

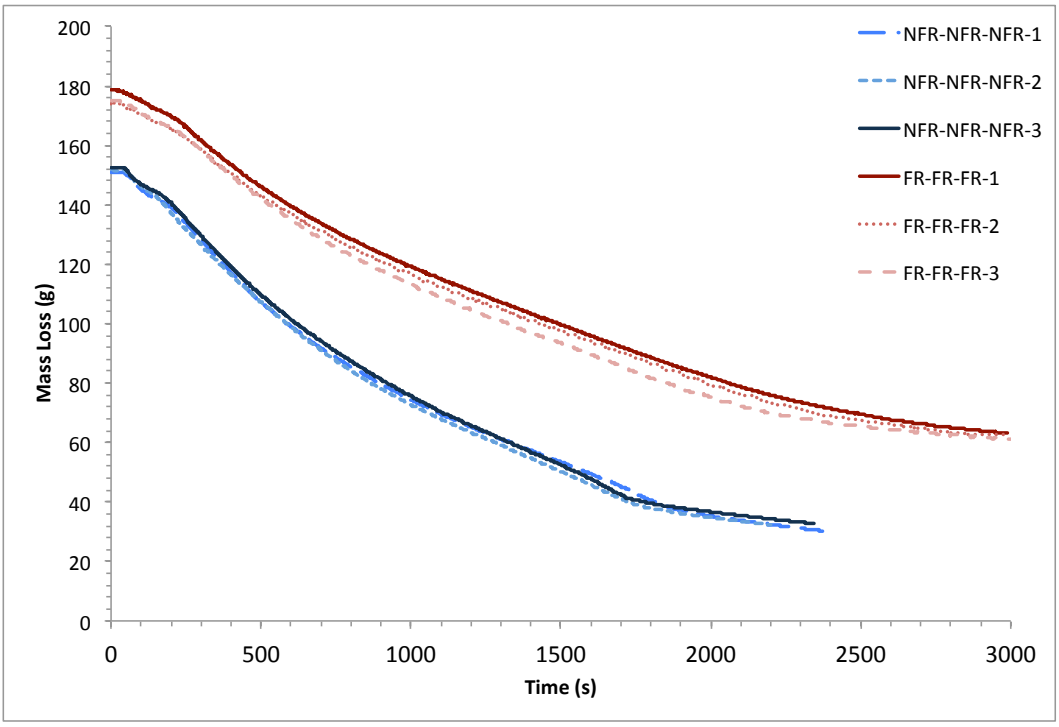


Figure 5.15: Full NFR and FR panel assemblies (glued) mass loss over time.

These observations led to the conclusion that, as a whole, the FR additives in the laminated panels are effective in enhancing the fire resistance of both the wood core and the plastic laminates contained within the glued assemblies. However, the parameters measured do not indicate the effect of the glue on either the fully FR or fully NFR samples. Thus, the next step is to look further into the effect of the glue by comparing the fire performance of the glued NFR-NFR-NFR samples to their un-glued counterparts and similarly comparing the performance of glued and un-glued FR-FR-FR samples. Table 5.6 summarizes the average values of the time to ignition, time to flame out, peak HRR, time to peak HRR and mass loss for the glued and un-glued fully NFR and FR samples.

Table 5.6: Comparison of full NFR and FR laminated panel assemblies (glued and un-glued).

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
NFR-NFR-NFR-G	51	2300	156.7	132	79
NFR-NFR-NFR-NG	44	2422	150.4	64	79
Difference (%)	**13**	**5**	**4**	**54**	**1**
FR-FR-FR-G	98	3100*	94.3	287	62
FR-FR-FR-UG	108	3100*	87.5	292	62
*Samples did not flame out, tested ended manually					
Difference (%)	**9**	**0**	**7**	**2**	**0**

As expected from the discussion above, the data in Table 5.6 does not show much deviation between fire performance characteristics of either the fully NFR or fully FR glued and un-glued samples. The time to ignition for fully NFR samples were within 13%, while for the fully FR samples the difference between glued and un-glued assemblies was only 9%. Similarly, the time to flame out for fully NFR samples only differed by 13% between the glued and un-glued samples, while for the fully FR samples, the time to flame out was the same since neither sample flames out before the time limit used in the cone calorimeter test. The peak HRRs were also similar between the glued and un-glued variants of fully NFR and fully FR samples, with differences of only 4% for the NFR and 7% for the FR samples respectively. The time to peak HRR and time to peak HRR after ignition showed some variability for the NFR samples with a difference of 54%. This was attributed to sample # 1 in the NFR-NFR-NFR series which reached a higher peak HRR value on ignition of the panel core (Figure 5.13). On the other hand, the fully FR samples demonstrated that there was little difference to the time at which peak HRR is reached with only 2% difference in values between the glued and un-glued specimens. Finally, the mass loss rates for the fully NFR and FR glued and un-glued samples demonstrated very

little difference.

The average HRR versus time is plotted for the glued and un-glued fully NFR and FR samples in Figures 5.16 and 5.17. These plots demonstrate that there are significant differences in the HRR with time for the glued versus un-glued assemblies. Looking at the graph for the fully NFR samples, it can be observed that the glued samples reached a higher second peak in HRR after ignition (when the core ignited) than observed for the FR samples. As the glued samples continued to burn and reach their flame out period, values of measured HRR dropped below what is measured for the un-glued samples. This type of behaviour was unexpected, since oxidation of the glue was expected to augment the values of HRR so that glued assemblies were expected to exhibit higher values of HRR throughout the entire duration of the test. In these tests, similar behaviour was also seen for the fully FR samples. Contrary to expectation, then, the results suggest that after the core has ignited, the glued samples exhibit lower HRR values when compared to the un-glued samples. This again merits additional investigation.

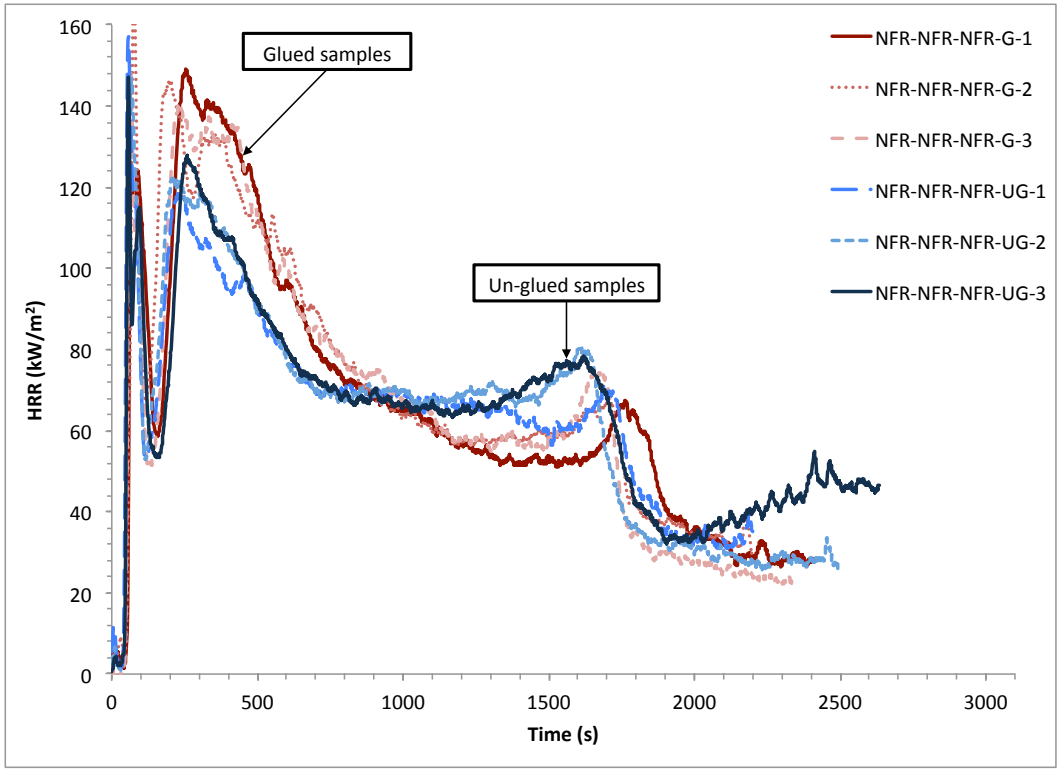


Figure 5.16: NFR-NFR-NFR panel assemblies (glued and un-glued) HRR over time.

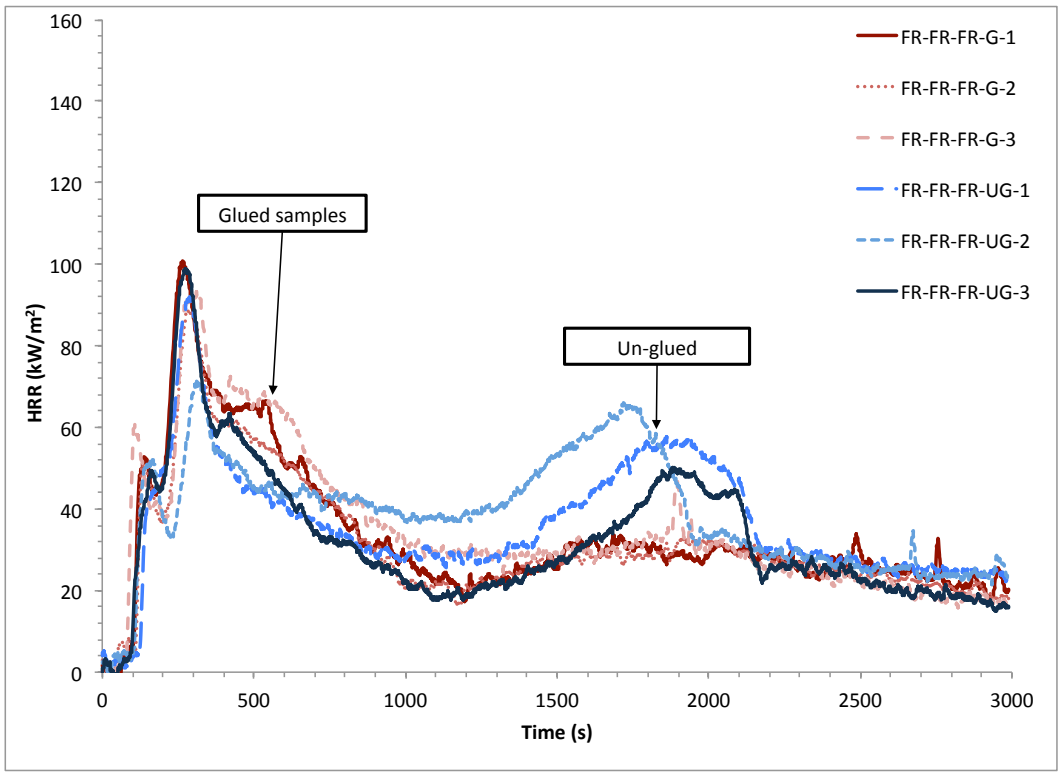


Figure 5.17: FR-FR-FR panel assemblies (glued and un-glued) HRR over time.

Mass loss rate data for the glued assemblies is plotted in Figures 5.18 and 5.19. These graphs demonstrate that there is a period of time around the middle of the burning period during which the slope of the mass loss differed between the fully NFR and FR glued specimens. This difference in slope was consistent with the differences in the HRR plots that have been noted previously. For the FR samples the mass versus time curves varied between the glued and un-glued samples; however, those differences might be attributed to the fact that the samples did not have exactly the same mass. On average the unglued samples were heavier because of a small change in the thickness of the core material that was provided by ECR. Even with this noticeable difference, the mass loss rates for both glued and un-glued samples stayed consistent until 1600-seconds into the test, when the mass loss rates for the un-glued samples increased significantly relative to those for the glued variants. By comparing mass loss rate curved to the HRR curves of the same samples, this increase corresponded to the sudden peak in HRR observed at the end of the flaming period before the smouldering period began.

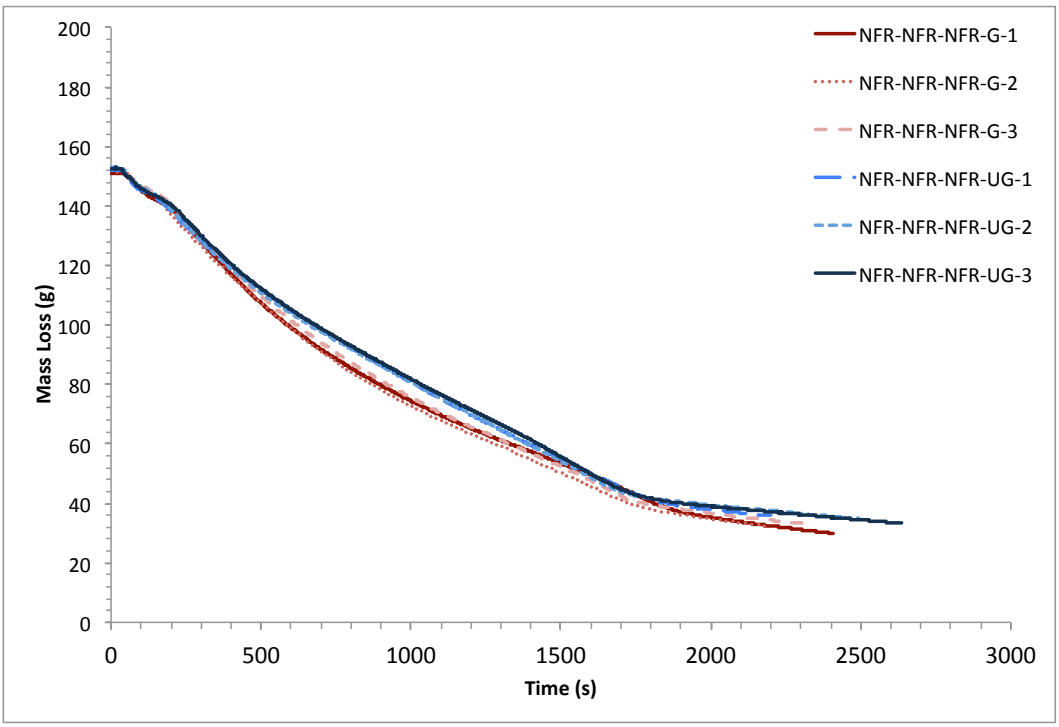


Figure 5.18: NFR-NFR-NFR panel assemblies (glued and un-glued) mass loss over time.

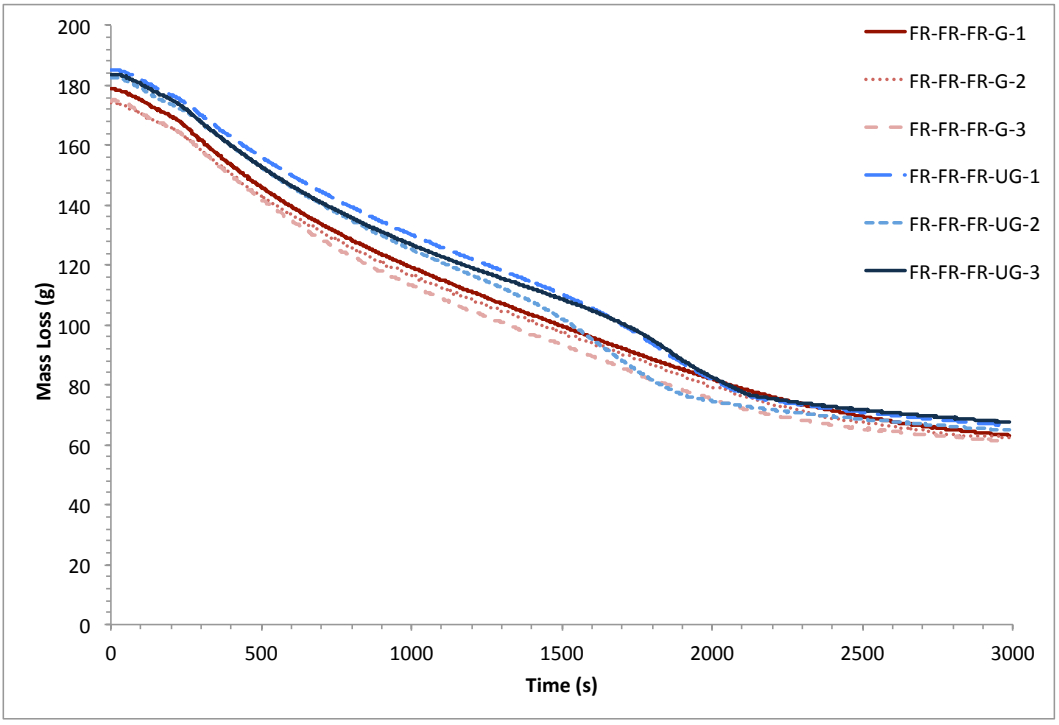


Figure 5.19: FR-FR-FR panel assemblies (glued and un-glued) mass loss over time.

Having looked at the HRR and mass loss rates, the next step was to look at the CO production rates over time for both glued and un-glued assemblies in their fully FR and NFR variants. Figures 5.20 and 5.21 show average values for CO production over time for the glued and un-glued fully FR and NFR laminates. For the NFR samples, the glued and un-glued specimens demonstrated a consistent difference in the recorded concentrations of CO. As a whole, the glued samples produced more CO than the un-glued specimens, consistent with the trends in both HRR and mass loss rates for those samples. For the FR samples, more contrasting behaviour is observed between the glued and un-glued samples. The glued samples generally took longer to flame out and, during the burning period, produced higher quantities of CO, thus producing higher peak values of CO before the sample began to smoulder.

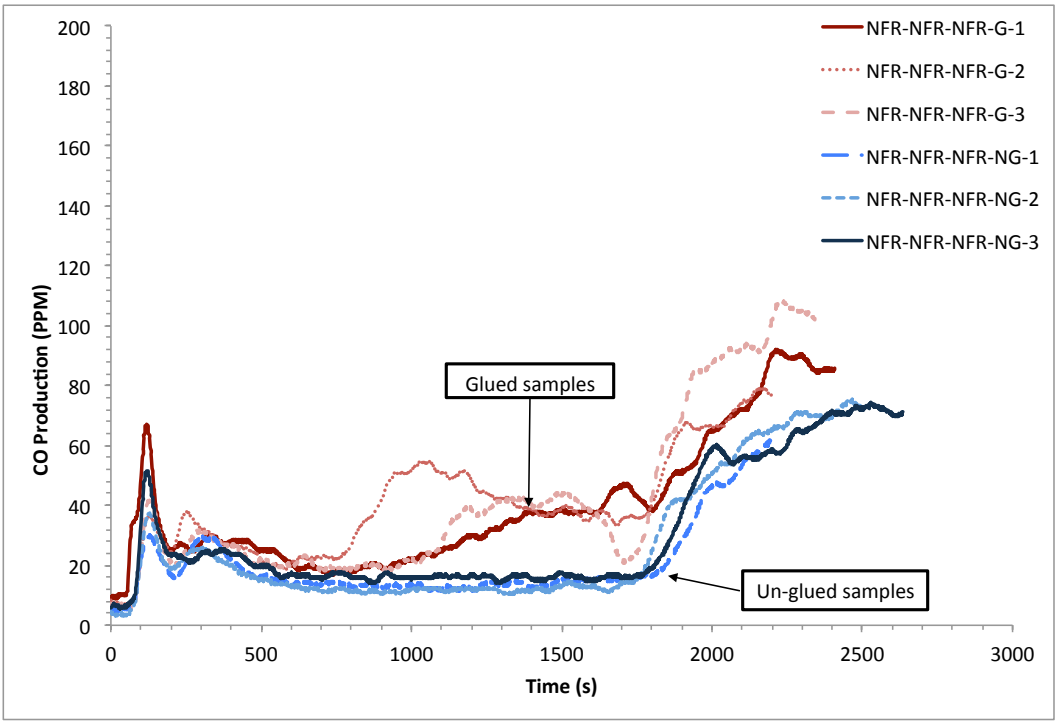


Figure 5.20: NFR-NFR-NFR panel assemblies (glued and un-glued) CO production over time.

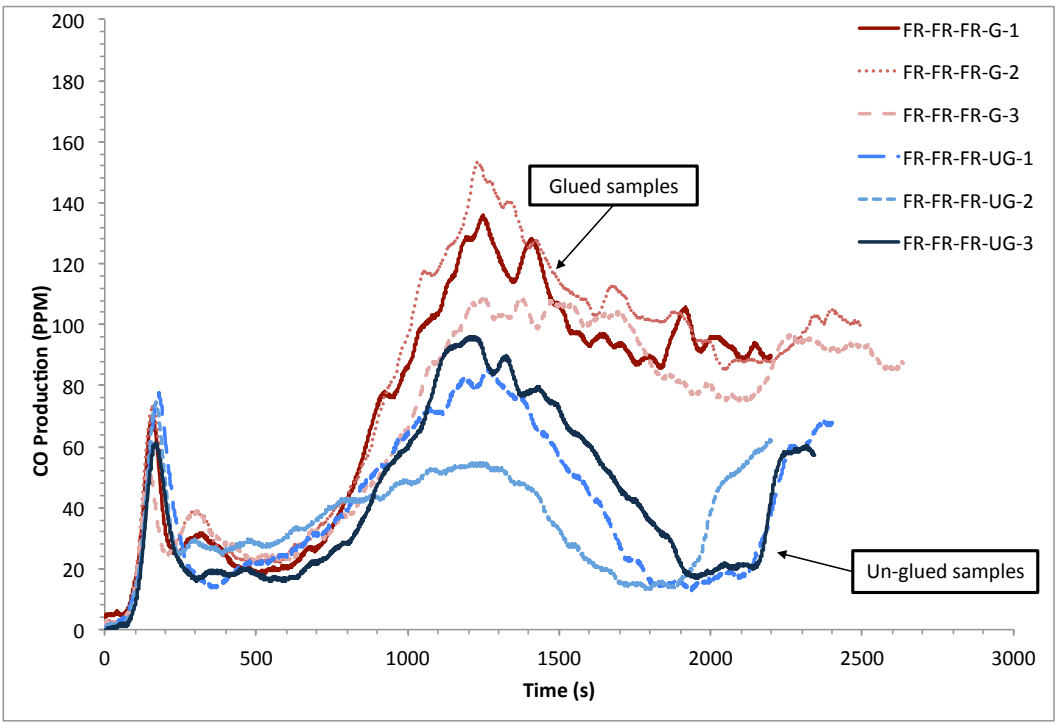


Figure 5.21: FR-FR-FR panel assemblies (glued and un-glued) CO production over time.

Based on the limited testing carried out on the glue in Chapter 4, the original hypothesis was that values of HRR would be higher and CO production lower for the glued samples due to exothermic oxidation of the glue enhancing the combustion of the panel materials. Analyzing the graphs for the HRR and the mass loss rate for both glued NFR and FR samples, it can be seen that initially the glued samples demonstrated higher values of HRR and a steeper mass loss rate than the unglued versions. When the tests reached about 1500 seconds, however, higher values of HRR and steeper mass loss rates were measured for the unglued samples, leading to the conclusion that these specimens may be burning more completely. One possible explanation for this behaviour can be attributed to the testing method used for the un-glued laminates. As will be discussed in Chapter 6, the unglued samples are held together by the cone calorimeter sample holder alone, which allowed the front, core and backer components to lose contact during the course of a test. The resulting change in availability of air local to the flaming region was then postulated to affect the HRR measurements. In Chapter 6, it is demonstrated that when all materials are pressed more tightly together (held externally within the sample holder), the HRR values recorded for the unglued panel assemblies are indeed lower as the test progresses.

5.2.2 Effect of Type of Front, Core and Back on Laminated Assembly (Glued)

During the analysis of the results of the laminated panel assembly without glue, the effect on the fire characteristics of having an FR front and an FR MDF core in turn shown to have a significant effect on the time to ignition, peak HRR and time to peak HRR. As shown in Section 5.1.1, there was a clear correlation between the results for the glued and un-glued samples, with an apparently small effect on the fire performance observed due to the presence of the glue. When Tables 5.5 and 5.1 are compared, it can be observed that there is a strong correlation between the results measured for comparable glued and un-glued sample assemblies. As such, it can be concluded that the effect of adding FR additives to the front, core and back panels in the glued laminates are similar to what is observed during the testing and analysis of the un-glued laminated samples.

From Table 5.5, it can be seen that the time to ignition is almost exclusively related to the type of front panel material. Figure 5.22 highlights the HRR versus time curves for samples in which the front material is kept constant and the core and back material type are exchanged. Furthermore Figure 5.23 shows the evolution of HRR over time when the MDF core was kept the same between samples while the front and back materials were varied. These figures show that the nature of the front panel had the biggest impact on time to ignition, while there was no indication that the core or back materials have an observable effect on this parameter. As also anticipated, an NFR front sheet or an NFR MDF core led to the highest values of HRR of any assembly. As shown in Figures 5.24 and 5.25 it is clear that measured values of CO production over time were also consistent with these observations.

During testing of the laminated panel assembly without glue, it was noted that the type of backing sample used (FR versus NFR) does not have an observable effect on any of the key parameters investigated in this study. Figure 5.26 shows that this was also true for the glued samples as there was no clear differentiation between the time to ignition or HRR over time for assemblies with NFR versus FR back panel materials.

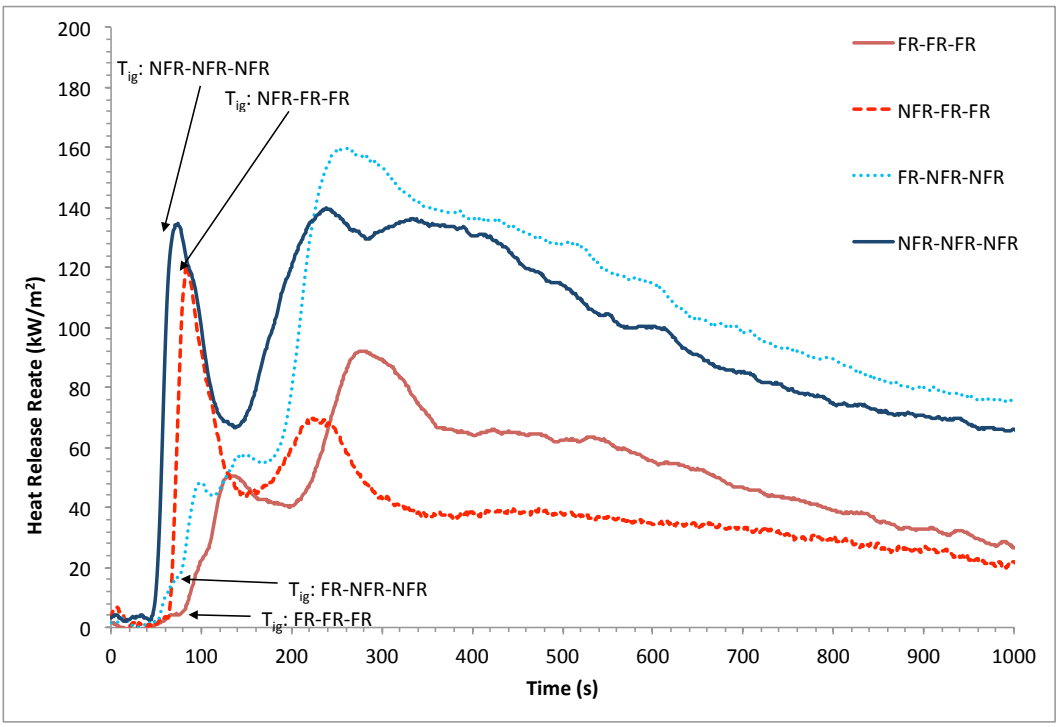


Figure 5.22: Effect of NFR and FR front on time to ignition within the panel assembly (glued).

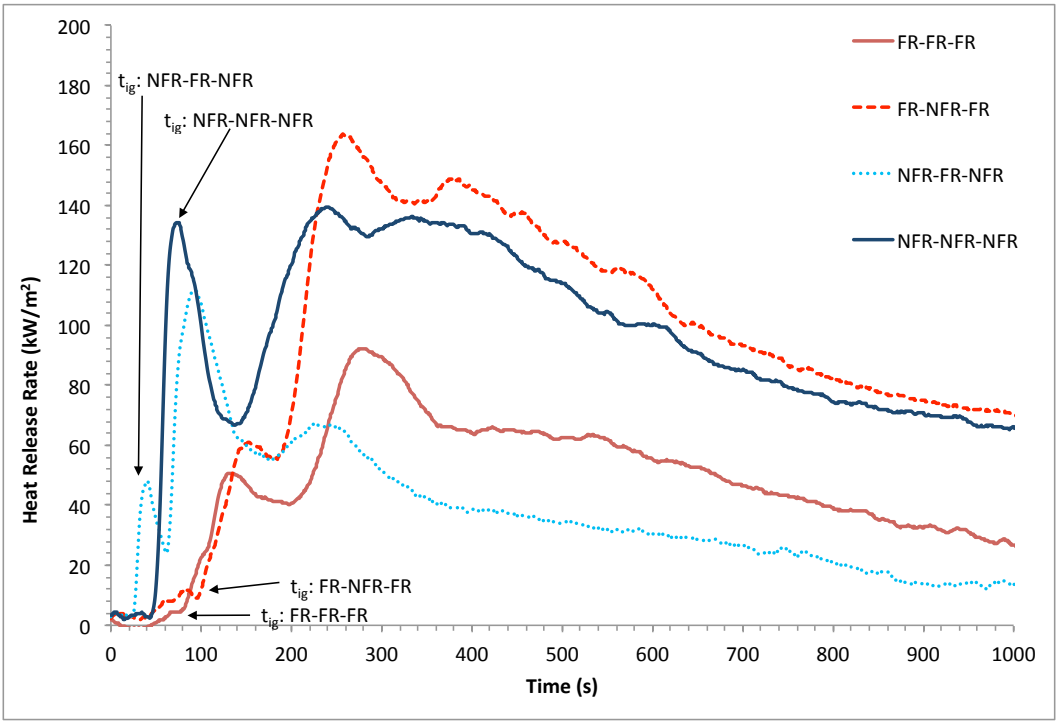


Figure 5.23: Effect of NFR and FR core on time to ignition within the panel assembly (glued).

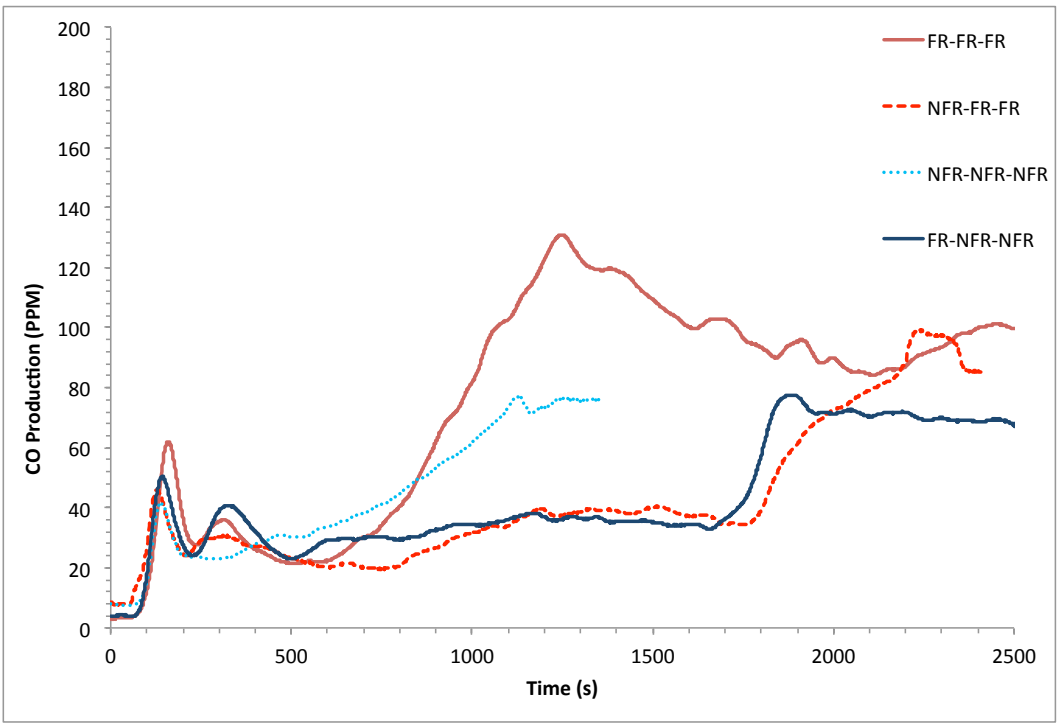


Figure 5.24: Effect of NFR and FR front on CO production within the panel assembly (glued).

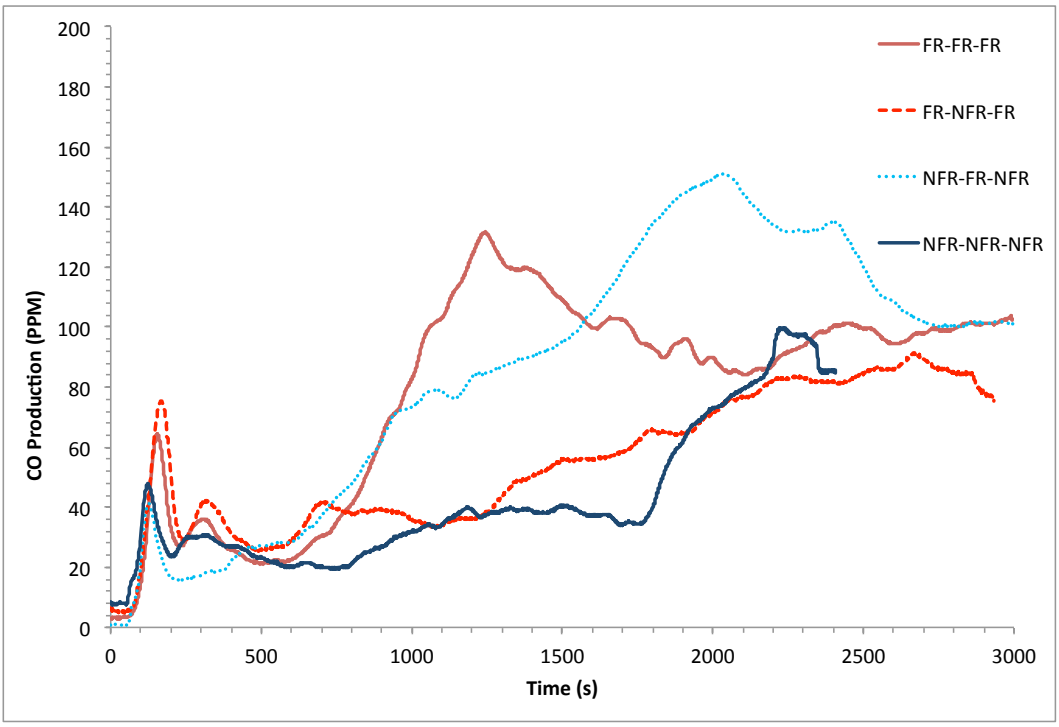


Figure 5.25: Effect of NFR and FR core on CO production within the panel assembly (glued).

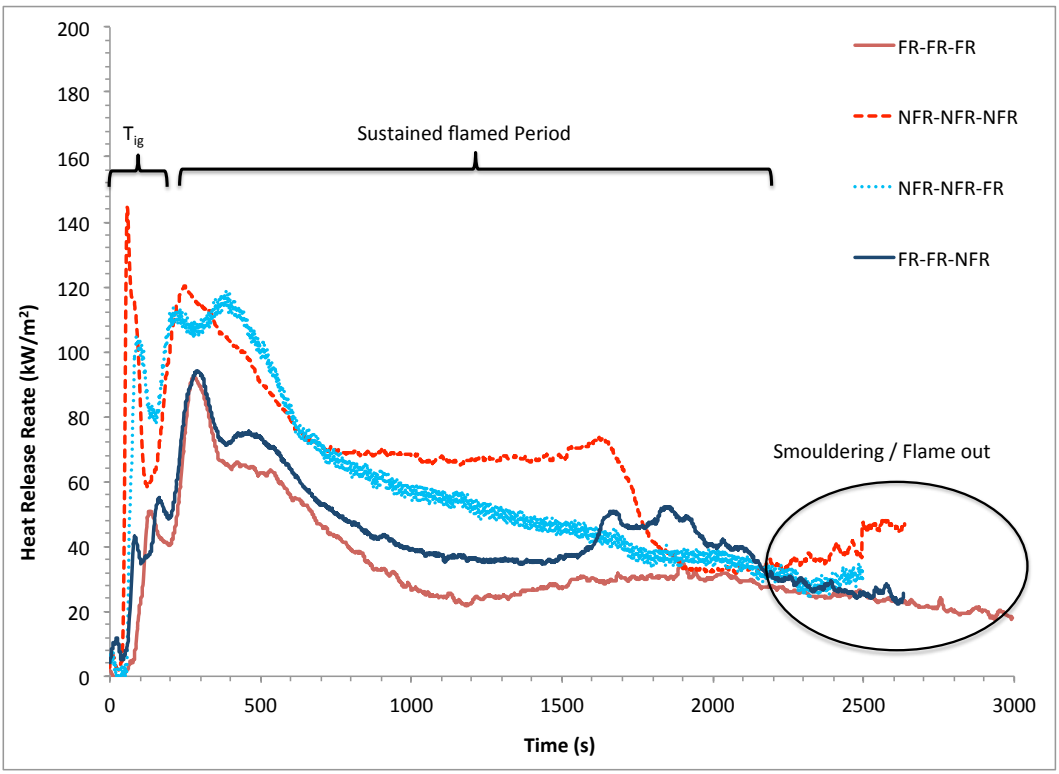


Figure 5.26: Effect of NFR and FR core on HRR within the panel assembly (glued).

In this chapter, the results for un-glued and glued laminated MDF panels are presented in turn and then compared against one another. In the next chapter, the potential sources of errors in the present results are presented, with explanations relating to the way in which these could have had an effect on the results presented in this and the previous chapter.

Chapter 6

Sources of Errors

Results of the cone calorimeter testing of individual panel materials, as well as of panels assembled from various combinations of material have been reported in the previous chapters. Due to the varied and extensive number of tests and specimens tested, several errors due to calculation uncertainty and unexpected sources of errors were identified in this work. Errors due calculation uncertainty were mainly related to the HRR calculations and the concept of oxygen calorimetry. Unexpected sources of errors were due to operator mistakes and machine breakdowns. This chapter discusses how these errors impacted the results presented in this work

6.1 Calculation Uncertainty

The ASTM E1354 uses the concept of oxygen calorimetry as the main tool for the determination and calculation of heat release rates. As it is explained in Chapter 2, equation 6.1 is used to calculate HRR for any type of material. This equation is shown below

$$q''(t) = E_{O_2}\left(\frac{\phi}{1+\phi(\alpha-1)}\right)\dot{m}_e\frac{M_{O_2}}{M^{\circ}_{air}}\left(1-X^{\circ}_{H_2O}-X^{\circ}_{CO_2}\right)X^{\circ}_{O_2} \tag{6.1}$$

From this equation it is clear that there are several sources of calculation uncertainty. The ASTM E1354 addresses one of the major components of uncertainty in the standard, E_{O_2}. In the standard it is stated that for most solid materials an assumed value at calibration of $E_{O_2} = 13.1x10^3$ kJ/kg an error band of $\pm 5\%$, which corresponds to 655 kJ/kg. Based on work done by Enright [21] it is demonstrated that in most cases, with regular maintenance, the values for the stack temperature and differential pressure across

the sample ring are almost negligible since these are calculated as a square root ratio. Furthermore, Enright explains that C is relatively constant and for most manufacturers an instrument uncertainty of 5% is considered acceptable. In their work they highlight that the measurement uncertainty which can influence the calculation in an unexpected manner, is the variability within the oxygen analyzer. During these tests the standard calibration method provided by FTT called for strict controls during the calibration of the oxygen analyzer which minimize the uncertainty in the calculations. Enright also provides a baseline of ± 100 *ppm* which equates to about 0.01% of uncertainty for the oxygen measurements. With these values it is concluded that a standard error band of $\pm 5\%$ for the HRR measurements presented in this work was acceptable.

6.2 Unexpected Sources of errors

6.2.1 Time to Ignition and Flame out Measurements

The time to ignition is measured by observing the sample and pressing a button on the cone calorimeter apparatus at the first indication of the presence of a flame. Therefore, after the material has been placed under the radiant heater in the cone calorimeter, the operator needs to continuously watch the material for any indication of the presence of a flame. Because this is an observational measurement, the test operator had to be vigilant. The two images shown in Figure 6.1 demonstrate two different materials at two stages near the beginning of a test. These figures illustrate the two main stages through which a material passes as it starts to off gas and is finally fully ignited.

From experience it was determined that an average reaction time for time to ignition would not be anymore than 2 seconds. The data presented for all materials tested demonstrated that on average the lowest time to ignition reported was 26 seconds (test 1 of backer NFR). Using an estimated error band of 2 seconds, this represents a 7% error in the measurement. For longer ignition times the percent error decreases. Since the error in the present measurements is anticipated to be less than the worst-case scenario above, this is deemed to be an acceptable uncertainty in the ignition time measurement. Lastly, the ConeCalc software plots the HRR after a 13 second time delay (the length of time it takes the gases to go from the sample to the sampling rings). This provides an additional method through which the operator can compare the measurements taken against the collected data to determine if the former are correct.

Due to the nature of the samples under study, the time to flame out was noted to be extremely erratic in the present study. In particular, samples did not flame out completely at a distinct time, but instead smouldered for very long periods of time (see Figure 6.2). In



(a) Sample off-gassing

(b) Sample under full ignition

Figure 6.1: Time to ignition evolution from off-gassing (a) to ignition (b).

fact, for the FR-FR-FR assemblies, both glued and un-glued, it was noted that the samples continued to burn past the time limit of a normal cone calorimeter test (3000 seconds). For other samples, flame out data varied up to 30%, a discrepancy noted throughout all the tests. As such, time to flame out was not considered to provide additional information in the present analysis, and was presented only to distinguish between those samples that flame out and those that continue to smoulder past the total test time allowed.

6.2.2 Sample Holder Clamping Force

During the testing of the un-glued laminated assemblies, it was noted that after the material started to combust and its mass (therefore thickness) began to decrease, the sample holder could no longer hold the layers tightly in place. For some tests, it appeared as though the layers were only loosely held together, which may possibly impact availability of oxygen to various layers, as well as altering the heat transfer from the cone heater through the various layers of the sample.

In order to assess if the clamping force had any effect on the test results presented for the



Figure 6.2: Specimen smouldering after flame out period.

un-glued panel assemblies, the sample holder was modified to maintain a consistent force on the specimens by using a set of springs on each side of the holder. This modification did not require any major changes to the sample holder and test setup, which made the results directly comparable to the tests carried out with the original sample holder. For this comparison two un-glued specimens FR-FR-NFR were tested. The tests results are summarized in Table 6.1. Note that the sample naming convention was modified with the second set of data shown to include a "C" which denotes the clamped samples.

Table 6.1: Sample holder clamping force comparison of FR-FR-NFR.

Specimen Type	Test #	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$ (s)	Mass Lost (%)
FR-FR-NFR	Test-1	90	2963	69.4	261	65
	Test-2	80	2947	82.3	448	65
	Test-3	56	2833	71.5	420	65
	Average	**75**	**2914**	**74.4**	**376**	**65**
FR-FR-NFR-C	Test-1	93	2988	81.9	274	64
	Test-2	101	2931	81.9	259	63
	Avg.	**97**	**2960**	**82**	**267**	**113**
Difference (%)		***22***	***2***	***9***	***29***	***1***

The data presented in Table 6.1 shows that there were differences in the behaviour of the clamped versus unclamped samples when they were tested under the same conditions in the cone calorimeter. To investigate further, the HRR and CO versus time graphs (shown in Figures 6.3 and 6.4) were examined. These demonstrate that there are clear differences between the two sets of samples. Higher levels of HRR and less CO were measured for samples held in the regular (unclamped) sample holder. This supports the hypothesis that, when the panel assemblies without glue were tested, the separation between the individual layers allows air to circulate within the assembly and thus aids in the combustion of the materials. It is clear that the clamping effect is more pronounced toward the end of the tests. This means that for the peak HRR, time to ignition and mass loss results used to compared the un-glued versus glued samples' fire safety performance, the observations made earlier remained unaffected.

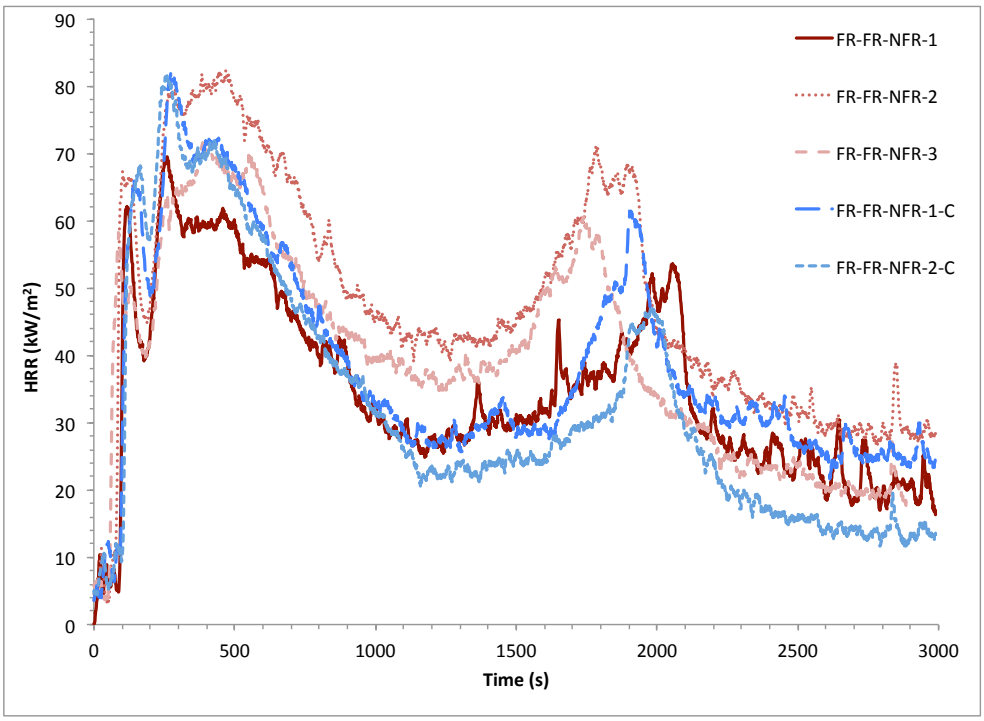


Figure 6.3: FR-FR-NFR panel assembly (un-glued) HRR over time - modified and regular sample holder

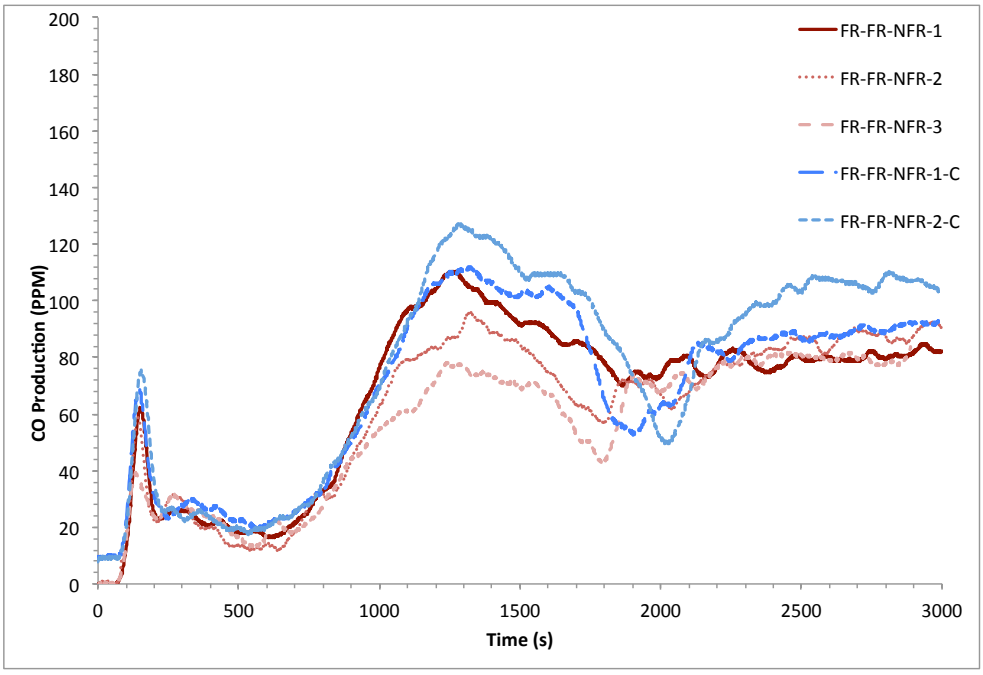


Figure 6.4: FR-FR-NFR panel assembly (un-glued) CO production over time - modified and regular sample holder.

In this chapter it was demonstrated that there are numerous sources of expected and unexpected errors that had been identified during the completion of this research, which included calculation uncertainty observational bias, specimen setup bias due to separation of layers and an instrumentation errors. All these errors were addressed and quantified to minimize their impact on the testing results presented in this chapter. The following chapter summarizes the major conclusions from this work, while taking in consideration the sources of errors demonstrated.

Chapter 7

Conclusions and Recommendations

The stated objective of this research was to assess the fire performance characteristics of laminated MDF panel assemblies. The cone calorimeter was chosen as the main apparatus to be employed in the testing. The investigation included the quantification of the impacts of FR additives on fire performance of wood based panel materials, not only when they are added to individual materials, but also when the individual materials are layered in various combinations into a complete, laminated MDF panel. In particular, the fire behaviour of Arborite laminated front and backer samples, as well as MDF core material and PermaGrip glue, was determined.

A thorough study of the fire performance of the individual front, core, backing materials and the glue used to create typical laminated MDF panels was undertaken. There was sufficient evidence of sample-to-sample consistency and repeatability of results, that some key conclusions could be drawn related to the use of NFR versus FR materials in elevator cabs. As a whole, FR additives improved not only the individual material performance when tested according to the cone calorimeter standard but also that of a complete, multi-layered assembly. With the addition of FR additives to the individual materials, the laminated MDF panels demonstrated a consistent improvement in time to ignition, along with a reduction in peak HRR and mass loss rates. There was an increase in the amount of CO produced from the addition of FR additives to all of the materials tested, but the detailed chemical composition of the fire gases was not within the scope of the present study so the trade-offs between time to ignition, HRR and fire gas composition cannot be fully discerned.

Even with some of the limitations already discussed, several more specific conclusions and recommendations can be made related to future use and application of multi-layered, laminated MDF core panels in applications similar to their current use in the interior finishing of elevator cabs.

More specific conclusions include:

1. **Time to ignition is dominated by type of front sheet used on the assembly.**

Because of the location and purpose of the front plastic laminate in the assembly, the time to ignition was found to be dependent exclusively on this material. The present results demonstrated that when an NFR front sheet was used instead of a FR front sheet, a decrease of up to 50% in the time to ignition is observed. Further, these results are independent of the type of core and backing material used.

2. **Peak HRR is determined by the type of front sheet material and MDF core that is used in the laminated panel.**

It was shown that the nature of the front panel and the core material have the largest effect on the peak HRR. When a NFR front sheet was used with a FR core, the peak HRR occurred shortly after ignition of the front panel material. This is followed by a short decrease in the HRR until a second, smaller peak in HRR occurs at the time of ignition of the MDF core sample. When a front FR panel was used with a NFR core, the peak HRR was observed as the MDF core ignited rather than during burning of the front panel. Such behaviour was consistent for both glued and un-glued panel assemblies.

It should further be noted that when both front and core materials are NFR, there are two almost identical peaks in the HRR curve, but on average a slightly higher value of HRR was still measured during burning of the NFR front sheet. In general, fully FR assemblies exhibited significantly lower levels of HRR than their NFR counterparts. For the application of elevator cab finishing panels in the present test context, materials that produce the lowest HRR values are most desirable. Because of this, it is recommended that for the biggest reduction in the HRR values, both the front and core panels be composed of FR materials.

3. **CO production increases with the use of FR additives.**

It was found that in concert with the decrease in the HRR seen for FR materials, there is an increase in the CO production rate. This inverse proportionality is noted in all of the tests, specifically a net increase in CO production is observed whenever FR samples are tested either as individual materials or in combination in a multi-layer, laminated panel assembly. This evidence is consistent with the notion that typical FR additives do affect the combustion process to reduce HRR and slow burning of the sample. Since the overall combustion chemistry changes as more CO is produced, details of the chemical composition of fire gases evolved from FR versus NFR panel materials and assemblies should be studied in future work.

4. **The nature of the backing material does not seem to improve the fire performance characteristics of a laminated MDF panel.**

During testing of the individual materials, it was demonstrated that the backer sheet behaved in a similar fashion to the front sheet in terms of time to ignition, peak HRR and CO production, for both NFR and FR variants. However when all the materials were tested as a complete assembly, there was no indication that the backing material affects the fire performance of the assembly in either a positive or a negative manner. It is hypothesized that due to the higher value in mass of the front and core of an assembly, the net effect of the backing material is minimized to a level where it was not noticeable. This means that the use of NFR backing material might be appropriate, particularly if it leads to significant savings in cost or weight of the overall panel assembly. The exception to this theory, would be if there is some demonstrated likelihood that a fire might start behind the laminated panel assembly such that the backer panel would be the first element exposed to the flames and hot gases.

5. The net impact of glue was the reduction of the fire resistance of the laminated MDF panel.

Glue was found to have an impact on the fire performance of the laminated MDF panels. For the fully NFR and FR panel assemblies, there was a net increase in peak HRR of 4% and 7% respectively between the samples without glue and those in which the layers were glued together. In general, this was seen as a fairly small increase in the net HRR early in the test, followed by a leveling off, or sometimes even a reduction in HRR about half way through the test. CO production from the glued samples was also relatively higher throughout the test leading to the conclusion that the glue aids in the production of CO.

During testing of the individual materials, it was found that the cone calorimeter was not an appropriate testing apparatus to study the fire performance characteristics of the glue in isolation. In order to assess the fire performance of different types of glue with or without fire additives, a different testing procedure must be used. Though not attempted here, an apparatus such as the pyrolysis-combustion flow calorimeter might prove useful to better characterize the combustion properties of a range of candidate adhesives appropriate for use in the construction of multi-layer MDF panels.

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APPENDICES

Appendix A

Cone Calorimeter Test Report Sample

A full test report of cone calorimeter test as per ASTM E1354 is included in this appendix. This is the test report that FTT's CONECALC software provides. It is three pages long and it includes specimen information, apparatus specifications, test conditions and summaries of key results. It also includes six graphs for Heat Release Rate, Total Heat Release, Total Smoke Release, Specimen Mass, CO(%) and CO2(%) versus time. For all the samples tested in this work, a report was created and can be requested if desired. The report presented here is for a NFR core sample and it has been scaled down to meet the University of Waterloo's typography requirements.

Cone Calorimeter Test Report

Laboratory name	UW Fire Research Lab
Operator	Sergio Suarez
Filename	D:\Masters\ECR\CORE FR\13100020.CSV
Report name	ECR-WC-6
Sample description	Individual Materials
Material name/ID	ECR-WC-6

Specimen information

E	13.1 MJ/kg	Specimen number	6	Conditioned?	No
Thickness	17.3 mm	Nominal duct flow rate	24 l/s	Temperature	N/A
Initial mass	142.0389 g	Edge frame used?	Yes	RH	N/A
Surface area	88.4 cm²	Grid used?	Yes		
Heat flux	50 kW/m²	Manufacturer	ECR		
Separation	25 mm	Sponsor	ECR		
Orientation	Horizontal				

Test

Standard used	ASTM E 1354
Date of test	16/10/2013
Time of test	16:07
Date of report	23/12/2013

Pre-test conditions

Ambient temperature	22°C
Ambient pressure	97.368 kPa
Relative humidity	48%

Test times

Time to ignition	80 s
Time to flameout	875 s
End of test criterion	ASTM E 1354
End of test time (for calculations)	1290 s

Apparatus specifications

C-factor	0.04168
Duct diameter	0.114 m
O2 delay time	11 s
CO2 delay time	10 s
CO delay time	10 s
OD corr. factor	1.0000

Initial conditions

Baseline ambient oxygen	20.678%
Baseline oxygen	20.952%
Baseline carbon dioxide	0.0436%
Mass at sustained flaming	140.7 g

Heat Release Results

THR (0-300)	15.71 MJ/m²
THR (0-600)	30.73 MJ/m²
THR (0-1200)	43.81 MJ/m²
Fuel load	2.80 MJ/kg

Test results (between 80 and 1290 s)

Total heat release	44.9 MJ/m²
Total oxygen consumed	31.1 g
Mass lost	67.5 g
Average specific MLR	6.55 g/(s·m²)
Total smoke release	18.2 m²/m²
Total smoke production	0.2 m²
MAHRE	53.9 kW/m²

	Mean	Peak	at time (s)
Heat release rate (kW/m²)	37.12	90.48	103
Effective heat of comb. (MJ/kg)	5.88	22.01	111
Mass loss rate (g/s)	0.056	0.159	97
Specific extinction area (m²/kg)	-14.89	708.84	1290
Carbon monoxide yield (kg/kg)	0.0277	48.8657	1019
Carbon dioxide yield (kg/kg)	0.58	1244.58	105

Test averages

from ignition to ignition plus...	1 min	2 min	3 min	4 min	5 min	6 min	0 s - 1297 s	80 s - 1297 s
Heat release rate (kW/m²)	82.72	73.72	70.62	68.86	66.87	64.55	35.03	37.00
Effective heat of comb. (MJ/kg)	7.28	6.68	6.63	6.72	6.70	6.80	5.82	5.89
Mass loss rate (g/s)	0.100	0.098	0.094	0.091	0.088	0.084	0.052	0.056
Specific extinction area (m²/kg)	-19.59	-18.51	-18.67	-18.02	-18.45	-18.46	-12.78	-14.79
Carbon monoxide yield (kg/kg)	0.0012	0.0024	0.0035	0.0043	0.0047	0.0052	0.0274	0.0280
Carbon dioxide yield (kg/kg)	0.64	0.72	0.72	0.71	0.70	0.71	0.56	0.58

Smoke results

Total smoke release: non-flaming phase (0 s - 80 s)	16.1 m²/m²
Total smoke release: flaming phase (80 s - 1290 s)	18.2 m²/m²
Total smoke release: whole test (0 s - 1290 s)	34.3 m²/m²

The test results relate to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the product in use.

Cone Calorimeter Test Report

Laboratory name	UW Fire Research Lab
Operator	Sergio Suarez
Filename	D:\Masters\ECR\CORE FR\13100020.CSV
Report name	ECR-WC-6
Sample description	Individual Materials
Material name/ID	ECR-WC-6

Additional specimen preparation information

Pre-test comments Core FR - Extra Testing

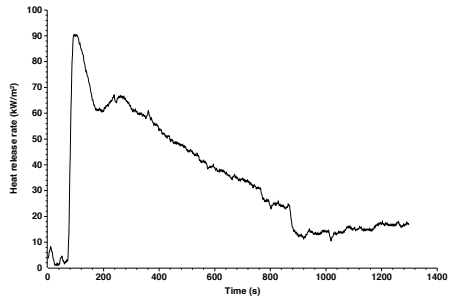
After-test comments

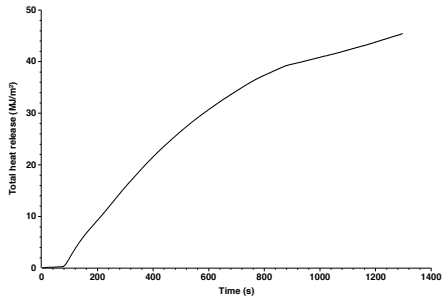
Recorded events

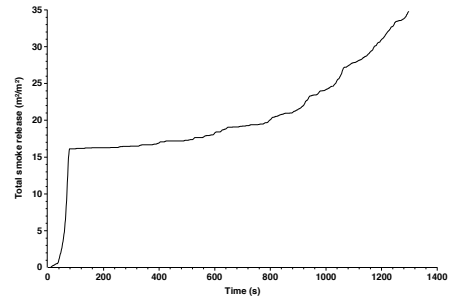
The test results relate to the behaviour of the test specimens of a product under the particular conditions of the test; they are not intended to be the sole criterion for assessing the potential fire hazard of the product in use.

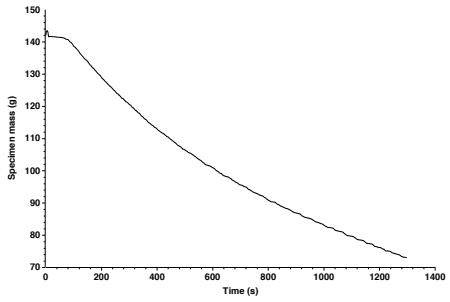
Cone Calorimeter Test Report

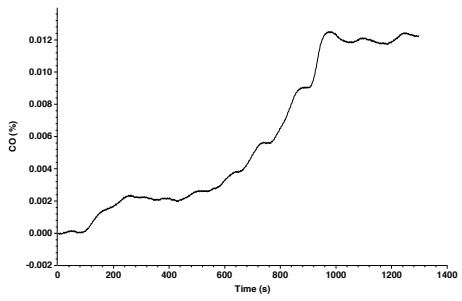
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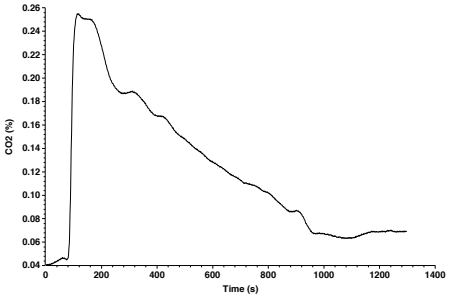












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Appendix B

Cone Calorimeter

The cone calorimeter used in this research is located at the University of Waterloo Fire Research Group[42]. The group laboratory is located at:

Waterloo Region Emergency Services Training and Research Complex
1001 Erb'S Road, RR 3
Waterloo, ON N2J 3Z4

The cone used in this work is manufactured by Fire Testing Technology (FTT)[25]. The specification of the cone is given below:

Name: Cone Calorimeter (Dual)
Model: ISO 5660 ASTM E 1354 Complaint
Serial Number: 2042186

Appendix C

Preliminary Cone Calorimetry Testing

In order to gain an understanding of the behaviour and fire performance characteristics that a laminated MDF panel would exhibit when tested in the cone calorimeter, an initial set of tests are carried out with different samples and different calorimeter configurations. The first tests are done using two FR-FR-FR samples and one NFR-NFR-NFR with a 50kW/m^2 heat flux and the standard 25mm separation between the bottom of the cone heater and the top surface of the sample. The following table summarizes the results:

Table C.1: Preliminary testing - first round.

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$(s)	Mass Lost (%)
FR-FR-FR-1	42	N/A	78	82	65
FR-FR-FR-2	67	N/A	253	50	
NFR-NFR-NFR-1	62	N/A	N/A	N/A	

The first two samples demonstrate that these specimens burn for a long period of time up to the maximum capacity of the Dierite filters on the cone calorimeter. More importantly, the NFR-NFR-NFR sample are observed to explode and damage the igniter arm of the cone calorimeter system.

For the second round of testing, two more FR-FR-FR samples are used with a modified heat flux of 35kW/m^2 and a sample to cone separation of 50mm. This test setup does not yield any results since the specimens fail to ignite with the lower incident heat flux and larger cone-to-sample spacing.

The last trial in these preliminary tests is conducted using a shield guard over the sample, but with the higher heat flux of 50kW/m^2 and smaller cone-to-sample separation distance of 25mm. Using this test setup, testing is successful leading to following results:

Table C.2: Preliminary testing - third round.

Specimen Type	t_{ig} (s)	t_{out} (s)	q_{peak} (kW/m^2)	$t_{q_{peak}}$(s)	Mass Lost (%)
FR-FR-FR	63	1081	168.2	80	40
FR-FR-NFR	251	1049	84.34	337	22

While these tests do not provide final, reliable data, they do provide a baseline set of conditions under which the testing in this thesis is carried out. The following conclusions are made and carried through the testing and analysis for the final results:

- laminated MDF panels may burn and smoulder long enough to reach the time limit of testing of 3100 seconds;
- an incident heat flux of 50kW/m^2 is required to ensure ignition and provide comparative results for different samples;
- a cone to sample separation of 25mm can be used as long as the shield guard is used; and
- since the preliminary samples do demonstrate some sample to sample variability, a least three samples of each specimen population should be tested.

Appendix D

Arborite Laminate Specifications

Arborite is a manufacturer of high pressure laminates. Their product range includes plastic, metal, epoxy and other types of laminates that are used for different finishes of wood panel materials and particle board laminates. ECR uses these laminates as their main offering to provide a fire rated front and back of their laminated PB. For further information on the technical specifications of the Arborite materials used in this work see the list below for the reference material.

- General Purpose Laminate - Front FR
  http://www.arborite.com/en/content/download/257/1608/version/19/file/Arborite+Postforming+%26+General+Purpose+Laminate+-+December+2013.pdf
- Backing Grade Laminate - Back NFR
  http://www.arborite.com/en/content/download/264/1633/version/8/file/Arborite+Backing+Laminate+-+September+2014.pdf
- Fire Rated Laminate - Front and Back FR
  http://www.arborite.com/en/content/download/260/1620/version/25/file/Arborite+Fire+Rated+Laminates+-+September+2014.pdf