Fire Performance of Ordinary, Non-listed and Non-metallic IBCs with Aqueous Solutions of Flammable and Combustible Liquids

Phase 1: Small Scale Testing of Solutions

Final Report

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FIRE RESEARCH

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FOREWORD

As part of the Fire Protection Research Foundation's mission to develop data to support NFPA technical committees, two previous research studies on IBCs with flammable and combustible liquids have been conducted. Each has provided information which is referenced in NFPA 30; however, the proliferation of IBCs used for storage in violation of NFPA 30 continues. There are several strategies which have been discussed by the members of NFPA 30 and others to address this situation, including increased enforcement of NFPA 30, education programs, development of new IBC technology, etc. There is a general agreement that a common understanding of the range of liquids that can be stored in ordinary non listed, non-metallic IBC's to meet the requirements of NFPA 30 is an important element.

The objective of the project is to develop credible independent data to support a low fire hazard designation (in consideration of NFPA 30) for a group of commonly used aqueous liquids and emulsions that may exhibit a flash point, though containing high concentrations of noncombustible substances. The consideration is storage of such mixtures in non-listed composite IBCs in a manner that will be recognized by NFPA 30 as "protected storage."

Fire Performance of Ordinary, Non-listed and Non-metallic IBCs with Aqueous Solutions of Flammable and Combustible Liquids

Phase 1: Small Scale Testing of Solutions

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Fire Performance of Ordinary, Non-listed and Non-metallic IBCs with Aqueous Solutions of Flammable and Combustible Liquids Phase 1: Small Scale Testing of Solutions

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CONTENTS

EXECUTIVE SUMMARY

Objectives

The overall objective of the project is to develop a set of flammability data for a group of commonly used aqueous liquids that may exhibit a flash point, with a particular emphasis on supporting a low fire hazard designation for certain kinds of liquid (in consideration of NFPA 30).

Phase 1 of the project consists of small scale testing of representative aqueous solutions of polar solvents in order to develop a proposed classification scheme based on performance in the tests, and to develop a full-scale validation test plan. It must be emphasised that any proposed classification scheme based on small-scale testing will require validation, through full-scale testing, before it could be reliably used.

Summary

Thirty aqueous blends of flammable / combustible solvents were selected and subjected to small scale testing: flash point, fire point and cone calorimetry. The data reveals that the fire behaviour of these solutions can be complex. However, a number of “strawman” criteria have been proposed for the identification of those blends considered to present a low fire hazard. These are :

- i) No flash to the onset of boiling in closed cup flash point testing;
- ii) Time to ignition of solution greater than typical sprinkler activation time, suggest > 20 seconds;
- iii) Low maximum *rate of heat release* in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 250 kW/m^2;
- iv) FPI > 0.08 m^2 s/kW (based on a time to ignition of < 20 seconds and a maximum rate of heat release of < 250 kW/m^2);
- v) Low *total heat release* per m^2 in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 100 MJ/m^2.

Recommendations

Large scale fire testing should be carried out both to evaluate the validity of the “strawman” criteria and to develop understanding of the fundamental phenomena that characterise the fire hazard.

Details of the proposed validation testing will be reported separately.

1 INTRODUCTION

There has been for some time concern regarding the fire hazard presented by the storage of flammable and combustible liquids within plastic and composite plastic / metal intermediate bulk containers (IBCs). As a result the U.S. National Fire Protection Association "Flammable and Combustible Liquids Code", NFPA 30, places restrictions on the permissible uses of such IBCs. Combustible Liquids (Classes II and III) are only allowed in rigid plastic / composite IBCs that have been listed following successful testing in a standard IBC fire test. Paragraph 9.4.1.1 of the 2008 edition of NFPA 30, "*Flammable and Combustible Liquids Code"*, states: "For protected storage, rigid nonmetallic intermediate bulk containers, as described in 9.4.1(5), shall be subjected to a standard fire test that demonstrates acceptable inside storage fire performance and shall be listed and labeled."

This restriction may be perceived as too severe by those organisations that abide by the Code but have products which they believe would not present a major fire hazard. Conversely, it is believed that there are widespread instances of the use of hazardous IBC / liquid combinations by organisations not abiding by the Code. Some organisations question the validity of the current listing scheme and also find the scheme difficult to implement outside the U.S.

NFPA 30 does allow certain liquids to be excluded (exempt) from the above requirements, as defined in Chapter 9, 9.1.4 (5) & (6):

> "(5) Liquids that have no fire point when tested in accordance with ASTM D 92, Standard Test Method for Flash and Fire Points by Cleveland Open Cup, up to the boiling point of the liquid or up to a temperature at which the liquid shows an obvious physical change
>
> (6) Liquids with a flash point greater than 95°F (35°C) in a water-miscible solution or water-miscible dispersion with a water and noncombustible solids content of more than 80 percent by weight, and which does not sustain combustion when tested in accordance with "Method of Testing for Sustained Combustibility," in accordance with Title 49, Code of Federal Regulations, Part 173, Appendix H, or the UN publication Recommendations on the Transport of Dangerous Goods"

However, it is possible that these criteria may fail to exclude other "low hazard" liquids and so the Fire Protection Research Foundation has a strategy to develop and verify the range of liquids that can be stored in ordinary non-listed, non-metallic IBCs to meet the requirements of NFPA 30.

The aim of this project is to develop a set of flammability data for a group of commonly used aqueous liquids that may exhibit a flash point, although containing high concentrations of non-combustible substances, with a particular emphasis on supporting a low fire hazard designation for certain kinds of liquid (in consideration of NFPA 30).

Phase 1 of the project consists of small scale testing of representative aqueous solutions of polar solvents in order to develop a proposed classification scheme based on performance in the tests. However, it must be emphasised that any proposed classification scheme based on small-scale testing will require validation, through full-scale testing, before it could be reliably used. It is Phase 1, i.e. the small-scale testing, that is the subject of this report.

2 OBJECTIVES AND ASSUMPTIONS

2.1 PHASE 1 PROJECT OBJECTIVES

Phase 1 of the overall project was subdivided into a number of objectives. The following sections, 2.1.1 to 2.1.3, reproduce the objectives given in the tasking document provided by NFPA Fire Research Foundation.

2.1.1 Project Scope and Detailed Work Plan:

Working with project sponsors, develop a list of common aqueous solutions of polar solvents and emulsions that will be the focus of the program. Carry out a literature review of small-scale test methods (building on work developed by a Foundation task force); and develop a candidate small-scale testing regime for review by the Project Technical Panel. The goal of the test regime is to serve as a classification method for liquids that may be referenced by NFPA. Tests may include flashpoint, fire point, and heat of combustion using agreed upon methods; small scale cone (HRR) testing should also be evaluated.

2.1.2 Small Scale Testing and Development of Strawman Performance Criteria:

Conduct tests on the solutions identified in Task 1 (estimate between 30 and 50 liquids) in accordance with the above protocol. Based on these results, evaluate the test methods and develop a proposed classification scheme based on performance in the tests for review by the Project Technical Panel.

2.1.3 Development of a Validation Plan:

Based on the results of Task 2 and guidance from the Panel, develop a full-scale validation test plan and cost estimate (testing will take place in Phase 2).

2.2 ASSUMPTIONS

Although the aim of this project is to provide data that can be used in the revision of U.S. National Fire Protection Association “Flammable and Combustible Liquids Code”, NFPA 30, it is assumed that the project will not specifically aim to test the validity of the existing exclusions in the current version of the Code, as described in Section 1 above. That is, it is not intended to deliberately test liquids that would currently be excluded by the existing criteria. However, if any new knowledge were to be established during the course of the project that contradicted the existing conditions for exclusion, this would be highlighted.

It is further assumed that chemical and physical interactions with the IBC itself are not to be considered in Phase 1, other than considering the potential for burning the plastic of the IBC bottle to present a radiant heat source for the liquid. Oxygenated organic solvents have previously been seen to interact less with HDPE, commonly used for IBC bottles, than unoxygenated organic solvents. However, this appears to depend on the size of the unoxygenated organic part of the solvent molecule; liquids such as glycols and glycol ethers may have a significant effect on the containment properties of the HDPE bottle on exposure to fire (Atkinson 2007).

3 DESCRIPTION OF THE HAZARD

There have been a number of serious fires that started or spread as the direct result of the use plastic / composite IBCs for combustible liquids. These incidents include fires at Magnablend, Waxahachie, Texas; a solvent distillation company at Sao Paulo, Brazil; Distillex, North Shields, U.K.; and P&R Laboratories, St. Helens, U.K.

The manner in which IBCs filled with flammable / combustible liquids contribute to fire development is discussed below.

3.1 FIRE DEVELOPMENT IN IBC STORES

There is a fundamental difference in the character of flame spread during a fire involving stored IBCs filled with flammable or combustible liquids as compared with “ordinary” goods that are protected by sprinkler systems. With stored regular solid (perhaps cartonised) goods flames spread rapidly upwards. There is a well-known feedback mechanism. Higher flames lead to ignition of more material above; the heat released from this newly ignited material leads to higher flames and so on. A sprinkler system must prevent this upwards spread of fire by wetting surfaces both in and above the flame.

The fire hazards associated with combustible liquids in plastic / composite IBCs have been recognised for some time (e.g. Scheffey 1996) and it has been previously established (e.g. Atkinson 2007) that flammable /combustible liquids may start to leak from plastic / composite IBCs quickly on exposure to a small fire. When an IBC loses its contents in a fire the liquid may spread widely. To some extent this can be controlled by careful use of drains and sumps but in an ordinary warehouse with a solid level floor the contents of a single IBC will spread for tens of metres covering an area of many hundreds of square meters. This liquid spread may occur in the midst of a rapidly developing fire or, for materials that are less prone to ignition, before any significant heat release has developed and before there is any possibility of sprinkler action.

It is the spread of fire across this pool that is the crucial process in advancing the fire in its initial growth phase. The primary purpose of a protection system in an IBC store should therefore be to prevent horizontal spread of fire on the pool of released liquid.

There is very little data available in the public domain regarding the flammability characteristics of aqueous blends of flammable and combustible solvents and how these relate to the resulting fire spreading behaviour. Hence it is necessary to establish a set of data for representative liquid blends, to propose criteria for classifying the liquids in terms of fire behaviour and then relate this data to large-scale validation tests.

4 SELECTION OF SMALE SCALE TESTS AND TEST METHODS

4.1 SELECTION OF TEST METHODS

The aim of Phase 1 of the project was to determine a means of identifying criteria by which the fire behaviour of aqueous liquids could be judged, with particular emphasis on identifying those that present a low hazard, by carrying out small-scale, widely-available standard test methods. To this end, following discussions with the sponsors and technical panel members, the test methods described below in Sections 4.1.1 to 4.1.3 were selected.

4.1.1 Closed Cup Flash Point, Seta Flash Rapid Equilibrium Method (BS EN ISO 3679:29004, equivalent to ASTM 3828)

The closed cup flash point temperature indicates the lowest temperature at which the vapour above a liquid surface may ignite and was therefore considered to be a potentially important parameter. This method was selected since it was expected to suffer less than the non-equilibrium Pensky-Martens test from loss of volatiles during testing, and hence artificially high measured flash points. The lower loss of volatile solvents in the Seta flash method seems to be supported by previous work with aqueous solutions (Scheffey & Taber, 1996).

4.1.2 Cleveland Open Cup Flash Point and Fire Point (ASTM D92)

The open cup flash point temperature indicates the temperature at which the vapour above a liquid surface may ignite in an open system, as would be expected for a spilled liquid, while the fire point indicates the temperature at which a liquid would continue to burn after ignition. Both of these parameters were considered to be potentially important in relation to liquid leaking from an IBC. Whilst the UN / CFR Sustained Combustion test is an alternative method of determining the sustained burning behaviour of liquids, the Cleveland open cup fire point was selected over the UN / CFR test for the following reasons: i) it also yields an open cup flash point temperature; ii) it yields an actual value for the fire point rather than simply a go / no go result at a limited number of specific temperatures.

4.1.3 Cone calorimetry (ASTM E1345)

Cone calorimetry is a test method commonly used to assess the fire hazard presented by materials due to their burning behaviour. The method can be used to evaluate the rate of heat evolution due to combustion, the total heat of combustion, the mass lost during burning and the degree of smoke generation. The assessment of the heat evolved by the combustion process is based on the general, approximate relationship that the net heat of combustion is proportional to the amount of oxygen consumed. The method therefore determines the amount of oxygen consumed while the sample burns and uses this to estimate the heat evolved.

The cone calorimeter is shown in Figures 1, 2, and 3.

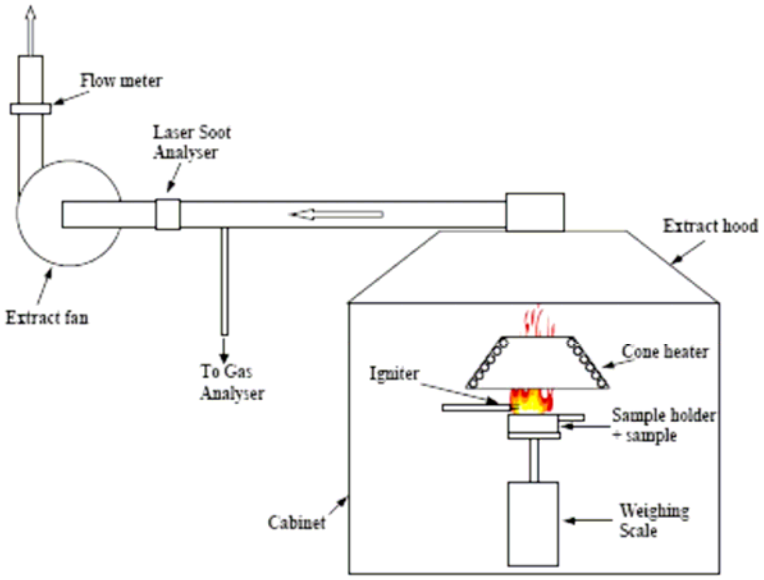


Figure 1 : Simplified schematic of Cone calorimeter

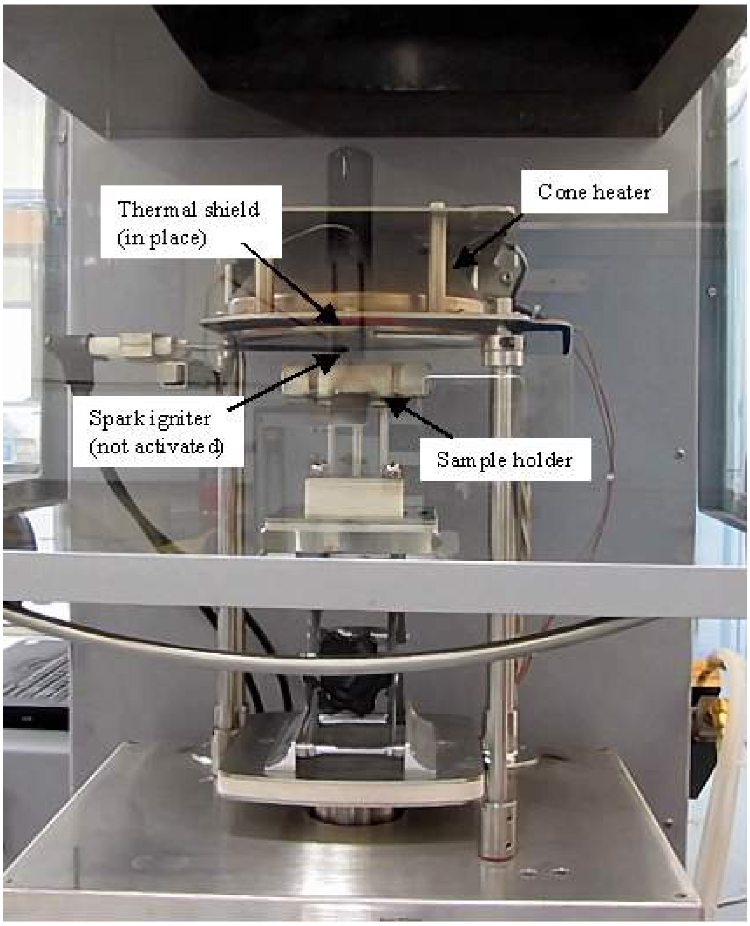


Figure 2 : Cone calorimeter shown with sample tray in place and thermal shield between the cone heater and the sample

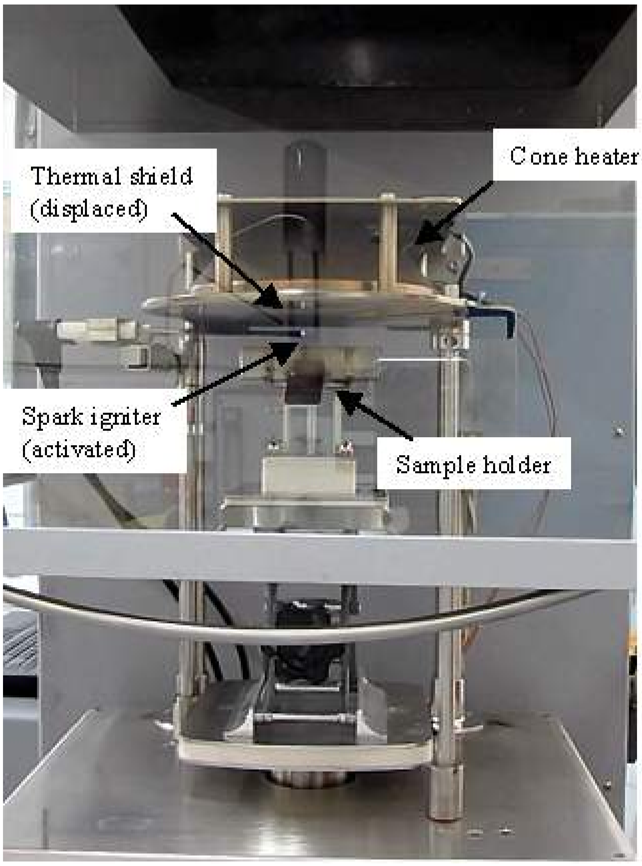


Figure 3 : Cone calorimeter shown with sample tray in place, the thermal shield displaced – i.e. no longer between sample and cone heater - and the spark ignition source active above the liquid surface.

The sample is placed in a sample holder and the weight of the sample is determined before testing. The sample and holder are positioned on a weighing system within a cabinet that is ventilated by an extract fan, and the extracted flow rate is measured. The sample can then be subject to heating using an electrically heated cone that is located above the sample. Note that the sample is not mechanically agitated during the test. The rate of heating applied by the cone can be changed in order to simulate the radiation that the test material would receive in relevant fire scenarios. A spark igniter is positioned just above the sample surface and is activated until the sample ignites, at which point it is removed. During testing the composition of the extracted air is analysed, the loss of oxygen due to combustion is determined and this is used to calculate the approximate heat of combustion. The loss in weight of the sample during testing is also determined.

Cone calorimetry is commonly used for testing solid materials when a figure of 13 MJ per kg of consumed oxygen is used; this figure was also used for the liquids tested in this work. It must be stressed that, although the cone calorimetry was carried out to the ASTM E1354 Standard, the test method is largely aimed at testing solid materials rather than liquids and there are physical phenomena, such as convection within the liquid sample, that may influence the results obtained. The main test parameters that may be varied are the area and depth of the liquid sample and the radiant heat flux applied. The parameters used during testing of the blends are not, therefore, from an agreed standard but were chosen by HSL based on the consideration of what heat flux could be expected in a developing fire scenario, and previous work involving cone calorimetry on liquids. The aim was to obtain results that would differentiate between the burning behaviour of the various test blends in terms of the time to ignition, the total heat released and rate of heat release from the liquids when ignited. Thus the data obtained would allow “ranking” of the blends rather than to provide absolute measures that could be used to exactly simulate large scale burning behaviour. The parameters used for the tests are discussed below.

The cone calorimeter method has been used on “pure” flammable liquids previously with reasonable success (Mealy, Benfer & Gottuk, 2011). In those tests, which used the standard 100 mm by 100 mm sample holder used for solids, the rate of heat release was found to depend upon the liquid depth, with the highest heat outputs determined at the maximum depth tested, 10 mm. Therefore, for consistency with that work, a 10 mm liquid depth was used for testing the blends.

The tests on the blends were carried out using an incident heat flux of 35 kW/m^2. This heat flux was chosen since it was considered to be representative of the early stages of the type of developing fire scenario that is of interest in this project. The heat flux from a fully developed fire would of course be somewhat higher than this (typically two to three times) although by that stage the fire situation would already be out of control.

In order to test the hypothesis that the chosen test parameters would yield results that could distinguish between blends that were expected to exhibit differing burning behaviours, five of the blends (15, 17, 25, 27 and 30) were initially tested and the results considered. Based on there being significant differences observed, it was decided to continue and test the remaining 25 blends using the same test conditions.

4.2 SELECTION OF TEST LIQUIDS

The liquids to be included in the tests were selected following input from the project sponsors and technical panel. In order that the selected liquids possessed a wide range of characteristics and were able, therefore, to generate useful data, the following parameters were considered:

i) The flash point and fire point of the flammable / combustible material present and the expected flash point and fire point of each blend.

ii) The potential total heat of combustion and rate of heat release. Both of these parameters would be expected to be a function of the type and concentration of the flammable / combustible material present.

iii) The boiling point of the flammable / combustible material compared to that of water. Those with a boiling point higher than water would be expected to become concentrated when exposed to heat, whereas those with a boiling point lower than water would be expected to evaporate faster than the water (i.e. loss of solvent versus loss of water on heating).

iv) The physical form of each blend, such as viscosity, emulsion versus single-phase blend, solids content, and changes in form / solubility on exposure to heat.

Lists of liquid blends were suggested by the project sponsors. Initially, aqueous silicone emulsions were included in sponsors’ lists. However, these were later withdrawn from the list after testing by FM Global, yet to be published, showed that the emulsions did not exhibit a fire point.

The number of suggested blends was greater than the number of liquids that could be accommodated within the project. Therefore, it was necessary to accept some and reject others.

The sponsor lists were considered with the aim of selecting blends that fitted the following :

i) Aqueous blends of soluble / miscible solvent(s) in water (not 100% materials nor immiscible mixtures at ambient temperature);

ii) Blends containing volatile, lower boiling point solvents (compared to water);

iii) Blends containing less volatile, higher boiling point solvents (compared to water);

iv) Multi-component blends containing mixtures of low & high volatility solvents in water;

v) Blends containing solvents with limited solubility or unusual solubility behaviour (e.g. decreasing solubility as temperature raised);

vi) Blends that provided a wide range of potential heats of combustion throughout a wide range of anticipated flashpoints.

In addition, the Technical Panel and HSL tried to avoid selecting too many liquids that could potentially be excluded by the existing criteria given in NFPA 30 (e.g. no fire point / very low potential heat of combustion).

A list of 30 liquid blends was developed, based on sponsors list but with two additions by HSL to fill “gaps” in blend range. The full list is given in Appendix 8.1.

5 RESULTS / ANALYSIS

5.1 OVERALL SUMMARY OF RESULTS

The test results for all of the thirty blends are summarised in Table 1. This table of results includes the closed and open cup flash point temperatures, the fire point temperatures, and the main outputs from the cone calorimetry testing. The detailed outputs from the cone calorimetry testing are reproduced in Appendix 8.2.

In order to obtain an appreciation for the range of liquids included in the tests, a chart of "Potential Heat of Combustion versus NFPA Flammability Class" is presented in Figure 4. The Flammability Class has been determined based on the closed cup flash point results.

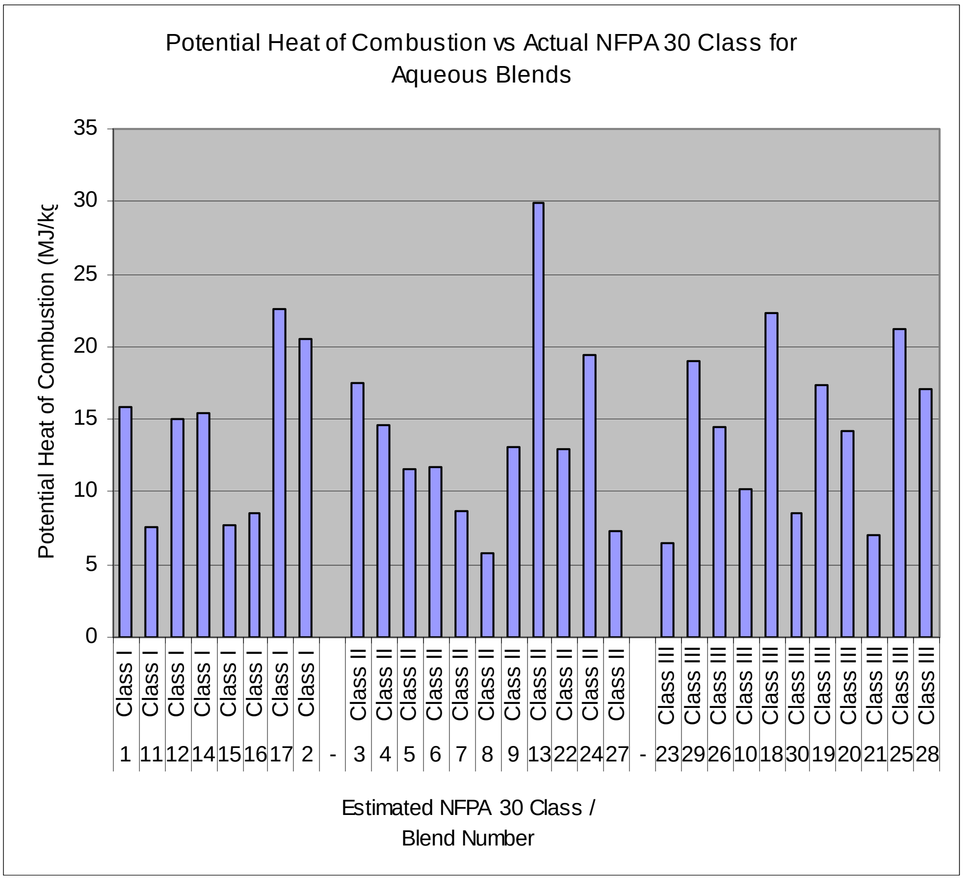


Figure 4 : Potential Heat of Combustion versus Flammability Class for the 30 Blends selected for testing

Blend No.	Composition (%wt/wt in water)	Closed Cup Flash Point - BS EN ISO 3679:2004		Open Cup Flash Point and Fire Point - ASTM D92-05a (IP 36/84 (89))		Cone Calorimetry (ISO 5660 / ASTM E1354)						
		Flash Point ºC (°F)	Observations	Flash Point ºC (°F)	Fire Point ºC (°F)	Time to Ignition, Ti (s)	Total Heat Released (MJ/m^2)	% of Potential Heat Released	Maximum Rate of Heat Release, HRRmax (kW/m^2)	% Mass Loss	FPI : =Ti/HRRmax (m^2 s/kW)	1/FPI
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	32 (90)		39 (102)	46 (115)	3	176.5	115	503.4	100	0.0060	167.8
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	36 (97)		46 (115)	50 122)	5	223.3	118	693.2	99	0.0072	138.6
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	39 (102)		52 (126)	52 (126)	2	195.6	118	601.5	100	0.0033	300.8
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	43 (109)		58 (136)	60 (140)	6	164.7	118	464.2	100	0.0129	77.4
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	51 (124)		66 (151)	84 (183)	14	134.5	120	376.3	100	0.0372	26.9
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	41 (106)		56 (133)	58 (136)	5	136.5	119	387.8	97	0.0129	77.6
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	50 (122)		64 (147)	80 (176)	9	87.6	102	383	67	0.0235	42.6
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	44 (111)		60 (140)	72 (162)	8	45.7	77	240.4	37	0.0333	30.1
9	90% Acetic Acid	48 (118)		66 (151)	92 (198)	5	157.5	115	445.2	97	0.0112	89.0
10	70% Acetic Acid	No Flash	65°C (149 F) burns at orifice	>104 (>219)	>104 (>219)	58	109.4	112	329.2	100	0.1762	5.7

Blend No.	Composition (%wt/wt in water)	Closed Cup Flash Point - BS EN ISO 3679:2004		Open Cup Flash Point and Fire Point - ASTM D92-05a (IP 36/84 (89))		Cone Calorimetry (ISO 5660 / ASTM E1354)						
		Flash Point ºC (°F)	Observations	Flash Point ºC (°F)	Fire Point ºC (°F)	Time to Ignition, Ti (s)	Total Heat Released (MJ/m^2)	% of Potential Heat Released	Maximum Rate of Heat Release, HRRmax (kW/m^2)	% Mass Loss	FPI : =Ti/HRRmax (m^2 s/kW)	1/FPI
11	25% Propanol	27 (81)		35 (95)	43 (109)	5	76.8	105	532.5	37	0.0094	106.5
12	50% Propanol	21 (70)		35 (95)	35 (95)	1	175.7	129	739.4	78	0.0014	739.4
13	90% Butanol	44 (111)		59 (138)	59 (138)	1	279.1	113	1199.7	100	0.0008	1199.7
14	50% Acetone	-12 (10)		<20 (<68)	<20 (<68)	1	144.1	101	1238.4	59	0.0008	1238.4
15	25% Acetone	-2 (28)		<20 (<68)	<20 (<68)	1	60.5	80	645.8	26	0.0015	645.8
16	25% Methyl Ethyl Ketone	-4 (25)		<20 (<68)	<20 (<68)	1	82.1	100	838.1	29	0.0012	838.1
17	75% 2-Propanol	19 (66)		32 (90)	32 (90)	1	218.5	114	894.4	96	0.0011	894.4
18	90% Butyric Acid	No Flash	98°C (208 F) No Flash	96 (205)	104 (219)	8	244.3	111	799.3	100	0.0100	99.9
19	70% Butyric Acid	-	Not tested	106 (223)	110 (230)	53	192.3	110	552.4	100	0.0959	10.4
20	50% Ethylene glycol monobutyl ether	No Flash	95°C (203 F)No flash	67 (153)	67 (153)	73	164.7	120	459	100	0.1590	6.3
21	25% Ethylene glycol monobutyl ether	No Flash	75°C (167 F) Small blue flame above cup	No Flash	73 (163)	80	55.9	83	441.7	43	0.1811	5.5
22	50% Propylene glycol monomethyl ether	53 (127)		73 (163)	77 (171)	18	145.9	113	437.8	100	0.0411	24.3
23	25% Propylene glycol monomethyl ether	65 (149)		95 (203)	95 (203)	93	6.6	10	96.7	20	0.9617	1.0
24	75% Propylene glycol monomethyl ether	45 (113)		59 (138)	61 142)	4	212.2	113	655.3	99	0.0061	163.8
25	75% Ethylene glycol monobutyl ether	No Flash	75°C (167 F) Small blue flame above cup	No Flash	71 (160)	19	236.4	118	1145.5	99	0.0166	60.3
26	70% Propionic acid	No Flash	65°C (149 F) Small blue flame above cup	57 (135)	57 (135)	22	167.7	114	393.4	98	0.0559	17.9
27	10% Propanol 30% Ethylene glycol	38 (100)		52 (126)	70 (158)	10	42.7	52	393.4	24	0.0254	39.3
28	40% Ethylene glycol monobutyl ether	No Flash	71°C (160 F) Small blue flame above cup	No Flash	79 (174)	46	190.1	117	737.3	100	0.0624	16.0

Blend No.	Composition (%wt/wt in water)	Closed Cup Flash Point - BS EN ISO 3679:2004		Open Cup Flash Point and Fire Point - ASTM D92-05a (IP 36/84 (89))		Cone Calorimetry (ISO 5660 / ASTM E1354)						
		Flash Point ºC (°F)	Observations	Flash Point ºC (°F)	Fire Point ºC (°F)	Time to Ignition, Ti (s)	Total Heat Released (MJ/m^2)	% of Potential Heat Released	Maximum Rate of Heat Release, HRRmax (kW/m^2)	% Mass Loss	FPI : =Ti/HRRmax (m^2 s/kW)	1/FPI
	20% Ethylene glycol monopropyl ether											
29	70% Dipropylene glycol	No Flash	96°C (205 F) Pilot flame extinguished	>122 (>252)	>122 (>252)	106	15.6	8	327.4	18	0.3238	3.1
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	No Flash	86°C (187 F) Flame lift off and extinguished	No Flash	91 (196)	155	18.3	22	265.6	34	0.5836	1.7

Table 1 : Summary of Results for all 30 Blends.

It is evident from the results that the total heat of combustion determined in the cone calorimetry often exceeded the theoretical maximum based on heat of combustion values from literature and the difference is outside the normal tolerances expected for cone calorimetry tests on solid materials. The nature of the discrepancy would suggest a systematic error, although it is understood that the cone calorimeter had previously been calibrated. Other sources of discrepancy, such as water vapour from the samples diluting the oxygen and leading to a higher energy determination, have been considered and dismissed on the basis of them being insignificant. Although the reason for the discrepancy is not known, and absolute energy values may be slightly over-estimated, it is considered that the method was successful in achieving its primary purpose, i.e. a ranking of the blends and giving approximate heat release rates.

The cone calorimetry tests were recorded on video and stills from some of the tests are given below (Figures 5 to 8) to demonstrate some differences in burning behaviour.

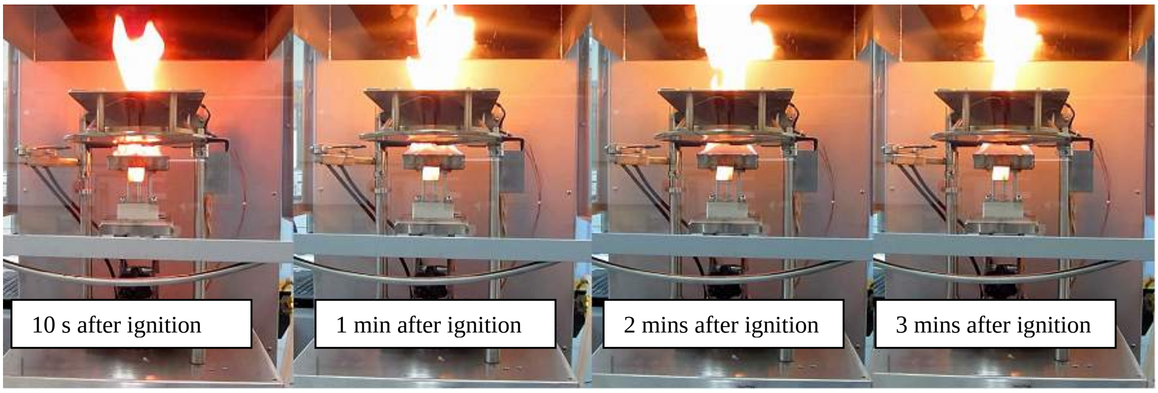


Figure 5 : Blend 13, 90% w/w butanol, quick ignition and fire development, sustained for full extent of fuel, high rate of heat release.

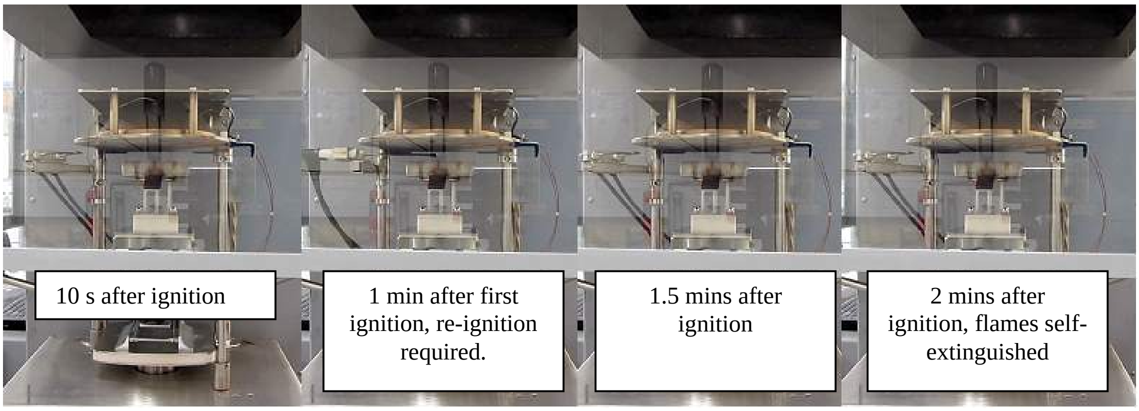


Figure 6 : Blend 23, 25% w/w propylene glycol monomethyl ether, ignition occurred after 93 seconds, low rate of heat release, flames self-extinguished and were re-ignited after 1 minute, only 10% of potential heat of combustion realised before flames self-extinguished again.

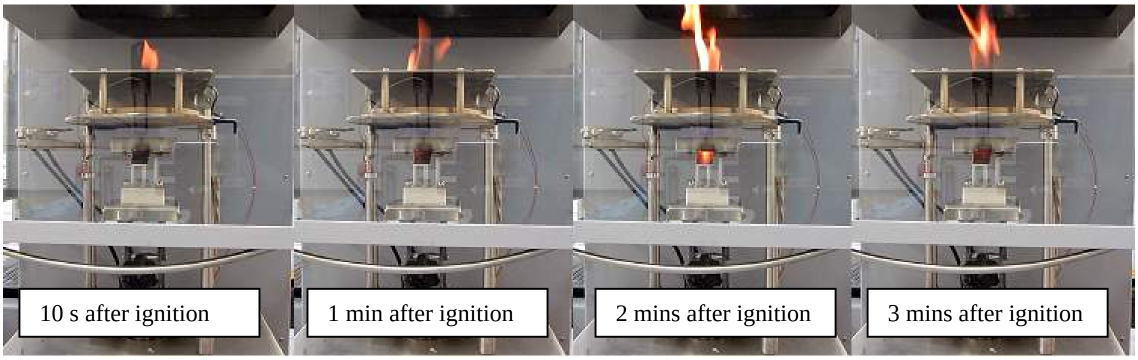


Figure 7 : Blend 4, 10% w/w isopropyl alcohol, 10% w/w n-butanol, 30% ethylene glycol monobutyl ether, ignition after a few seconds, all fuel consumed, medium rate of heat release.

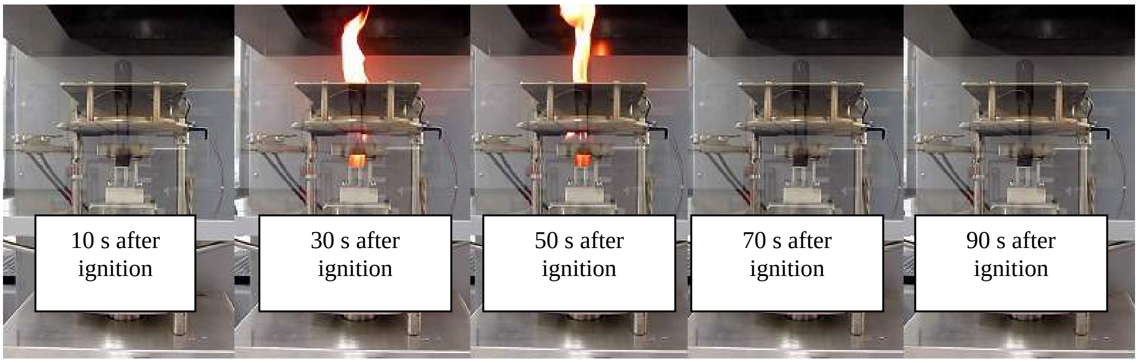


Figure 8 : Blend 29, 70% dipropylene glycol, 106 seconds to ignition, fairly low heat release rate, less than 10% of potential heat realised before the flames self- extinguished.

In addition to the direct test results, Table 1 also includes the calculated values for the Fire Performance Index (FPI), the percentage of potential heat of combustion actually realised, and the percentage mass loss for each blend. The FPI is the quotient of the time to ignition, T_i, divided by the maximum rate of heat release, HRR_{max}. FPI is quoted as an important parameter when considering the fire hazard presented by solid materials since it relates to the time to flashover (Beyer 2006). The higher the value of the FPI the lower the fire hazard presented, e.g. untreated paper = 0.03, paper + flame retardant 1.73 (US Patent No. 6,372,360 B1).

The Fire Performance Index versus Blend number is shown in Figure 9.

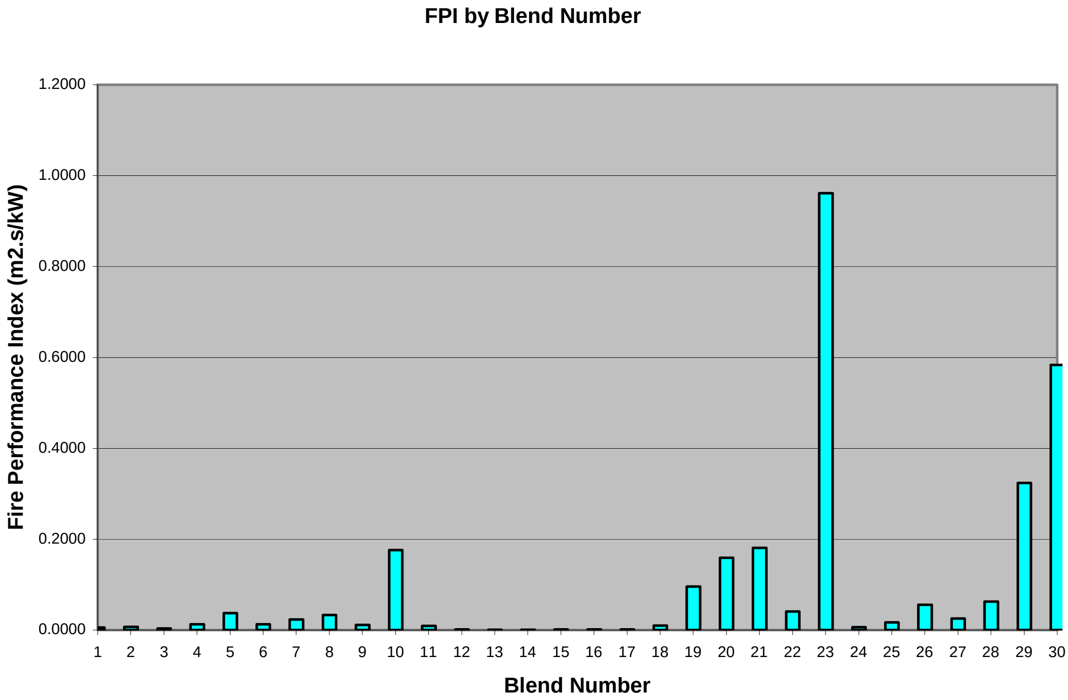


Figure 9 : FPI versus Blend number

5.2 ANALYSIS OF RESULTS

5.2.1 Identification of Overall Trends

The following tables, 2 to 8, show the results for closed cup flash point, open cup flash point, fire point, time to ignition, total heat released, rate of heat release and FPI. In each table the blends are listed in order of fire hazard indicated by the result, with the greatest fire hazard at the top and the lowest fire hazard at the bottom.

Blend No.	Composition (%wt/wt in water)	Closed Cup Flash Point – BS EN ISO 3679:2004 °C (ºF)
14	50% Acetone	-12 (10)
16	25% Methyl Ethyl Ketone	-4 (25)
15	25% Acetone	-2 (28)
17	75% 2-Propanol	19 (66)
12	50% Propanol	21 (70)
11	25% Propanol	27 (81)
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	32 (90)
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	36 (97)
27	10% Propanol 30% Ethylene glycol	38 (100)
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	39 (102)
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	41 (106)
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	43 (109)
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	44 (111)
13	90% Butanol	44 (111)
24	75% Propylene glycol monomethyl ether	45 (113)
9	90% Acetic Acid	48 (118)
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	50 (122)
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	51 (124)
22	50% Propylene glycol monomethyl ether	53 (127)
23	25% Propylene glycol monomethyl ether	65 (149)
10	70% Acetic Acid	No Flash
18	90% Butyric Acid	No Flash
19	70% Butyric Acid	Not tested, no flash expected based on 90% result
20	50% Ethylene glycol monobutyl ether	No Flash
21	25% Ethylene glycol monobutyl ether	No Flash
25	75% Ethylene glycol monobutyl ether	No Flash
26	70% Propionic acid	No Flash
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	No Flash
29	70% Dipropylene glycol	No Flash
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	No Flash

Table 2 : Closed Cup Flash Point Temperature for all 30 Blends

Blend No.	Composition (%wt/wt in water)	Open Cup Flash Point – ASTM D92-05a (IP 36/84 (89)) ºC (°F)
14	50% Acetone	<20 (<68)
15	25% Acetone	<20 (<68)
16	25% Methyl Ethyl Ketone	<20 (<68)
17	75% 2-Propanol	32 (90)
11	25% Propanol	35 (95)
12	50% Propanol	35 (95)
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	39 (102)
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	46 (115)
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	52 (126)
27	10% Propanol 30% Ethylene glycol	52 (126)
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	56 (133)
26	70% Propionic acid	57 (135)
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	58 (136)
13	90% Butanol	59 (138)
24	75% Propylene glycol monomethyl ether	59 (138)
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	60 (140)
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	64 (147)
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	66 (151)
9	90% Acetic Acid	66 (151)
20	50% Ethylene glycol monobutyl ether	67 (153)
22	50% Propylene glycol monomethyl ether	73 (163)
23	25% Propylene glycol monomethyl ether	95 (203)
18	90% Butyric Acid	96 (205)
10	70% Acetic Acid	>104 (>219)
19	70% Butyric Acid	106 (223)
29	70% Dipropylene glycol	>122 (>252)
21	25% Ethylene glycol monobutyl ether	No Flash
25	75% Ethylene glycol monobutyl ether	No Flash
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	No Flash
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	No Flash

Table 3 : Open Cup Flash Point Temperature for all 30 Blends

Blend No.	Composition (%wt/wt in water)	Open Cup Fire Point - ASTM D92-05a (IP 36/84 (89)) °C (ºF)
14	50% Acetone	<20 (<68)
15	25% Acetone	<20 (<68)
16	25% Methyl Ethyl Ketone	<20 (<68)
17	75% 2-Propanol	32 (90)
12	50% Propanol	35 (95)
11	25% Propanol	43 (109)
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	46 (115)
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	50 (122)
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	52 (126)
26	70% Propionic acid	57 (135)
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	58 (136)
13	90% Butanol	59 (138)
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	60 (140)
24	75% Propylene glycol monomethyl ether	61 (142)
20	50% Ethylene glycol monobutyl ether	67 (153)
27	10% Propanol 30% Ethylene glycol	70 (158)
25	75% Ethylene glycol monobutyl ether	71 (160)
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	72 (162)
21	25% Ethylene glycol monobutyl ether	73 (163)
22	50% Propylene glycol monomethyl ether	77 (171)
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	79 (174)
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	80 (176)
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	84 (183)
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	91 (196)
9	90% Acetic Acid	92 (198)
23	25% Propylene glycol monomethyl ether	95 (203)
10	70% Acetic Acid	>104 (>219)
18	90% Butyric Acid	104 (219)
19	70% Butyric Acid	110 (230)
29	70% Dipropylene glycol	>122 (>252)

Table 4 : Open Cup Fire Point Temperature for all 30 Blends

Blend No.	Composition (%wt/wt in water)	Time to Ignition, Ti (s)
12	50% Propanol	1
13	90% Butanol	1
14	50% Acetone	1
15	25% Acetone	1
16	25% Methyl Ethyl Ketone	1
17	75% 2-Propanol	1
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	2
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	3
24	75% Propylene glycol monomethyl ether	4
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	5
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	5
9	90% Acetic Acid	5
11	25% Propanol	5
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	6
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	8
18	90% Butyric Acid	8
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	9
27	10% Propanol 30% Ethylene glycol	10
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	14
22	50% Propylene glycol monomethyl ether	18
25	75% Ethylene glycol monobutyl ether	19
26	70% Propionic acid	22
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	46
19	70% Butyric Acid	53
10	70% Acetic Acid	58
20	50% Ethylene glycol monobutyl ether	73
21	25% Ethylene glycol monobutyl ether	80
23	25% Propylene glycol monomethyl ether	93
29	70% Dipropylene glycol	106
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	155

Table 5 : Time to Ignition for all 30 Blends

Blend No.	Composition (%wt/wt in water)	Total Heat Released (MJ/m^2)
13	90% Butanol	279.1
18	90% Butyric Acid	244.3
25	75% Ethylene glycol monobutyl ether	236.4
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	223.3
17	75% 2-Propanol	218.5
24	75% Propylene glycol monomethyl ether	212.2
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	195.6
19	70% Butyric Acid	192.3
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	190.1
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	176.5
12	50% Propanol	175.7
26	70% Propionic acid	167.7
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	164.7
20	50% Ethylene glycol monobutyl ether	164.7
9	90% Acetic Acid	157.5
22	50% Propylene glycol monomethyl ether	145.9
14	50% Acetone	144.1
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	136.5
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	134.5
10	70% Acetic Acid	109.4
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	87.6
16	25% Methyl Ethyl Ketone	82.1
11	25% Propanol	76.8
15	25% Acetone	60.5
21	25% Ethylene glycol monobutyl ether	55.9
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	45.7
27	10% Propanol 30% Ethylene glycol	42.7
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	18.3
29	70% Dipropylene glycol	15.6
23	25% Propylene glycol monomethyl ether	6.6

Table 6 : Total Heat Released by each of the 30 Blends

Blend No.	Composition (%wt/wt in water)	Maximum Rate of Heat Release, HRRmax (kW/m^2)
14	50% Acetone	1238.4
13	90% Butanol	1199.7
25	75% Ethylene glycol monobutyl ether	1145.5
17	75% 2-Propanol	894.4
16	25% Methyl Ethyl Ketone	838.1
18	90% Butyric Acid	799.3
12	50% Propanol	739.4
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	737.3
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	693.2
24	75% Propylene glycol monomethyl ether	655.3
15	25% Acetone	645.8
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	601.5
19	70% Butyric Acid	552.4
11	25% Propanol	532.5
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	503.4
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	464.2
20	50% Ethylene glycol monobutyl ether	459
9	90% Acetic Acid	445.2
21	25% Ethylene glycol monobutyl ether	441.7
22	50% Propylene glycol monomethyl ether	437.8
26	70% Propionic acid	393.4
27	10% Propanol 30% Ethylene glycol	393.4
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	387.8
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	383
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	376.3
10	70% Acetic Acid	329.2
29	70% Dipropylene glycol	327.4
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	265.6
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	240.4
23	25% Propylene glycol monomethyl ether	96.7

Table 7 : Maximum Rate of Heat Release for all 30 Blends

Blend No.	Composition (%wt/wt in water)	FPI (Ti/HRRmax)
13	90% Butanol	0.0008
14	50% Acetone	0.0008
17	75% 2-Propanol	0.0011
16	25% Methyl Ethyl Ketone	0.0012
12	50% Propanol	0.0014
15	25% Acetone	0.0015
3	15% 1-Butanol 15% 2-Propanol 30% Ethylene glycol monobutyl ether	0.0033
1	20% Propanol 12% Ethylene glycol 30% Propylene glycol monomethyl ether	0.0060
24	75% Propylene glycol monomethyl ether	0.0061
2	20% 1-Butanol 20% 2-Propanol 30% Ethylene glycol monobutyl ether	0.0072
11	25% Propanol	0.0094
18	90% Butyric Acid	0.0100
9	90% Acetic Acid	0.0112
4	10% 1-Butanol 10% 2-Propanol 30% Ethylene glycol monobutyl ether	0.0129
6	10% 1-Butanol 10% 2-Propanol 20% Ethylene glycol monobutyl ether	0.0129
25	75% Ethylene glycol monobutyl ether	0.0166
7	5% 1-Butanol 5% 2-Propanol 20% Ethylene glycol monobutyl ether	0.0235
27	10% Propanol 30% Ethylene glycol	0.0254
8	5% 1-Butanol 5% 2-Propanol 10% Ethylene glycol monobutyl ether	0.0333
5	5% 1-Butanol 5% 2-Propanol 30% Ethylene glycol monobutyl ether	0.0372
22	50% Propylene glycol monomethyl ether	0.0411
26	70% Propionic acid	0.0559
28	40% Ethylene glycol monobutyl ether 20% Ethylene glycol monopropyl ether	0.0624
19	70% Butyric Acid	0.0959
20	50% Ethylene glycol monobutyl ether	0.1590
10	70% Acetic Acid	0.1762
21	25% Ethylene glycol monobutyl ether	0.1811
29	70% Dipropylene glycol	0.3238
30	20% Ethylene glycol monobutyl ether 10% Propylene glycol monomethyl ether	0.5836
23	25% Propylene glycol monomethyl ether	0.9617

Table 8 : FPI for all 30 Blends

Of the blends tested, the following generalisations can be made :

i) Only Blend 10 and Blend 29 could potentially be eligible for being excluded from the requirements in NFPA 30 under the existing scheme, since they did not exhibit a fire point before they started to boil (i.e. undergo a physical change).

ii) All of the blends containing volatile solvents at a level of more than 10% wt/wt ignited quickly in the cone calorimetry tests (within 10 seconds). Those containing 90% wt/wt of less volatile solvents (i.e. acetic acid, butyric acid and n-butyl alcohol) also ignited quickly.

iii) Note that while all of those blends with a fire point less than approximately 60ºC exhibited short ignition times (i.e. a few seconds), those blends with high fire point temperatures did not always exhibit a significantly longer ignition time. This was especially true of blends containing high levels of solvent. A similar lack of definitive behaviour was evident in the open cup flash point temperature.

iv) Most of the blends exhibited a maximum rate of heat output at least as large as that expected from a typical NFPA Class III commodity, such as cardboard. The following values have been reported for cardboard; 220 kW/m^2 for 6 mm thick board at an irradiance of 50 kW/m^2, and 125 kW/m^2 for 2.5 mm thick board at an irradiance of 20 kW/m^2. Only Blend 8 (at 240 kW/m^2), Blend 23 (at 97 kW/m^2) and Blend 30 (at 266 kW/m^2) exhibited a maximum rate of heat output comparable, or less than that of cardboard.

v) For most of the blends, essentially all of the potential heat of combustion was realised during testing in the cone calorimeter. Those blends where significantly less was realised were : Blend 8 (only 20% w/w total of medium volatility solvents present in the blend), Blend 23 (25% w/w of a medium volatility solvent - flash point 31ºC / 88ºF), Blend 27 (only 10% w/w isopropyl alcohol with 30% w/w ethylene glycol which is not very volatile), Blend 29 (70% w/w dipropylene glycol which is not very volatile) and Blend 30 (30% w/w total of medium volatility solvents).

It is interesting to compare the fire properties of the liquid blends tested in this project and the behaviour of some undiluted solvents. Table 9 gives properties of some undiluted solvents versus the range of values determined for the blends in this work.

Material	Closed cup flash point (°C)	Potential Heat of Combustion (MJ/kg)	Maximum Rate of Heat Release in Cone Calorimetry (kW/m^2)
Gasoline*	-43	44.1	427
Kerosene*	58	43.1	415
Diesel*	71	42.9	386
Denatured Alcohol*	7	26.8	463
n-Heptane*	-4**	44.4	534
Texanol	122***	31.2****	No data
Maximum Value for Blends Tested	No flash up to boiling point	29.9	1238
Minimum Value for Blends Tested	-12	6.0	97

Table 9 : Comparison of Test Blends with some Undiluted Solvents

* Data from Mealy, Benfer & Gottuk (2011); maximum heat release rate determined for 10 mm depth, incident radiation unknown.
** Data from Aldrich Catalogue, 2005-2006.
*** Texanol MSDS, version 3, Eastman Chemicals
**** Product Data Sheet, Eastman Chemicals

It can be seen that the combustion characteristics of the blends tested have a wide range of values, in some cases less severe than typical solvent values and in some cases more severe.

5.2.2 Trends within Blend "Families"

A number of the blends can be considered as members of "families" of similar compositions since they contain the same components but included at different levels.

5.2.2.1 Ethylene glycol monobutyl ether / water blends

Blends containing 25% w/w, 50% w/w and 75% w/w in water were tested and the following trends identified. The time to ignition decreased from 80 seconds to less than 20 seconds as the % inclusion was increased, while the maximum heat release rate increased from just over 400 kW/m^2 to over 1100 kW/m^2. No clear trend was seen in fire point temperature. These results are shown in Figures 10, 11 and 12 below.

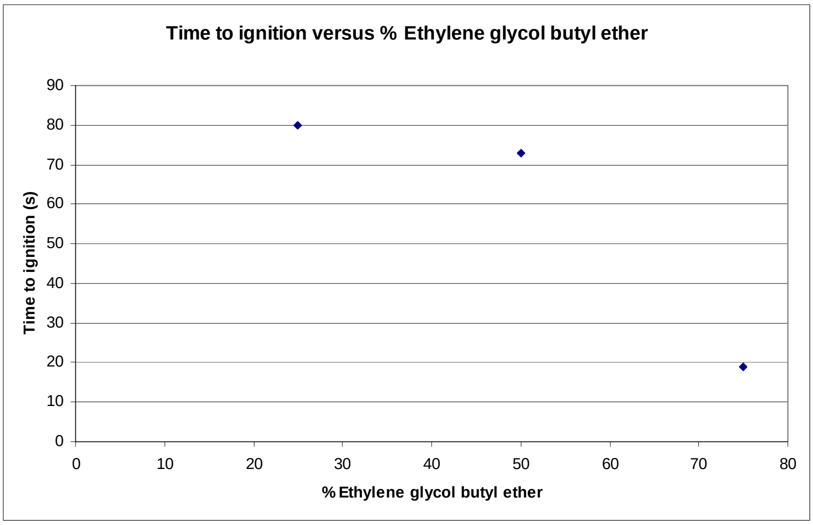


Figure 10 : **Time to ignition versus Concentration of Ethylene glycol butyl ether**

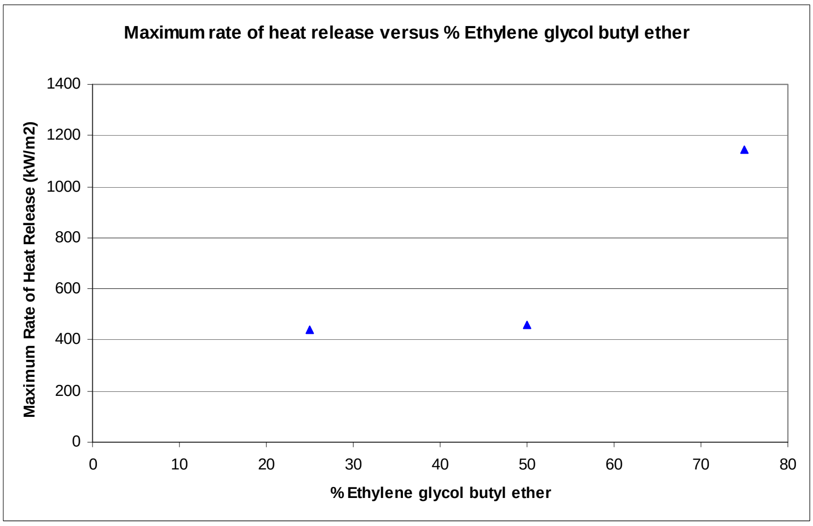


Figure 11 : **Maximum rate of heat release versus Concentration of Ethylene glycol butyl ether**

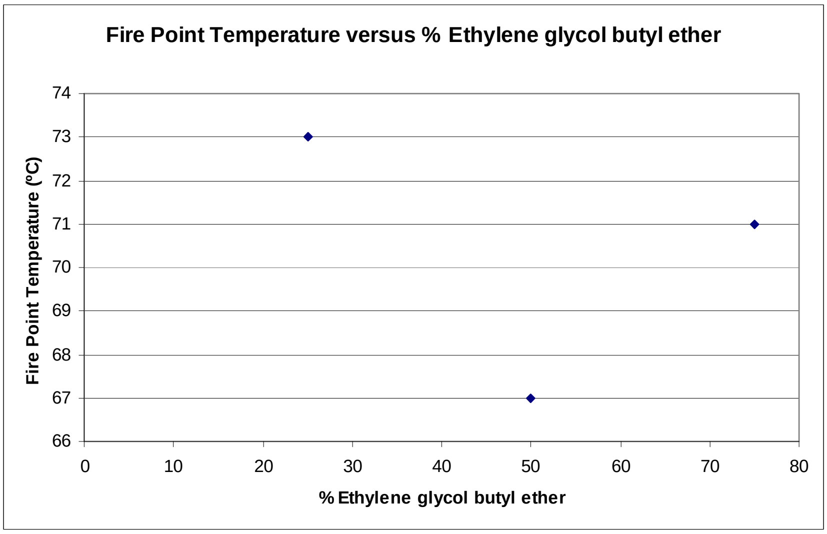


Figure 12 : **Fire point versus Concentration of Ethylene glycol butyl ether**

5.2.2.2 Propylene glycol methyl ether / water blends

Blends containing 25% w/w, 50% w/w and 75% w/w in water were tested and the following trends identified. The time to ignition decreased from over 90 seconds to less than 10 seconds as the % inclusion was increased, while the maximum heat release rate increased from just less than 100 kW/m^2 to over 650 kW/m^2. The closed cup flash point temperatures decreased by about 20ºC, while the open cup flash point temperatures and the fire point temperatures decreased by about 35ºC as the inclusion level was increased. These results are shown in Figures 13 and 14 below.

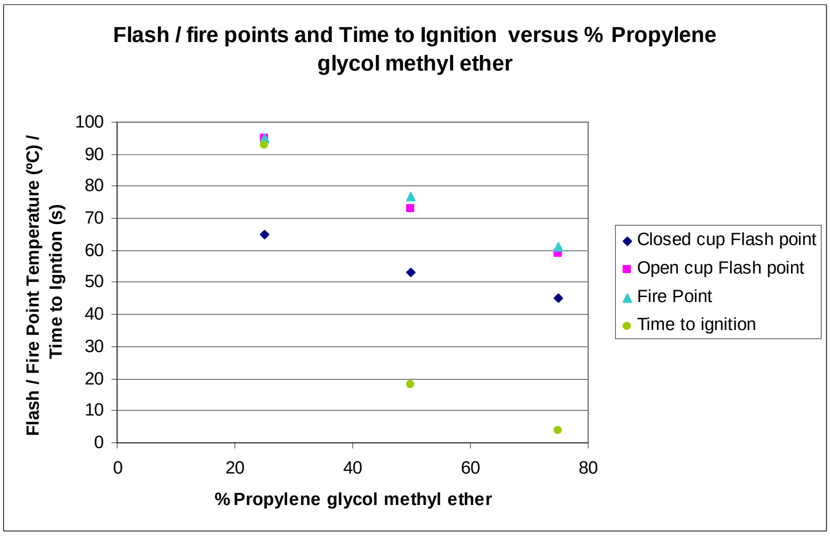


Figure 13 : Flash point, Fire point and Time to ignition versus concentration of Propylene glycol methyl ether

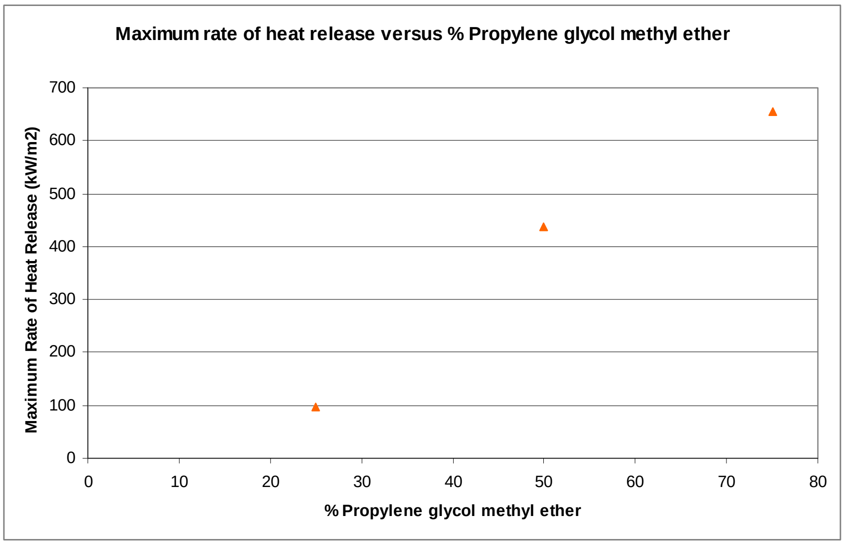


Figure 14 : Maximum rate of heat release versus concentration of Propylene glycol methyl ether

5.2.2.3 *Ethylene glycol monobutyl ether / isopropanol / n-butanol / water blends*

A range of blends was tested containing various levels of these components. In some cases, the level of ethylene glycol monobutyl ether was varied whilst the total alcohol content remained the same while in others the total level of ethylene glycol monobutyl ether remained constant whilst the total alcohol level was varied. The isopropanol and n-butyl alcohol levels were kept in a 1:1 ratio throughout.

Unsurprisingly, as the total amount of alcohol was increased, the flash point and fire point temperatures decreased, and the maximum rate of heat release increased. The time to ignition also fell, although the ignition times were all short (less than 10 seconds). This is shown in Figures 15 and 16.

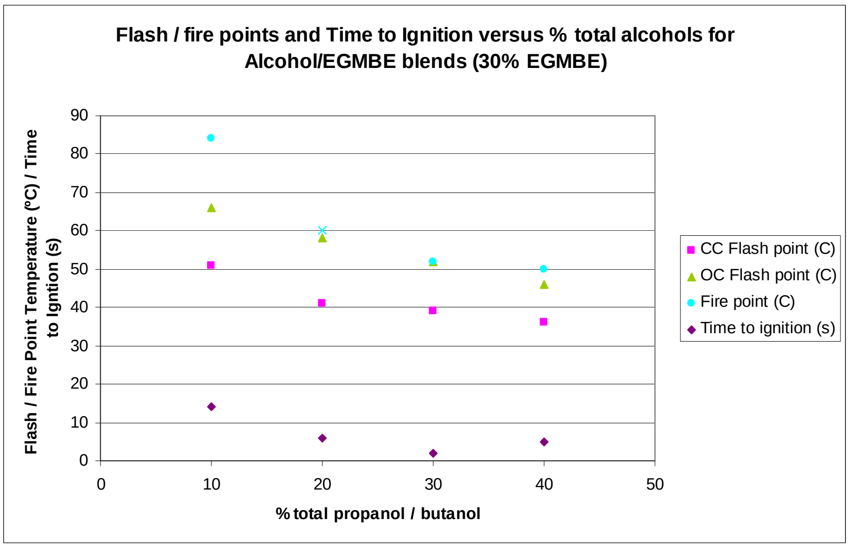


Figure 15 : Flash point, Fire point and Time to ignition versus concentration of total alcohol in 30% Ethylene glycol butyl ether blends

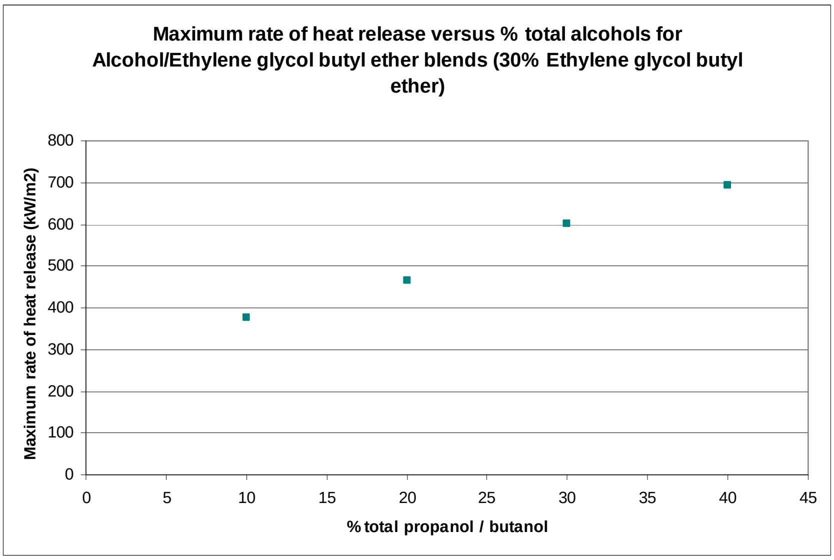


Figure 16 : Maximum rate of heat release versus concentration of total alcohol in 30% Ethylene glycol butyl ether blends

As the total amount of ethylene glycol monobutyl ether increased, the maximum rate of heat release also increased (see Figure 17). However, the flash point and fire point temperatures also increased, albeit by only about 10ºC (see Figure 18). This may be due to the presence of the glycol ether suppressing the vapour pressure of the alcohols, and serves to demonstrate the complexity of the behaviour of these aqueous multi-component blends.

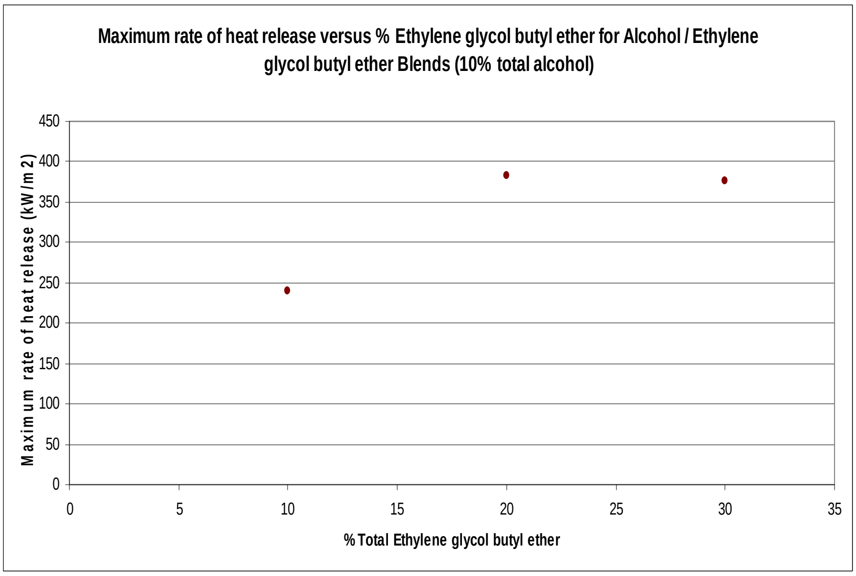


Figure 17 : Maximum rate of heat release versus concentration of Ethylene glycol butyl ether in 10% total alcohol blends

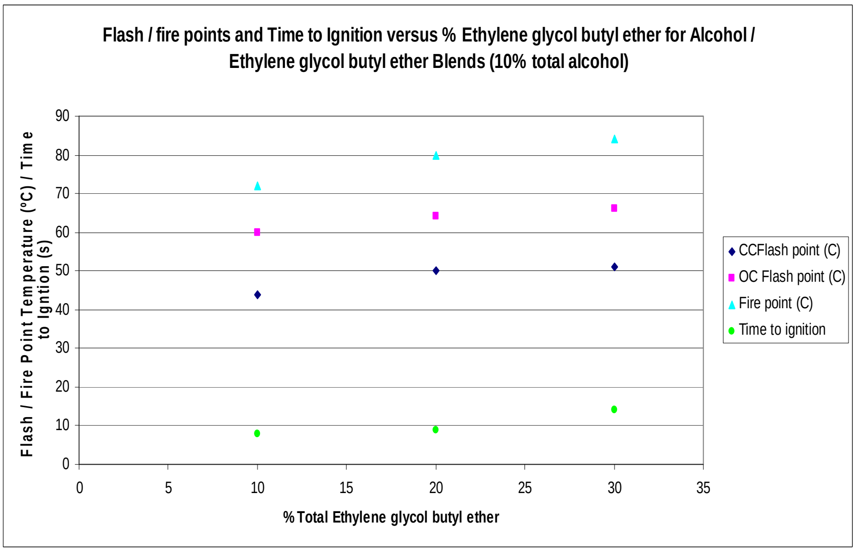


Figure 18 : Flash point, Fire point and Time to ignition versus concentration of Ethylene glycol butyl ether in 10% total alcohol blends

6 DISCUSSION / DEVELOPMENT OF STRAWMAN

6.1 DISCUSSION

It can be seen from the results that many solutions containing highly volatile solvents, such as isopropanol and acetone, ignited almost immediately in the cone calorimetry tests and continued burning until all of the available heat of combustion had been released from the blend. Such blends will clearly present a significant fire hazard.

Some of the blends took a significant time to ignite in the cone calorimetry tests, and some of those needed to be further ignited since the flame self-extinguished after a relatively short period. Such materials are likely to present a low fire hazard.

The fire point test alone does not appear to provide a reliable indication of time to ignition other than in the case where the fire point is lower than approximately 60ºC, where a fast ignition may be expected.

Those blends not exhibiting a flash point in the closed cup test generally exhibited a longer time to ignition; the minimum time was 8 seconds in the case of 90% w/w butyric acid with the rest of the blends taking over 18 seconds, many significantly so.

It would appear that the Fire Performance Index (FPI) is largely dominated by the time to ignition in the case of the aqueous blends tested, since the peak heat release rate varied by a maximum of only one order of magnitude, whereas the time to ignition varied by over two orders of magnitude. Furthermore, the seven fastest blends to ignite also had the lowest FPI, while the seven with the longest time to ignition also had the highest FPI. On that basis, it would appear that time to ignition would be at least as suitable a criterion as FPI.

Assuming that the liquid does ignite, then the heat output and rate of heat output would be considered important in the development of the fire. Since existing sprinkler systems could be expected to control a fire involving NFPA Class III commodities such as cardboard, it could be expected that fires involving aqueous blends possessing similar heat outputs would also be controlled providing that the flame spread was slow and the burning occurred close to the origin of the fire.

6.2 STRAWMAN CRITERIA FOR "LOW HAZARD" AQUEOUS BLENDS

Based on the results of the small scale testing described here, "strawman" criteria for identifying "low hazard" aqueous blends are proposed. These are :

i) No flash to the onset of boiling in closed cup flash point testing – this appears to coincide with long ignition times;

ii) Time to ignition of solution greater than typical sprinkler activation time, suggest > 20 seconds;

iii) Low maximum rate of heat release in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 250 kW/m^2;

iv) FPI > 0.08 m^2 s/kW (based on a time to ignition of < 20 seconds and a maximum rate of heat release of < 250 kW/m^2);

v) Low total heat release per m^2 in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 100 MJ/m^2.

It could be envisaged that a testing protocol would be developed in which an aqueous product were subject to a particular sequence of testing in order to classify the material. For example, fire point testing could initially be used to establish if the material would be excluded under current NFPA 30 guidance. If the material exhibited a fire point, this could be followed by closed cup flash point determination. Then, if the flash point result was still insufficient to establish the fire hazard classification, cone calorimetry testing could be carried out to further refine the classification.

It should be noted that any criteria suggested in this report for classification of the fire risk of the aqueous blends will need to be validated in large-scale tests before they could be adopted.

Details of the proposed large-scale validation tests will be reported separately. However, it is suggested that the testing be carried out in three stages :

i) Observing the fire spread across a pool of the test liquid with *no* fire mitigation (e.g. sprinklers) present.
ii) Observing the fire spread across a pool of the test liquid *with* fire mitigation (e.g. sprinklers) present.
iii) Observing the fire spread when multiple IBCs are present.

7 CONCLUSIONS

Thirty aqueous blends of flammable / combustible solvents were selected with the intention that these blends would possess a wide range of flash point temperatures and potential heats of combustion. These were subjected to small scale testing; flash point, fire point and cone calorimetry. The results of the tests confirmed that a wide range of combustion behaviours was presented by the blends.

Although the fire behaviour of these solutions is complex, a number of "strawman" criteria have been proposed for the identification of those blends considered to present a low fire hazard. These are :

i) No flash to the onset of boiling in closed cup flash point testing;
ii) Time to ignition of solution > 20 seconds;
iii) Low maximum rate of heat release in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 250 kW/m^2;
iv) FPI > 0.08 m^2 s/kW (based on a time to ignition of < 20 seconds and a maximum rate of heat release of < 250 kW/m^2);
v) Low total heat release per m^2 in cone calorimetry tests (in comparison to a typical NFPA Class III commodity, such as wood or cardboard, of a similar thickness); suggest < 100 MJ/m^2.

It must be emphasised that the "strawman" criteria described above will require validation by carrying out large-scale tests.

Details of the proposed validation testing will be reported separately.

8 APPENDICES

8.1 FULL LIST OF THE 30 BLENDS TESTED

Component	Flash point °F	Flash point °C	Boiling Point °F	Boiling Point °C	Heat of Combustion (BTU/lb)	Heat of Combustion (MJ/kg)
Acetic acid	102	38.9	243	117.2	6256	14.6
Propionic acid	129	53.9	286	141.1	8886	20.7
n-butyric acid	162	72.2	324	162.2	10685	24.9
Methanol	52	11.1	148	64.4	9774	22.7
isopropyl alcohol	53	11.7	180	82.2	12960	30.1
n-butyl alcohol	95	35.0	242	116.7	14262	33.2
Acetone	1	-17.2	132	55.6	13292	30.9
Methyl ethyl ketone	21	-6.1	176	80.0	14618	34.0
Ethylene glycol	232	111.1	389	198.3	7297	17.0
Ethylene glycol monobutyl ether	143	61.7	338	170.0	12195	28.4
Propylene glycol mono methyl ether	88	31.1	248	120.0	11115	25.9
Dipropylene Glycol	245	118.3	420	215.6	11650	27.1
Ethylene glycol monopropyl ether	118	47.8	301	149.4	12209	28.4

Weight %

Component	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Acetic acid									90%	70%					
Propionic acid															
n-butyric acid															
Methanol															
isopropyl alcohol	20%	20%	15%	10%	5%	10%	5%	5%			25%	50%			
n-butyl alcohol		20%	15%	10%	5%	10%	5%	5%					90%		
Acetone														50%	25%
Methyl ethyl ketone															
Ethylene glycol	12%														
Ethylene glycol monobutyl ether		30%	30%	30%	30%	20%	20%	10%							
Propylene glycol mono methyl ether	30%														
Dipropylene Glycol															
Ethylene glycol monopropyl ether															
Total Solvent Concentration	62%	70%	60%	50%	40%	40%	30%	20%	90%	70%	25%	50%	90%	50%	25%
Water	38%	30%	40%	50%	60%	60%	70%	80%	10%	30%	75%	50%	10%	50%	75%
TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Class I:Class II/III Ratio (% of total organic)	81	57	50	40	25	50	33	50	0	0	100	100	100	100	100
No. of Components	4	3	3	3	3	3			2	2	2	2	2	2	2
Theoretical Blend BTU's/lb	6802	9103	7742	6381	5020	5161	3800	2581	5630	4379	3240	6480	12836	6646	3323
Theoretical Blend MJ/kg	16	21	18	15	12	12	9	6	13	10	8	15	30	15	8
Estimated blend closed cup flashpoint °F	50 - 100	57 - 72	57 - 77	57 - 90	57 - 106	57 - 90	57 - 106	57 - 106	120	No Flash to boil	77	70	104	<32	<32
Anticipated NFPA Flammability Class	I	I	I	I	II	I	II	II	II	III	I	I	II	I	I
Comments															

Weight %

Component	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Acetic acid															
Propionic acid											70%				
n-butyric acid			90%	70%											
Methanol															
isopropyl alcohol		75%										10%			
n-butyl alcohol															
Acetone															
Methyl ethyl ketone	25%														
Ethylene glycol												30%			
Ethylene glycol monobutyl ether					50%	25%				75%			40%		20%
Propylene glycol mono methyl ether							50%	25%	75%						
Dipropylene Glycol														70%	
Ethylene glycol monopropyl ether													20%		10%
Total Solvent Concentration	25%	75%	90%	70%	50%	25%	50%	25%	75%	75%	70%	40%	60%	70%	30%
Water	75%	25%	10%	30%	50%	75%	50%	75%	25%	25%	30%	60%	40%	30%	70%
TOTAL	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Class I:Class II/III Ratio (% of total organic)	100	100	0	0	0	0	100	100	100	0	0	25	0	0	0
No. of Components	2	2	2	2	2	2	2	2	2	2	2	3	3	2	3
Theoretical Blend BTU's/lb	3655	9720	9617	7480	6098	3049	5558	2779	8336	9146	6220	3485	7320	8155	3660
Theoretical Blend MJ/kg	9	23	22	17	14	7	13	6	19	21	14	8	17	19	9
Estimated blend closed cup flashpoint °F	32	65	No Flash to boil	No Flash to boil	No Flash to boil	No Flash to boil	>140	No Flash to boil	>140	>140	No Flash to boil	>140	No Flash to boil	No Flash to boil	No Flash to boil
Anticipated NFPA Flammability Class	I	I	III	III	III	III	II	III	III	III	III	III	III	III	III
Comments	Close to limit of solubility of MEL in water				Inverse solubility effect ?	Inverse solubility effect ?						To obtain potential IIIA liquid with Lower Heat content			

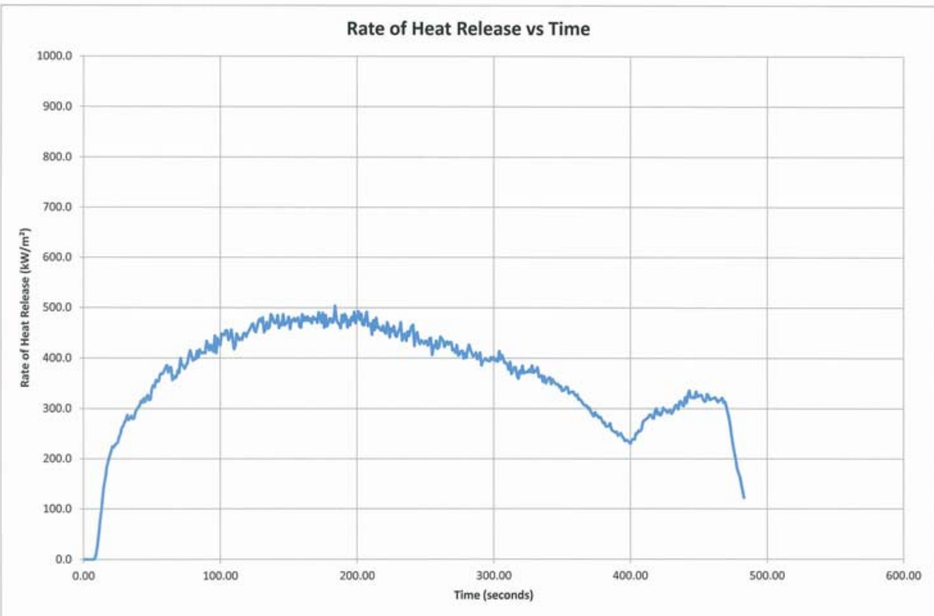
References :
Sigma-Aldrich Catalogue 2005-6
CRC Handbook of Chemistry & Physics (58th Ed)
Cameo Chemicals MSDS for Dipropylene Glycol
"Flash Points of Aqueous Solutions of Flammable Solvents", Astbury et al, IChemE Symposium Series No 150
"Flash Point and Ignition Point of Aqueous Alcohol Solutions", Pharmaceutical Industry Journal Vol 11, No 7
"Flash points of Oxygenated Solvents in Aqueous Systems", Eastman Chemical Company Publication M-208C
Eastman Chemicals MSDS for ethylene glycol monobutyl ether
Eastman Chemicals MSDS for propylene glycol monomethyl ether

8.2 DETAILED DATA FROM CONE CALORIMETRY TESTS

The following data and graphs are extracted from the full report "Fire Tests on Liquid Solvents", generated by ITRI Innovations and dated 14th December 2011.

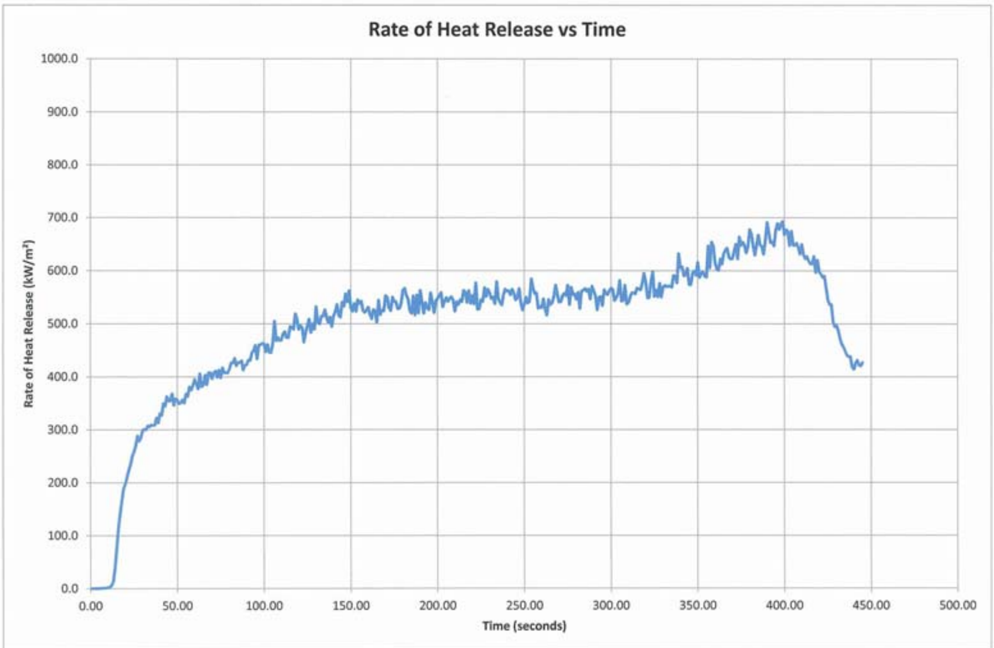
<u>Blend 1</u>

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 01	
Test ID	HSL0601	
Material	Blend 01	
Orientation	Horizontal	
Heat Flux	50	kW/m²
Time to Sustained Ignition	3.05	seconds
Peak Rate of Heat Release	503.4	kW/m²
Time of Peak RHR	184	seconds
Average RHR over 60 seconds	242.4	kW/m²
Average RHR over 180 seconds	377.5	kW/m²
Average RHR over 300 seconds	402.7	kW/m²
Total Heat Released	176.5	MJ/m²
Avg Effective Heat of Combustion	18.26	MJ/kg
Initial Mass	96.56	g
Final Mass	-0.14	g
Sample Mass Loss	9.67	kg/m²
Avg Mass Loss Rate (10% to 90%)	22.3	g/m²s
Avg SEA	3267.38	m²/kg
Time of Peak SEA	477	seconds
CO Yield	0.00256	kg/kg
CO2 Yield	1.24496	kg/kg
Pre test notes		
Post test notes		



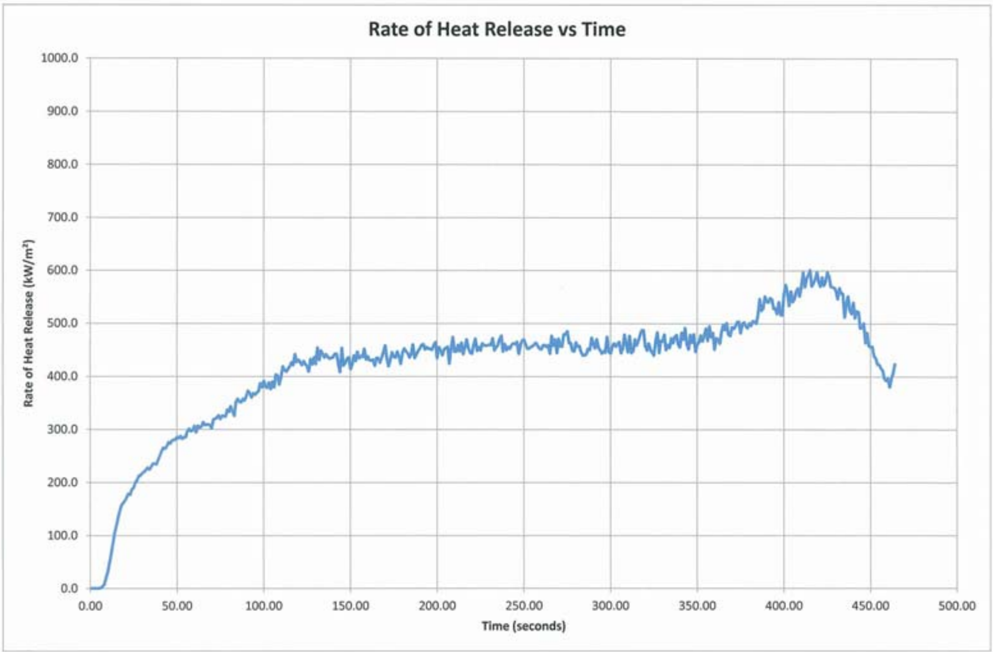
Blend 2

Test	ASTM E1354
Laboratory	ITRI Innovation Ltd.
Operator	AWM
Material	Blend 02
Test ID	HSL0701
Material	Blend 02
Orientation	Horizontal
Heat Flux	35 kW/m²
Time to Sustained Ignition	5.4 seconds
Peak Rate of Heat Release	693.2 kW/m²
Time of Peak RHR	399 seconds
Average RHR over 60 seconds	260 kW/m²
Average RHR over 180 seconds	411.1 kW/m²
Average RHR over 300 seconds	466.2 kW/m²
Total Heat Released	223.3 MJ/m²
Avg Effective Heat of Combustion	25.17 MJ/kg
Initial Mass	89.31 g
Final Mass	0.6 g
Sample Mass Loss	8.87 kg/m²
Avg Mass Loss Rate (10% to 90%)	22.2 g/m²s
Avg SEA	4919.67 m²/kg
Time of Peak SEA	437 seconds
CO Yield	0.00276 kg/kg
CO2 Yield	1.4895 kg/kg
Pre test notes	
Post test notes	



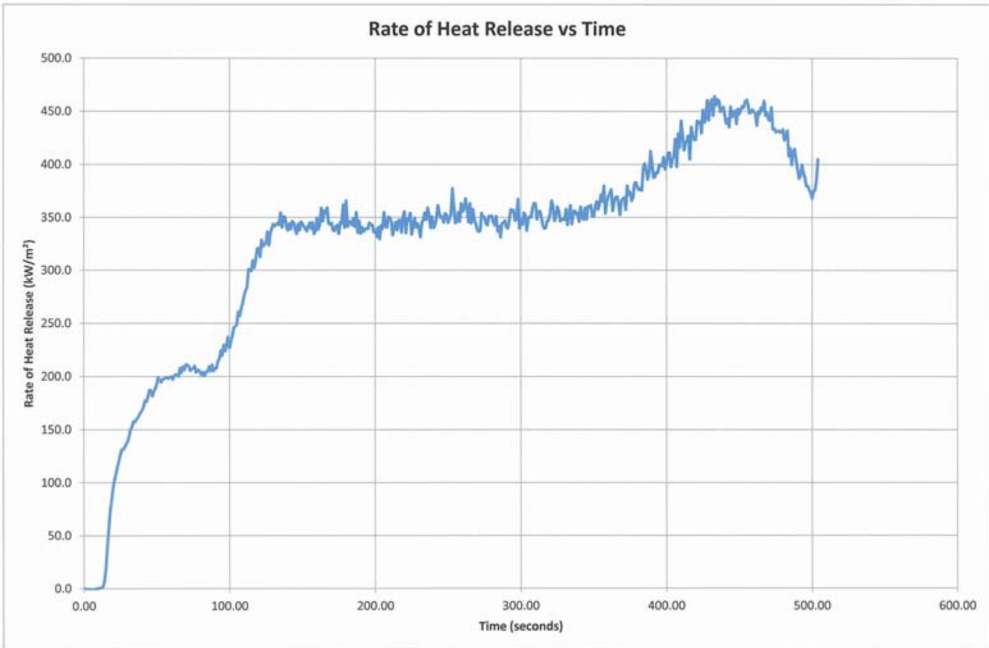
Blend 3

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 03	
Test ID	HSL0801	
Material	Blend 03	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	2.05	seconds
Peak Rate of Heat Release	601.5	kW/m²
Time of Peak RHR	415	seconds
Average RHR over 60 seconds	193.9	kW/m²
Average RHR over 180 seconds	330.8	kW/m²
Average RHR over 300 seconds	380.8	kW/m²
Total Heat Released	195.6	MJ/m²
Avg Effective Heat of Combustion	21.19	MJ/kg
Initial Mass	91.64	g
Final Mass	-0.67	g
Sample Mass Loss	9.23	kg/m²
Avg Mass Loss Rate (10% to 90%)	21.9	g/m²s
Avg SEA	3545.04	m²/kg
Time of Peak SEA	464	seconds
CO Yield	0.00245	kg/kg
CO2 Yield	1.22271	kg/kg
Pre test notes		
Post test notes		



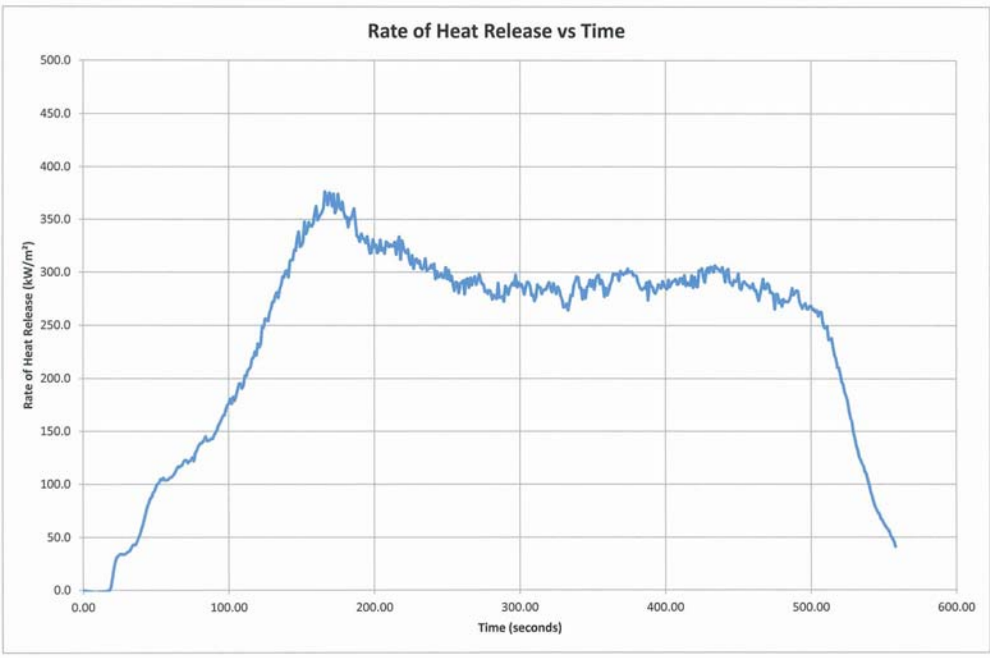
Blend 4

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 04	
Test ID	HSL0901	
Material	Blend 04	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	6.25	seconds
Peak Rate of Heat Release	464.2	kW/m²
Time of Peak RHR	433	seconds
Average RHR over 60 seconds	135.4	kW/m²
Average RHR over 180 seconds	241.1	kW/m²
Average RHR over 300 seconds	283.3	kW/m²
Total Heat Released	164.7	MJ/m²
Avg Effective Heat of Combustion	17.1	MJ/kg
Initial Mass	94.01	g
Final Mass	-2.3	g
Sample Mass Loss	9.63	kg/m²
Avg Mass Loss Rate (10% to 90%)	21.3	g/m²s
Avg SEA	2348.28	m²/kg
Time of Peak SEA	502	seconds
CO Yield	0.00213	kg/kg
CO2 Yield	0.97768	kg/kg
Pre test notes		
Post test notes		



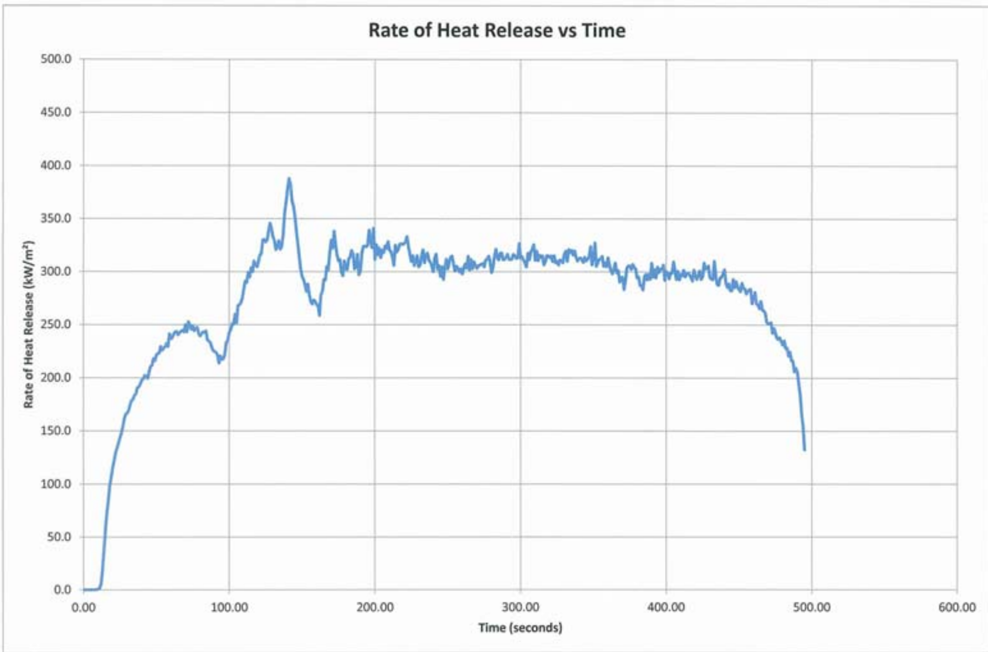
Blend 5

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 05	
Test ID	HSL1001	
Material	Blend 05	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	14.45	seconds
Peak Rate of Heat Release	376.3	kW/m²
Time of Peak RHR	166	seconds
Average RHR over 60 seconds	70.3	kW/m²
Average RHR over 180 seconds	200.3	kW/m²
Average RHR over 300 seconds	240	kW/m²
Total Heat Released	134.5	MJ/m²
Avg Effective Heat of Combustion	13.92	MJ/kg
Initial Mass	95.91	g
Final Mass	-0.74	g
Sample Mass Loss	9.67	kg/m²
Avg Mass Loss Rate (10% to 90%)	20.4	g/m²s
Avg SEA	1755.17	m²/kg
Time of Peak SEA	515	seconds
CO Yield	0.00249	kg/kg
CO2 Yield	0.988	kg/kg
Pre test notes		
Post test notes		



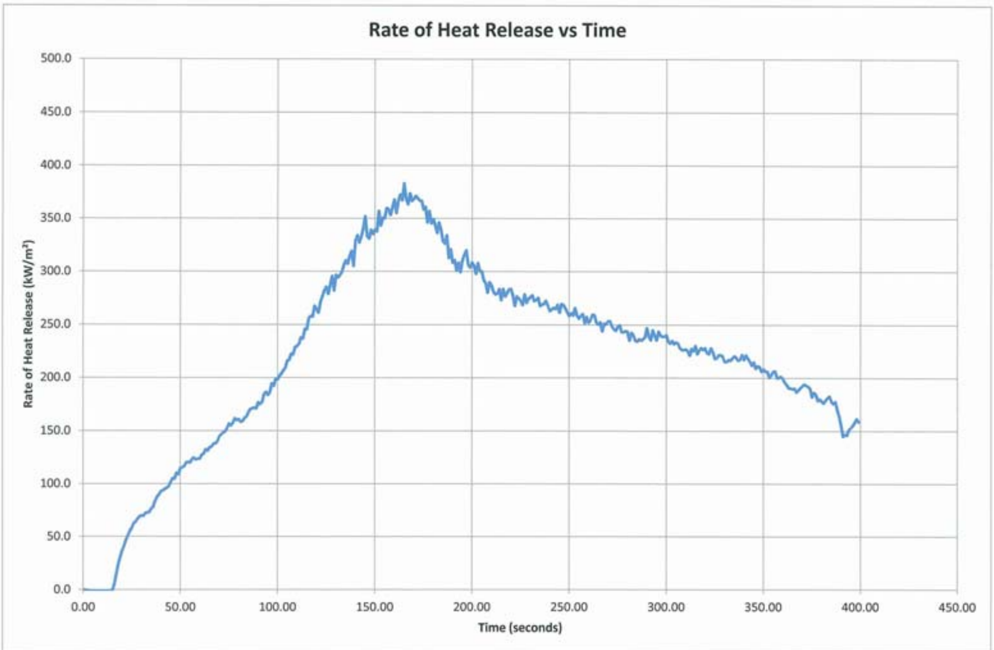
Blend 6

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 06	
Test ID	HSL1101	
Material	Blend 06	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	4.8	seconds
Peak Rate of Heat Release	387.8	kW/m²
Time of Peak RHR	141	seconds
Average RHR over 60 seconds	156.2	kW/m²
Average RHR over 180 seconds	243.2	kW/m²
Average RHR over 300 seconds	271.2	kW/m²
Total Heat Released	136.5	MJ/m²
Avg Effective Heat of Combustion	14.76	MJ/kg
Initial Mass	95.69	g
Final Mass	3.21	g
Sample Mass Loss	9.25	kg/m²
Avg Mass Loss Rate (10% to 90%)	20.3	g/m²s
Avg SEA	1701.73	m²/kg
Time of Peak SEA	399	seconds
CO Yield	0.0022	kg/kg
CO2 Yield	0.9345	kg/kg
Pre test notes		
Post test notes		



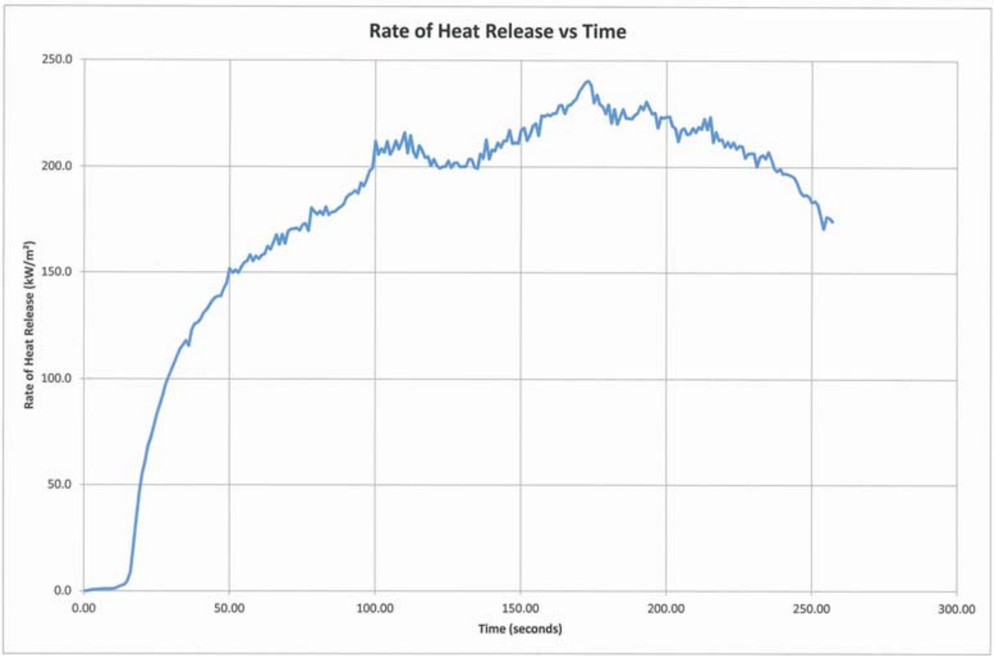
Blend 7

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 07	
Test ID	HSL1201	
Material	Blend 07	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	8.5	seconds
Peak Rate of Heat Release	383	kW/m²
Time of Peak RHR	165	seconds
Average RHR over 60 seconds	78.6	kW/m²
Average RHR over 180 seconds	207.8	kW/m²
Average RHR over 300 seconds	230.7	kW/m²
Total Heat Released	87.6	MJ/m²
Avg Effective Heat of Combustion	13.4	MJ/kg
Initial Mass	97.04	g
Final Mass	31.63	g
Sample Mass Loss	6.54	kg/m²
Avg Mass Loss Rate (10% to 90%)	18.7	g/m²s
Avg SEA	1152.95	m²/kg
Time of Peak SEA	302	seconds
CO Yield	0.00266	kg/kg
CO2 Yield	0.97668	kg/kg
Pre test notes		
Post test notes		



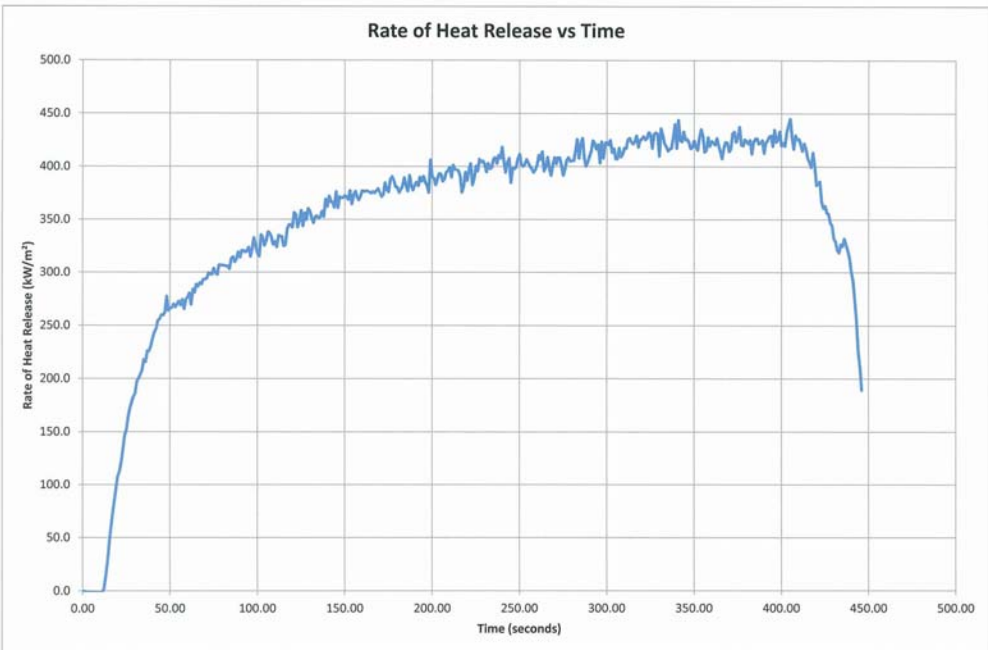
Blend 8

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 08	
Test ID	HSL1301	
Material	Blend 08	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	7.85	seconds
Peak Rate of Heat Release	240.4	kW/m²
Time of Peak RHR	173	seconds
Average RHR over 60 seconds	106	kW/m²
Average RHR over 180 seconds	172.6	kW/m²
Average RHR over 300 seconds	not available	
Total Heat Released	45.7	MJ/m²
Avg Effective Heat of Combustion	12.42	MJ/kg
Initial Mass	98.69	g
Final Mass	61.93	g
Sample Mass Loss	3.68	kg/m²
Avg Mass Loss Rate (10% to 90%)	15	g/m²s
Avg SEA	549.63	m²/kg
Time of Peak SEA	251	seconds
CO Yield	0.00222	kg/kg
CO2 Yield	0.68829	kg/kg
Pre test notes		
Post test notes		



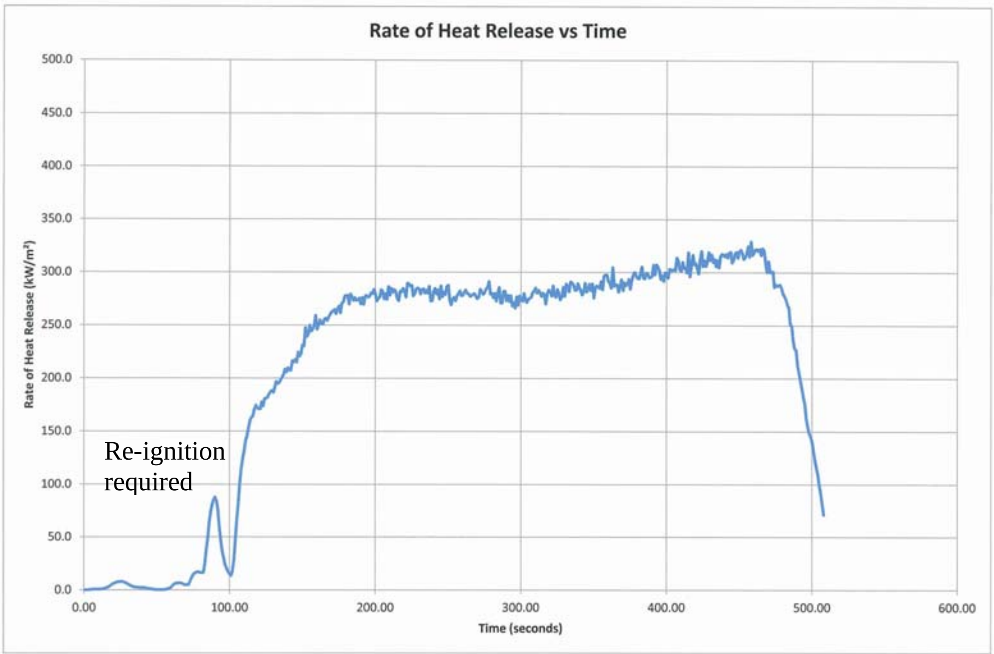
Blend 9

Test	ASTM E1354
Laboratory	ITRI Innovation Ltd.
Operator	AWM
Material	Blend 09
Test ID	HSL1401
Material	Blend 09
Orientation	Horizontal
Heat Flux	35 kW/m²
Time to Sustained Ignition	5.2 seconds
Peak Rate of Heat Release	445.2 kW/m²
Time of Peak RHR	405 seconds
Average RHR over 60 seconds	179.2 kW/m²
Average RHR over 180 seconds	289.5 kW/m²
Average RHR over 300 seconds	334.1 kW/m²
Total Heat Released	157.5 MJ/m²
Avg Effective Heat of Combustion	15.48 MJ/kg
Initial Mass	104.3 g
Final Mass	2.58 g
Sample Mass Loss	10.17 kg/m²
Avg Mass Loss Rate (10% to 90%)	25.4 g/m²s
Avg SEA	1984.6 m²/kg
Time of Peak SEA	446 seconds
CO Yield	0.00261 kg/kg
CO2 Yield	1.30063 kg/kg
Pre test notes	
Post test notes	



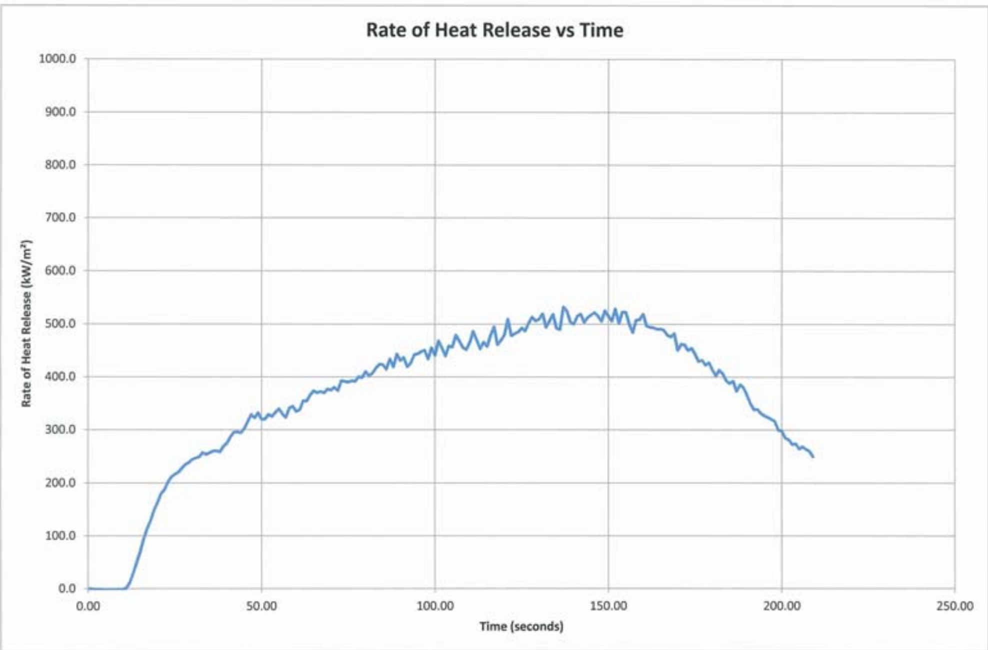
Blend 10

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 10	
Test ID	HSL1501	
Material	Blend 10	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	57.7	seconds
Peak Rate of Heat Release	329.2	kW/m²
Time of Peak RHR	458	seconds
Average RHR over 60 seconds	50.8	kW/m²
Average RHR over 180 seconds	184.7	kW/m²
Average RHR over 300 seconds	222.9	kW/m²
Total Heat Released	109.4	MJ/m²
Avg Effective Heat of Combustion	11.27	MJ/kg
Initial Mass	95.86	g
Final Mass	-1.18	g
Sample Mass Loss	9.7	kg/m²
Avg Mass Loss Rate (10% to 90%)	22.8	g/m²s
Avg SEA	1035.63	m²/kg
Time of Peak SEA	502	seconds
CO Yield	0.00241	kg/kg
CO2 Yield	0.95188	kg/kg
Pre test notes		
Post test notes		



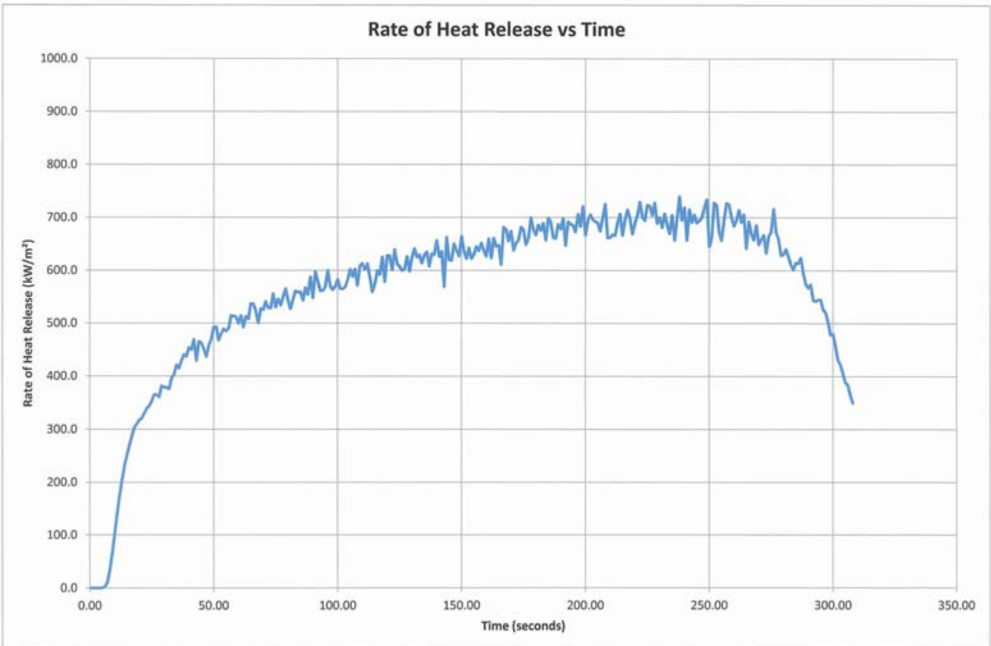
Blend 11

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 11	
Test ID	HSL1601	
Material	Blend 11	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	5.35	seconds
Peak Rate of Heat Release	532.5	kW/m²
Time of Peak RHR	137	seconds
Average RHR over 60 seconds	226.1	kW/m²
Average RHR over 180 seconds	382.3	kW/m²
Average RHR over 300 seconds	not available	
Total Heat Released	76.8	MJ/m²
Avg Effective Heat of Combustion	21.64	MJ/kg
Initial Mass	97.22	g
Final Mass	61.73	g
Sample Mass Loss	3.55	kg/m²
Avg Mass Loss Rate (10% to 90%)	19.1	g/m²s
Avg SEA	1705.89	m²/kg
Time of Peak SEA	179	seconds
CO Yield	0.0024	kg/kg
CO2 Yield	1.44681	kg/kg
Pre test notes		
Post test notes		



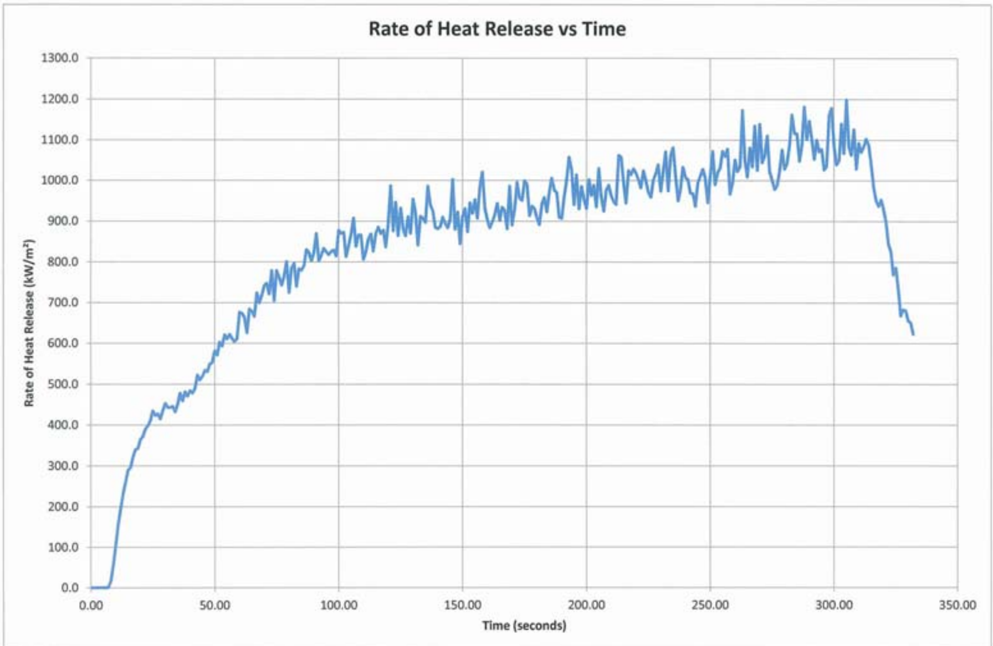
Blend 12

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 12	
Test ID	HSL1701	
Material	Blend 12	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	1.4	seconds
Peak Rate of Heat Release	739.4	kW/m²
Time of Peak RHR	238	seconds
Average RHR over 60 seconds	336.4	kW/m²
Average RHR over 180 seconds	512.9	kW/m²
Average RHR over 300 seconds	574.5	kW/m²
Total Heat Released	175.7	MJ/m²
Avg Effective Heat of Combustion	25.13	MJ/kg
Initial Mass	90.06	g
Final Mass	20.16	g
Sample Mass Loss	6.99	kg/m²
Avg Mass Loss Rate (10% to 90%)	24.7	g/m²s
Avg SEA	4249.92	m²/kg
Time of Peak SEA	293	seconds
CO Yield	0.00318	kg/kg
CO2 Yield	1.58887	kg/kg
Pre test notes		
Post test notes		



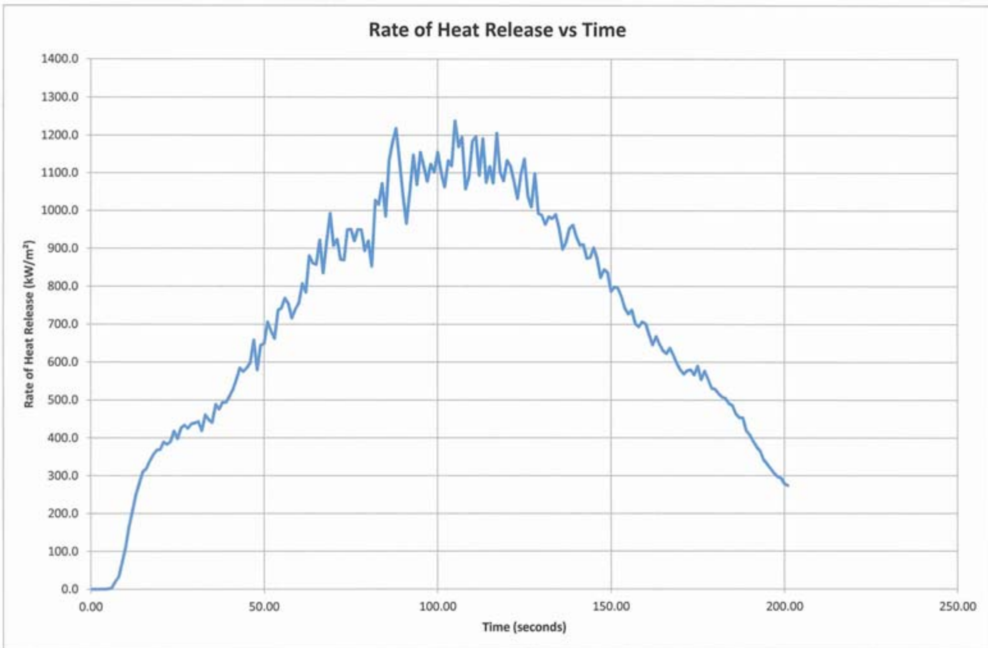
Blend 13

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 13	
Test ID	HSL1801	
Material	Blend 13	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	1.4	seconds
Peak Rate of Heat Release	1199.7	kW/m²
Time of Peak RHR	305	seconds
Average RHR over 60 seconds	391.1	kW/m²
Average RHR over 180 seconds	703.9	kW/m²
Average RHR over 300 seconds	830.7	kW/m²
Total Heat Released	279.1	MJ/m²
Avg Effective Heat of Combustion	33.18	MJ/kg
Initial Mass	82.86	g
Final Mass	-1.28	g
Sample Mass Loss	8.41	kg/m²
Avg Mass Loss Rate (10% to 90%)	27.9	g/m²s
Avg SEA	64603.96	m²/kg
Time of Peak SEA	267	seconds
CO Yield	0.00449	kg/kg
CO2 Yield	2.17335	kg/kg
Pre test notes		
Post test notes		



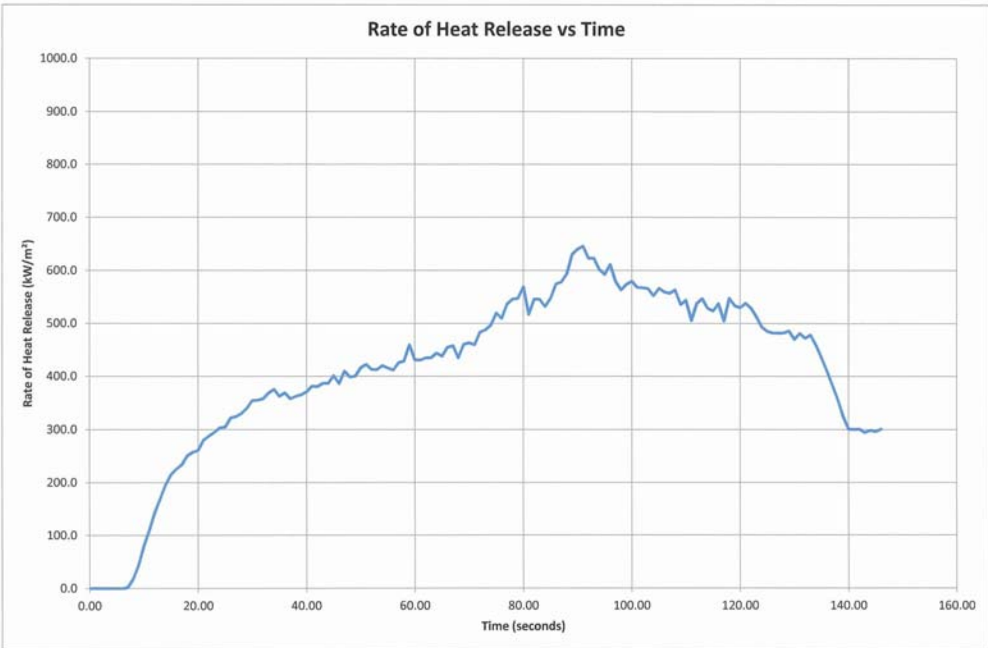
Blend 14

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 14	
Test ID	HSL1901	
Material	Blend 14	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	1.1	seconds
Peak Rate of Heat Release	1238.4	kW/m²
Time of Peak RHR	105	seconds
Average RHR over 60 seconds	427.5	kW/m²
Average RHR over 180 seconds	754.4	kW/m²
Average RHR over 300 seconds	not available	
Total Heat Released	144.1	MJ/m²
Avg Effective Heat of Combustion	26.28	MJ/kg
Initial Mass	92.29	g
Final Mass	37.46	g
Sample Mass Loss	5.48	kg/m²
Avg Mass Loss Rate (10% to 90%)	30	g/m²s
Avg SEA	3307.81	m²/kg
Time of Peak SEA	202	seconds
CO Yield	0.00407	kg/kg
CO2 Yield	2.01414	kg/kg
Pre test notes		
Post test notes		



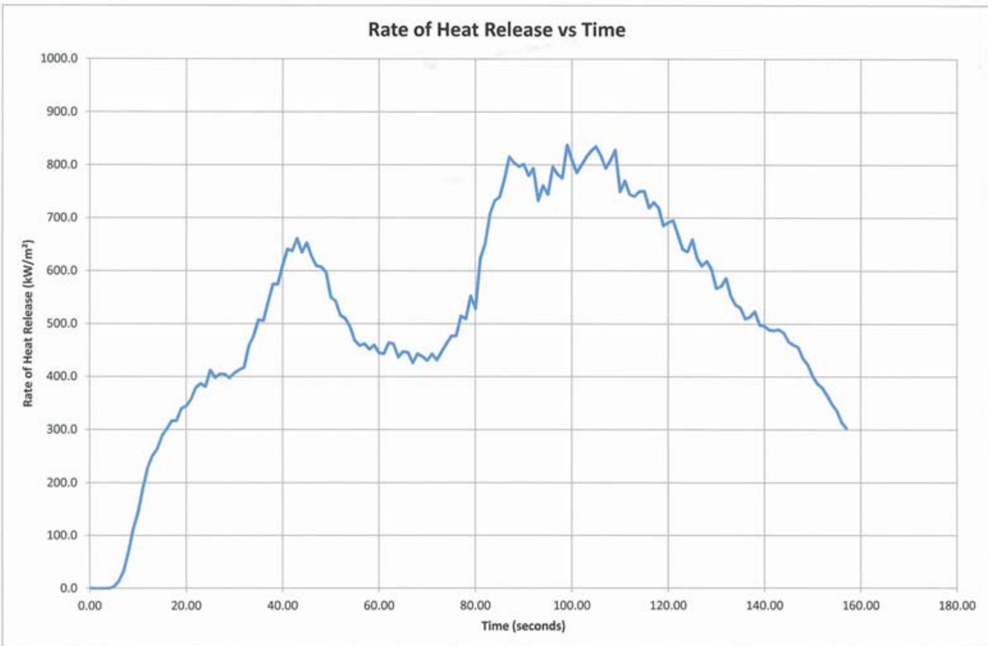
<u>Blend 15</u>

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 15	
Test ID	HSL0101	
Material	Blend 15	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	1.3	seconds
Peak Rate of Heat Release	645.8	kW/m²
Time of Peak RHR	91	seconds
Average RHR over 60 seconds	290	kW/m²
Average RHR over 180 seconds	not available	
Average RHR over 300 seconds	not available	
Total Heat Released	60.5	MJ/m²
Avg Effective Heat of Combustion	24.04	MJ/kg
Initial Mass	97.37	g
Final Mass	72.2	g
Sample Mass Loss	2.52	kg/m²
Avg Mass Loss Rate (10% to 90%)	20.1	g/m²s
Avg SEA	1632.53	m²/kg
Time of Peak SEA	146	seconds
CO Yield	0.00228	kg/kg
CO2 Yield	1.74007	kg/kg
Pre test notes		
Post test notes		



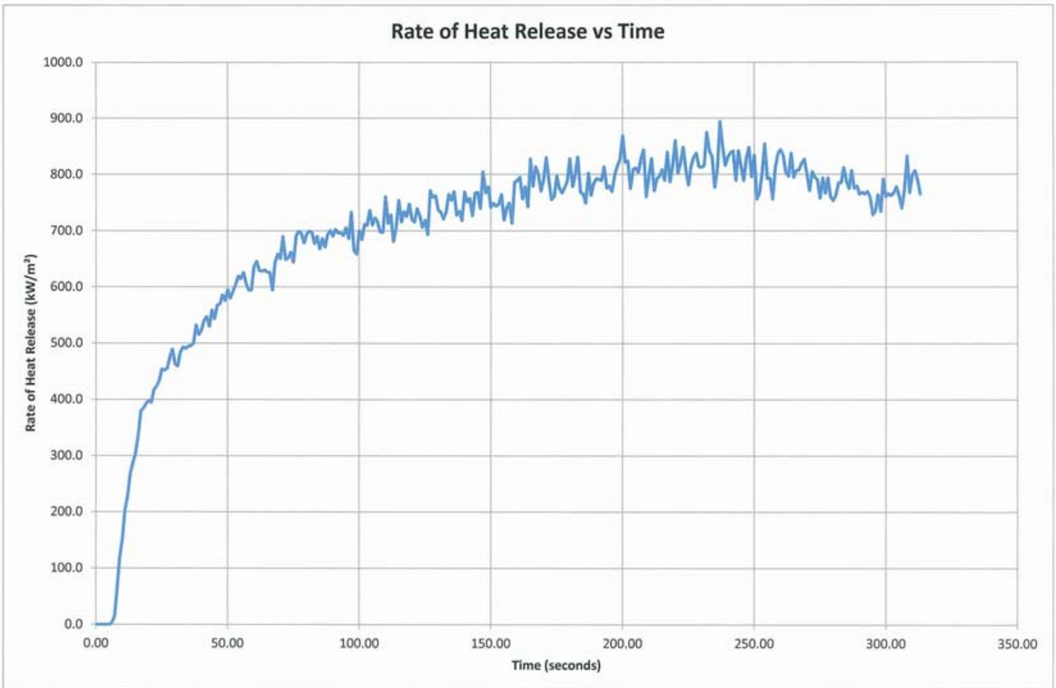
Blend 16

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 16	
Test ID	HSL2001	
Material	Blend 16	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	0.8	seconds
Peak Rate of Heat Release	838.1	kW/m²
Time of Peak RHR	99	seconds
Average RHR over 60 seconds	391.2	kW/m²
Average RHR over 180 seconds	not available	
Average RHR over 300 seconds	not available	
Total Heat Released	82.1	MJ/m²
Avg Effective Heat of Combustion	28.96	MJ/kg
Initial Mass	96.65	g
Final Mass	68.3	g
Sample Mass Loss	2.83	kg/m²
Avg Mass Loss Rate (10% to 90%)	20.4	g/m²s
Avg SEA	2476.32	m²/kg
Time of Peak SEA	146	seconds
CO Yield	0.00283	kg/kg
CO2 Yield	2.00898	kg/kg
Pre test notes		
Post test notes		



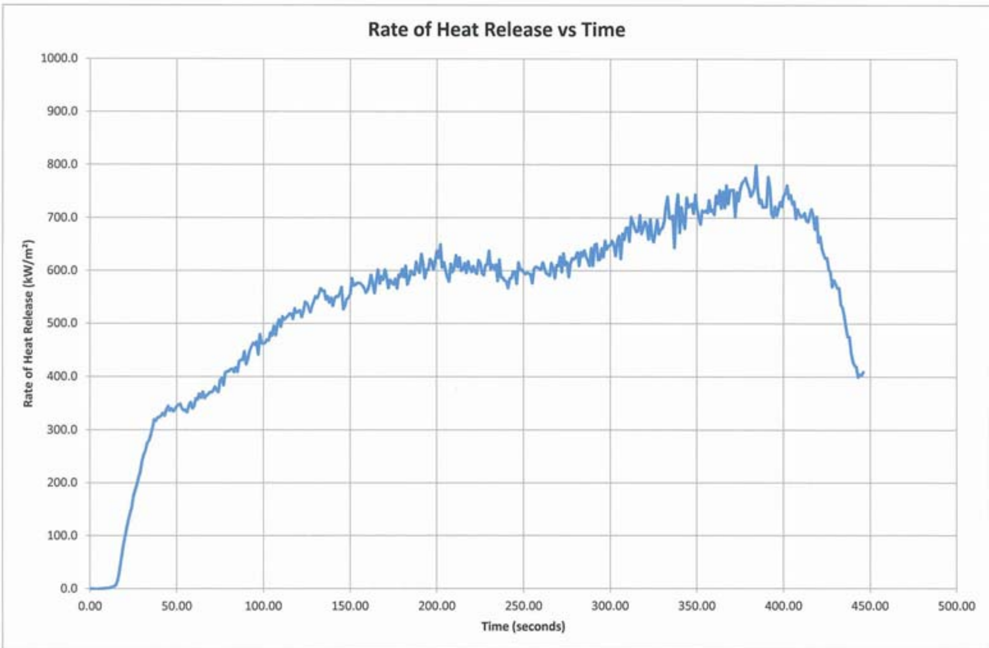
Blend 17

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 17	
Test ID	HSL0401	
Material	Blend 17	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	0.65	seconds
Peak Rate of Heat Release	894.4	kW/m²
Time of Peak RHR	237	seconds
Average RHR over 60 seconds	416.3	kW/m²
Average RHR over 180 seconds	621.7	kW/m²
Average RHR over 300 seconds	693.4	kW/m²
Total Heat Released	218.5	MJ/m²
Avg Effective Heat of Combustion	26.84	MJ/kg
Initial Mass	84.53	g
Final Mass	3.13	g
Sample Mass Loss	8.14	kg/m²
Avg Mass Loss Rate (10% to 90%)	27.4	g/m²s
Avg SEA	3667.91	m²/kg
Time of Peak SEA	314	seconds
CO Yield	0.00351	kg/kg
CO2 Yield	1.52488	kg/kg



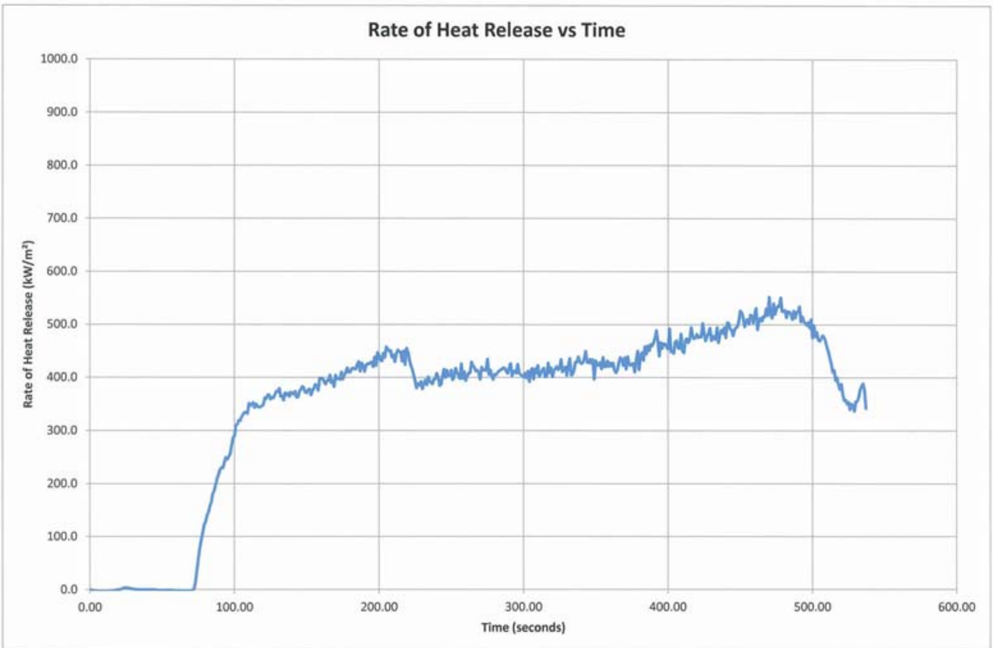
Blend 18

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 18	
Test ID	HSL2101	
Material	Blend 18	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	7.9	seconds
Peak Rate of Heat Release	799.3	kW/m²
Time of Peak RHR	384	seconds
Average RHR over 60 seconds	242.1	kW/m²
Average RHR over 180 seconds	423.8	kW/m²
Average RHR over 300 seconds	499.3	kW/m²
Total Heat Released	244.3	MJ/m²
Avg Effective Heat of Combustion	24.83	MJ/kg
Initial Mass	98.21	g
Final Mass	-0.18	g
Sample Mass Loss	9.84	kg/m²
Avg Mass Loss Rate (10% to 90%)	24.8	g/m²s
Avg SEA	4174.82	m²/kg
Time of Peak SEA	436	seconds
CO Yield	0.0035	kg/kg
CO2 Yield	1.85906	kg/kg
Pre test notes		
Post test notes		



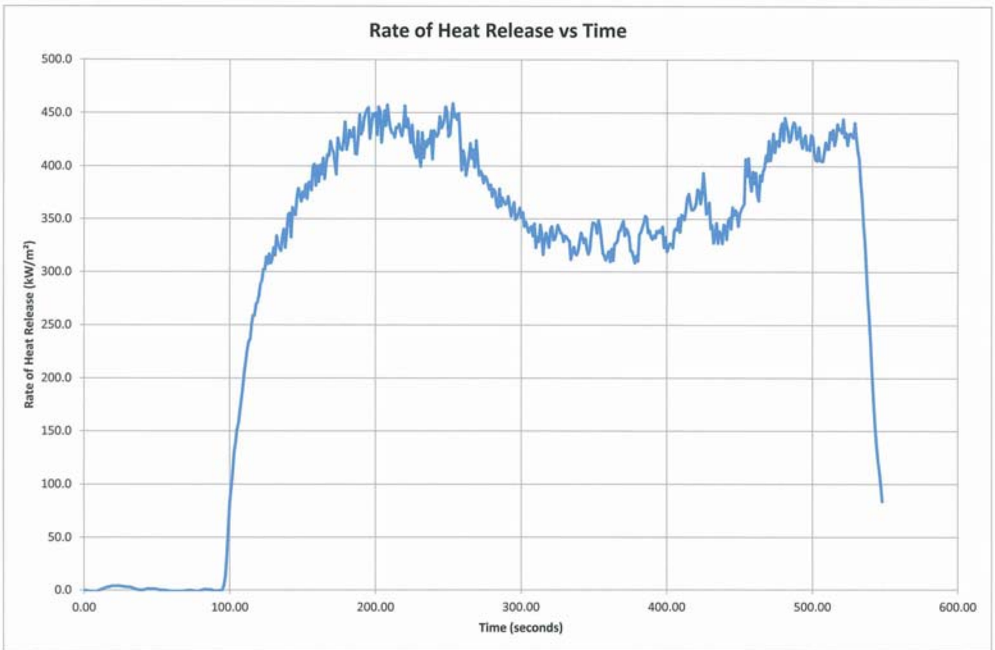
Blend 19

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 19	
Test ID	HSL2201	
Material	Blend 19	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	53.15	seconds
Peak Rate of Heat Release	552.4	kW/m²
Time of Peak RHR	470	seconds
Average RHR over 60 seconds	152.2	kW/m²
Average RHR over 180 seconds	316.3	kW/m²
Average RHR over 300 seconds	354.6	kW/m²
Total Heat Released	192.3	MJ/m²
Avg Effective Heat of Combustion	19.16	MJ/kg
Initial Mass	100.45	g
Final Mass	0.11	g
Sample Mass Loss	10.03	kg/m²
Avg Mass Loss Rate (10% to 90%)	22.1	g/m²s
Avg SEA	2929.51	m²/kg
Time of Peak SEA	535	seconds
CO Yield	0.00255	kg/kg
CO2 Yield	1.36462	kg/kg
Pre test notes		
Post test notes		



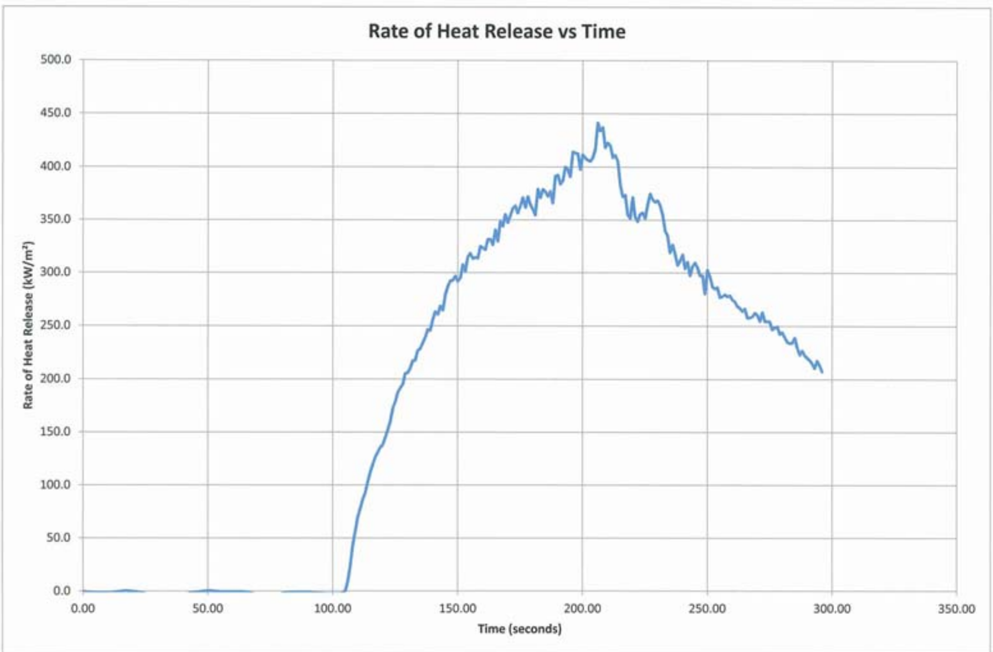
Blend 20

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 20	
Test ID	HSL2301	
Material	Blend 20	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	72.6	seconds
Peak Rate of Heat Release	459	kW/m²
Time of Peak RHR	253	seconds
Average RHR over 60 seconds	135	kW/m²
Average RHR over 180 seconds	320.7	kW/m²
Average RHR over 300 seconds	334.1	kW/m²
Total Heat Released	164.7	MJ/m²
Avg Effective Heat of Combustion	16.82	MJ/kg
Initial Mass	97.16	g
Final Mass	-0.81	g
Sample Mass Loss	9.8	kg/m²
Avg Mass Loss Rate (10% to 90%)	21.8	g/m²s
Avg SEA	2596.78	m²/kg
Time of Peak SEA	382	seconds
CO Yield	0.00222	kg/kg
CO2 Yield	1.09349	kg/kg
Pre test notes		
Post test notes		



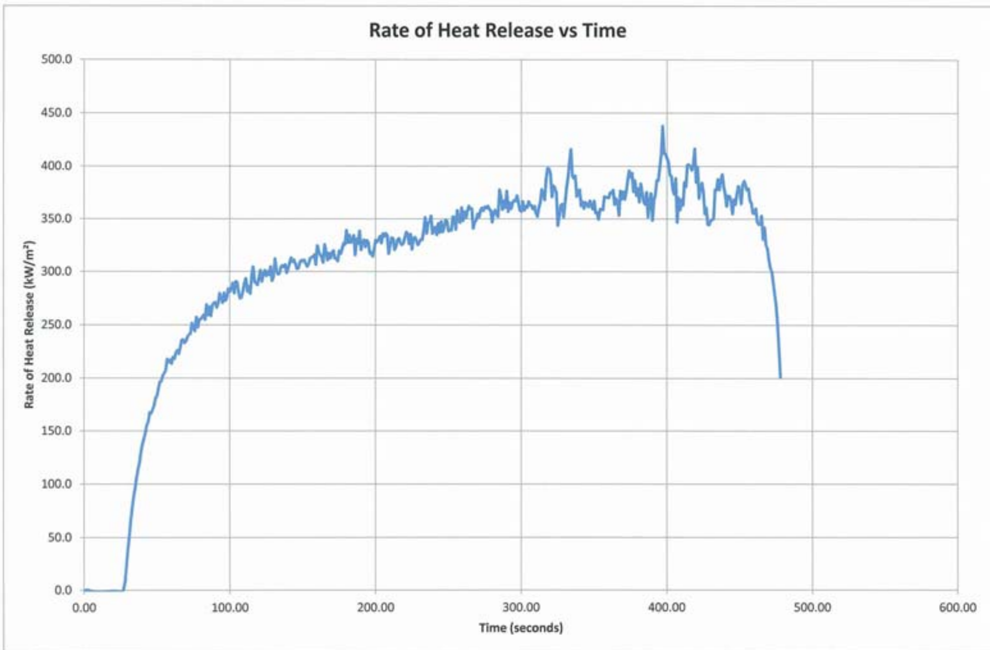
Blend 21

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 21	
Test ID	HSL2401	
Material	Blend 21	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	79.8	seconds
Peak Rate of Heat Release	441.7	kW/m²
Time of Peak RHR	206	seconds
Average RHR over 60 seconds	87.8	kW/m²
Average RHR over 180 seconds	259.7	kW/m²
Average RHR over 300 seconds	not available	
Total Heat Released	55.9	MJ/m²
Avg Effective Heat of Combustion	13.75	MJ/kg
Initial Mass	94.84	g
Final Mass	54.34	g
Sample Mass Loss	4.05	kg/m²
Avg Mass Loss Rate (10% to 90%)	18.4	g/m²s
Avg SEA	813.46	m²/kg
Time of Peak SEA	237	seconds
CO Yield	0.00166	kg/kg
CO2 Yield	0.96615	kg/kg
Pre test notes		
Post test notes		



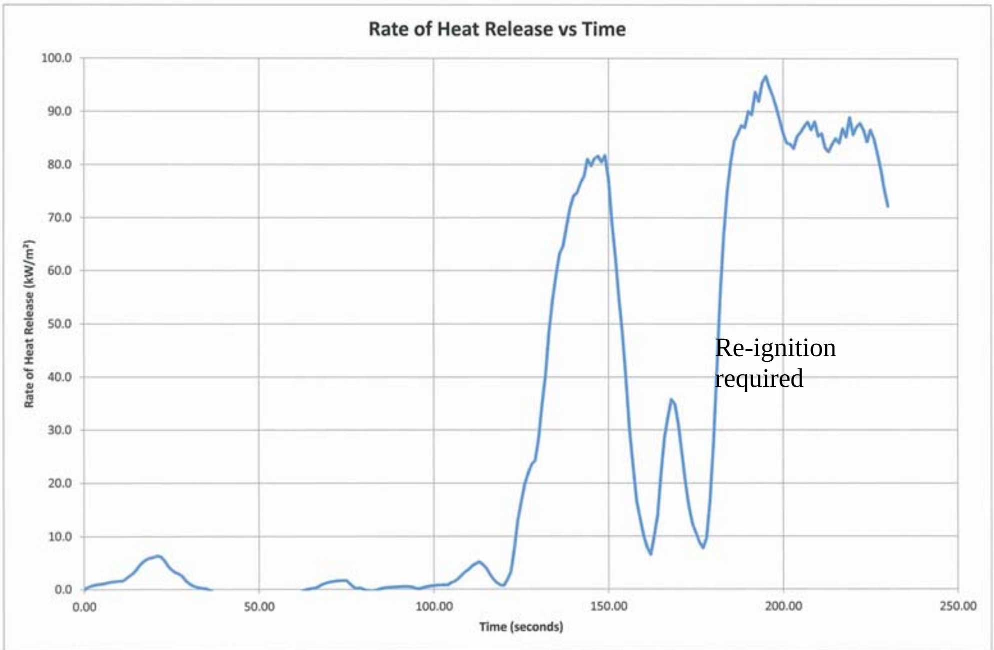
Blend 22

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 22	
Test ID	HSL2501	
Material	Blend 22	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	18.05	seconds
Peak Rate of Heat Release	437.8	kW/m²
Time of Peak RHR	397	seconds
Average RHR over 60 seconds	148	kW/m²
Average RHR over 180 seconds	249.7	kW/m²
Average RHR over 300 seconds	289.1	kW/m²
Total Heat Released	145.9	MJ/m²
Avg Effective Heat of Combustion	14.52	MJ/kg
Initial Mass	99.63	g
Final Mass	-0.82	g
Sample Mass Loss	10.05	kg/m²
Avg Mass Loss Rate (10% to 90%)	23.1	g/m²s
Avg SEA	1751.4	m²/kg
Time of Peak SEA	476	seconds
CO Yield	0.00199	kg/kg
CO2 Yield	0.92222	kg/kg
Pre test notes		
Post test notes		



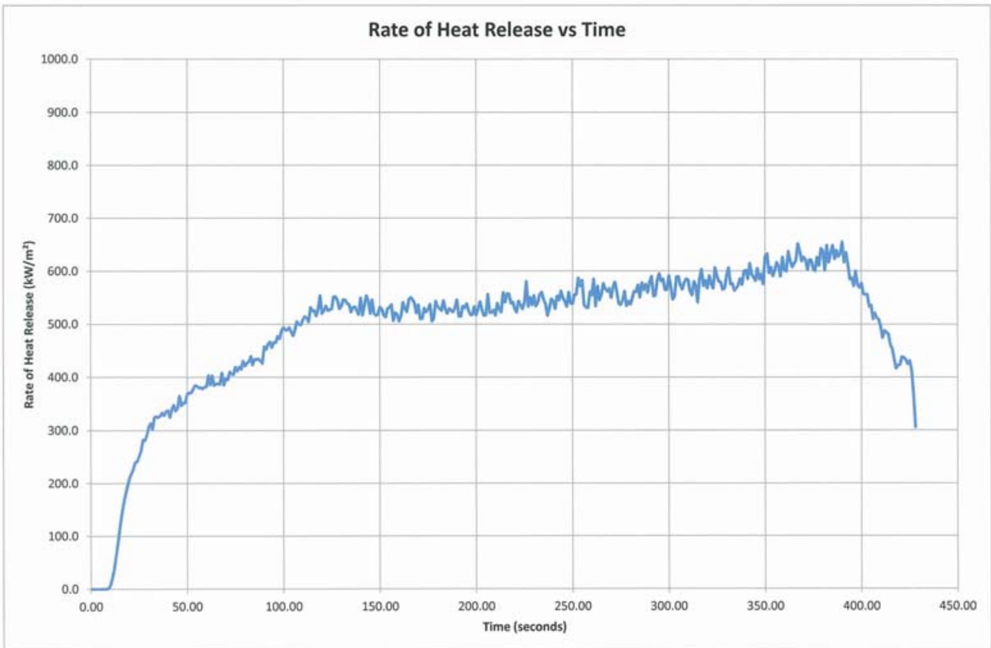
Blend 23

Test	**ASTM E1354**
Laboratory	ITRI Innovation Ltd.
Operator	AWM
Material	Blend 23
Test ID	HSL2601
Material	Blend 23
Orientation	Horizontal
Heat Flux	35 kW/m²
Time to Sustained Ignition	92.75 seconds
Peak Rate of Heat Release	96.7 kW/m²
Time of Peak RHR	195 seconds
Average RHR over 60 seconds	29 kW/m²
Average RHR over 180 seconds	not available
Average RHR over 300 seconds	not available
Total Heat Released	6.6 MJ/m²
Avg Effective Heat of Combustion	3.29 MJ/kg
Initial Mass	99.71 g
Final Mass	79.43 g
Sample Mass Loss	2.03 kg/m²
Avg Mass Loss Rate (10% to 90%)	10.2 g/m²s
Avg SEA	113.53 m²/kg
Time of Peak SEA	127 seconds
CO Yield	0.00109 kg/kg
CO2 Yield	0.06242 kg/kg
Pre test notes	
Post test notes	



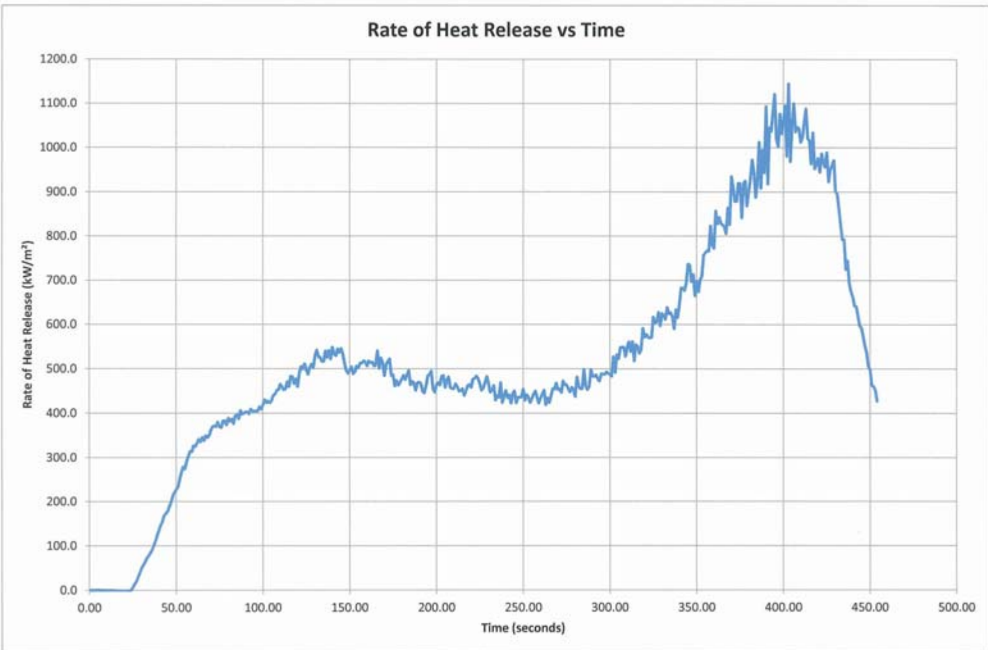
Blend 24

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 24	
Test ID	HSL2701	
Material	Blend 24	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	3.95	seconds
Peak Rate of Heat Release	655.3	kW/m²
Time of Peak RHR	390	seconds
Average RHR over 60 seconds	262.2	kW/m²
Average RHR over 180 seconds	418.2	kW/m²
Average RHR over 300 seconds	470	kW/m²
Total Heat Released	212.2	MJ/m²
Avg Effective Heat of Combustion	22.26	MJ/kg
Initial Mass	96.54	g
Final Mass	1.21	g
Sample Mass Loss	9.53	kg/m²
Avg Mass Loss Rate (10% to 90%)	25	g/m²s
Avg SEA	4213.17	m²/kg
Time of Peak SEA	426	seconds
CO Yield	0.00265	kg/kg
CO2 Yield	1.47977	kg/kg
Pre test notes		
Post test notes		



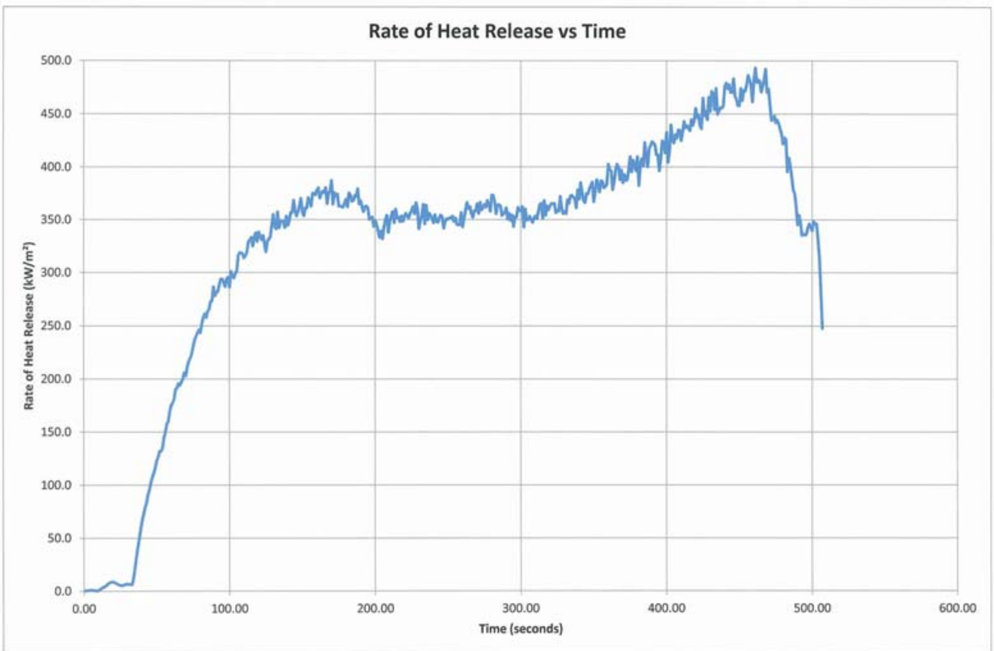
Blend 25

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 25	
Test ID	HSL0201	
Material	Blend 25	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	18.75	seconds
Peak Rate of Heat Release	1145.5	kW/m²
Time of Peak RHR	403	seconds
Average RHR over 60 seconds	206.5	kW/m²
Average RHR over 180 seconds	385.2	kW/m²
Average RHR over 300 seconds	418.8	kW/m²
Total Heat Released	236.4	MJ/m²
Avg Effective Heat of Combustion	25.33	MJ/kg
Initial Mass	94.2	g
Final Mass	0.87	g
Sample Mass Loss	9.33	kg/m²
Avg Mass Loss Rate (10% to 90%)	23.4	g/m²s
Avg SEA	3926.3	m²/kg
Time of Peak SEA	448	seconds
CO Yield	0.00266	kg/kg
CO2 Yield	1.68834	kg/kg
Pre test notes		
Post test notes		



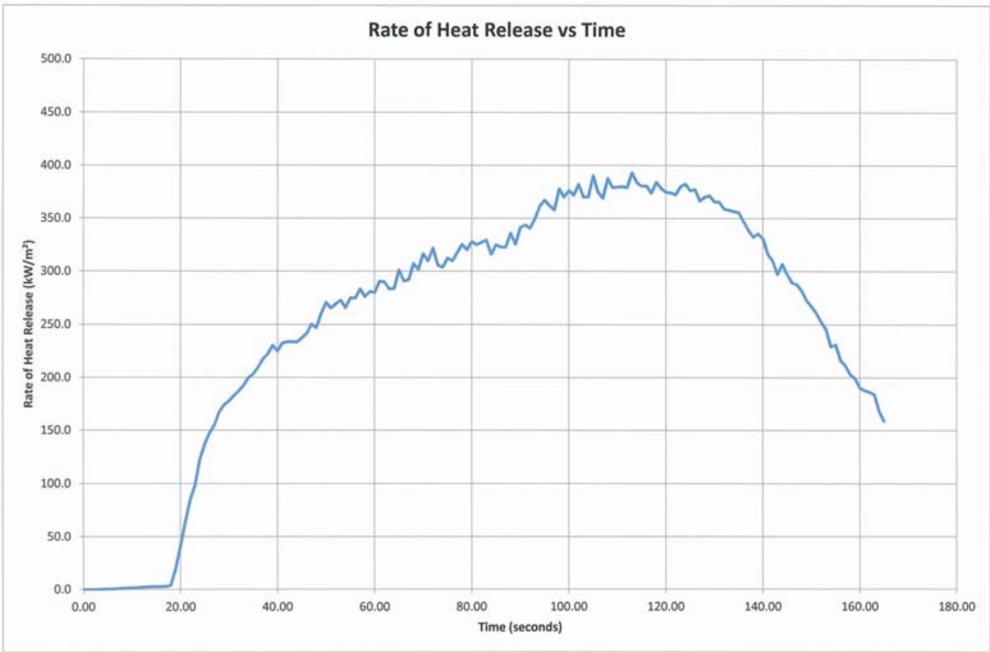
Blend 26

Test	ASTM E1354	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 26	
Test ID	HSL2801	
Material	Blend 26	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	22.25	seconds
Peak Rate of Heat Release	493.5	kW/m²
Time of Peak RHR	461	seconds
Average RHR over 60 seconds	124	kW/m²
Average RHR over 180 seconds	268.3	kW/m²
Average RHR over 300 seconds	302.9	kW/m²
Total Heat Released	167.7	MJ/m²
Avg Effective Heat of Combustion	16.78	MJ/kg
Initial Mass	101.81	g
Final Mass	1.87	g
Sample Mass Loss	9.99	kg/m²
Avg Mass Loss Rate (10% to 90%)	22.9	g/m²s
Avg SEA	2124.64	m²/kg
Time of Peak SEA	502	seconds
CO Yield	0.00259	kg/kg
CO2 Yield	1.27415	kg/kg
Pre test notes		
Post test notes		



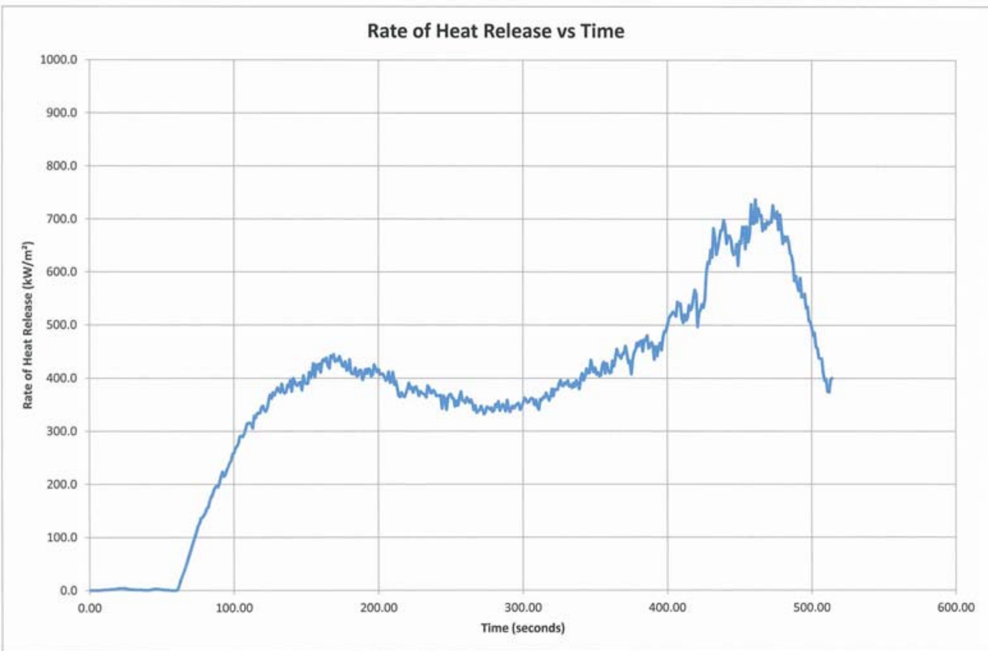
Blend 27

Test	**ASTM E1354**
Laboratory	ITRI Innovation Ltd.
Operator	AWM
Material	Blend 27
Test ID	HSL0301
Material	Blend 27
Orientation	Horizontal
Heat Flux	35 kW/m²
Time to Sustained Ignition	10.2 seconds
Peak Rate of Heat Release	393.4 kW/m²
Time of Peak RHR	113 seconds
Average RHR over 60 seconds	191.1 kW/m²
Average RHR over 180 seconds	not available
Average RHR over 300 seconds	not available
Total Heat Released	42.7 MJ/m²
Avg Effective Heat of Combustion	17.79 MJ/kg
Initial Mass	101.33 g
Final Mass	77.35 g
Sample Mass Loss	2.4 kg/m²
Avg Mass Loss Rate (10% to 90%)	15.6 g/m²s
Avg SEA	860.7 m²/kg
Time of Peak SEA	166 seconds
CO Yield	0.00169 kg/kg
CO2 Yield	1.16473 kg/kg
Pre test notes	
Post test notes	



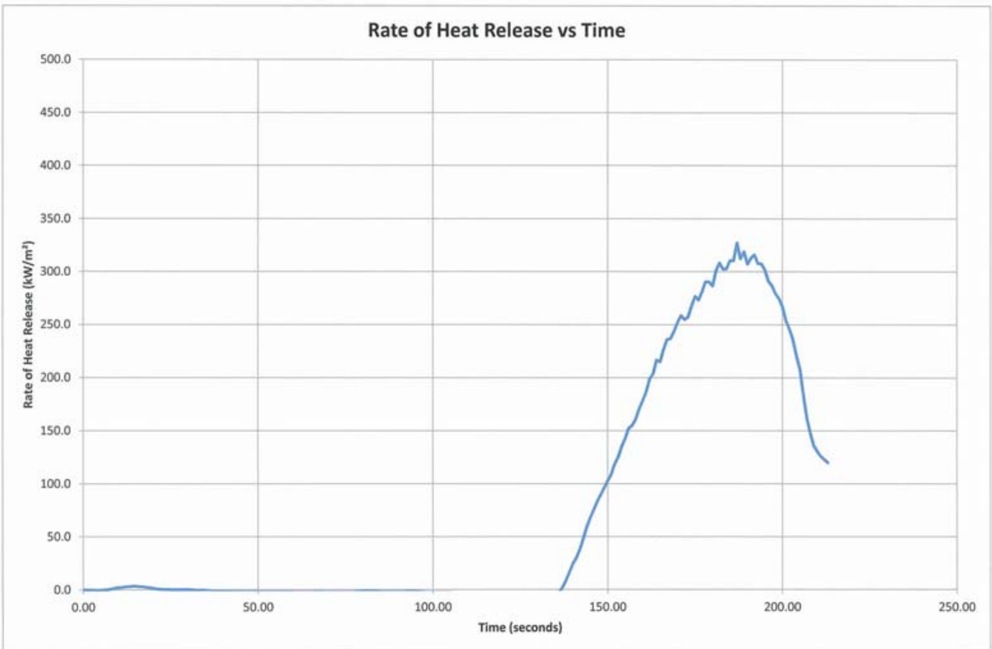
Blend 28

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 28	
Test ID	HSL2901	
Material	Blend 28	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	46.25	seconds
Peak Rate of Heat Release	737.3	kW/m²
Time of Peak RHR	461	seconds
Average RHR over 60 seconds	121.5	kW/m²
Average RHR over 180 seconds	300.7	kW/m²
Average RHR over 300 seconds	325.9	kW/m²
Total Heat Released	190.1	MJ/m²
Avg Effective Heat of Combustion	19.81	MJ/kg
Initial Mass	95.76	g
Final Mass	-0.27	g
Sample Mass Loss	9.6	kg/m²
Avg Mass Loss Rate (10% to 90%)	21.8	g/m²s
Avg SEA	3164.64	m²/kg
Time of Peak SEA	514	seconds
CO Yield	0.00239	kg/kg
CO2 Yield	1.28602	kg/kg
Pre test notes		
Post test notes		



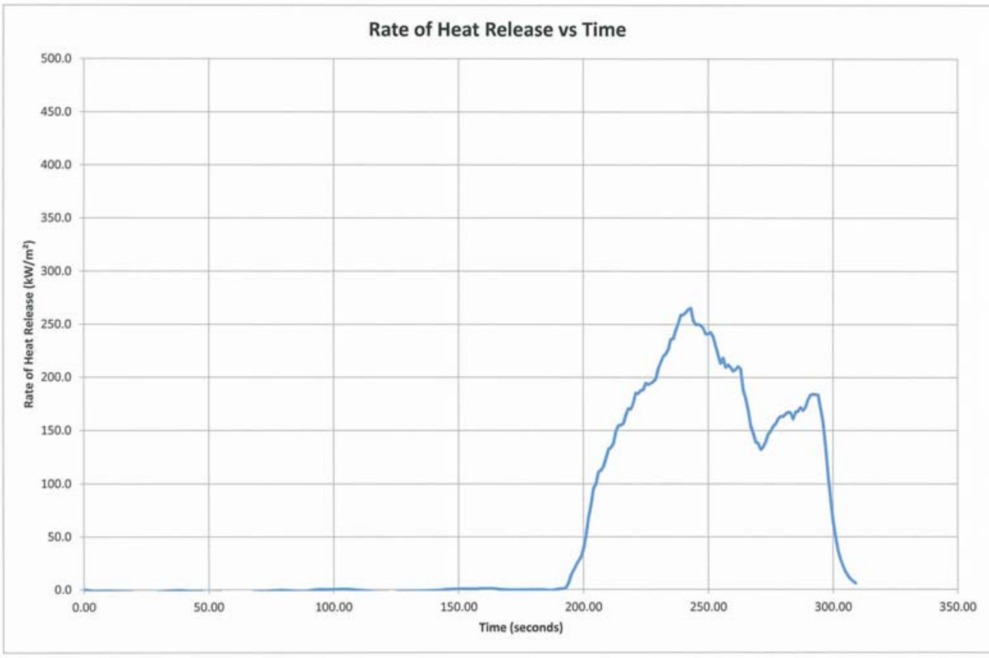
Blend 29

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 29	
Test ID	HSL3001	
Material	Blend 29	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	105.5	seconds
Peak Rate of Heat Release	327.4	kW/m²
Time of Peak RHR	187	seconds
Average RHR over 60 seconds	53.8	kW/m²
Average RHR over 180 seconds	not available	
Average RHR over 300 seconds	not available	
Total Heat Released	15.6	MJ/m²
Avg Effective Heat of Combustion	8.26	MJ/kg
Initial Mass	101.36	g
Final Mass	82.71	g
Sample Mass Loss	1.87	kg/m²
Avg Mass Loss Rate (10% to 90%)	9.7	g/m²s
Avg SEA	166.03	m²/kg
Time of Peak SEA	12	seconds
CO Yield	0.00022	kg/kg
CO2 Yield	0.17583	kg/kg
Pre test notes		
Post test notes		



Blend 30

Test	**ASTM E1354**	
Laboratory	ITRI Innovation Ltd.	
Operator	AWM	
Material	Blend 30	
Test ID	HSL0501	
Material	Blend 30	
Orientation	Horizontal	
Heat Flux	35	kW/m²
Time to Sustained Ignition	154.75	seconds
Peak Rate of Heat Release	265.6	kW/m²
Time of Peak RHR	243	seconds
Average RHR over 60 seconds	30.2	kW/m²
Average RHR over 180 seconds	not available	
Average RHR over 300 seconds	not available	
Total Heat Released	18.3	MJ/m²
Avg Effective Heat of Combustion	5.46	MJ/kg
Initial Mass	99.01	g
Final Mass	65.81	g
Sample Mass Loss	3.32	kg/m²
Avg Mass Loss Rate (10% to 90%)	13.1	g/m²s
Avg SEA	179.25	m²/kg
Time of Peak SEA	4	seconds
CO Yield	0.00045	kg/kg
CO2 Yield	0.24087	kg/kg
Pre test notes		
Post test notes		



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