Critical Factors Determining the Onset of Backdraft Using Solid Fuels

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Abstract. Backdraft is an explosive fire phenomenon which typically occurs during fire-fighting activities, occasionally leading to fire-fighter fatalities. Real backdraft incidents involve complex fuel gas mixtures consisting of the products of underventilated burning and pyrolysis following burnout. However, most experimental research into backdraft has used methane gas or flammable liquids as fuel. Some aspects of real backdraft behavior may have been overlooked as a consequence of this simplicity. A reduced scale series of compartment fire tests have been carried out to investigate the critical factors governing the onset of backdraft, using polypropylene and high density polyethylene samples as fuel. It is established that there are critical temperatures for auto-ignition of the pyrolysis gases leading to backdraft which vary with fuel properties. For polypropylene the highest temperature in the compartment must be above 350°C for auto-ignition of the fuel gases, while mixtures in the presence of a pilot source can be ignited down to about 320°C. Backdraft cannot occur when the compartment temperature is below 320°C. For polyethylene, the corresponding temperature for auto-ignition is 320°C. In parallel with these tests, a series of pyrolysis investigations have been carried out using the fire propagation apparatus, with FTIR gas analysis. The observed critical temperatures for backdraft correlate well with the evolved pyrolysis gases. Analysis shows that higher temperatures are required for backdraft when the CO/CO_2 ratio is small, and that below the auto-ignition temperature, backdraft can only occur above a CO/CO_2 ratio of about 35%. It is concluded that the crucial factors determining whether backdraft occurs or not are the maximum temperature and the CO/CO_2 ratio in the compartment, prior to opening the door.

1. Introduction

Backdraft (or 'backdraught' if the British spelling is preferred) is a fire phenomenon which typically occurs late in the development of a fire and is usually triggered due to the interventions of fire-fighters, often with fatal consequences. It remains one of the primary unresolved issues in fire science [1].

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A backdraft can only occur when there is a hot, fuel-rich fire compartment with a limited air supply, such that the fire becomes highly ventilation-limited or is extinguished, possibly with residual smoldering or hot spots remaining [2]. If a door or window is opened or breaks, the inflowing air mixes with the hot, fuel-rich compartment gases, creating a flammable gas mixture. If the mixture is above auto-ignition temperature, or if some pilot source is present, the gas ignites, typically resulting in a fireball driven through the opening, with potentially fatal consequences for those outside the compartment. Backdraft is not instantaneous however, and there is often a significant delay between the opening of the door and the onset of the backdraft [1, 3], the delay can be as long as several minutes.

There has been sporadic research into backdraft and related phenomena over the past two decades or so, but many questions remain unresolved or have only been answered approximately.

Fleischmann et al. [3–5] pioneered backdraft research in the early 1990s, using a lab-scale chamber (2.4 × 1.2 × 1.2 m) with a methane burner to test and observe backdraft development. They observed the 'gravity current' flow, the delay time, and deduced factors crucial to the occurrence of backdraft. They concluded that 10% of unburned fuel in the compartment gases was the critical concentration to allow backdraft.

Subsequently, Weng and Fan [6–8] conducted a series of backdraft tests using an apparatus half the size of Fleischmann's, but with the same geometry. They also found the concentration of unburned methane is a key parameter in determining the occurrence of backdraft, and found that the critical value varied with the location of the inlet; for some locations, a gas concentration as low as 7% could result in a backdraft [7].

The 'gravity current' observed by Fleischmann has been the subject of most backdraft research to date [3, 6, 9–14]. When the door between a hot compartment and a cooler external atmosphere is opened, the buoyancy differential means that hot gases from the compartment will spill out the top of the opening, and a flow of cooler air will flow in through the bottom of the opening, under the hot gases. This phenomenon has been labelled the 'gravity current'. The rate of gravity current flow is largely dependent on the temperature difference between the two fluids; a higher temperature and density difference between the two gas mixtures will lead to a fast flow situation, with strong turbulent mixing. Provided there is sufficient fuel in the hot gas and sufficient oxygen in the cooler gas, this turbulent mixing will rapidly create a cloud of flammable gas. If this gas is ignited, the resulting deflagration is described as a backdraft [2].

The mixing process is not instantaneous. It is commonly assumed that the delay time between door opening and backdraft occurring is the same as the time taken by the gravity current to travel to the rear wall of the compartment. Thus, prediction of the delay time can be made if the geometry of the compartment and the density difference between the gases is known. This reasoning assumes that the backdraft is triggered by a pilot source at the rear of the compartment, as in Fleischmann's and Weng and Fan's experiments. This, of course, may not correspond to reality in many backdraft situations.

To date, most experimental and modelling studies of backdraft have used methane as the fuel source, and while the conclusions regarding the crucial conditions for backdraft have often been expressed in general terms, these conclusions are strongly limited by the fuel used. In reality, backdraft events occur in compartments filled with complex mixtures of partially burnt products of pyrolysis from solid fuels such as wood, plastics and foams. Such pyrolysis gases have a range of flammability limits, and may only be flammable at elevated temperatures. Methane, on the other hand, is flammable at ambient temperature, so any dependence on temperature of the onset of backdraft in real situations cannot have been observed, and has not been defined using methane. This limitation of the literature studies is the primary motivation for the study presented here.

Some investigation of backdraft using liquid [2, 15, 16] and solid [16, 17] fuels has also been carried out, but these studies have generally involved small experimental campaigns, focused largely on quantification of the critical fuel mass fraction for backdraft in the compartment gases. The study by Chen et al. [16] used n-Heptane and wooden fuels in a compartment with a pilot source. As n-Heptane vapor is flammable at room temperature, these test results share the same limitation as tests using methane, as mentioned above. The tests by Chen et al. using wood are closer to real backdraught scenarios, and therefore of relevance to the present study. The study by Gottuk et al. [2] artificially introduced known quantities of diesel fuel into a hot compartment as a fine spray. This enabled them to quantify the critical fuel mass fraction accurately, but has little else to say to the scenario of a real comaprtment backdraft, where the gas phase fuel mixture is generated by underventilated burning before burnout, and pyrolysis due to residual heat after burnout. Tsai & Chiu [17] carried out three full scale experiments with real furniture. While backdraft occurred in their tests, the limited number of tests makes it impossible to observe any trends in these data.

The fuel types used in previous experimental studies of backdraft are summarised in Table 1.

Table 1
Backdraft Experiments in the Literature and the Fuel Studied

Fuel	Authors	Year	References
Methane	Fleischmann et al.	1994	[5]
	Bolliger	1995	[18]
	Gojkovic	2000	[10]
	Weng and Fan	2002–2003	[6, 7]
	Tsai and Chiu	2013	[17]
LPG	Wu et al.	2011	[19]
Propane	Fleischmann et al.	1993	[4]
Diesel	Gottuk et al.	1999	[2]
Heptane	Chen et al.	2011	[16]
	Mao et al.	2011	[15]
Wood	Chen et al.	2011	[16]
Furniture	Tsai and Chiu	2013	[17]

Although the study by Gottuk et al. [2] relied on auto-ignition of the fuel/air mixtures to generate backdraft, most previous research has generally focused on piloted ignition of backdraft, with the pilot flame or spark generally being positioned at the other end of the compartment from the opened door. Observations made about the delay time between opening the door and the onset of backdraft have therefore been largely related to compartment geometry. Auto-ignition of backdraft has not been widely studied. To address this deficiency in the literature, both piloted and auto-ignition conditions have been investigated in this study.

This research aims to identify critical temperatures and flammable gas concentrations for backdraft relating to different solid fuels, for both auto-ignition and piloted ignition backdraft events. Furthermore, this study aims to map out these critical conditions for backdraft, providing a robust method for predicting whether the onset of backdraft is possible in a given scenario.

2. Experimental Setup and Procedure

2.1. Experimental Apparatus

Previous research has shown that the occurrence of backdraft is not dependent on the size of compartment used [18], therefore these studies may be carried out at laboratory scale. This not only enables a greater number of experiments to be carried out, but also reduces the risks inherent in the experiments to manageable levels.

A small-scale fire compartment (0.8 m × 0.4 m × 0.4 m) was designed and built for backdraft research, see Figs. 1 and 2.

It is instrumented with 7 thermocouple trees (24 type K thermocouples (1 mm diameter) in total). TC trees 3 and 6 are positioned on the centerline of the compartment, at 0.4 m and 0.6 m from the back wall of the compartment. On these trees, there are TCs fixed at 0, 0.1 m, 0.2 m, 0.3 m, and 0.4 m below the ceiling. Trees 2 and 4 are positioned on either side of tree 3, halfway between the centerline of the compartment and the wall. Similarly, trees 5 and 7 are positioned on either side of tree 6. Trees 2, 4, 5 & 7 have TCs at 0.1 m, 0.2 m and 0.3 m below the ceiling. Tree 1 is positioned in line with trees 2 and 5, not on the centerline, as this is the location of the fire, it only has TCs at 0.1 m and 0.3 m. The fuel bed is contained in a steel tray, which is 20 × 20 × 5 cm, and was positioned 10 cm from the rear wall. The compartment was constructed out of two-layers of expanded insulating vermiculate boards, for which the maximum working temperature is 1100°C. An electric spark apparatus was installed on the rear wall for the tests investigating piloted ignition.

There are three removable baffles which may be positioned across the opening of the compartment, to investigate the effects of opening size. In all the experiments described here, the upper two baffles were kept in place, such that the opening was fixed at 0.13 m × 0.4 m wide. Other door opening sizes and configurations will be tested in the future, and the findings will be published in due course. A sliding outer door is used to seal and open the compartment, this
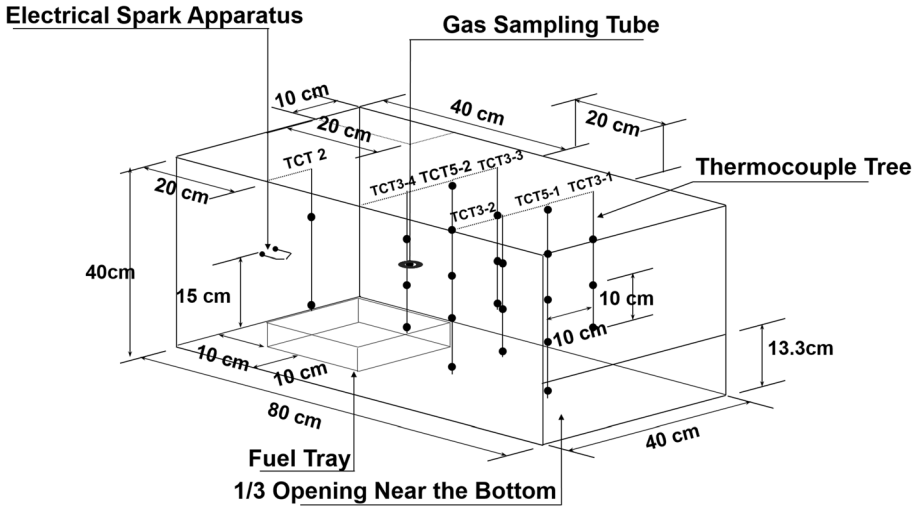
Figure 1. Diagram showing the locations and dimensions of the compartment, the thermocouples, the 20 × 20 × 5 cm fuel tray, the electrical spark and the door opening.
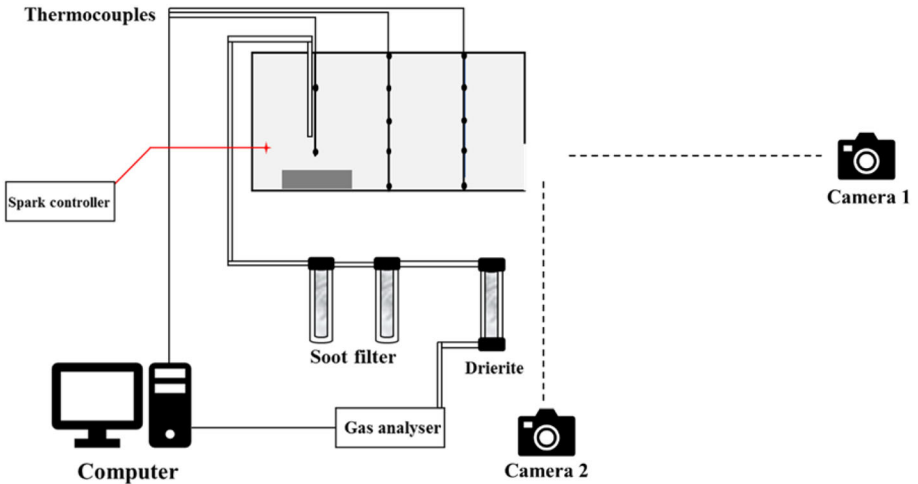
Figure 2. Sketch of the experimental apparatus used.

ensures that the experimenter is safely to the side of the compartment when the door is opened, and is well out of the way of any ejected flames.

A portable gas analyzer manufactured by Crestline Instruments (model 7911) was used to characterize the gas for a few seconds before opening the door in several of the tests. The apparatus was calibrated with accuracies of ± 1%, ± 3%, and ± 3% for O_2, CO and CO_2, respectively. The gas sampling tube was installed in line with TC 3–1 and 3–3 for some tests investigating the gas composition

immediately before the door was opened. In these tests, a gas sample with a flow rate of 1 L/min, was extracted in the 8 s to 10 s period before opening the door. The reason for this very short sampling time was to limit the influence of the sampling procedure on the compartment fire dynamics; a longer sampling duration would significantly change the conditions in the compartment and therefore influence the outcomes. In these tests, the sampled gases extracted less than 0.013% of the total volume of the compartment. In practice, a shorter sample duration could not be used as the gas analyzer required a few seconds of sampling to reach a stable reading.

2.2. Experimental Procedure

In this project, different solid fuels have been used to investigate the relationship between the onset of backdraft with material type. Here we present results for polypropylene (PP) and high-density polyethylene (HDPE) fuels. These fuels melt and do not char, so the conclusions from these tests cannot be generalized to all solid fuels, but these were chosen for their relative simplicity, as a first step in a series of investigations. Future research will involve other fuels including wood.

The conditions for backdraft can be achieved after a fire has become well established, but it has already been demonstrated that fire growth to flashover is not required [20]. Flashover, when it occurred, was identified during these tests by a rapid increase in burning rate, a significant increase in temperature, and external plume burning. In these experiments, the fire was initiated using a small quantity (150 mL) of n-heptane (C_7H_{16}) to accelerate the fire, this liquid fuel was consumed in the first 5 min of each test, so it is assumed that negligible quantities of n-heptane remained in the fuel during the periods of door closure, which were generally initiated more than 7 min after ignition, as will be described.

In tests using PP fuel, 300 g of pellets were used as fuel, in the square fuel tray. The pellets were nominally spherical and about 3 mm in diameter ($\pm$ 10%). If the door was left open, this quantity of fuel exhibited a 'steady burning' phase from about 7 min to 12 min after ignition, followed by a rapid growth to flashover between 12 min and 14 min after ignition and the fuel began to run out about 16 min after ignition. The steady burning phase is characterised by a gradual and consistent increase in temperature of all thermocouples in the compartment. Figure 3 shows a photograph of the PP fuel in the tray.

In tests using HDPE fuel, which has a similar heat of combustion to PP [21], about 300 g of short strips of the material (see Fig. 4) were used as fuel, in the same pan as used for the PP experiments. The strips were 2 mm thick, approximately 20 mm wide and 100 mm long. The HDPE fuel load generally took longer to become established but exhibited a steady burning phase from about 13 min to 18 min after ignition, growing to flashover after about 20 min to 22 min after ignition.

In each test, the temperatures within the compartment were monitored and the door was closed at the temperature of interest, which varied from test to test, as will be discussed. This rapidly led to an oxygen-starved fire in the compartment and flaming ceased. Without the fire to maintain the heat balance, the box and

Figure 3.   The PP fuel pellets in the fuel tray. The tray is 20 × 20 cm, the pellets are nominally 3 mm spheres.
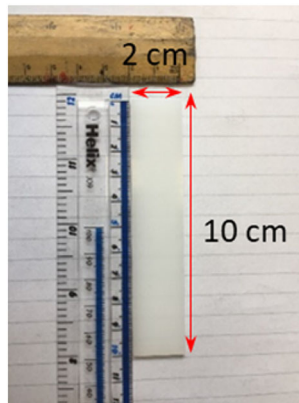
Figure 4.   Photograph of one of the HDPE fuel strips, 20 × 100 × 2 mm thick.

the gases in it began to cool. During this phase the temperatures were monitored closely and the door was opened once the gas cooled to the temperature to be investigated; again, this varied from test to test. Following this there was usually a short delay (as discussed below), followed by one of three things:

1. a backdraft event (sudden ignition of compartment gases resulting in a signifi- cant fireball emerging from the compartment opening),

2. a reignition event (sudden ignition of compartment gases within the compartment, and pool fire re-established, but no significant external flaming or fireball), or
3. no reignition or backdraft.

The primary objective of this research is to identify the minimum set of conditions (temperature, gas concentrations, etc.) required to allow the establishment of a backdraft.

Temperatures were generally monitored using one specific thermocouple in the upper part of the compartment. This reference thermocouple consistently showed the highest temperature reading in all tests, both when the door was open and when it was closed. Previous work [16] has shown that the onset of backdraft correlates better with the maximum temperature in the compartment than with an average value; the cooler parts of the compartment seem to play no role in determining whether or not backdraft will occur. In all discussion of temperature that follows it should be remembered that the temperature quoted is characteristic of the highest temperatures found in the box, and is not an average or characteristic temperature within the box.

In every experiment that resulted in no backdraft or reignition, the fuel pan was found to contain a significant quantity of residual fuel, so it may be assumed that the lack of reignition or backdraft in these tests was due to factors other than availability of fuel.

Figure 5 shows the temperature variations in the apparatus during a typical test with PP fuel. In this instance, the door was closed at 14 min, just after the com-
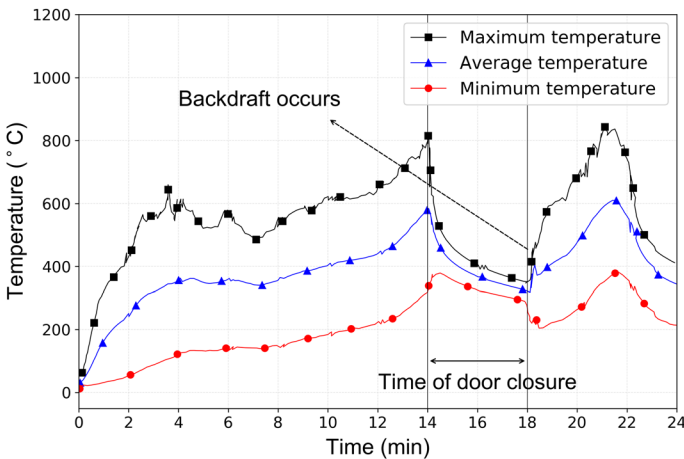
Figure 5. Temperature variations during a typical test with PP fuel, door closed after flashover, pilot spark was not used. Plots show maximum recorded compartment temperature, average compartment temperature and minimum recorded compartment temperature.

partment transitioned to flashover. The door was kept closed for 4 min, and then opened. A backdraft occurred after a 10.5 s delay.

Figure 6 shows the temperature variations in the apparatus during a typical test with HDPE fuel. In this instance, the door was closed at 18 min, just after the compartment transitioned to flashover. The door was kept closed for 7.5 min, and then opened. A backdraft occurred after a 29.7 s delay in this instance.

It is clear from Figs. 5 and 6 that the temperature gradients in the compartment are considerably reduced when the door is closed. In most experiments, the temperature difference between the highest recorded temperature and the lowest recorded temperature in the compartment, just before the door is opened, was about 50°C.

Attempts have been made to try and obtain accurate mass loss data for the fuel tray in the period between door closure and door opening. Unfortunately, to date, it has not been possible to obtain sufficient acceptable data, or to distinguish between burning and pyrolysis following flame-out. The most reliable data obtained so far, for door closures at around flashover for either fuel, show that the PP fuel tray lost 28.8 g in mass during a 257 s door closure, and the HDPE fuel tray lost 65.4 g during a 446 s closure. This shows a higher average mass loss rate per second for HDPE compared to PP, approximately 0.15 g/s compared to 0.11 g/s, respectively. It should be noted that as the temperature in the compartment is gradually diminishing when the door is closed, it is assumed that the pyrolysis rate will also diminish across this time, so it is unwise to infer anything from average mass loss rates, particularly when comparing tests with different door closure times.
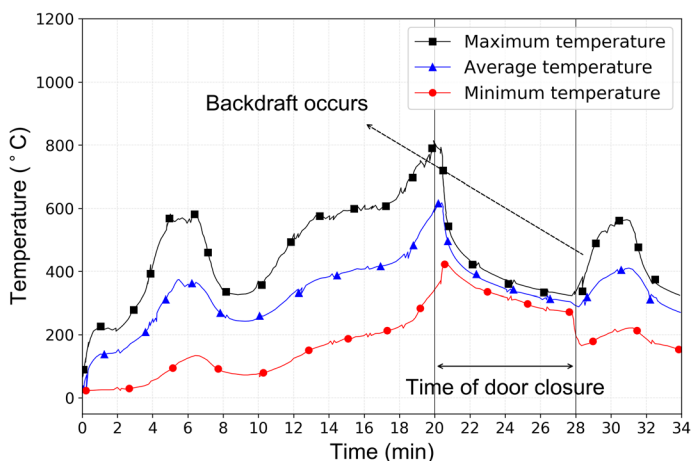
Figure 6. Temperature variations during a typical test with HDPE fuel, door closed after flashover, pilot spark was not used. Plots show maximum recorded compartment temperature, average compartment temperature and minimum recorded compartment temperature.

Also, the effect of geometry on gas concentrations was investigated. Three experimental series with different compartment sizes (narrower compartments, varied by adjusting the position of the internal walls) were investigated to further understand gas concentrations during tests. The purpose of these tests was to observe CO and CO_2 gas species variations before door opening, with the same location of the gas tube, and if the changes can be correlated to the occurrence or not of backdraft.

A series of 123 experiments using PP fuel have been carried out to map out the conditions under which backdraft may occur, both in the presence and absence of a pilot spark. These tests were to investigate the influence of temperature on backdraft occurrence. The final 33 experiments using PP were conducted with gas analysis. 8 further experiments using HDPE fuel were also carried out. The results are presented in Sect. 3, below.

2.3. Pyrolysis Gas Analysis

Once the compartment door is closed, the fire will rapidly use up much of the remaining oxygen in the apparatus and will then burn out. Following flame-out, the compartment remains hot and the fuel pool will continue to pyrolyze for some time, provided the compartment remains hot enough. In order to understand the chemistry which may lead to backdraft conditions it is essential to know what the products of pyrolysis are.

It is not possible to adequately characterise these pyrolysis gases in situ, during a backdraft experiment, so a series of pyrolysis experiments have been carried out using the fire propagation apparatus (FPA) [18] at reduced oxygen levels, together with a Fourier transform infrared spectroscopy (FTIR) system [19], to determine what the likely products of pyrolysis are.

The FPA was used to expose all samples tested to a constant incident radiation of 50 kW/m^2. This is a higher heat flux than might be expected in typical compartment fires, but was chosen to ensure rapid and complete pyrolysis of the samples. The mass of each sample was recorded before testing and the test was terminated once the sample had completely pyrolyzed. Pyrolysis was studied at three oxygen concentrations: 13%, 9% and 0%. A pilot flame was not used, and ignition was not observed in any of the experiments.

In each test, the plastic material (PP in pellets, HDPE in thin strips, as in the backdraft experiments) was placed in a sample holder measuring $85 \times 85 \times 20$ mm, and the initial mass of each sample was about 40 g. The duration of exposure varied between experiments, as the objective was to ensure complete pyrolysis. The tests varied between 420 s and 510 s.

A quartz tube was used to enclose the pyrolysis chamber in the FPA. A nominal inlet flow of reduced oxygen air of 100 L/min was kept constant before and during each test. The FTIR probe was positioned near the top of the quartz tube, 900 mm above the sample surface. In each experiment, the concentration of 11 chemical signatures (listed in Table 2) was estimated using the FTIR. In each test it became clear that there appear to be four primary pyrolysis product families (in terms of maximum concentrations and ratio with other species), but that these are

Table 2
**Dominant Chemical Species Identified Using FTIR in the Pyrolysis Tests**

Species	PP	HDPE
Water vapor H_2O	–	–
Carbon dioxide CO_2	–	–
Carbon monoxide CO	–	X
Methane CH_4	–	X
Ethylene C_2H_4	–	–
Ethane C_2H_6	–	X
Propane C_3H_8	–	–
Butane C_4H_{10}	X	–
Pentane C_5H_{12}	X	–
Hexane C_6H_{14}	X	X
Benzene C_6H_6	X	–

different for PP and HDPE. Table 2 shows all measured species and highlights the primary gases identified for PP and HDPE. While water vapor and carbon dioxide were detected for both sample types, neither of these gases were among the four dominant species for either fuel.

It should be noted that the FTIR system does not identify specific chemicals, but rather identifies modes of bending of chemical bonds and structures characteristic of the chemicals named. For example, when 'Benzene' is identified by the FTIR system, the pyrolysis products might not actually contain benzene, but will certainly contain some compounds with aromatic ring structures, like benzene. For simplicity in the analysis that follows, however, we will use the various named chemicals as shorthand for the family of chemicals they may represent.

2.3.1. HDPE Pyrolysis Figure 7 shows the concentration of carbon monoxide, methane, ethane and hexane for the pyrolysis of HDPE in hypoxic atmospheres. In each test, following a period of 200 s after the start of the exposure where the generation of gases was comparatively low, the material degraded rapidly, and the concentration of flammable gases increased sharply. The concentration of CO gas is higher for higher oxygen concentrations and diminishes with diminishing oxygen; there appears to be an equivalent trend for the other three primary gases, although this is less apparent. Of course, the dominant species, carbon monoxide, requires oxygen for its formation, but the reducing trend in the other gases is less explicable. It would appear that the presence of oxygen assists the process of fragmentation of the polymer to shorter chain hydrocarbons. Aside from carbon monoxide, the dominant pyrolysis product appears to be hexane, with lighter hydrocarbons also being produced.

2.3.2. Polypropylene Pyrolysis Figure 8 shows the concentrations of the hexane, benzene, butane and pentane families during pyrolysis of PP. For all cases, the concentration of pentane is the highest, followed by hexane. The maximum con-
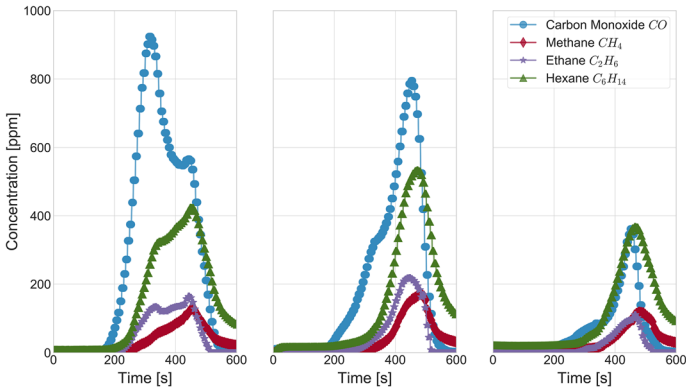
Figure 7. The four primary pyrolysis products from ethylene samples.
Left: 13% O_2, centre: 9% O_2 and right: 0% O_2.
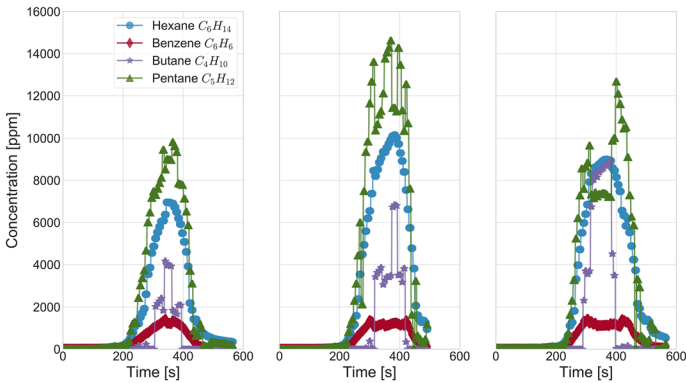
Figure 8. The four primary pyrolysis products from polypropylene
samples. Left: 13% O_2, centre: 9% O_2 and right: 0% O_2.

centration of these two gases is much lower at the highest oxygen level, showing that partial oxidation may be occurring with this amount of oxygen present. Aromatic hydrocarbons are also produced, but these are at a lower level and will be discounted in the discussion that follows. Under the controlled conditions of the FPA, the highest concentrations of the four primary gases were attained for the 9% O_2 test.

It should be noted that the maximum concentrations are an order of magnitude higher than those for HDPE, which has a direct impact on the attainment of concentrations of these gases sufficient to generate a potentially flammable mixture in an enclosed chamber.

3. Results

3.1. Polypropylene

3.1.1. Temperature Factor 123 experiments have been carried out using PP fuel. No backdraft was observed in 37 of these tests. Figure 9 shows the results in summary. Each data point represents a single test. The data here indicate the duration of door closure and the temperature at the time of door opening, information about how long after ignition the door was closed is not visualized here; some of these data represent tests where the door was closed long before flashover could have happened, while others attained flashover before the door was closed. The temperature plotted here indicates the maximum recorded temperature in the compartment at the time the door was reopened, this is not a measure of the average temperature in the compartment. (Note, 4 tests with very long door closure times are not shown in the figure for reasons of clarity; in these instances the door was closed after flashover and backdraft occurred on door opening, in the presence of a pilot source, when the temperature was below 300°C).

It is clear that in all tests where the temperature was above 400°C before door opening, backdraft occurred. Likewise, it is clear that in all tests when the temperature had dropped below 330°C, no backdraft or reignition occurred unless a pilot source was present. The main focus of our investigation therefore lies between these limits.

When the temperature at opening was above 350°C, backdraft generally occurred, except in those cases where the period of door closure was short. It is supposed that the relatively cool box and the short duration of closure in these few
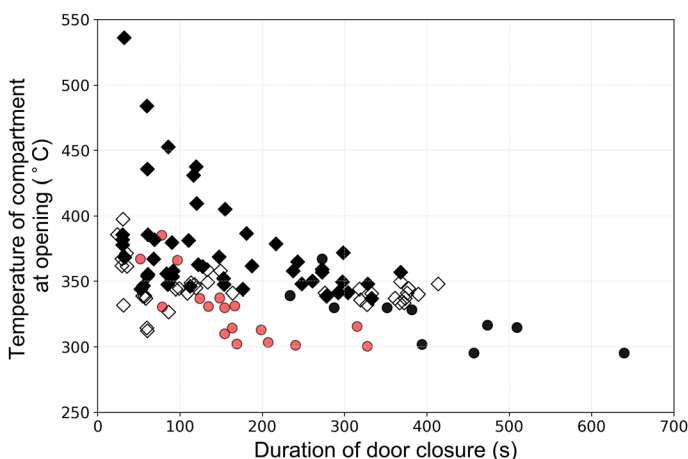
Figure 9.   Temperature at time of door opening for tests using PP fuel. Diamonds indicate non-piloted experiments, circles indicate the presence of a pilot spark. Solid markers indicate backdraft events, shaded/pink markers indicate reignition, and empty markers indicate no backdraft or reignition (Color figure online).
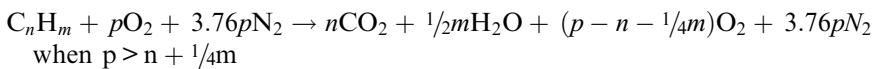
tests meant that insufficient pyrolysis gases accumulated in these tests and no flammable mixture could be generated.

When the temperature at opening was between 340°C and 350°C, and no pilot spark was used, backdraft occasionally occurred, but more often there was no backdraft. It would seem that there is a critical temperature in this range, above which backdraft generally does occur and below which backdraft generally does not occur. No instances of backdraft in the absence of a pilot spark were observed below 340°C. Further analysis of the data reveal that the instances of backdraft triggered below 340°C all featured a high temperature before door closure (close to, or post-flashover), a relatively long duration of door closure, and the presence of a pilot spark. These results are discussed in more detail in [16]. Reignition events only occurred when a pilot spark was present, and for tests where the duration of door closure was short, or the compartment temperature was comparatively low before door closing.

The series of tests carried out aimed to cover a wide range of experimental conditions. Given the range of conditions to be 'mapped out' it was decided that repeat tests with identical conditions would not be carried out, but each test would occupy a unique space in the domain. While this means that uncertainties and errors on specific data points cannot be estimated with precision, the data does allow any clear trends among the data to be observed. Given the number of tests carried out, the degree of confidence in these trends is sufficiently high to draw justifiable conclusions.

3.1.2. Gas Concentrations In the previous section, it is shown that temperature is one of the crucial factors in determining the onset of backdraft. A temperature in the range from 340°C to 350°C seems to be a critical value when PP is used as fuel. It is, however, of interest to investigate other measurable factors to explore the other necessary conditions for backdraft to occur.

In well ventilated conditions, most hydrocarbon fires tend towards complete combustion, generating primarily water vapor and carbon dioxide as products, as follows:

$$C_nH_m + pO_2 + 3.76pN_2 \rightarrow nCO_2 + \tfrac{1}{2}mH_2O + (p - n - \tfrac{1}{4}m)O_2 + 3.76pN_2$$
$$\text{when } p > n + \tfrac{1}{4}m$$

When there is insufficient air, that is, in ventilation controlled fire conditions, complete combustion cannot occur and carbon monoxide will be one of the products:

$$C_nH_m + pO_2 + 3.76pN_2 \rightarrow qCO_2 + rCO + \tfrac{1}{2}mH_2O + 3.76pN_2$$
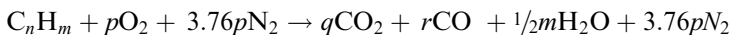
where $p = q + 2r$; when $n + \tfrac{1}{4}m > p > \tfrac{1}{2}n + \tfrac{1}{4}m$, neglecting soot production. . (Note, it is highly unlikely that burning can be sustained as p tends towards $> \tfrac{1}{2}n + \tfrac{1}{4}m$, except at highly elevated temperatures.)
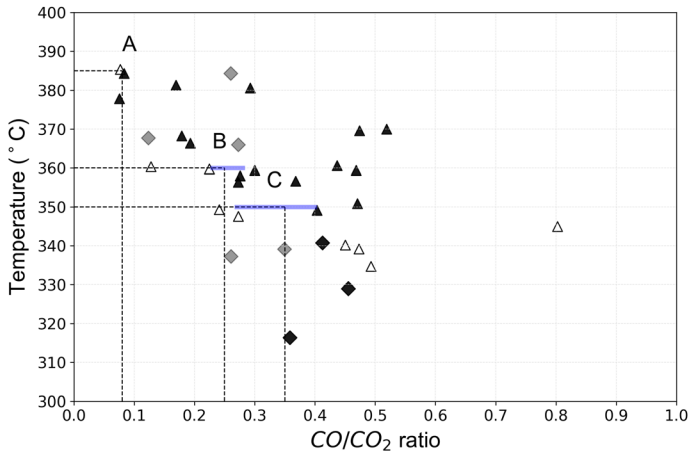
Figure 10. **CO/CO$_2$ ratio versus compartment temperature for the PP tests with gas analysis. Experiments with backdraft occurrence are shown using solid black markers, re-ignition without fireball is shown in grey, and those tests did not result in backdraft or reignition are shown using empty markers. Both piloted and auto-ignition conditions were tested, and are indicated using diamonds and triangle markers, respectively.**

It is hypothesized that the relative quantities of CO and CO$_2$ could provide information about the amount of underventilated burning during the time of door closure, and this might be correlated with the onset or otherwise of backdraft.

Figure 10 shows the relevant experimental data for CO/CO$_2$ ratio immediately prior to door opening. (Note that the cluster of unfilled triangles between 0.4 and 0.5 CO/CO$_2$ ratio are below 340°C and would not be expected to lead to backdraft without a pilot source, as previously discussed. The two re-ignition events at a CO/CO$_2$ ratio of about 0.27 appear anomalous, it might be expected that these should be full backdraft events, however these two tests featured a short period of door closure, so it is understood that there had been insufficient time available to form the fuel mixture necessary for a full backdraft.)

In terms of auto-ignition experiments (consider only the triangles in Fig. 10), it is clear that when the maximum temperature was above 350°C and the CO/CO$_2$ ratio was higher than 0.4, backdraft occurred. However, it is clear that temperature is not the only factor leading to backdraft. The three dashed lines in Fig. 10 indicate the apparent boundaries between backdraft and non-backdraft events. The point denoted 'A' in Fig. 10 represents a test which did not result in backdraft, even though tests with very similar temperature and gas concentrations did. It may be that there is a boundary between backdraft/no backdraft conditions at a CO/CO$_2$ ratio of about 0.08, but this cannot be concluded on the basis of only a single test. What is clearer is that when the temperature dropped to about 360°C, a new boundary appears to be located between 0.22 and 0.27, see the data near point B. At 350°C, it can be seen that the boundary condition changes again

to 0.27 to 0.4, see point C. This implies that the suitable conditions for onset of backdraft vary with a combination of burning status and the temperature conditions inside the fire compartment.

Considering only the diamond markers, that is, when a pilot spark was present, either backdraft (black markers) or fire re-ignition (grey markers) always occurred in these tests. It is observed that when CO/CO_2 was above 0.35, backdraft occurs, lower than this value, the spark can only ignite the unburned smoke and re-ignite the fuel tray only, with no obvious fireball indicating backdraft. It should be noted that even with an extremely long time of door closure with lower temperature about 200°C, a re-ignition is still possible, for details see [20]. It should also be noted that there were only three instances of backdraft observed in this series of eight piloted ignition tests, so it is hard to define the boundary between backdraft and non-backdraft events with any confidence. Further research will be required.

Measurements of the CO/CO_2 ratio provide useful information on the burning conditions, a higher value implies a relatively oxygen starved situation. CO_2 does not assist fire combustion, quite the opposite, but CO is flammable and may contribute to the tendency towards backdraft. Further research is required, but it appears that CO measurements may provide a means to predict if a possible backdraft is coming.

In Fig. 11, it can be observed that there is similar boundary between backdraft and non-backdraft events, as in Fig. 10. The markers in Fig. 11 have the same meanings as in Fig. 10.
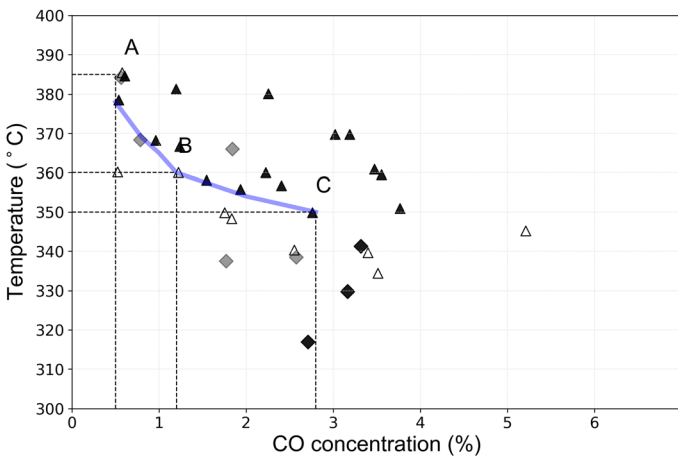
Figure 11. CO concentration versus compartment temperature for PP tests with gas analysis. Experiments with backdraft occurrence are shown using solid black markers, re-ignition without fireball is shown in grey, and those tests did not result in backdraft or reignition are shown using empty markers. Both piloted and auto-ignition conditions were tested, and are indicated using diamonds and triangle markers, respectively.

Based on the test carried out, 0.6% CO (by volume) appears to be the transition between backdraft and no backdraft conditions, irrespective of temperature. It should be noted that this transition is based on only a small number of tests, so must remain speculative until confirmed with further detailed exploration. At temperatures below 350°C, backdraft only occurs when there is more than 2.8% CO (by volume) and, as previously demonstrated, in the presence of a pilot spark. Between these conditions, there is an apparent boundary (indicated by the line from A to C on Fig. 11) between backdraft and non-backdraft events which varies with both temperature and CO concentration.

It should be noted that one test with a pilot spark, which sits significantly above the apparent boundary did not result in backdraft, but only in a reignition. It should be stressed that any correlation drawn on the basis of only temperature and CO concentration is only an indicator of the likelihood of backdraft occurrence, not an absolute predictor.

Production of CO during the period of door closure will initially have been due to underventilated burning of the fuel as the oxygen in the compartment was used up, followed by pyrolysis of the fuel in low oxygen conditions after the fire had extinguished. It has not been possible in this research to identify when the fire reached extinction conditions, or to quantify pyrolysis after that, so the quantity of CO used here as an indicator for backdraft must be understood to be due to both processes, but the relative importance of each has yet to be determined.

3.2. HDPE

A shorter series of 8 tests were carried out using the HDPE fuel. In each instance, the fire was allowed to grow to flashover conditions before the door was closed. Door opening temperatures from 400°C down to 300°C were tested with no pilot spark. Figure 12 shows that backdraft was observed in all tests with door opening temperatures above 320°C, while backdraft did not occur below this limit.

4. Discussion

The tests have clearly identified that the critical temperature in allowing the onset of backdraft by auto-ignition varies between PP and HDPE. For PP, the limit is in the range 340°C to 350°C, while for HDPE it is about 320°C. This is explained by consideration of the pyrolysis gas signatures, described above. The largest component of the pyrolysis gases in the case of PP is pentane, with hexane being the second most abundant flammable gas present. For HDPE, the pyrolysis gas (in low oxygen conditions, where CO is not produced) is predominantly hexane.

The auto-ignition temperatures for stoichiometric mixtures of pentane and hexane gases in air are 260°C and 215°C, respectively [4]. For gas mixtures closer to the upper flammability limit we would expect the auto-ignition temperatures to be considerably higher, but we would expect the limit for pentane to remain higher than that for hexane. Thus, it is to be expected that a mixture of pentane and hexane would exhibit a higher auto-ignition temperature, close to the upper
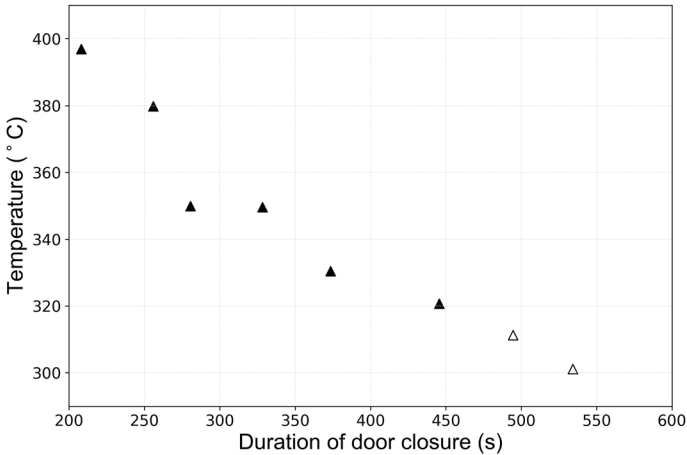
Figure 12. Temperature at time of door opening for tests using HDPE fuel; solid markers indicate backdraft events and unfilled indicate no backdraft.

flammability limit, than a mixture that is predominantly hexane. This is consistent with the trend observed in the tests described above.

This means that the critical temperature for backdraft is dependent on the pyrolysis chemistry of the fuels present. Unfortunately, this means that it is impossible to generalize a critical temperature for backdraft that could be of use by brigades in fire and rescue interventions. Future investigation of a wider range of solid fuels will enable the variations with different materials to be mapped out.

As discussed above, when a spark is present backdraft may be triggered at temperatures lower than the critical temperature for backdraft by auto-ignition. However, in this temperature range full backdraft events (that is, with external fireball) were sometimes observed, while re-ignition events (no external fireball) were also sometimes observed. Similarly, when the door was closed early in the steady burning period, re-ignition rather than a typical backdraft was occasionally observed, even for door opening temperatures above 350°C.

A series of tests were carried out using PP fuel along the identified 'backdraft boundary' (with and without the pilot spark active) using the gas analyzer to try to identify the characteristics of compartment gases which would lead to backdraft. The minimum observed CO/CO_2 ratio in any test was 8%, but this only occurred at higher temperatures. When the temperature was about 350°C, backdraft occurred when the CO/CO_2 ratio was above about 30%, see Fig. 10.

In all the tests carried out here with the spark active, backdraft or reignition occurred, but there was quite a variation in the observed backdraft behavior. Therefore, the gas analyzer was used to try to identify the characteristics of gases which would lead to re-ignition, which is a considerably less violent and dangerous fire phenomenon. Table 3 and Fig. 11 show the findings, correlated with the CO/CO_2 ratio. It is clear that in all the tests carried out a re-ignition event occur-

Table 3
Temperature at Time of Door Opening for Tests Using HDPE Fuel, Indicating Backdraft and Non-backdraft Events

Pre-burn time (min)	Duration of closure (s)	Characteristic temperature (°C)	CO_2%	CO%	O_2%	CO/CO_2 ratio	Backdraft
9	52	368	6.40	0.80	8.89	0.12	No
11	124	337	6.92	1.79	7.07	0.26	No
12	95	366	6.81	1.86	6.66	0.27	No
12	148	338.79	7.41	2.57	5.70	0.35	No
12	78	383.91	2.19	0.57	11.89	0.26	No
13	234	341.11	8.13	3.34	3.51	0.41	Yes
F.O.	382	329.63	6.94	3.16	1.69	0.46	Yes
F.O.	474	316.67	7.60	2.72	2.33	0.36	Yes

red, but only when the CO/CO_2 ratio was above 35%, did a backdraft with a fire ball occur, below this limit there was a less violent re-ignition.

As demonstrated above, CO is not a significant product of the pyrolysis of PP, even in relatively high oxygen conditions, thus the high CO/CO_2 ratio suggests that the duration of the period of underventilated burning may have some control over the onset of backdraft or otherwise. At the same time, CO concentration provides a similar trend to CO/CO_2 ratio, which shows that the auto-ignition temperature varies with the accumulated CO. This suggests that the auto-ignition temperature of backdraft in fires does not have a constant value, which is to be expected from established flammability limit theory [22].

As previously demonstrated [16], when the door is closed at a high temperature, and the door remains closed for a long time, backdraft may be triggered at temperatures considerably below the 350°C critical temperature. These conditions will lead to longer periods of under ventilated burning and greater gaseous fuel production.

Some previous studies [5–7] have investigated the possibility that CO itself is one of the crucial fuels determining the conditions for the onset of backdraft. The literature remains inconclusive on this factor. Here, the role of CO in determining the conditions for backdraft seems to be more of an indicator of the duration of underventilated burning and pyrolysis, and less as an active agent in the behavior, but this will need further research to reach a firm conclusion.

5. Conclusion

A reduced scale series of compartment fire tests have been carried out to investigate the critical factors governing the onset of the phenomenon of backdraft, using solid (but non-charring) polymeric materials as fuel.

It has been established that there is a critical temperature for auto-ignition of the pyrolysis gases leading to backdraft which varies with fuel properties. When fire has developed to near flashover conditions before door closing, for polypropy-

lene fuel, the critical temperature is between 340°C and 350°C. For polyethylene fuel, the critical temperature is about 320°C. This temperature is the maximum within the compartment, it is not an average temperature.

These temperatures are consistent with known auto-ignition properties of the gases evolved in a parallel investigation of the pyrolysis products from the two polymers considered, carried out in the fire propagation apparatus, under reduced oxygen conditions, and analyzed using FTIR spectroscopy.

An investigation into gas properties along the boundary between backdraft and non-backdraft outcomes revealed that a CO concentration of at least 0.6% in the compartment, before the door was opened, was necessary for backdraft to occur without a pilot spark. At higher CO concentrations, backdraft may occur at slightly lower temperatures. At temperatures slightly below the critical temperature for auto-ignition of backdraft, a CO concentration of above 2.8% and a pilot source are essential conditions for the occurrence of backdraft.

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