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Effects of Fire-Fighting on a Fully Developed Compartment Fire: Temperatures and Emissions

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ABSTRACT

This study evaluates the effects and consequences of fire-fighting operations on the main characteristics of a fully-developed compartment fire. It also presents data and evaluation of the conditions to which fire-fighters are exposed. A typical room enclosure was used with ventilation through a corridor to the front access door. The fire load was wooden pallets. Flashover was reached and the fire became fully developed before the involvement of the fire-fighting team. The progression of the fire-fighters through the corridor and the main-room suppression attack - in particular the effect of short, medium and long water pulses on either the hot gas layer or the fire seat - was charted against the compartment temperatures, heat release rates, oxygen levels and toxic species concentrations. The fire fighting team was exposed to extreme conditions, heat fluxes in excess of 35 kW/m^2 and temperatures of the order of 250 ^{o}C even at crouching level. The fire equivalence ratio showed rich burning with high toxic emissions in particular of CO and unburnt hydrocarbons very early in the fire history and a stabilisation of the equivalence ratio at about 1.8. The fire fighting operations made the combustion temporarily richer and the emissions even higher.

KEYWORDS: Compartment fires; Fire-fighting; Fire temperatures; Fire toxicity; Full scale fire

1. INTRODUCTION

1.1 Conditions in the fire compartment at the time of initiation of attack by Fire and Rescue Service

Often the assessment of the effectiveness of fire-fighting tactics used in training is based on subjective reports and global outcomes which do not facilitate the refinement and improvement of such tactics [1]. This work was carried out with a well characterised fire, full compartment temperature instrumentation and toxic gas analysis so that the conditions in the fire during fire fighting operations could be determined. The aim was to improve the training of fire fighters by providing quantitative information on the effectiveness of fire fighting procedures. The size of the fire, and the conditions inside the compartment at the time of onset of fire-fighting operations (first application of water) by the Fire and Rescue Service (FRS) is important for the safety of the fire-fighting

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team, in determining the resources required (man-power and equipment), the fire-fighting techniques to be employed and the effectiveness of such techniques.

UK fire statistics [2] show that, for example in 2008 - in fires where an alarm was present, operated and raised the alarm - 61% of all dwelling fires were discovered in less than 5 minutes. Even in fires where an alarm was absent or failed 51% of fires were discovered in less than 5 minutes. For the purposes of this illustration we will use time from ignition to FRS call of 2 minutes as this is not the controlling time in terms for determining the size of the fire at the time of first application of water.

Fire Rescue Service (FRS) response times to reportable fires were shown to increase by about 18% (from 5.5 to 6.5 minutes) for the period 1996 to 2006 for all English FRSs [3]. A recent American (NIST) study [4] reporting on 60 laboratory and residential fire ground experiments designed to quantify the effects of various fire department deployment configurations on a residential type fire was partly evaluated on the basis of a response time (defined as above) of 5.5 minutes for fast and 7.5 minutes for slow response. No data could be found (from the immediately available UK statistics) on the time to set up/deploy and apply water to the fire but NIST [4] reported measurements of this time to be 4 minutes for a 5-person crew and 6 minutes for a 2-person crew. Taking the alarm time as 2 minutes, response time 6.5 minutes and set-up time of 5 minutes, the total time from ignition to water application is 13.5 minutes.

It can be shown with fire engineering calculations [5] that for a typical room (4x4x3 m^3) with a standard door (1x2m^2) fully open that a t^2 fast growing fire is likely to reach flashover conditions in 3 to 4 minutes whilst a slow growth fire will take about 14 minutes to reach flashover. These timings correspond with a heat release rate (HRR) of 2 MW and a hot layer temperature of 600 ^oC. The post-flashover fire would then settle at a maximum HRR, controlled by the ventilation of around 4 MW, with compartment temperatures over 900 ^oC.

Assuming that at the time of raising the alarm the fire is a small flaming fire (as opposed to a smouldering or incipient fire) and given the times discussed above for the FRS response time and the set up time, then it is clear that it is likely that fire-fighters will be faced with a sizable fire and severe compartment conditions either about to flashover or having flashed-over. It is also possible that the fire-fighters creating access to the fire room may increase the oxygen availability which could result in potential backdraft conditions.

These conditions are very dangerous for the attacking fire-fighting team in terms of the composition of the atmospheric gases and of fire temperature (600 to 1000 ^oC). Furthermore, these temperatures will be associated with high heat fluxes. For flashover to occur it is generally accepted that heat fluxes of the order of 20 kW/m^2

are required at floor level, but these increase dramatically for post flashover fires [6-8]. Babrauskas [9] concluded that a heat flux of 150 kW/m^2 would represent the environment in a post-flashover room fire, while Lawson [10] reported NIST experiments with measured heat fluxes as high as 170 kW/m^2 in the post-flashover phase.

The level of thermal radiation required to produce a given level of damage is commonly defined in thermal dose units:

$$\text{Thermal Dose, TD} = I^{4/3} \cdot t \qquad (1)$$

Where, I is the incident thermal flux (kW/m^2) and t is time (s). (1 Thermal Dose Unit (TDU) = 1 $(kW/m^2)^{4/3} \cdot s$)

Rew [11] derived an LD50 criterion for thermal radiation, where LD50 denotes a dose at which 50% human fatalities are expected. He proposed 2000 TDU as the equivalent LD50 for incident thermal radiation onshore. For the better clothed/covered offshore workers O'Sullivan and Jagger [12] reported that in the interest of setting a guiding figure the 100% fatality level is estimated at 3500 TDU. However, 100% fatality may occur at slightly lower doses. At 3500 TDU, un-piloted ignition of clothing will occur, thus even 100% clothed individuals will not survive. At this level of thermal dose, self-extinguishment is unlikely due to injury from heat transmitted through the clothing.

The limit of 3500 TDU coincides with the calculated values from Chang et al. [13] for significant damage to fire-fighters PPE, and consequent large coverage of 3rd degree burns. Chang et al tested different types/makes of fire-fighter clothing under engulfment conditions. He states that the incident heat flux was 84 kW/m^2 but he does not list the exposure time. He refers to the standard test requirements provided by ISO DIS 13506 [14]. The standard provides for exposures for engulfment times of 2 to 10 seconds. Assuming that Chang used the longest time this would correspond to a maximum thermal dose of 3679 TDU.

Figure 1 shows the calculated thermal doses for the range of heat fluxes likely to be encountered in compartment fire for exposure times of 1, 3, 5 and 10 s. These are compared with the 100% fatality limit for offshore workers, which also approximately coincides with the thermal dose limit shown to result in significant heat damage of fire-fighting PPE, as discussed above. It is clear that in post-flashover fires with incident heat fluxes of the order of 150 kW/m^2 are likely to result in severe injury even for fully protected fire-fighters for short exposures of the order of even a few seconds.

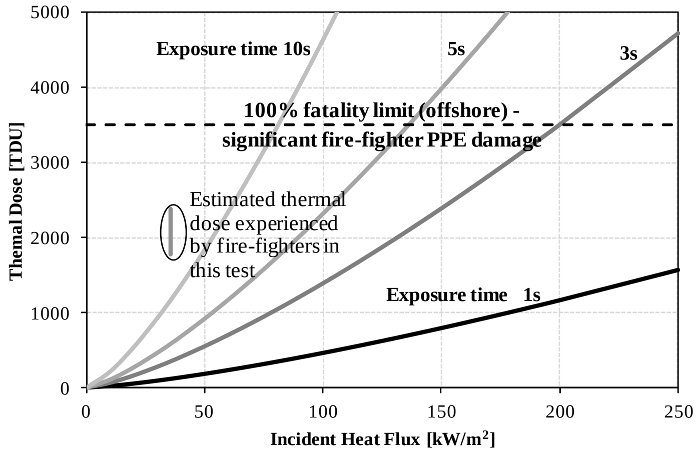


Fig. 1. Thermal dose as a function of incident flux and exposure time, and in the shaded area the thermal dose estimated to have been experienced by the fire fighters in this test in their first attempt (15-20 s exposure).

DCLG [15] reports the findings from a series of tests by the Fire Experimental Unit in which they arranged for a fire-fighter to carry specially designed instrumentation whilst taking part in fire training exercises. The findings are summarised in Fig. 2. With regard to tolerated conditions they reported that in tests at ambient temperature, 10 kW/m^2 was tolerated for 1 minute but damage was sustained to equipment and these conditions would not be acceptable operationally. The report identifies as “critical conditions” temperature >235 °C and thermal flux >10 kW/m^2. This environment could be life threatening and they note that a fire-fighter would not be expected to operate in these conditions. However, in a rapidly changing environment fire fighters may encounter conditions which are much more severe than the above and we will show that under these conditions exit timing is extremely critical for survival and it is important for fire-fighters to appreciate this. It should be noted that the temperature and heat flux conditions shown in Fig. 2 refer to those measured on the body of the fire-fighter and NOT to the compartment conditions.

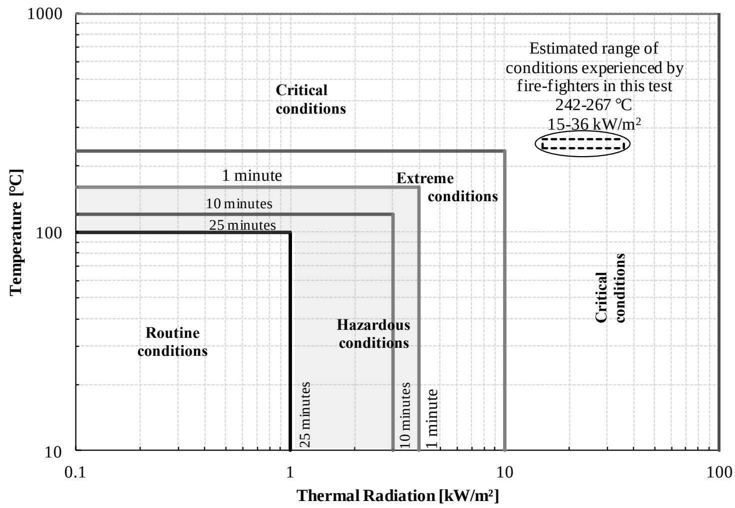


Fig. 2. Fire-fighters exposure conditions in standard BA kit with proposed time limits [15]. Conditions estimated to be faced by fire-fighters in this test, are presented by the highlighted area.

Compartment fires about to flashover or after flashover are likely to generate conditions in all parts of the compartment that exceed of the lower limits of “Critical conditions” and are life-threatening to the fire-fighters. Most residential fires by the time of first attack by the FRS are likely to have reached these critical conditions within the fire compartment but the FRS may still need to control (if not suppress) the fire, in order to carry out search and rescue operations and to prevent escalation to neighbouring buildings. Therefore, the fire-fighting team progressing towards the fire compartment and the fire seat, must ensure that the environment conditions around the team and directly ahead are reduced to tolerable levels within which they can operate. Similarly when retreating, because of the inability to control the fire growth, flashover becomes imminent and the retreating team must control the hazard arising from the increasingly hotter gases flowing above the retreat route. The main method for achieving and maintaining control is through the water application tactics, which are explained below.

1.2 Water application tactics during fire-fighting

In most scenarios for fighters to get within range for direct attack on the fire seat they must first deal with the hot gases overhead [16-18]. The three dimensional (3-D) fire fighting tactics can be summarized as a combination of

- Short pulses (typical 1 s duration) with the hose nozzle pointing at the hot gas layer at a forward 45^o angle, using medium spray cone angle of 60^o delivering fine water droplets and mist (fog) into the hot gas layer,

- When possible, longer pulses (2-5 seconds) of solid stream water and large droplets (30^o spray cone angle) directly onto the fire seat.

At its boiling point, water vapourises into steam expands 1700 times and extracts about 2.6 MJ/kg water from the ceiling gas energy. Thus the action of the water is to cool and expel ceiling gases. The intention of relatively short bursts of water delivery is to keep the amount of water that is used at a minimum as this reduces steam production which influences visibility and the displacement of air by the steam and it also reduces the danger of hot steam engulfment of the fire-fighters.

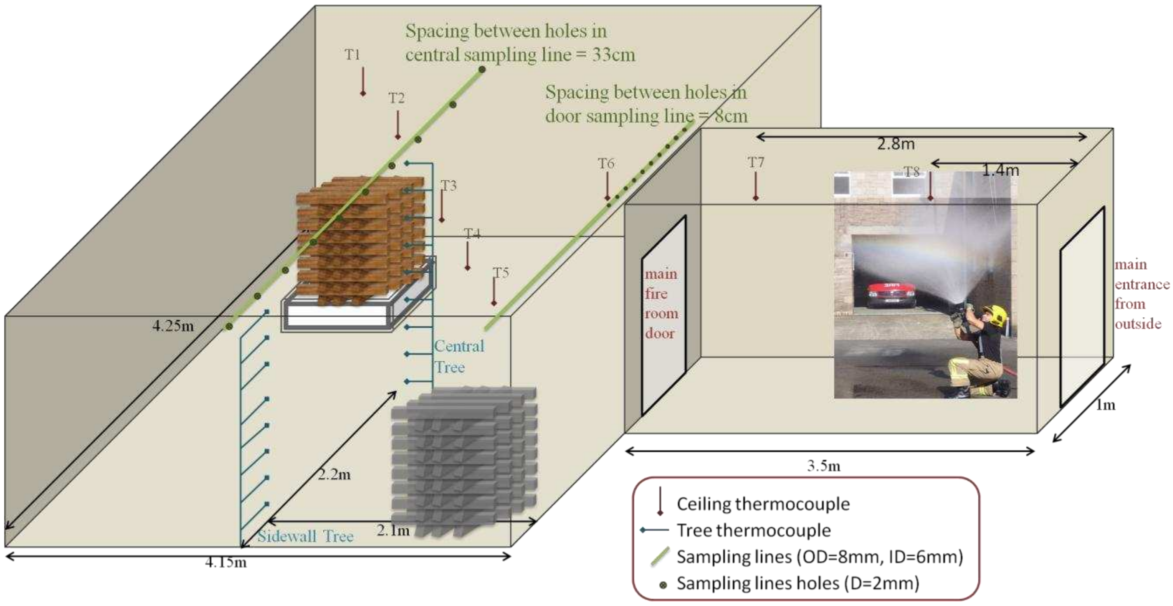
1.3 Objectives

In this work we quantify, for the first time, the thermal and toxic environments in fire compartments that can be generated around the fire-fighting team and the response of this environment to the fire-fighting tactics. This could be used to improve the crew safety and fire-fighting tactics. The detailed data gathered are also useful in fire investigation and in fire model validation.

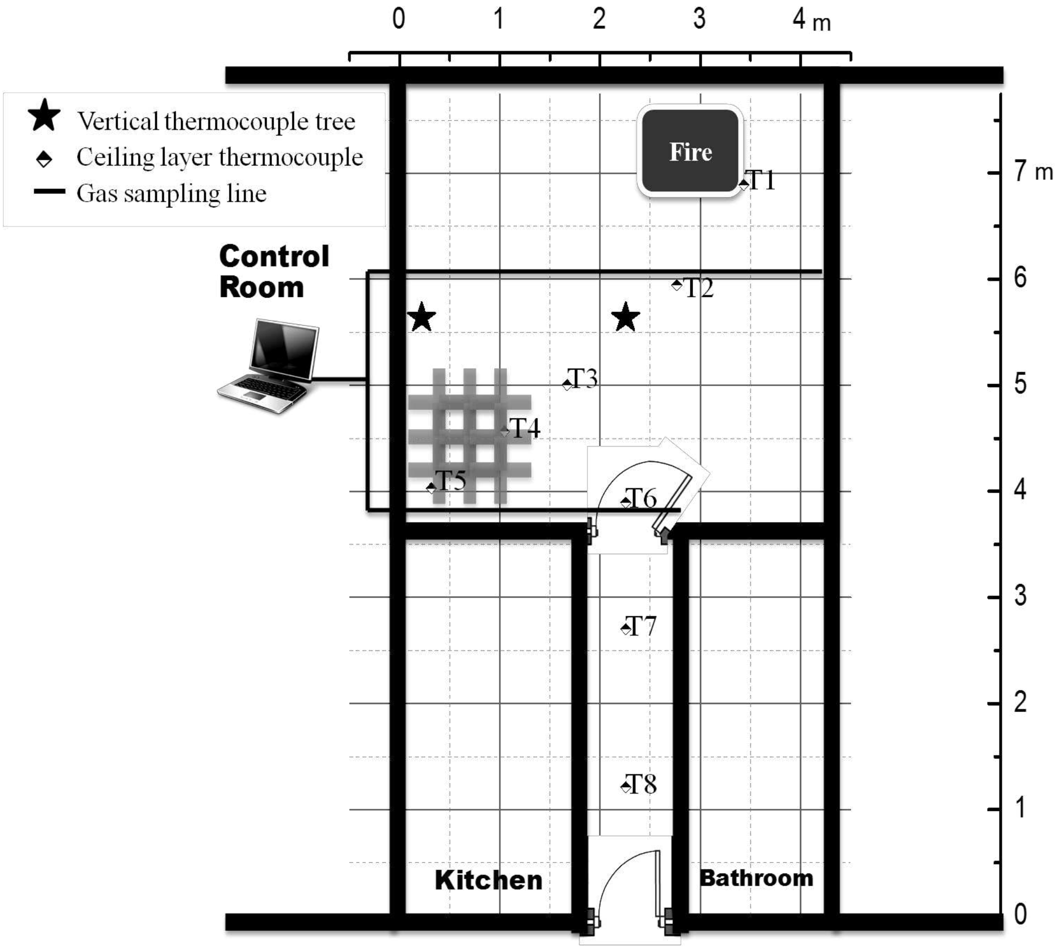
2. METHODOLOGY

2.1 The building

The tests were carried out in abandoned bungalows about to be demolished. The bungalows were constructed in the 1960's and were of traditional build, 100 mm brick wall outside and 100 mm concrete block work inside with 50mm cavity between the two layers. The bungalow consisted of a small hallway with kitchen and bathroom off of this, two small cupboards and a single main living room, as shown in Fig. 3. The ceilings in the burn room (living room) were double lined with 12.5 mm plaster board. The back wall to the living room was also double lined. This effectively gave the room one hour fire protection and also ensured that any air for the fire was only coming from the door.



(a)



(b)

Fig. 3. Compartment dimensions with locations of fuel and instrumentations. (a) 3D illustration. (b) 2D Plan view of the general layout.

2.2 Fire Load

The fire load was wood pallets which were stacked on top of one another (9 in total) with a total weight of 143 kg; the pallets measured 1.22 m x 1.22 m x 0.140 m and located on the corner opposite the door see Fig. 3. The stack was ignited using a small metal tray (200 mm square) with 400 ml of methanol to the centre of the fuel mass. Another wooden pallet stack (intended to be identical to the first one) with a total weight of 144 kg was positioned on the opposite corner, to assess the pyrolysis effect between the two stacks, this did not ignite in the fire. The British Standards guidance [19] suggests that the average fuel load in dwellings is 780 MJ/m^2, which for this compartment is 786 kg of wood, so that the fire is lightly loaded. The front door was the main ventilation path and it will be shown that the fire was ventilation controlled so that the relatively low fire loading was not a major factor in the fire development.

2.3 Instrumentation

The pallet fire was supported on an insulated platform, supported on a load cell. The test compartment was instrumented with thermocouple arrays located as shown in Fig. 3. Toxic gases were sampled through a multi-hole sampling probe across the ceiling which extracted a mean ceiling gas sample. This gas sample was transported through heated sampling lines, pumps and filters to a heated FTIR and then the sample was cooled and the water extracted and then analysed for oxygen using a paramagnetic analyser (Servomex Series 1400) and for CO and CO_2 using NDIR analysis (Hartmann and Braun). The fire development and the fire fighting activity were recorded by video and still photography. The fire was allowed to become fully developed to reach steady burning before the involvement of the fire-fighting team was initiated.

Temperatures within the fire compartment were monitored using 25 type K mineral insulated exposed junction, 1.5mm bead, 613 stainless steel sheathed thermocouples. The thermocouple temperature readings are used to represent the surrounding gas temperature when in fact they are the temperatures of the metal thermocouple junctions themselves which are different to the actual gas temperatures. The main heat transfer mechanisms are convective heat exchange between the gas and the thermocouple bead, and radiative heat exchange between the bead and the surrounding environment (which is usually taken to be the enclosure walls). In the hot gas layer the thermocouple tends to lose heat by radiation while it gains heat by radiation in the cold layer. Accurate evaluation of the errors requires full knowledge of local convective heat transfer coefficients, temperatures of the bead and of the surrounding surfaces and gases, their respective emissivities (as well as the temperature dependence of these emissivities). Evaluation of such errors is therefore not a routine task.

Based on the work of [20] and [21] it is possible to get an approximation of the error for the range of conditions in the present tests. For upper layer temperatures of 900-1000K, lower layer temperatures of 500-600K and wall temperatures assumed below 600K, the absolute error at upper layer measurement was 10-15% and of the order of 5% at the lower layer but increases significantly if the walls are taken to be at higher temperatures. However, the assumption of a clear gas volume (non-participating media) on which [21] & [22] are based in not really valid in typical compartment fires as the flame and smoke would have a high soot content and thus would be involved in radiation exchange with the thermocouples.

In more realistic full scale sooty (polyurethane and furniture) fires Luo [22] showed that the reading from a bare thermocouple could be more than 100 K higher than the gas temperature obtained from the suction pyrometer during the flaming fire stage and more than 200 K higher during the flashover stage. For a clean burning propane burner flame at steady-state the radiation error was negligible in the hot upper level near the ceiling. However, the thermocouple significantly overestimated the gas temperature by more than 80 K in the cool lower level near the floor because of the radiation effects.

The thermocouples were divided into; central vertical tree (9 Thermocouples), sidewall vertical tree (8 Thermocouples) and a ceiling array on a diagonal axis (5 Thermocouples) in addition to three other ceiling thermocouples; inside the room before the door, in the corridor close to the door and closer to the exit door in the corridor. The approximate positioning of the vertical thermocouple trees and ceiling thermocouples is shown in Fig. 3(b). The ceiling thermocouple tips were 155mm below the ceiling.

Four 80 kg, NovaTech, F256 DFSOKN compression load cells were used at the 4 corners of the fire platform, which was a steel frame covered with two layers of plaster board on which the fire load was placed. Up to 320 kg of fuel could be supported and the mass loss monitored to a combined output resolution of 10g and maximum non linearity error at around 40 g. The load cells were protected by a thick high temperature resistance Morgan ceramic fibre ‘super-wool’ blanket. All four load cells survived the extreme fire conditions.

For toxic species measurements a heated TEMET GASMET CR2000-Series portable FTIR was used. The sample cell volume was 0.22 L and the multi-pass fixed path length was 2 m. The resolution was 2 ppm per species with an accuracy of 2% of the measurement range. It had a separate heated sample line, filter and pump and the FTIR sample cell was also heated to 180 ºC so that all analysis was on a hot wet basis and no acidic gases were lost by condensation. It was calibrated, by the manufacturers, to detect more than 50 combustion product species simultaneously.

Measurements from all instrumentation were fed into the data logger at a sampling rate of 1 reading every 5 seconds.

A CE Flash EA2000 combustion based elemental analyser was used to determine the elemental composition of the wood from which the stoichiometric A/F by mass was determined as 5.0. The fire global A/F by mass was determined from the ceiling gas sample by carbon balance method [23, 24] and from this the global fire equivalence ratio was determined.

2.4 Fire-fighting approach

Water application in the fire-fighting phase was performed by the attending FRS personnel using real fire-fighting tactics; hot layer gas cooling was carried out to make safe entry into the compartment then when the team reached the ideal position direct attack on the fire was conducted, using a cone approximately 30° alternating to 60° as needed with a droplet size of 30 µm. Key fire compartment conditions (ceiling and lower compartment temperatures, oxygen levels and toxicity levels) were continuously monitored and communicated to the fire ground incident commander, fire-fighting and support crews. Dura-line layflat 38mm low pressure hose was used with internal diameter 38 mm, 15 m length (2 lengths were used), giving a flow of 340 L/min at 7 bar. Tests on the flow rate meter gave 1 L/s with a short pulse 30/60° and 2 L/s with a long pulse.

3. RESULTS AND DISCUSSION

3.1 Mass Loss and Heat Release Rate

The mass of the pallet-stack as a function of time is shown in Fig. 4, which also shows the onset of flashover (discussed in section 3.4) and the start of fire-fighting activities. Approximately 50 kg of wood was consumed in the duration of the test, 60% of which was lost before the start of the fire-fighting operations.

The elemental analysis of the wood gave the formula of $CH_{1.54}O_{0.82}$ in a dry ash free basis (daf) and from this the stoichiometric A/F by mass was determined as 5.0.The net calorific value (CV) of the material was 15.4 MJ/kg , based theoretical oxygen consumption requirements [16].

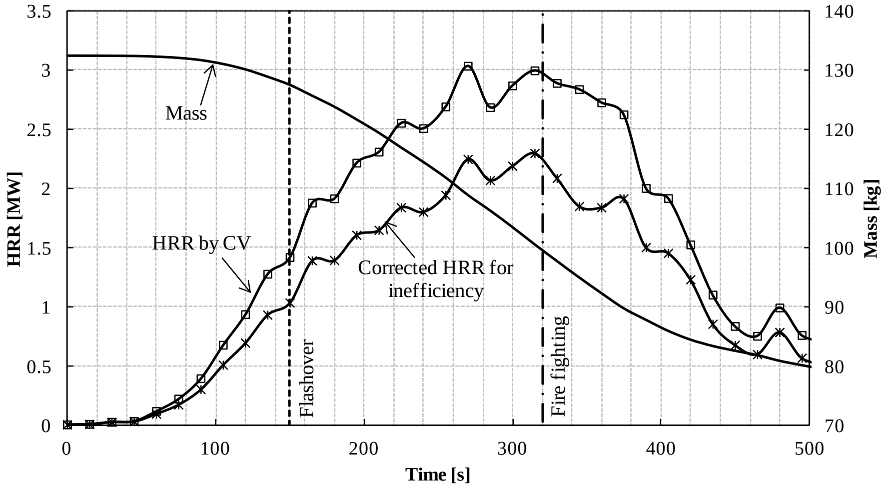


Fig. 4. Mass change with time and associated HRR based on the mass loss rate. Also shown is an adjusted HRR, based on inefficiency of combustion as derived from the unburnt hydrocarbons and CO measurements.

The heat release rate (HRR) based on the mass loss rate and the Calorific Value (CV) of the wood is shown in Fig. 4. This evaluation of the HRR effectively assumes complete combustion and release of all the available energy. Carbon monoxide, unburnt hydrocarbons (Total Hydrocarbons, THC) and soot are all evidence of incomplete combustion and therefore unreleased energy, which is quantified as the combustion inefficiency. Soot yields need to be >1% to be significant, but were not determined in the present work which based the combustion inefficiency on the CO and THC using procedures common in the automotive emissions area [25]. Aljumaiah et al. [26] showed that THC were particularly important in correctly evaluating the HRR in under-ventilated wood crib fires. The combustion efficiency deteriorated as the compartment ventilation increased and was as low as 50% for the highest ventilation rate (all fires were under-ventilated overall) [26]. The flame seen outside the compartment in real fires is the combustion of the unburnt CO, HC and hydrogen released in the rich burning fires, it is also the source of backdraft when air is admitted through opening a door to a fire burning with low combustion efficiency.

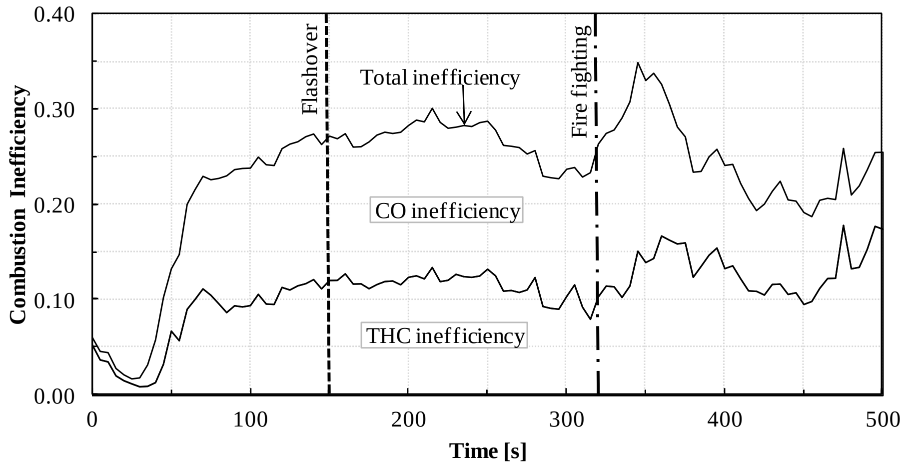


Fig. 5. Total combustion inefficiency as a function of time with contributions from CO and THC.

In the present full scale work only CO and THC yields, presented in Fig. 9(b) were taken into account in correcting the HRR shown in Fig. 4, using Eq. 2 [27].

$$\text{Inefficiency}=\left(Y_{CO}\times\frac{CV_{CO}}{CV_{Fuel}}\right)+\left(Y_{THC}\times\frac{CV_{THC}}{CV_{Fuel}}\right) \quad (2)$$

The combustion inefficiency is shown in Fig. 5 to grow relatively quickly to over 20% and to stabilize between 20 and 30% for the test duration. Figure 5 clearly demonstrates the large contribution of the THC to the combustion inefficiency. These combustion inefficiencies are similar to those found by Aljumaiah et al. [26] for ventilation controlled pine wood crib fires. On the onset of the fire-fighting operations the combustion inefficiency was increased to a peak of 35% for a short period after the onset of fire-fighting, as the fire fighters blocked the entrainment of air into the fire from the air feed corridor. Once the fire fighters were out of the corridor and in the room this air blockage ceased and the combustion inefficiency fell back to near 20%.

The HRR corrected for the combustion inefficiency in Fig. 4 reached 1 MW in about 140 s which, on the basis of a t^2 fire, would give a growth rate of about 0.05 kW/s^2. This is the fire growth rate of a “fast” fire and is similar to the measurement of Alpert & Ward [28] for stacks of wood pallets of different heights, burning in the open. The corrected maximum HRR per unit area in the present tests was less than half the corresponding value for the open tests [28] demonstrating the effects of ventilation control and combustion inefficiency.

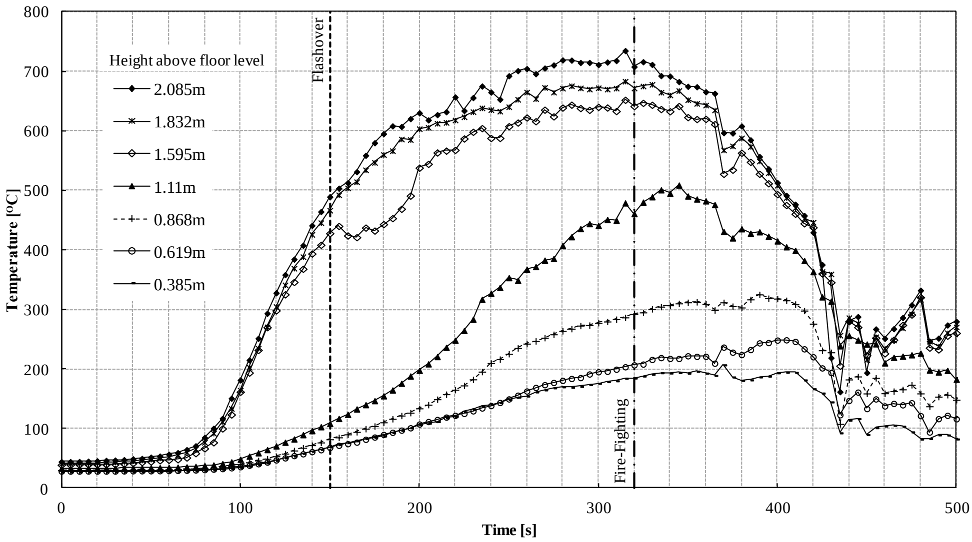
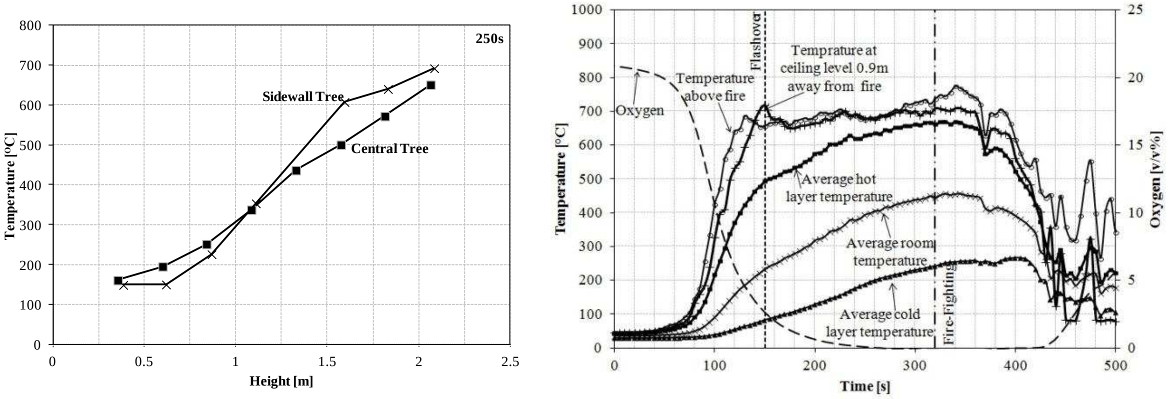


Fig. 6. Temperatures at different heights from floor level in the fire room as measured by the vertical thermocouple tree on the sidewall of the compartment

3.2 Temperatures

Figure 6 shows the fire temperatures as a function of time, from the thermocouples at different heights on the sidewall tree. After 100 s there was a rapid rise in temperature for all the thermocouples above 1.5 m, indicating the fast descent of the hot layer. Hot layer temperatures were fairly uniform with height from the start of the combustion with maximum temperatures between 650 and 730 °C after the onset of flashover. Figure 6 also shows that the lower level (below 1.2 m) temperatures were high at over 400 °C and these would have generated a hazardous convective heat environment for the fire-fighters – even if in the crouching position.

The central vertical-thermocouple-tree recorded a similar range of temperatures from the bottom to the top of the compartment. However the temperature vertical gradients were more uniform for the central tree as shown in Figure 7(a). This was due to the position of this tree in the path of the main flows in and out of the compartment which resulted in more mixing of the layers.



(a) (b)

Fig. 7. Temperatures and Oxygen levels (a) Vertical temperature variation at 250 s (b) Top ceiling temperatures in the vicinity of the fire and average hot layer temperatures (top 3 thermocouples from each vertical tree plus thermocouples T1, T2, T3 at ceiling level), average cold layer temperature (bottom 3 thermocouples from each vertical tree), average room temperature (average of all thermocouples on the two vertical trees).

Figure 7(b) shows that the temperature of the ceiling thermocouple T1, nearest to the burning stack plume, reached a maximum of 780 ^oC. For most of the "steady" burning period this temperature was 680 to 730 °C, which is comparable to the top sidewall and central tree temperatures, similar range was produced in other full scale experimental fires [29]. This indicates a fairly uniform temperature across the room near the ceiling plane. In contrast, the temperature of the upper layer in the corridor (shown in Fig. 8) was significantly lower than the room temperature, indicating a higher degree of mixing of the exiting hot gases with the incoming cold air.

3.3 **Oxygen Levels**

The oxygen concentration, measured across the ceiling layer using the central sampling line, as shown in Fig. 7(b). There was a very rapid reduction in oxygen at the time of the fast temperature rise and the fast fire growth rate, between 80 and 120 s from ignition. After this time the oxygen levels dropped below 5% reaching zero at 260 s. This shows that the fire became ventilation controlled and this was accompanied by the hot layer temperatures levelling off.

3.4 **Onset of flashover**

The most commonly accepted definition of flashover is "transition to a state of total surface involvement in a fire of combustible materials within an enclosure" [30]. In the present test this definition would have corresponded with the ignition of the second stack. There was no clear evidence of this happening, although there was charring at the top of the stack. The fire-fighters reported that there were no flames on top of the second stack when they entered the compartment. However, there was an overall reduction of the weight of the stack by 5.1 kg (3.68% of the overall stack weight) or in terms of the top pallet on its own, the mass loss was 1.45 kg or 12.4% of the original mass. Thus the top pallet average pyrolysis rate was 3.4 g/m^2s over the 300 s (from 100 to 400 s). This was sufficiently high to support ignition [31] under normal oxygen concentrations and therefore this would be evidence of sufficient heat to cause ignition of the second stack. The top of the stack was immersed in the hot layer which had low oxygen to support combustion. Delichatsios [31] showed that for non–flame–retarded plywood the critical mass flux for ignition (at high heat fluxes) was raised from about 3 to 7 g/m^2s as oxygen was reduced from 21 to 15%. Therefore at oxygen concentration levels below 15%, pyrolysis mass fluxes higher than 7 g/m^2s would be needed for ignition to occur.

Other phenomena associated with onset of flashover include

- Upper layer between 500 – 600 °C [6, 7] – in this test the average upper layer temperature reached 500 °C at around 155 s
- Heat flux of 20 kW/m^2 at floor level [7, 8] – this was not measured in the present tests. Calculation of the heat flux at floor level from the hot layer at 1.2 m above floor level (based on visual evidence) and at temperature of 500 °C and using view factors between finite parallel plates [32] and an emissivity of 0.8 gives a value of 13 kW/m^2 at floor level. This would appear lower than expected but it does not account for radiation from the fuel package and the flames through and above it, which can be shown to contribute an additional 4 to 10 kW/m^2 to floor targets depending on the distance from the flame – this part of the calculation was performed using view factors between perpendicular finite rectangles [32], to represent the vertical flame and a target on the floor, a flame temperature of 900 °C and a calculated flame emissivity of 0.5.

On this basis it was considered that the most likely timing of the onset of flashover and ventilation controlled burning occurred at 155 s from ignition.

3.5 Fire-fighting and the Thermal Environment

Fire-fighting was initiated when it was deemed that the fire had reached steady burning rate, which was at 320 s as shown in Fig. 8. The progress into the access corridor and the room, of a group of 3 fire-fighters (with one charged water line) was tracked from the video recordings and the length of hose fed into the enclosure and is shown in Fig. 8 by the star symbols. The bar lines in Fig. 8 are an indication of the spray pattern, timing and duration of water spray discharge by the advancing team. The short bars indicate a short water pulse towards the ceiling while the longer bars indicate longer pulses directed onto the fire seat, as discussed in Section 1.2.

On entering the corridor the fire-fighting team adopted the crouching or kneeling position, trying to keep below the outflowing smoke layer, whilst directing a series of short water pulses towards the corridor ceiling and then the compartment ceiling ahead of them. The spray had an immediate effect in reducing the smoke layer temperature as shown in Fig. 8 from the temperatures in the ceiling layer. It can be seen that the water pulses were more effective in dropping the temperature in the corridor by about 100 degrees, but the temperature drop achieved by the spray in main fire compartment was much smaller.

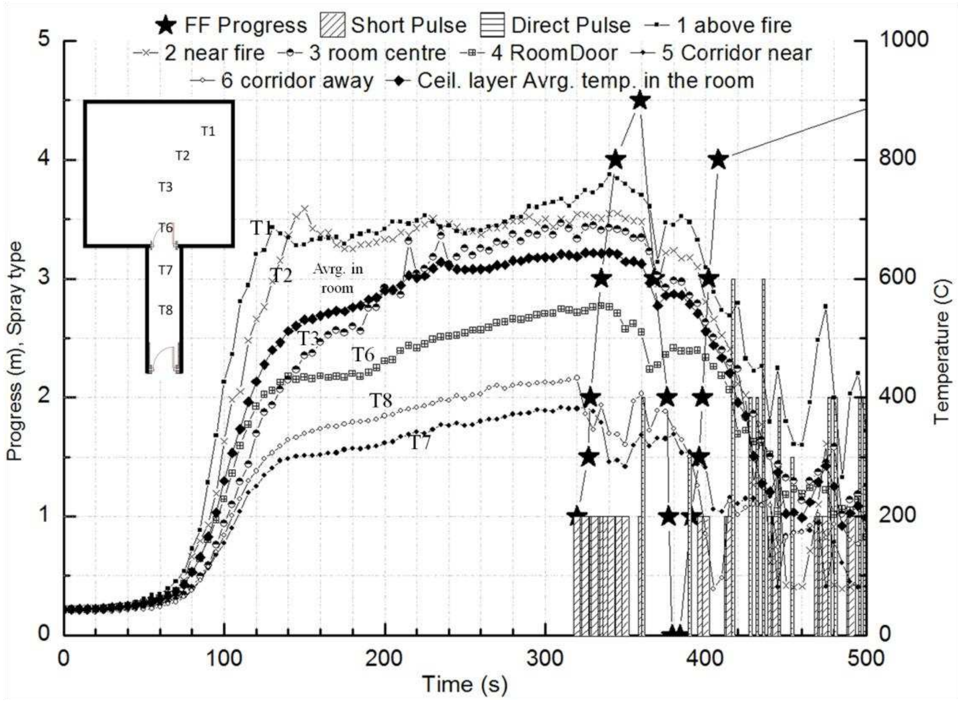


Fig. 8. Ceiling temperatures along the corridor and into the fire room.

On entering the fire compartment the fire fighters tried to manoeuvre and position themselves in the near right hand corner of the room close to the door. This would have allowed all three men to be inside the room during fire extinguishment. However, for the few seconds that it took the leader to adjust his position he stopped pulsing water and this, in combination with the prevailing conditions resulted in the team experiencing unbearable heat levels and an immediate retreat was ordered, accompanied by a long water pulse directly to the seat of fire. From the fire room entry to room exit there was only a 20 s interval.

The team retreated all the way to the outside regrouped and re-entered the corridor immediately starting with a direct pulse towards the fire and then 3 short pulses as they positioned themselves in the entrance just inside the room. Figure 7(b) the average lower layer temperature of the gases surrounding the crouching fire-fighters was in the range of 242 to 267 °C. This is above the 235 °C limit and therefore in the critical range, as defined by DCLG [15] and shown in Fig. 2.

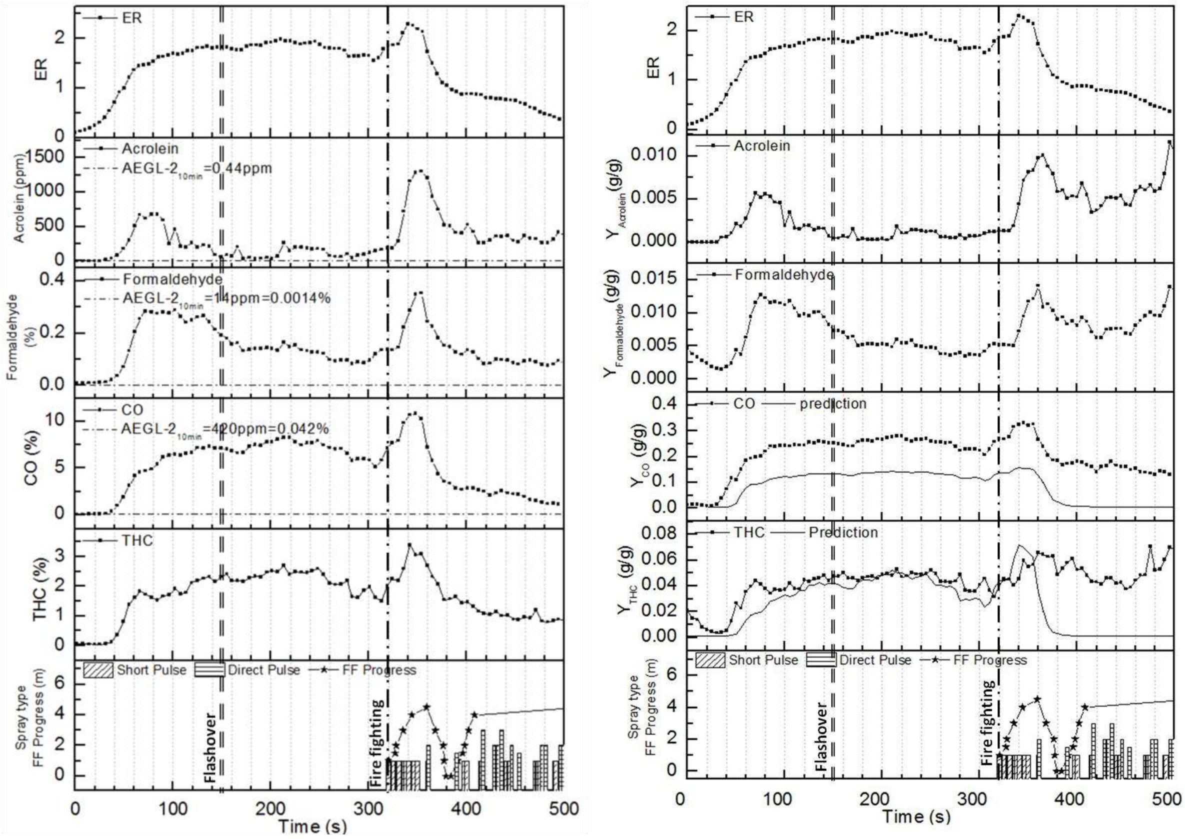
To define the locus of the thermal conditions experienced we also needed to determine the likely heat flux at the fire-fighter level within the fire compartment, both from the hot layer and the flames, using view factors and flame and hot layer temperatures and emissivities as described in Section 3.4. This resulted in estimates of heat fluxes ranging from 15 to 36 kW/m^2, for vertical and horizontal body parts at varying heights from the floor, as depicted in Fig. 2. This heat flux is well above the 10 kW/m^2 limit delineating the extreme from the critical conditions [15].

In terms of the thermal dose received by the fire fighters it was estimated that during the first 15 seconds in the compartment they received 1800 TDUs which built up to around 2400 TDUs during the next 5 seconds of retreat time. This is marked on Fig. 1. The calculation shows that they would have exceeded the threshold limit of damage to their protective equipment (PPE) if they delayed their exit by 10 seconds more. This is congruent with the very fast build-up of physical discomfort that the fire-fighters reported on debrief. They also reported experiencing hot temperatures on their knees where their clothing was compressed against the skin. This again agrees with the high ambient temperatures measured at low level.

The very short time to unbearable conditions experienced by the team and our estimate of 30 s to PPE thermal damage levels, demonstrates and quantifies the very short time available for fully protected fire-fighters to move to a safer location in an escalating or fully developed fire.

3.6 Fire-fighting and the Toxic Environment

Measurements of toxic compound concentrations escaping from the fire compartment into a common corridor is important in evaluating the risk to the rest of the building occupants and in designing appropriate dilution and purging ventilation rates. Usually such systems are evaluated using CFD modelling and the usual input is the mass yield of the toxic species per unit mass of fuel burnt. Most measurements of such yields are based on well ventilated fires and there is need for more yield data in under-ventilated compartment fires [26, 33-35].



(a) (b)

Fig. 9. Combustion toxic products in line with equivalence ratio and fire-fighting activities. (a) Toxic products concentrations in volume basis [v/v]. (b) Combustion toxic yields and Tewarson's yield prediction [36].

The combustion Equivalence Ratio (ER) was calculated as a function of time and is shown in Fig. 9. The ER plot shows that the fire started burning rich after 50 s and reached a value of near 1.8 and steadied off at this value, indicating that the fire reached a ventilation controlled steady state earlier than our estimated timing for flashover. On entry of the fire-fighters in the corridor there was a further increase of ER due to the physical blockage to the incoming fresh air path by the bodies of the fire crew. The combustion became even richer at the initial application of water, this effect was due to the increase in the combustion inefficiency, as shown in Fig. 5. After the second fire attack the ER dropped as the fire was brought under control.

Figure 9(a) also shows the variation of the concentrations of the main toxicants. Carbon monoxide and THC showed similar behaviour with a rapid increase after 40 s reaching steady high levels during the steady state period of the fire. Acrolein and formaldehyde showed a reduction of concentrations during the steady state phase. This occurred at the same time as the oxygen was reduced to its minimum value and flashover occurred. Aldehydes form at low temperatures in the presence of hydrocarbons and oxygen. Comparison with the oxygen levels in Fig. 7(b) aldehydes peaked at about 400 ^{o}C and 10% oxygen, at the start and end of the fire. It is the peak early in the fire which is of most concern as this occurs pre-flashover and would tend to impair escape from the fire.

The relative toxicity of each species is usually determined by the ratio to an appropriate standard concentration with known effects to humans [37]. There is considerable debate and development in this area [26]. For the purposes of this work the species concentrations were compared to the AEGL-2 10 min values which are particularly relevant to impairment of escape in fires. "AEGL-2 is the airborne concentration of a substance above which the general population could experience an impaired ability to escape" [38]. This limit is marked on Fig. 9(a) as a straight line and it is shown to have been exceeded for most of the duration of the fire. The concentrations of the different species at specific key times of the fire history are listed in Table 1 where the ratios to AEGL-2_{10min} are also shown. These ratios are effectively the dilution levels required for any ventilation system to bring the concentration of the individual species below the critical limit being considered. It can be seen that for CO this dilution level is of the order of 200 whilst for acrolein the dilution required is of the order of several hundred rising to about 3000 during fire-fighting operations. These dilution levels are for the individual species and a combined requirement needs to be worked out using a procedure like the N-Gas model [26, 39, 40].

Table 1. Measured toxic species concentrations and yields at important stages of the fire development extracted from Fig. 9.

	Flashover (at 155 s)			**Steady state (at 250 s)**			**Start of Fire-Fighting (at 320 s)**			**During fire-fighting, Peak of most gases (at 355 s)**		
	ER=1.82			ER=1.87			ER=1.86			ER=2.14		
Species	**Conc. [v/v%]**	**R-AEGL [a]**	**Yield [g/g]**	**Conc. [v/v%]**	**R-AEGL [a]**	**Yield [g/g]**	**Conc. [v/v%]**	**R-AEGL [a]**	**Yield [g/g]**	**Conc. [v/v%]**	**R-AEGL [a]**	**Yield [g/g]**
CO	6.98	166	0.250	7.44	177	0.261	7.65	182	0.269	10.22	243	0.327
Formaldehyde	0.19	137	0.007	0.13	91	0.005	0.14	99	0.005	0.35	253	0.012
Acrolein	0.01	136	0.000	0.02	409	0.001	0.02	432	0.001	0.13	2977	0.008
THC (CH_4 equivalent)	2.33		0.048	2.60		0.052	2.02		0.041	3.10		0.057

[a] R-AEGL=Ratio to AEGL-2_{10min}

Mechanical ventilation systems for corridors are typically designed to give 100 times dilution of the combustion products seeping out to the corridor through leakage paths. The ventilation throughput is usually doubled during fire fighter operations, i.e. prior to opening the door to the fire compartment, mainly in an attempt to mitigate the much larger volume of combustion products coming into the corridor. As can be seen from the above discussion these ventilation rates would be inadequate if applied to the test under discussion, and this indicates an area where more research is needed.

In designing suitable ventilation systems computational fluid dynamics software (such as FDS) are usually used and an important input in these models are the species yields such as soot and CO. Most measurements of such yields have been performed under well ventilated conditions (such as the Cone Calorimeter) [41-44] and these are not suitable for compartments fires due to the effect of inadequate ventilation on these emissions. A number of researchers [26, 27, 33-35, 42, 45-48] have in recent years reported toxic species yields under variable ventilation conditions that show much higher yields than measured under free ventilation conditions.

The main toxic species yields in the present experiment are given in Fig. 9(b). Tewarson [36] empirically correlated the main species emissions to the equivalence ratio for different fuels. His predictions for CO and THC yields from wood combustion for the equivalence ratios in the present experiment, are also shown in Fig. 9(b). The Tewarson THC predictions show remarkable agreement with the present measurements. The CO predicted yields however fall short (about half) of those measured, suggesting that a refinement to the model is needed.

4. CONCLUSIONS

This report evaluates the effects and consequences of standard fire-fighting operations on the main fire characteristics in fully-developed, compartment fires. It also presents data and evaluation of the conditions to which fire-fighters are exposed. A typical room enclosure was used with ventilation through a corridor to the front access door. The fire load was wooden pallets. Flashover was reached and the fire became fully developed before the involvement of the fire-fighting team. The progress of the fire-fighters through the corridor and the main-room was monitored and the effect of short, medium and long water pulses on either the hot gas layer or the fire seat (3-D fire-fighting) - was determined in terms of the compartment temperature, heat release rates, oxygen levels and toxic species concentrations. The effect of the fire fighting tactics was clearly shown.

The fire fighting team was exposed to extreme conditions, heat fluxes in excess of 35 kW/m^2 and temperatures of the order of 250 ^oC even at crouching level. This is in line with the extreme discomfort experienced by the fire fighting team and forced the abandonment of the first attempt and retreat from the compartment, within 20 s of exposure. Calculations show that had they persevered for another 10 s they would have received thermal doses in excess of 3500 TDUs, sufficient to cause damage to their PPE. |This demonstrates and quantifies the very short time available for fully protected fire-fighters to move to a safer location in an escalating or fully developed fire.

The fire equivalence ratio showed rich burning with high toxic emissions, in particular of CO and unburnt hydrocarbons, very early in the fire history and a stabilisation of the equivalence ratio at about 1.8 until the fire fighting operations started which made the combustion temporarily richer and the emissions even higher.

The high levels of toxic yields measured in this work, would require significantly higher dilution levels of the fire gases leaking into common corridors and escape routes, than currently practiced by building ventilation systems.

This research demonstrates that with appropriate planning and suitable instrumentation target fire conditions and environments can be generated and fire-fighting tactics can be objectively (quantitatively) monitored and assessed. For the first time the effects of fire fighting operations on toxic emissions are reported.

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