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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 °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.

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 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 min. Even in fires where an alarm was absent or failed 51% of fires were discovered in less than 5 min. For the purposes of this illustration we will use time from ignition to FRS call of 2 min 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 min) for the period 1996–2006 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 min for fast and 7.5 min 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 min for a 5-person crew and 6 min for a 2-person crew. Taking the alarm time as 2 min, response time 6.5 min and set-up time of 5 min, the total time from ignition to water application is 13.5 min.

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It can be shown with fire engineering calculations [5] that for a typical room ($4\times4\times3\ m^3$) with a standard door ($1\times2\ m^2$) fully open that a t^2 fast growing fire is likely to reach flashover conditions in 3–4 min whilst a slow growth fire will take about 14 min to reach flashover. These timings correspond with a heat release rate (HRR) of 2 MW and a hot layer temperature of 600 °C. The post-flashover fire would then settle at a maximum HRR, controlled by the ventilation of around 4 MW, with compartment temperatures over 900 °C.

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 (600–1000 °C). Furthermore, these temperatures will be associated with high heat fluxes. For flash-over 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:

$$\text{Thermal dose,}\ \ TD = I^{4/3}\cdot t \tag{1}$$

where I is the incident thermal flux (kW/m^2) and t is the time (s). (1 thermal dose unit (TDU) = 1 (kW/m^2)$^{4/3}$ 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 2–10 s. Assuming that Chang used the longest time this would correspond to a maximum thermal dose of 3679 TDU.

Fig. 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.

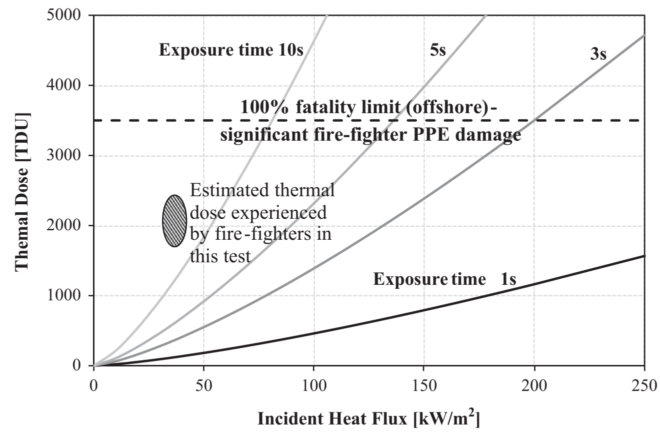

Fig. 1. Thermal dose as a function of incident flux and exposure time, and in the shaded area the thermal dose estimated to have been experienced by the fire fighters in this test in their first attempt (15–20 s exposure).

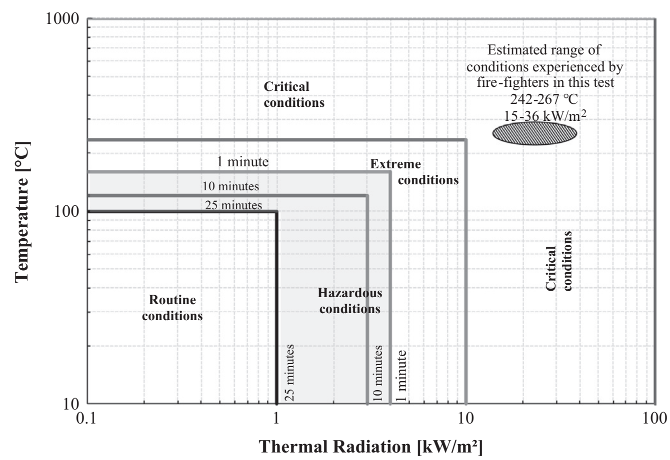

Fig. 2. Fire-fighters exposure conditions in standard BA kit with proposed time limits [15]. Conditions estimated to be faced by fire-fighters in this test, are presented by the highlighted area.

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 min 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.

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