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What Kills People in a Fire? Heat or Smoke?

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ABSTRACT

This paper reviews the main causes of casualties in fires, investigates the composition of the smoke in typical compartment fire and assesses the contribution of each component to the overall potency of the smoke. The leading cause of death for fire victims around the world has been smoke inhalation for many decades. Also fires occurring in buildings are responsible for over 75% of total fire fatalities. Several major fire accidents, where fire toxicity was the cause of death for almost all victims, are highlighted. Statistical reviews of fire casualties for several decades in the UK and the USA show that fire toxicity is the major cause of death for fire victims. The analysis of the smoke species in a typical compartment fire with wood pallets as fuel, clearly demonstrates that acrolein is the major component of smoke responsible for incapacitation while CO is the main species responsible for the lethality.

[150 words]

Key Words: Fire, Toxicity, Smoke Inhalation, Fire Victims, Statistics, Interdisciplinary.

1. INTRODUCTION

Fire is one of the first discoveries of humanity, and arguably the most important one. The known hazards of fire for the early generations for humanity were limited to thermal hazards only. With the advancement in civilization and the increase of population, the way people live their lives has changed, including their homes i.e. space, ceiling heights, insulation, and ventilation. With the modern way of living accidental fires are more probable to occur in compartments than in open outdoor areas. The production of toxic smoke in fires has become recently (the past few decades) a major threat to victims of accidental fires. The need for effective methods to quantify and measure these toxic hazards is crucial at this stage of the advancement of the fire safety research.

Fire science is an interdisciplinary field where fundamental research is rapidly forming and contributions from different fields are an integral part in establishing such a recently identified research area. A list of example areas that can contribute to fire science one way or another includes: physiology, human psychology, combustion science, fluid dynamics, thermodynamics and optics, computing, statistics, material science, ecology, toxicology, most forms of engineering and forensic science.

Fire science can contribute in solving and adapting various issues of safe enjoyment of our changing modern lifestyle. Such as designing buildings, materials or systems with the objective of preventing, detecting or eliminating fire hazards. Additionally fire science can be crucially important in management areas such as risk analysis and designing safe evacuation plans for challenging designs, also it is important for fire fighting activities. Fire science can contribute even after the fire incident where understanding the causes and impact are required. The main objective of Fire science is to provide a safer environment and reduce losses by utilising scientific evidence to produce practical solutions that can deliver that objective.

The objective of this paper is to introduce the basic understanding of fire toxicity generated from compartment fires, also the major drivers for fire toxicity research are explored by reviewing statistical studies and showcasing some of the most significant incidents where high number of fatalities occurred due to smoke inhalation. Finally an example of fire toxicity assessment on evaluating the impairment of escape to the building occupants on a real case fire experiment is demonstrated.

2. FOUNDAMENTALS OF FIRES IN ENCLOSURES

One of the major challenges of studying fires is their randomness. Combustion studies mainly applicable for pre-designed systems that seek the improvement of performance depending on the application and fuel targeted. With fire studies there are no designed systems to be perfected but absolute randomness and the main task is to understand fire development in different circumstances and evaluate the hazards generated at different stages. Then suggest practical solutions that can manage these hazards to acceptable levels. Combustion fundamental studies provide significantly important understanding of the actual reaction that is applicable for the fire studies. These fundamentals should not be ignored, and their limitations and applicability ranges should be observed, and then it can be developed to cover the fire research needs.

2.1 Typical Fire Growth Patterns in an Enclosure

Majority of fire fatalities (more than 75%) occur in buildings (DCLG, 2015, FEMA, 2015a). Enclosure fires begin typically by ignition and a small fire (Drysdale, 1999, Karlsson and Quintiere, 2000, Quintiere, 2006), which then start progressing by producing more heat and smoke. In this early stage, the fire would not be affected by the enclosure element in the process, as it is fuel-controlled. Then the fire grows at a slow or fast rate, depending on the fuel type and the ventilation conditions. A smouldering fire may have a very long growth period, and may extinguish itself without reaching a fully developed state. On the other side a flaming fire usually would progress to a fully developed fire after experiencing flashover.

Flashover is the transition between the growth period and the fully developed fire stage which was defined in the literature by many expressions. Flashover is the transition from a fuel-controlled fire to ventilation-controlled fire. A formal definition given by the International Standards Organisation, British Standards Institute and European Committee for Standardization (BS EN ISO13943, 2010) is the "transition to a state of total surface involvement in a fire of combustible materials within an enclosure." Flashover characteristics are temperature of the upper layer is 500 – 600 ˚C, radiation at the ground level of the compartment reaches 15 – 20 $kW \cdot m^{-2}$, or flames appearing from the compartment vents.

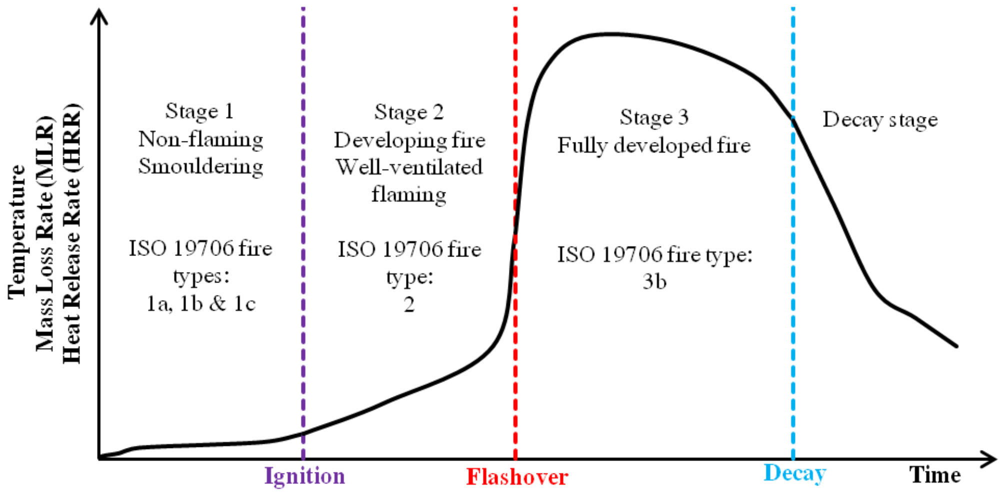

Figure 1: Different phases in the development of a compartment fire.

Fully developed fire stage (post-flashover) is the phase when the heat release rate in an enclosure fire peaks and often the fire size would be restricted by the availability of the oxygen, this is a ventilation-controlled fire. Unburnt gases are typically produced at this stage to be accumulating at ceiling level. As these hot (700-1200 ˚C) unburnt gases leave through the openings they burn creating flames outside the enclosure openings. At this stage, yields of toxic products are generally much larger than at the fuel-controlled fire conditions. Most of the fire load in the compartment is consumed during fully developed fire stage. Subsequently the heat release rate diminishes as the fuel becomes consumed, cooling down the temperature of the upper layer entering the Decay stage of the fire. Typically at this phase the fire turns from a ventilation-controlled fire to a fuel-controlled fire.

3. MAJOR DRIVERS FOR THE INCREASED ATTENTION TO FIRE TOXICITY RESEARCH

Toxic products from fires started to be recognized as a major threat to fire victims in the 1970s and 1980s, calling for the attention of the scientific community to study and analyse this hazard. The driving forces behind that recognition were fire disasters with the majority of their victims died as a result toxic smoke inhalation. Also statistical reviews of fire casualties highlighted (at the time) the increased risk of smoke on fires victims. This section will showcase some of these major incidents with the outcomes of the main investigation reports. Then a review of the statistical findings will be presented.

3.1 Case Studies

3.1.1 Saudi Airline Flight SV163, Riyadh, Saudi Arabia (1980)

Figure 2: Debris of Saudi Airline SV163 airplane (tailstrike.com, 2015).

The 1980 Saudi Arabian Airline flight 163 (PCV, 1980) is an example of the large number of deaths that can occur from toxic gases in aircraft passenger compartment fires. The fire broke through from a cargo hold into the main cabin through the cabin floor. The pilot managed to land the aircraft but no one managed to open the airplane door to escape, as everybody was incapacitated by toxic emissions. The doors remained closed until they were opened by the rescue services from outside.

3.1.2 British Airtours Flight 28M, Manchester, England (1985)

Figure 3: Aftermath of British Airtours flight 28M accident (Air Accidents Investigation Branch, 1988).

On August 22nd, 1985, Boeing 737-236 was set to fly from Manchester to Corfu (Greek Islands) and during the take off, the left engine caught fire forcing the pilot to abort the take off and stop the aircraft to undertake the evacuation plan. According to the official investigations, it is believed that after a minute from stopping the aircraft the fire penetrated the passengers' cabin sidewalls in the area between seats 17A to 19A as shown in Figure 4. Then, the fire started burning the interior furniture of the cabin producing highly toxic emissions. This incident claimed the lives 55 people toxic gas inhalation was the cause of death for 48 of them while 15 other person suffered severe injuries.

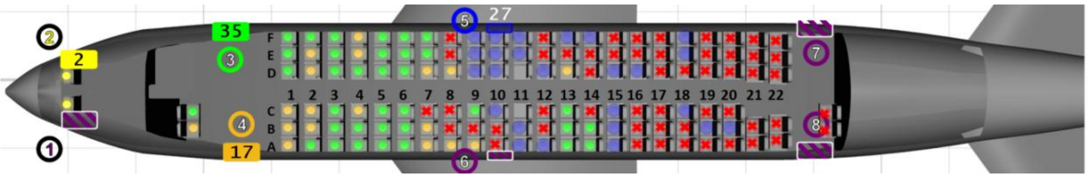

Figure 4: Passengers seating plan by exit used – red crosses represent fatalities (Anybody, 2008).

This incident had a significant impact on the air safety as the investigation report concluded that stricter limitations on the toxic gases emissions from the aircrafts' interior cabin materials should be applied (Air Accidents Investigation Branch, 1988).

3.1.3 MGM Grand Hotel, Las Vegas, NV (1980)

Figure 5: Picture of the MGM hotel during the fire showing the smoke dispersing from various areas in the building (Clark County Nevada Fire Department, 2010).

The fire broke out in the Casino at the ground level of the MGM Grand Hotel in the morning of November 21st, 1980, the Casino was closed at that time which resulted in the late discovery of the fire. Of the 85 people killed and more than 600 injured (including 318 were admitted to hospital) most were in the top high-rise tower floors who suffered from smoke inhalation. Even though the development of the fire was limited by the horizontal expansion, that did not prevent the toxic smoke emissions from travelling vertically through the elevators' shafts , (designed to be smokeproof) stairwells, and the air conditioning system ductwork.(Figure 6).

Toxic smoke inhalation was the cause of death for 79 of the people killed that day, 3 killed because of burns and smoke inhalation, while different causes of death for each of the left three fatalities; burns, skull fracture and myocarditis. As part of the official investigation a full toxicological blood tests had been undertaken for victims (Best and Demers, 1982, Emmons, 1988).

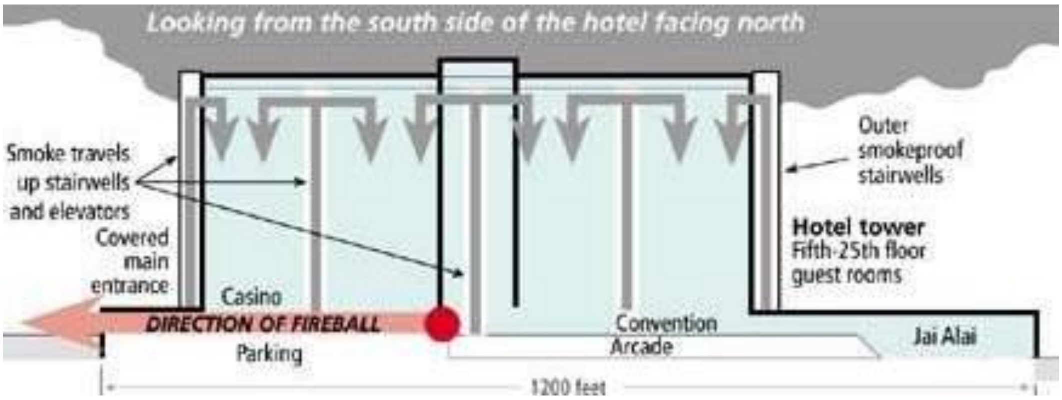

Figure 6: Fire and smoke spread in MGM Grand Hotel fire (Clark County Nevada Fire Department, 2010).

3.1.4 Rosepark care home, Uddingston, Scotland (2004)

On the morning of January 21, 2004, a fire broke out at Rosepark care home claiming the lives of 14 residents. According to the official investigation report by Brian Lockhart (Lockhart, 2011) which includes an experimental research by BRE, the origin of the fire was found to be an electric fault in the back the cupboard shown in Figure 7. The cupboard contents were reported by Strathclyde Police to be flammable materials in the form of aerosols and a fair amount of combustible material such as, books cardboard game boxes, disposable aprons, and body care products which produced a sustainable flaming fire. The reported main cause of death for all the fatalities was toxic smoke inhalation.

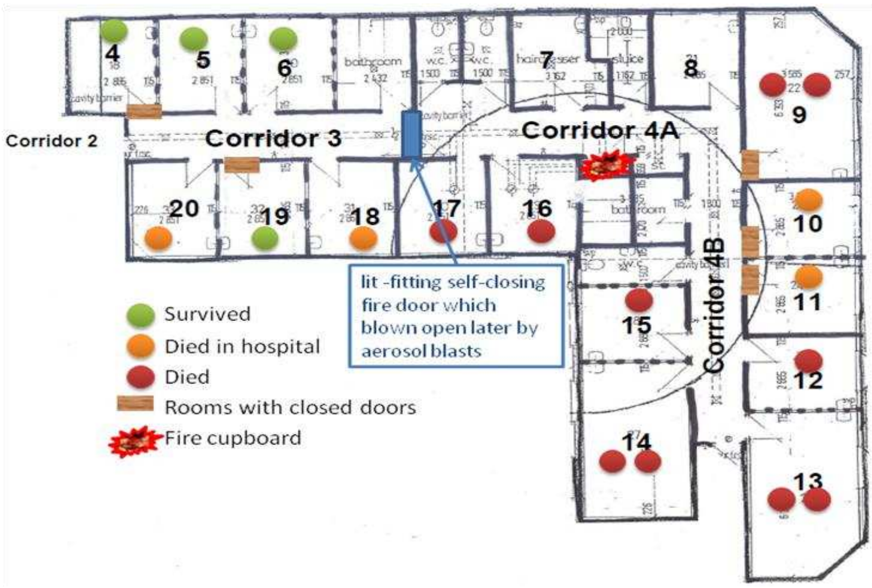

Figure 7: Schematic of the upper floor part involved in Rosepark care home fire. Original building plans taken from (BRE Ltd, 2004).

The report addressed the electrical installation hazards and recommended proper safety measures to be maintained. Also the provision of self-closing fire doors with smoke seals for all the bedrooms was recommended as most of victims who died in the premises had their doors wedged open or ajar as shown in Figure 7. Subdividing of corridor 4 was also strongly recommended as it can be seen the effect of even the poorly fitted fire door between corridor 3 and corridor 4 where four of corridor 3 residents survived and the other two died in the hospital, while all corridor 4 residents were killed in the incident. The report also raised the concerns of the management level as the incident was reported to the fire service after ten minutes of the first fire alarm activation at 4:28 am which believed that some victims have died by the time the fire brigade arrived as a clock in room 12 found burnt and stopped at 4:40 (BRE Ltd, 2004).

3.2 Statistical Review: Causes of Fatalities and Injuries in Domestic Fires

Recent official statistics released by the fire and rescue service in the United Kingdom in January 2015 (DCLG, 2015) showed that the major cause of death and injury in 2013/14 fires in the UK was being overcome by toxic smoke. 41% of the fatalities died from smoke inhalation and 46% of injuries (excluding first aid and precautionary checkups) were caused by smoke inhalation as illustrated in Figure 8. Similar findings were observed across the Atlantic as reported by U.S. Fire Administration, summarised in Figure 9, where smoke inhalation was the major cause of death for 39% of fire fatalities in residential buildings while smoke inhalation and breathing difficulties were the primary symptoms for 46% of civilian fire injuries in residential buildings.

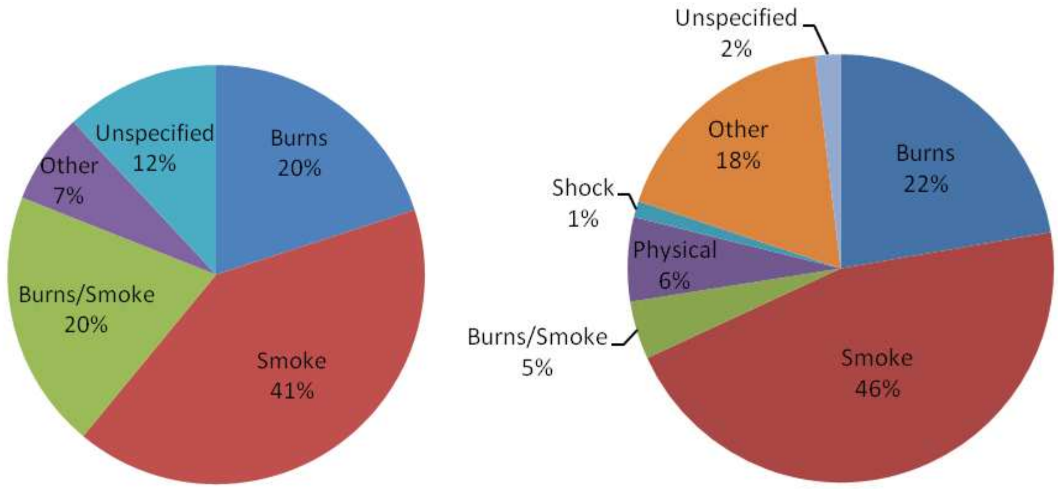

Figure 8: Left: UK fire fatalities. Right: UK non-fatal fire casualties (excluding first aid and precautionary checkups) by cause in 2013/14 (DCLG, 2015).

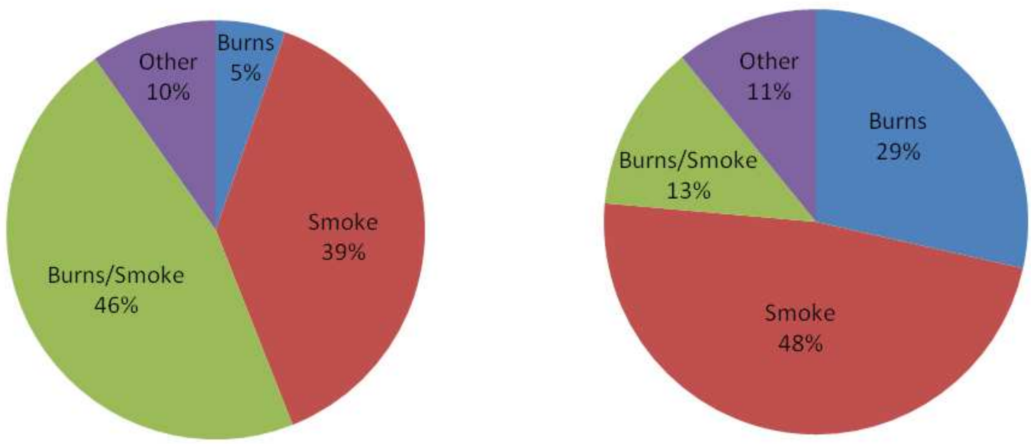

Figure 9: Left: US fire fatalities (FEMA, 2015a). Right: US non-fatal fire casualties (FEMA, 2015b). By cause between 2011-2013.

A statistical review of fire casualties between 1955 and 2007 for cause of death or injury was conducted by Purser (D. A. Purser, 2010b). The total number of fatalities showed a rising pattern from 1950s until mid-1980s when the number of fatalities started dropping while at the same time the number of casualties increased dramatically. This can be attributed to the new regulations that were introduced in 1988 (Forth, 1988) outlawing renting furnished property containing non-fire retardants furniture, as well as banning the sale of such furniture. Also, it was the same period when low-cost smoke alarms were introduced to the market. A similar review was conducted by Hall Jr. based on death certificated database issued cause of death for fire victims in the period from 1979 to 2007, summarised in Figure 10. This shows similar trends to those observed by Purser in the UK in terms general reduction of the number of fire casualties and smoke inhalation staying as leading cause of death.

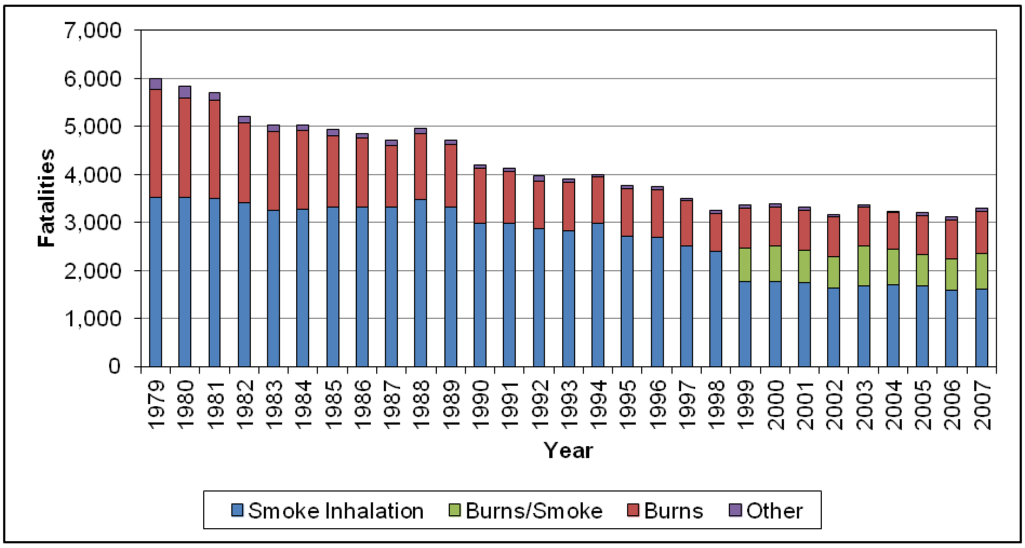

Figure 10: US fire fatalities between 1979 and 2007. Original data reported by (Hall Jr, 2011) from The US National Center for Health Statistics (NCHS) death certificate database.

In general the proportion of fire deaths from smoke inhalation reported in the UK has increased dramatically in the past decades (almost four times between 1950s and 2000s as shown in (Purser, 2010b)). There are a few explanations for the statistical increase, one of the explanations was that this rise is a result of increasing the awareness of the fire department of the toxic smoke effect on victims, implying that this rise is not real and can be considered "statistical anomaly". Purser (David A. Purser, 2002) dismissed this reasoning attributing the increase to three major factors that contributed to the rise of fire toxicity victims. Firstly, the increased use of complex materials e.g. polymers that burn inefficiently and produce incomplete complex combustion emissions. Secondly, the influence of modern energy efficient building construction, smaller rooms and lower ceiling heights for conserving energy that would increase the temperature of burning creating a faster fire growth. Finally, ventilation restrictions of modern day designs can aid in slowing down the fire spread, by not having enough oxygen, however this also complicates the combustion process and enhances the production of incomplete combustion products. These factors aided with the change in the lifestyle, such as the increase in the amount of furniture (fire loads), its layout and material composition are the main reasons for the increase of fire causalities from toxic smoke inhalation.

Based on these factors the fire toxicity research agenda should follow certain directions. Firstly, we need to understand and quantify the toxicity potential of the different materials that we use in our buildings and develop suitable models that allow the toxic exposure levels to be quantified within the fire compartment but also within the rest of the building and ideally beyond to the outside environment. This will allow the evaluation and implementation of suitable protection strategies such smoke control measures that reduce the exposure of people to levels that are not harmful. Secondly, research should be directed towards developing materials and products that are inherently safer by having a slower burning rate and low toxic species yields

4. TOTAL TOXIC POTENCY OF SMOKE AND THE CONTRIBUTION OF ITS INDIVIDUAL MAIN COMPONENTS

The composition of the toxic species in fire effluents can be very complex, and each component has different effects on human beings. Additive models for toxicity assessment of fire effluent mixtures were introduced to quantify the fire toxicity effects using threshold limits for lethality or incapacitation (BS ISO 13344, 2004, D. Purser, 2012, D. A. Purser, 2010c). Threshold limits for lethality (e.g. LC50: lethal concentration which kills half the test animals group exposed to a specific gas for a specified time (BS ISO 13344, 2004)) or impairment of escape (e.g. AEGL-2: acute exposure guideline level 2 representing emergency exposure that would result in impairment of escape for the general public taking into consideration “susceptible individuals” (National Research Council, 2015)). It is important to highlight that this toxicity assessment method is dependent on the point of exposure/sampling. FEC (Fractional Effective Concentration) represents the ratio of the exposed/sampled concentration to the lethal or impairment of escape exposure limits for each species (D. A. Purser, 2010a). Accumulated value of FECs can be presented by summing all FECs of individual toxic gases. This approach is presented below in Figures 11 and 12 for a fully instrumented full-scale fire experiment that was conducted by Leeds fire toxicity research group, where wooden pallets were the fuel in a full size room fire. Full details of the setup and results can found elsewhere (Alarifi et al., 2014). Figure 11 illustrates the scale of the exceeding the lethality limit with a peak point of 35 times the suggested LC50 limit and 3,500 times the suggested AEGL-2 limit for impairment of escape. Based on the latter, the implied safe approach is that the smoke from this fire would need to be diluted by a factor of 3500 in order to prevent incapacitation. Typically in current designs, smoke control systems dilute by a factor of 100, which is obviously inadequate.

By having a closer look into the composition of the fire effluents by each species contribution to the overall lethality and impairment of escape in Figure 12, illustrates the importance of highlighting the species that impair fire victims from escaping, in this case Acrolein has more than 70% influence for the majority of time, before lethal dose of other components are inhaled or flames reaching the victims causing a casualty.

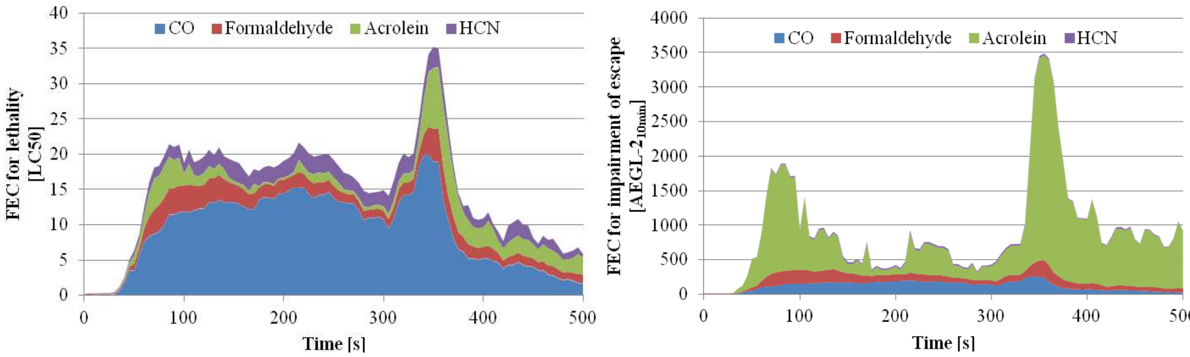

Figure 11: Wooden pallets compartment fire effluents accumulated FEC of lethality (Left) and impairment of escape (Right).

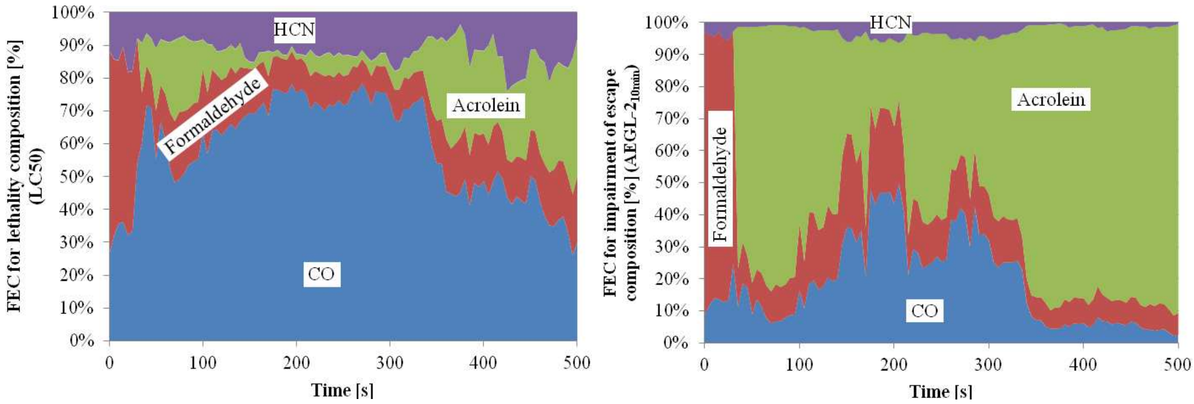

Figure 12: Wooden pallets compartment fire major effluents contribution by species to lethality (Left) and impairment of escape (Right).

5. CONCLUSIONS AND FUTURE WORK

This paper illustrates the severity of fire toxicity on human lives based on statistical reviews from the UK and USA, the objective of stopping smoke inhalation from being the leading cause of death has not been achieved yet. The roots for the problem were explored and approaches of tackling the issue were identified. Applications of fire toxicity research were demonstrated showing the toxic potency in full size fire experiment. It was demonstrated that the composition of the smoke mixture responsible for impairment of escape has Acrolein as the lead contributor to the overall toxicity, in comparison to lethality which has carbon monoxide as the lead contributor to the overall toxicity.

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