

FIRE SIZE IN TUNNELS

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Abstract

In recent years, a number of high profile accidental fires have occurred in several road and rail tunnels throughout the world. Many of these fires grew rapidly to catastrophic size and claimed many lives. The processes involved in the rapid growth and extremely severe of these fires are not adequately understood as yet.

The introduction to this thesis reviews a number of these accidental fires and describes much of the previous experimental research which has brought about the current understanding of tunnel fire behaviour. A detailed review of the relevant parts of elementary fire dynamics is also presented.

This thesis addresses two main questions:

1. What is the influence of longitudinal ventilation on fire size in tunnels?
and
2. What is the influence of tunnel geometry on fire size?

The answers to both these questions are determined using a probabilistic method called Bayes Theorem. This provides a method of answering the above two questions using the handful of experimental data which are available.

It is found that the heat release rate (HRR) of a heavy goods vehicle (HGV) fire may be greatly increased in magnitude by longitudinal ventilation, for example by about a factor of 5 with a longitudinal ventilation velocity of 3ms^{-1} . It is also found that longitudinal ventilation may cause a significant increase in the HRR of large pool fires, but may cause a decrease in the HRR of small pool fires and car fires.

An equation is derived to predict the influence of tunnel geometry on HRR. It is found that HRR varies principally with the width of the tunnel and the width of the fire object. The HRR of a fire in a tunnel may be increased up to four times due to the geometry of the tunnel.

Dedication

This thesis is dedicated to my father

Jim Carvel (1923-2004)

who didn't quite manage to see its completion

and to my mother

Maybelle Carvel

who never expected to have a doctor in the family!

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This thesis would not have been possible without the vision, supervision and guidance of Dr. Alan Beard, so the first acknowledgement must go to him. Thanks must also go to Prof. Paul Jowitt (SISTech; Heriot-Watt University) and Prof. Dougal Drysdale (University of Edinburgh) for insight and advice throughout both projects.

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Thanks to Dad for his constant badgering to get this thesis finished and to Fiona for knowing when to pester and when to be patient. Love (as always) to Fiona, Rowan and Eilidh.

Declaration

Except where reference is made to the work of others, this thesis is believed to be original and has not been submitted for any other degree.

Richard O. Carvel (candidate)

Dr. Alan N. Beard (supervisor)

Date

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Glossary

<i>Abbreviation</i>	<i>Meaning</i>
CCTV	Closed-circuit Television
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
FOA	The Swedish Defence Research Establishment
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
HSL	Health & Safety Laboratory (Buxton, UK)
MTFVTP	Memorial Tunnel Fire Ventilation Test Program
OEP	Oversized Exhaust Ports
PPV	Positive Pressure Ventilation
SES	Subway Environmental Simulator
SMS	Safety Management System
SP	The Swedish National Testing and Research Institute
SPE	Single Point Extraction
SVS	Supplementary Ventilation System
VTT	The Finnish National Research Centre

List of publications by the author

Book:

- R. Carvel & A. Beard (Eds) “**The Handbook of Tunnel Fire Safety**” Thomas Telford, London (2004). ISBN 0727731688 (*in press*)
 - Chapter 1: R. Carvel & G. Marlair “*Accidental fires in tunnels: a history*”
 - Chapter 6: R. Carvel “*Fire protection in concrete tunnels*”
 - Chapter 9: R. Carvel & A. Beard “*Tunnel ventilation: effect on fire*”
 - Chapter 10: R. Carvel & G. Marlair “*Experimental tunnel fires: a history*”

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- R.O. Carvel, A.N. Beard, P.W. Jowitt & D.D. Drysdale “*The influence of tunnel geometry and ventilation on the heat release rate of a fire*” *Fire Technology*, Volume 40 (2004) pp. 5-26.
- R.O. Carvel, G.O. Thomas & C.J. Brown “*Some observations of detonation propagation through a gas containing dust particles in suspension*” *Shock Waves Journal*, Volume 13 (2003) pp. 83-89.
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Chapter 1. Introduction

During the last few decades the increasing need for better and more efficient transport networks has generated a huge increase in the construction rate of vehicle tunnels. Advances in engineering have meant that tunnels longer than 50km are now an everyday reality, and the length of tunnels is ever on the increase. In recent years France has been linked to the UK by the Channel Tunnel (51km) and Honshu and Hokkaido in Japan have been linked by the Seikan Tunnel (54km). There are even plans to link Africa and Europe by a tunnel under the straits of Gibraltar.

There is obviously a great deal of concern over safety in these large underground structures, and fire safety in particular. To date there have been relatively few serious fires in underground transport systems, but where fires have occurred the destruction and loss of life has often been phenomenal.

1.1 A history of fires in tunnels

Vehicle fires start for a variety of reasons, in passenger cars the most common reason is an electrical fault, in heavy goods vehicles (HGVs) the most common cause is the brakes overheating on a long downward slope [1]. Fires may also start as a result of a collision. There does not seem to be any statistical evidence that fires occur more or less frequently in tunnels than in the open air, however any fires that do occur in tunnels do tend to have more serious consequences.

1.1.1 Fires on passenger trains in tunnels

On the 11th of November 2000, a fire started on a funicular railway carrying skiers up to the Kitzsteinhorn glacier, near Kaprun in Austria. Had the train been travelling up the side of the mountain rather than through a tunnel it is unlikely that the fire would have made the news outside of Austria, but due to the confines of the tunnel the fire was directly responsible for the deaths of 151 people on the train, the driver of a second train in the tunnel and three people near the top opening of the tunnel. The handful of survivors were those who fled down the tunnel, those trying to escape the fire by going up the tunnel were all killed by the smoke [2].

The reports on the Kaprun incident indicate that the majority of the passengers on the train did not manage to get off the train before they succumbed to the poisonous smoke [2]. This was also the case in the fire incident on a Baku underground train on the 28th of October 1995. The bodies of 220 passengers were found on the train itself while a further 80 passengers succumbed to the fumes making their way along the tracks toward the station [3].

In both these cases the lack of a safety management system (SMS) was partly responsible for the number of deaths; in the Kaprun incident the train was held to be “fire proof” so the consequences of a fire onboard had never been considered, and the possibility that some of the passengers could be carrying potentially flammable materials also appears not to have been considered. In the Baku incident the lack of communication and the “knee jerk” operation of the ventilation system also led to fatalities; some 15 minutes after the fire started the emergency ventilation system was switched on which directed the smoke towards the majority of the passengers – lack of communication meant that those in the control room had no idea what was going on at the site of the fire [3].

Aside from these two incidents, large scale fires rarely happen on passenger trains. There is comparatively little fuel to burn and usually many people are able to extinguish the fire while it is still small. This is not the case for goods trains.

1.1.2 Fires involving goods trains in tunnels

On the evening of the 18th November 1996 one of the heavy goods vehicles (HGVs) onboard a HGV carrier shuttle in the Channel Tunnel caught fire. Upon entering the tunnel the fire size has been estimated to have been about 1.5MW, when the fire reached its maximum extent the size was as much as 350MW and involved ten HGVs and their carrier wagons. Unlike the Baku underground and the Kaprun funicular tunnels, the Channel Tunnel is a very well equipped modern tunnel with good communications and a carefully planned safety management system. This utilises frequent cross passages to the service tunnel along the length of the tunnel, a supplementary ventilation system (SVS) to control smoke movement and a positive pressure ventilation (PPV) system in the service tunnel to prevent smoke entering the cross passages. Although the SVS was not fully operational until some 30 minutes after

the fire was first detected, the SMS enabled the escape of all the HGV drivers and the crew into the service tunnel with no fatalities and only two escapees requiring significant hospital attention [4]. After all the people were successfully evacuated, the SVS maintained a ventilation velocity of 2.5ms^{-1} in the tunnel which may have helped fan the fire to grow to such a size. The main fire was extinguished by fire-fighters, working in relays, by 5am the following day, some seven hours after the fire was first detected. Minor smouldering and fires were still in evidence 24 hours later. The damage to the tunnel lining and the train can be seen in Figure 1.01.



Figure 1.01 – The aftermath of the Channel Tunnel fire (18.11.96) [20]

Possibly the largest train fire in a tunnel also produced no fatalities. On the 20th of December 1984, a goods train pulling 13 petrol tankers derailed in the Summit tunnel, near Rochdale, England. The resulting fire burned for three days and the flames from the fire reached heights of 120m above the top of the tunnel ventilation shafts, see Figure 1.02. Remarkably the train driver escaped unharmed [5].

Although there have been a number of fire incidents on trains in tunnels, it seems that fires in road tunnels are more frequent: possibly because rail transport is more organised than road transport and the vehicle drivers are trained to a higher level. However, the number of fatalities in road tunnel incidents generally seems to be far smaller than in train fires: possibly because individual passenger trains can carry hundreds of people, whereas road vehicles do not.



Figure 1.02 – Flames emerging from the tunnel vents during the Summit Tunnel fire
(20.12.84) [20]

1.1.3 Fires in road tunnels

On the 24th of March 1999 a HGV travelling through the 11km long Mont Blanc tunnel from France to Italy caught fire, possibly due to the engine overheating. This HGV stopped 6km into the tunnel when the driver became aware of the fire; he was unable to put it out and fled, on foot, towards Italy. Within minutes the tunnel operators were aware of the fire and prevented further vehicles from entering the tunnel, however, 18 HGVs, 9 cars, a van and a motorcycle had entered the tunnel from France after the first HGV and before the tunnel was closed. Of these 29 vehicles, four HGVs managed to pass the burning HGV and travel on towards Italy in safety, the other 25 vehicles became trapped in the smoke and eventually became involved in the fire. Nobody in any of these vehicles survived. Due to the prevailing wind direction (from the south) and the different ventilation regimes at either end of the tunnel (all ventilation ducts at the Italian end were set to supply fresh air, whereas at the French end some ducts were set to supply and some to exhaust) virtually all the smoke from the fire was carried towards France, and as the airflow velocity was more than 1ms^{-1} , the smoke did not remain stratified^A; within minutes there was no fresh air in the tunnel downstream of the fire. The fire grew to involve the 25 vehicles behind the first HGV, 8 HGVs which had been abandoned by their drivers travelling from Italy to France (the nearest one being some

^A The 1ms^{-1} airflow criterion is a commonly applied ‘rule of thumb’ regarding smoke stratification.

290m from the initial HGV fire), and the first fire-fighting vehicle which entered the tunnel from the French side (which was almost half a kilometre from the nearest vehicle on fire). It is unclear how the fire managed to spread such distances, although explanations such as backdraught, burning liquid fuels and the involvement of pavement materials in the fire have been proposed. At the height of the fire the blaze was estimated to have been about 190MW in size with temperatures in the tunnel exceeding 1000°C. The fire took 53 hours to extinguish and “hot spots” were still being dealt with after five days. 38 tunnel users and one fire-fighter died as a result of the fire, 27 in their vehicles, two in an emergency shelter (designed to protect life in the event of a fire) and the rest on the roadway trying to reach the French portal [6]. This was the greatest loss of life in any road tunnel fire^B. A photograph of the aftermath of the fire is shown in Figure 1.03.



Figure 1.03 – The remains of the vehicles after the Mont Blanc tunnel fire (24.3.99)

(Photo © AP. Used with permission)

The incident in the Mont Blanc tunnel was the 18th HGV fire recorded in the tunnel since it opened in 1965. Of the other 17 incidents most were minor and only five required the intervention of the fire brigade; none of these incidents resulted in any fatalities. The fire in the Mont Blanc tunnel became a tragedy due to a combination of factors including the weather conditions, the different ventilation regimes at either end

^B Except possibly the Salang tunnel fire (1982), see Appendix B.

of the tunnel and the highly flammable nature of the trailer (insulated with polyurethane foam) and its cargo (margarine and flour) on the initial HGV.

There have of course been many other fire incidents in vehicle tunnels. A comprehensive list of tunnel fire incidents is presented in Appendix B. The majority of fires in road tunnels which have led to fatalities or significant destruction of vehicles seem to be due to collisions or vehicles shedding their loads. Two more road tunnel fires deserve further comment.

On the 7th of April 1982 a collision in the Caldecott tunnel, Oakland, USA came about when a passenger car, driven by a drunk driver, collided with the roadside barrier (raised walkway) and came to an abrupt halt. The stationary car was struck by a petrol tanker and subsequently the tanker was struck by a bus, causing the tanker to turn over, partially rupturing and spilling some of its load. This soon ignited and the blaze grew to involve the tanker, the car and four other vehicles in the tunnel. Seven people were killed [7]. Although some of the petrol spilled out of the tanker, it appears that a large quantity of the fuel remained in the tank. Once the fire had reached a sufficient temperature to melt the aluminium walls of the tanker, the “top” of the tanker (i.e. the side that was uppermost after the crash) collapsed creating a large, deep pool of petrol which ignited and burned fiercely for over two hours until fire-fighters were able to extinguish it [8].

On the 11th of July 1979 a collision in the Nihonzaka tunnel, near Yaizu City, Japan, resulted in a fire which destroyed 173 vehicles. However, the seven fatalities which occurred during the incident were all as a result of the crash, not as a result of the fire; over two hundred people escaped the tunnel on foot before the fire established itself. The Nihonzaka tunnel is unique amongst those described here, in that it had a spray system to suppress fires. This automatic system began sprinkling the tunnel only eleven minutes after the crash, and this successfully suppressed fire growth for about half an hour – long enough for all the people in the 2km long tunnel to walk out. After this time, however, the unburned fuel vapours reignited and the fire established itself once more. One hour later the sprinkler reservoirs ran dry and the fire grew dramatically. It was two days before the blaze was “under control” and a further five days before it was extinguished [9].

1.2 Fire safety in tunnels

A quick survey of fires in tunnels (see Appendix B) suggests that large scale fires in tunnels may be becoming more frequent (the majority of large fires in tunnels have occurred in the past 20 years), this is probably due to the increasing rate of tunnel construction and use; there are far more tunnels in use today than there were twenty years ago, and these tunnels are far longer and carry a much higher density of traffic than before. To try to ensure that the number of large scale tunnel fire incidents does not increase at the same rate as our use of tunnels, modern tunnels incorporate sophisticated fire detectors, suppression systems and ventilation systems to control and restrict fire spread.

1.2.1 Ventilation systems

Tunnels have had ventilation systems in them for many years, but it is only relatively recently that the ventilation systems have been seen as a fire safety measure. The earliest ventilation systems were simply vertical shafts cut through the ground above the tunnel. These provided some fresh air in the tunnel by means of the chimney effect; the air in the tunnel (particularly if it was a steam train tunnel) would generally be warmer than the air outside, so this warm air would rise up the shafts and fresh, cold air would be gently pulled in the tunnel portals. This system of course does not work for tunnels which go under obstacles like rivers, rather than through obstacles like hills, so when these tunnels became commonplace, mechanical ventilation systems were installed in some tunnels for the first time [10].

The mechanical ventilation technology was originally developed for use in underground mines, and was adapted, with only minor changes, to be used in tunnels. The purpose of this ventilation was to supply fresh air through the tunnel and to disperse pollutants such as smoke and steam from trains. The ventilation system was not considered to be a fire safety device. Indeed the first interaction between fires and ventilation systems that was considered was the “throttling” effect of a fire on the ventilation. If there is a fire in part of a network of mine tunnels, it has the effect of restricting the airflow through that part of the tunnel, equivalent to replacing that part of the tunnel with a tunnel of smaller dimensions, or effectively constricting or “throttling” the tunnel [11,12]. The idea that a

ventilation system might exacerbate the fire in any way does not seem to have been considered at all until recent years.

Over the years these tunnel ventilation systems have evolved into three main types:

1. Fully transverse ventilation – fresh air is supplied to the tunnel through vents positioned at regular intervals along the tunnel's length, these are opposed by exhaust air vents to extract pollutants etc. from the tunnel.
2. Semi-transverse ventilation – fresh air is supplied through periodic vents as in the previous case, however, in this case the exhaust air is extracted through only one or two large vents, usually at or near each of the main portals.
3. Longitudinal ventilation – fresh air is forced along the length of the tunnel, generally by jet fans mounted on the roof. This system is often used in tunnels with the

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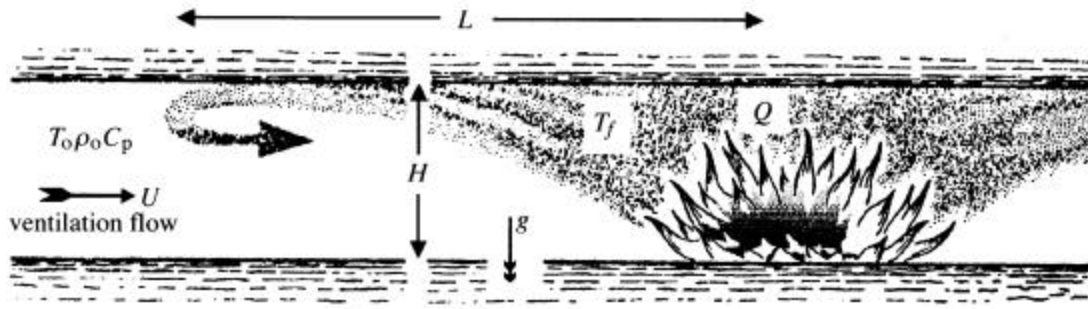


Figure 1.04 – Backlayering in a tunnel fire [14]

Backlayering (also known as “back-flow”) is the name given to the phenomenon when smoke from a fire is observed to move against the direction of the airflow in the tunnel, see Figure 1.04. Eisner & Smith [14] proposed that it is essential for fire fighters to be able to get to within 11-14m of a fire in a tunnel in order to effectively attack the fire. In practical terms this means that backlayering must be prevented or sufficiently controlled. The ventilation velocity required to prevent backlayering is known as the “critical velocity” (designated U_{cr}) and various different methods have been proposed for calculating it over the years [15-19]. The first relationships to be proposed seem to hold for small fire sizes, but become unreliable for larger fires [20]. Critical velocity varies not only with fire size but also with tunnel size and shape; Wu *et al.* [21] have demonstrated that it varies with the mean hydraulic diameter of the tunnel (the ratio of four times the perimeter of the tunnel cross-section to its area) and not with any other characteristic dimension of the system (e.g. tunnel height). It should be noted that “critical velocity” is the airflow velocity required to prevent *all* backlayering. Smaller airflow velocities may be able to “hold” backlayering to a fixed length (designated L in Figure 1.04) upstream of the fire; if backlayering is held at less than 11-14m from the fire then Eisner & Smith’s criterion [14] has been met using less ventilation than the critical velocity.

There are no international standards for ventilation flow in vehicle tunnels. Many countries do not even have national standards. In a recent study of national approaches, it was found that those countries that do have a recommended airflow for smoke control in vehicle tunnels recommend that a ventilation velocity of 3ms^{-1} should be maintained in the vicinity of the fire for evacuation purposes [22]. However, this recommendation does not take into account the effect of the ventilation systems on the severity of the fire itself, the question that will be addressed in Chapter 4, and following, of this thesis.

1.2.2 Detection systems

Having an emergency ventilation response ready to be used in the event of a fire in a tunnel is useless if there is no system in the tunnel to detect a fire. Some modern tunnels are equipped with closed circuit television systems (CCTV), temperature sensors, smoke detectors and sometimes gas analysers monitoring the levels of carbon monoxide (CO) and other toxic gases. These systems either alert the tunnel operators to hazards or potentially hazardous situations, so that they may take the appropriate action, or the systems automatically respond to the situation, initiating emergency ventilation, sprinklers, warning signals etc. In Japan some automatic systems have been designed to actively monitor the backlayering of smoke from a fire and adjust the ventilation accordingly, in order that the backlayering is maintained at an acceptable level [23]. These systems were specifically designed to use the absolute minimum ventilation necessary to control smoke in order to minimise the scale of the fire. In the UK, Norway and France, on the other hand, no road tunnels have any fire detection systems – operators rely on members of the public alerting them to any incidents [24].

1.2.3 Suppression systems

The use of sprinklers (or “deluge systems” as they are frequently referred to today) in tunnels remains a topic of much debate [25]. Those in favour tend to argue that the sprinklers will protect the tunnel and allow the occupants time to escape. Those against hold that the sprinklers will probably not extinguish a vehicle fire (e.g. if a car is on fire the water will not get inside the car, it will merely cool the outer shell), that they will not deal with combustible vapours which will probably ignite at some later stage and that in some instances where a pool of liquid fuel is on fire they may cause an explosion. Some countries require that sprinklers are installed although they are not generally recommended for use in road tunnels. The world road association (PIARC) report on “Fire and Smoke Control in Road Tunnels” [26] summarises its recommendations with the following:

“No European country uses sprinklers on a regular basis. In some tunnels in Europe sprinklers have been used for special purposes. In Japan some sprinklers are used in tunnels with important length or traffic to cool down vehicles on fire. In the United States only a few tunnels carrying hazardous

cargo have some form of sprinkler. The reason why most countries do not use sprinklers in tunnels is that most fires start in the motor room (engine compartment) or the [passenger] compartment, and sprinklers are of no use until the fire is open. [...] Experiences from Japan show that sprinklers are effective in cooling down the area round a fire, so that fire fighting can be more effective.

However, the use of sprinklers raises a number of problems which are summarised in the following points:

- ◆ *Water can cause explosion in petrol and other chemical substances if not combined with appropriate additives.*
- ◆ *There is a risk that the fire is extinguished but flammable gases are still produced and may cause an explosion.*
- ◆ *Vaporised steam can hurt people.*
- ◆ *The efficiency is low for fires inside vehicles.*
- ◆ *The smoke layer is cooled down and de-stratified, so that it will cover the whole tunnel.*
- ◆ *Maintenance can be costly.*
- ◆ *Sprinklers are difficult to handle manually.*
- ◆ *Visibility is reduced.*

As a consequence, sprinklers must not be started before all people have been evacuated.

Based on these facts, sprinklers cannot be considered as an equipment useful to save lives. They can only be used to protect the tunnel once evacuation is completed.”

1.3 The future of tunnel fire safety systems

In the past it has seemed sufficient to adopt a trial-and-error approach to testing fire safety systems, and those systems which have been found to be successful in certain tunnel fire incidents have been adopted for use in other tunnels. The number of tunnel users is increasing at a great rate, for example, the average daily number of HGV

travelling through the Mont Blanc Tunnel was about 125 in 1965 when the tunnel opened, but this had increased to 2100 by the time of the fatal incident in 1999 [6]. Considering this great increase, it has become necessary to look more closely at the very nature of fire in order to design and install fire safety systems which are able to deal with tunnel fires with sufficient efficiency. Only by understanding fire dynamics and designing appropriate fire safety systems can an acceptable level of protection from fire be achieved in tunnels.

Chapter 2. Tunnel fire dynamics

For a more in-depth discussion of fire dynamics, the reader is directed to the text book “*An Introduction to Fire Dynamics*” [27] upon which much of the early part of this chapter is based.

2.1 Introduction to fire and fuels

All fires involve a chemical reaction between some combustible fuel^C and oxygen. Although “fire” is a manifestation of a chemical reaction, it should be noted that the mode of burning may depend more on the physical state and location of the fuel than its chemical nature. For example, a pile of wooden sticks will burn in a substantially different manner to a single log of the same weight. Also a pile of sticks in the corner of a room will burn in a different manner to a similar pile of sticks in the centre of a room. Flaming combustion is a gas phase phenomenon and the burning of a solid or liquid fuel must involve some evaporative boiling or pyrolysis^D to yield gaseous fuel.

There are two distinct regimes in which gaseous fuels may burn. In one the fuel and oxygen are mixed before burning, this gives rise to a *premixed* flame. In the other the fuel and oxygen are initially separate but burn in the region where they mix, this gives rise to a *diffusion* flame. This discussion will only concern diffusion flames as explosions resulting from premixed flames are outwith the scope of this research project.

In diffusion flames, the rate of burning is dependent on the rate of supply of gaseous fuel. For jet flames and gas burners this is independent of the combustion processes. For other fuels, including pools of liquid fuel, wood, and vehicles, the rate of supply of gaseous combustibles is directly linked to the rate of heat transfer from the flame (and

^C In this chapter the word “fuel” will be used to denote the combustible species involved in a fire. This may be a liquid fuel such as petrol, but may equally be a gas or a solid combustible object such as a pile of wood or a car seat.

^D ‘Pyrolysis’ is the chemical decomposition of a solid fuel to smaller gaseous substances when exposed to heat.

any other sources of heat) to the fuel. The rate of burning (mass loss, per unit area, per unit time) can be expressed generally as:

$$\dot{m}'' = \frac{\dot{q}_s'' - \dot{q}_L''}{L_V} \text{ gm}^{-2}\text{s}^{-1} \quad [2.1]$$

where \dot{q}_s'' is the heat flux supplied by the flame^E and other heat sources (kWm^{-2}), \dot{q}_L'' is the losses expressed as a heat flux through the fuel surface (kWm^{-2}) and L_V is the heat required to produce the gaseous combustibles (kJg^{-1}) which, for a liquid, is simply the latent heat of evaporation.

2.2 Heat release rate

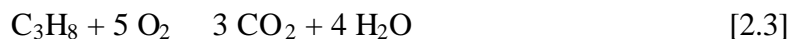
The rate at which energy is released, generally known as the ‘heat release rate’ (HRR, denoted \dot{q}_c) is the most important variable which characterises the behaviour of a fire [28]. It is defined by:

$$\dot{q}_c = \chi \dot{m}'' A_f \Delta H_c \text{ kW} \quad [2.2]$$

where A_f is the fuel surface area (m^2), ΔH_c is the heat of combustion of the gaseous combustibles (kJg^{-1}) and χ is a factor (between 0 and 1) included to account for incomplete combustion [29]. If χ is known, the HRR of an experimental fire can be calculated from mass loss data, it can also be experimentally measured using oxygen consumption calorimetry.

All combustion reactions release energy. This may be quantified by defining the heat of combustion (ΔH_c) as the total amount of heat released when unit quantity of fuel is oxidised completely (at 298K and at atmospheric pressure). For a hydrocarbon fuel like propane (C_3H_8) the products would be carbon dioxide and water, thus:

^E The embellishment '' denotes that a quantity is measured per unit area, e.g. \dot{q}'' or \dot{m}'' . Similarly, ' and ''' denote quantities measured per unit length and per unit volume, respectively. The dot above the quantity denotes that it is a flux.



This is a stoichiometric reaction – the amounts of fuel and oxygen are exactly balanced. The reaction is also exothermic (i.e. heat is produced). The value of $\Delta H_c(\text{C}_3\text{H}_8)$ is -2044 kJmol^{-1} assuming that the water produced remains in vapour form (a reasonable assumption to make when considering fires). This may also be expressed as -46.45 kJg^{-1} (one mole of propane is 44g).

Heats of combustion are often determined using a “bomb” calorimeter – a closed vessel in which a known quantity of fuel is burned completely in an atmosphere of pure oxygen [30]. Assuming no heat loss, the amount of heat released can be calculated from the temperature rise of the calorimeter and its contents. The difference between the *enthalpy* change of the system (ΔH) and the change in internal energy (ΔU) is due to the work done in the expansion process ($P\Delta V$):

$$\Delta H = \Delta U + P\Delta V \quad [2.4]$$

$P\Delta V$ may be estimated using the ideal gas law:

$$P\Delta V = \Delta nRT \quad [2.5]$$

where (for the propane reaction given in equation 2.3) $\Delta n = +1$ (there are seven moles of products from six moles of reactants) and $T = 298\text{K}$.

The use of bomb calorimetry has meant that the heats of formation (ΔH_f) of many compounds have been accurately determined. The heat of formation is defined as the enthalpy change when a compound is formed in its standard state (at one atmosphere pressure and 298K) from its constituent elements, also in their standard states. If the heats of formation of the products and reactants of any chemical reaction are known, the total enthalpy change can be calculated. For the combustion of propane given in equation 2.3 this is:

$$\Delta H_c (\text{C}_3\text{H}_8) = 3 \Delta H_f(\text{CO}_2) + 4 \Delta H_f(\text{H}_2\text{O}) - \Delta H_f(\text{C}_3\text{H}_8) - \Delta H_f(\text{O}_2) \quad [2.6]$$

where $\Delta H_f(\text{O}_2) = 0$ (by definition). This incorporates Hess's law of heat summation, which states that the change in enthalpy of a system depends only on the initial and final states of the system and is independent of the intermediate steps.

Determining the heat release rate of the combustion of a pure fuel is simple using the above formulae. However, in real life, fires rarely involve chemically pure fuels and rarely burn at 100% efficiency. Yet, information on the HRR of a fire is often required in engineering calculations [28]. In recent years a method of directly measuring the HRR of a fire has been developed. It relies on the fact that the heat of combustion of most common fuels is constant if it is expressed in terms of the oxygen consumed. For the example of propane given above, it can be said that 2044 kJ are evolved for each mole of propane burnt or for every 5 moles of oxygen consumed. The heat of combustion could be expressed as $\Delta H_{c,ox} = -408.8 \text{ kJmol}^{-1}$ or -12.77 kJg^{-1} (one mole of oxygen is 32g). Huggett [31] observed that most typical organic liquids and gases (excluding ethene and ethyne) have $\Delta H_{c,ox} = -12.72 \pm 3\% \text{ kJg}^{-1}$ of oxygen and polymers (excluding polyoxymethylene) have $\Delta H_{c,ox} = -13.02 \pm 4\% \text{ kJg}^{-1}$. So if the rate of oxygen consumption can be measured, the rate of heat release can be estimated directly. This is the basis for the cone calorimeter [32] and many other types of flammability apparatus. All these apparatuses have some form of hood and duct assembly with the combustion products being guided through a duct of known cross-sectional area in which measurements of temperature, velocity, and the concentrations of oxygen, carbon dioxide and carbon monoxide are made. Assuming complete combustion of the fuel (i.e. the concentration of carbon monoxide in the duct is negligible), the HRR may be calculated from:

$$\dot{q}_c = (0.21 - \zeta_{\text{O}_2}) V 10^3 \tilde{n}_{\text{O}_2} \Delta H_{c,ox} \quad [2.7]$$

where V is the volumetric flow of air (m^3s^{-1}), \tilde{n}_{O_2} is the density of oxygen (kgm^{-3}) at normal temperature and pressure, and ζ_{O_2} is the mole fraction of oxygen in the "scrubbed" gases (i.e. water vapour and acid gases have been removed).

$\Delta H_{c,ox}$ is generally taken to be $-13.1 \text{ kJg}^{-1}(\text{O}_2)$ assuming complete combustion. It has been suggested that if combustion is incomplete (i.e. carbon monoxide or soot particles are formed) the effect on the calculated HRR will be small [33]. This method would

give a higher HRR value than reality (up to 30%) if carbon monoxide was produced but a smaller HRR value if soot was formed (20-25% lower) – as these variations are in opposite directions they will mostly cancel each other out and it is likely that the calculated HRR will be within 5% of the true value. Current research techniques are able to perform these estimations more accurately by measuring the concentration of carbon monoxide and correcting the calculations accordingly.

As fires are usually supplied with oxygen from the air rather than as a pure gas, it is frequently more useful to consider $\Delta H_{c,air}$ rather than $\Delta H_{c,ox}$. $\Delta H_{c,air}$ is usually considered to be $3.03 \pm 2\% \text{ kJg}^{-1}$ unless considering carbon monoxide, ethene or ethyne. In practice a value of 3 kJg^{-1} is good enough for making estimates.

In a fire it is usually more important to know the rate at which heat is released rather than the total heat released. For a fire in an enclosed space, the HRR can be estimated if the inflow of air is known. Assuming that all the oxygen is consumed in the enclosure the HRR is given by:

$$\dot{q}_c = \dot{m}_{air} \Delta H_{c,air} \quad [2.8]$$

The temperatures achieved depend on the rate of heat release of the fire and the rate of heat loss from the vicinity of the reacting system.

2.3 Heat transfer

When considering fires in tunnels and other enclosed spaces, it is necessary to consider how the heat from the fire is (or isn't) dissipated. A basic understanding of heat transfer is therefore necessary before trying to predict the behaviour of any fire in an enclosed space. There are three basic mechanisms of heat transfer; conduction, convection and radiation.

2.3.1 Conduction

Conduction determines the rate of heat flow through solids. It also occurs in fluids but is usually dominated by convective processes. Generally heat flows from a region of high temperature to one of lower temperature; this can be expressed as a heat flux:

$$\dot{q}_x'' = -k \frac{\Delta T}{\Delta x} \quad [2.9]$$

where ΔT is the temperature difference over distance Δx . In differential form this is:

$$\dot{q}_x'' = -k \frac{dT}{dx} \quad [2.10]$$

where $\dot{q}_x' = \frac{dq_x}{dt} / A$, A being the area through which the heat is being transferred (perpendicular to the x direction). This is Fourier's Law of Heat Conduction. The constant k is the thermal conductivity of the material and generally is expressed in units of $\text{Wm}^{-1}\text{K}^{-1}$. Tables of k (as a function of T) are available for many pure materials (e.g. in Kaye & Laby [34]) but values of k for building materials and many other combustible solids are not as easy to find.

2.3.2 Convection

Convection is the mode of heat transfer to or from a solid involving movement of a surrounding fluid. The empirical relationship first discussed by Newton is:

$$\dot{q}'' = h\Delta T \quad \text{Wm}^{-2} \quad [2.11]$$

where h is known as the convective heat transfer coefficient. h is not a material constant, it depends on the characteristics of the system, the geometry of the solid and the properties of the fluid, it is also a function of ΔT . Typically h values lie in the range $5\text{-}25 \text{ Wm}^{-2}\text{K}^{-1}$ for free convection and up to 500 for forced convection in air.

2.3.3 Radiation

Unlike conduction and convection, radiation does not require any substance between the source of the heat and the receiver. Heat is transmitted by means of electromagnetic waves. Radiation is the dominant mode of heat transfer for fires involving fuel beds larger than about 0.3m in diameter. According to the Stefan-Boltzmann equation, the

total energy emitted by a body is proportional to the fourth power of its temperature (in Kelvin):

$$E = \dot{a}\sigma T^4 \text{ Wm}^{-2} \quad [2.12]$$

where \dot{a} is the emissivity of the surface (its efficiency as a radiator – a perfect “black body” radiator has an emissivity value of one) and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$).

The electromagnetic waves that transfer radiative heat range from wavelengths of 0.4 to 100 μm (from visible light to the far infra-red). As a body is heated and its temperature rises it will lose heat partly by convection (which dominates at low temperatures: 150-200°C) and also by radiation (dominant above ~400°C). At ~550°C sufficient visible radiation is emitted from a body to give a dull red glow. As the temperature increases, the body will change to emitting cherry red light (~900°C), orange light (~1100°C) or white light (~1400°C). An ideal black body radiator will exhibit a smooth distribution curve of emissive power, $E_{b\check{\epsilon}} = f(\check{\epsilon})$, whereas a real body will exhibit an irregular variation of emissive power with wavelength. It is useful to introduce the concept of a “grey body” (or an “ideal, non-black” body) for which \dot{a} is independent of wavelength. This is an approximation, but it allows the use of the Stefan-Boltzmann equation [2.12].

The Stefan-Boltzmann equation [2.12] gives the total heat flux emitted by a surface. In order to calculate the radiant intensity at a point distant from the radiator an appropriate “configuration factor” f needs to be determined (taking into account the geometrical relationship between the emitter and the receiver). This may be expressed as:

$$\dot{q}'' = \phi \epsilon \sigma T^4 \quad [2.13]$$

Equation [2.13] can be used, for example, to determine whether or not remote ignition of a second object near to a radiating body will occur.

In a tunnel fire radiating objects will include the fire object itself, the walls & ceiling of the tunnel (once they have been heated up by the fire), the flame and the hot smoke produced by the fire. For fires larger than about 1m in diameter, the flame and smoke

produced by the fire may be considered to behave like a black or grey body (for smaller fires, the emission of the flame and plume may be dominated by the emission spectra of the carbon dioxide and water vapour in it). The emissive power of the flame depends on the concentration of soot particles in it. A useful measure of this can be found by determining the “smoke point” of the flame (the minimum height of the flame at which smoke is produced). The height of the smoke point has been found to vary inversely with the amount of the heat of combustion lost through radiation from the flame [35]. Soot production (and therefore smoke point and the radiation from the flame) depends on the chemical nature of the fuel as well as geometrical and ventilation conditions.

2.4 Fire plumes

In gas-burner flames, the momentum of the fuel vapour determines the behaviour of the flame. Flames associated with the burning of solid and liquid fire objects on the other hand are dominated by buoyancy. The momentum of the burning volatiles is relatively unimportant. The relative importance of momentum and buoyancy in the flame will determine the type of fire and as a useful means of classification, the *Froude number* is used:

$$Fr = \frac{U^2}{gL} \quad [2.14]$$

where U is the velocity of the fuel gases, L is a characteristic dimension of the system (e.g. the diameter of the fire object or the height of the tunnel) and g is the acceleration due to gravity. In many fires it is impossible to directly measure the velocity of the fuel gases, but it is possible to derive U from the heat release rate of the fire:

$$U = \frac{\dot{q}}{\Delta H_c \sqrt{\rho L^2/4}} \quad [2.15]$$

(assuming a circular fire pool of diameter L , fuel density \tilde{n} and heat of combustion of the fuel vapour $\ddot{A}H_c$). Comparing [2.14] and [2.15] it can be seen that the Froude number is proportional to \dot{q}^2/L^5 , a scaling criterion that will be discussed later.

The behaviour of the flame and the plume from a fire is dependent on the air entrained into it, thus it may be significantly affected by the proximity of the fire to walls or a ceiling which may restrict this entrainment. As the temperature profile in the fire plume is dependent on the amount of air entrained into it, if a fire is close to a wall or in the corner of a room the temperature will decrease less rapidly with height than would result from a similar fire in the open, due to reduced entrainment. It has been stated that the temperature profile above a fire next to a wall is best modelled by imagining that the real fire has a virtual reflection beyond the wall and calculating the temperature profile from the combined real-virtual fire source. However, the flame height of a fire next to a wall is similar to the flame height of a similar unconfined fire even though the air entrainment is reduced by about 40% [36]. A fire in a corner will exhibit a flame height about 20% higher than a similar unconfined fire. If the air is entrained into the plume asymmetrically (due to the proximity to a wall) the plume will be directed towards the wall (or corner) by the directional momentum of the airflow. In other words, the plume will tend to “hug” the wall. This effect will tend to encourage fire spread up vertical or sloping flammable surfaces as well as encouraging fire spread from burning items to adjacent vertical surfaces.

This effect was in part responsible for the rapid growth and severity of the fire that claimed the lives of 31 people in the underground station at Kings Cross in London on the 18th of November 1987. On that occasion, a fire involving the steps and sides of a wooden escalator did not behave in the manner that anyone (including several of the fire experts involved in the enquiry) would have expected: the flames and plume from the fire did not rise from the fire location toward the ceiling of the escalator tube, but rather they tended to hug the steps and sides of the escalator all the way up and into the ticket hall at the top of the escalator. This was because, due to the geometry of the situation, there was virtually no air entrained into the fire from up the escalator slope or from the sides; all the airflow directed towards the fire came up the escalator from the platforms below, this has become known as the “trench effect”. As the escalator seems to have been pre-heated by a fire involving the grease and detritus under the escalator track, the upper steps and sides of the escalator were easily ignited by the flames hugging them and so the fire grew from a seemingly small blaze to a deadly ‘flashover’ in a matter of minutes [37].

(‘Flashover’ is the term used for the rapid transition in a compartment fire from localised burning to generalised burning. That is, after flashover all combustible surfaces in a compartment will be involved in the fire. It is generally held that survival is not possible in a post-flashover compartment fire.)

If a ceiling obstructs the upward flow of the fire plume, the hot gases will be deflected as a horizontal *ceiling jet*, defined as “the relatively rapid gas flow in a shallow layer beneath the ceiling surface which is driven by the buoyancy of the hot combustion products” [38]. This ceiling jet spreads radially from the point of impingement on the ceiling. For flat ceilings in large rooms (if the fire is not close to any of the walls) the maximum temperature in the ceiling jet is to be found very close to the ceiling (approximately 1% of the room height away from the ceiling) with a rapid reduction in temperature away from the ceiling (ambient temperatures being reached approximately 12% of the room height away from the ceiling) [39]. These results are only valid if the horizontal flow of the ceiling jet is unconfined and a static layer of hot gases does not accumulate under the ceiling. The rate of air entrainment into the ceiling jet is lower than the rate of entrainment into a vertical plume. In the vertical plume the entrainment is proportional to $H^{-5/3}$ (where H is the height above the fire location), whereas in the ceiling jet the entrainment is proportional to $r^{-2/3}$ (where r is the radial distance from the point of impingement). This entrainment is controlled by the *Richardson number*:

$$Ri = \frac{g(\rho_0 - \rho_{layer})h}{\rho_{layer} V^2} \quad [2.16]$$

where $\tilde{\rho}_{layer}$ and h are the density & depth of the layer and V is its velocity relative to the layer below [40]. Mixing of the hot and ambient layers is suppressed at high values of Ri . If the fire below the ceiling is also beside a wall or in a corner, the temperature will be greater due to the restricted entrainment and the restricted flow across the ceiling.

If a flame is of sufficient height (or if a ceiling is sufficiently low) for the flame itself to impinge upon the ceiling, the part of the flame that is deflected horizontally will become part of the ceiling jet. If only the upper part of a flame is deflected, it may be considered to be “fuel-lean” (i.e. the flow of burning gas contains excess air) and the reduced entrainment across the ceiling may be of little consequence. In these circumstances the total flame length (height to ceiling plus horizontal extent) will

probably be less than the total flame height from a similar unconfined fire. However, if the flame is fuel rich considerable flame extension can occur across the ceiling. The greatest extension to flame length will occur in a tunnel or corridor-like configuration, this will be further increased if the ceiling surface is combustible [41].

Airflow near the fire plume (e.g. wind or forced ventilation) will deflect the flame and the plume of the fire. The extent of the deflection will depend on the air velocity. A ‘rule of thumb’ that is commonly used is that a 2ms^{-1} wind will tend to bend a flame in the open by 45° and will cause the flame to hug the ground for $\sim 1/2L$ (where L is the diameter of the fire) downwind of the fire source [42]. The deflection of the flame and plume of a fire in a tunnel is much larger than the deflection observed for a fire, subject to a similar airflow, in the open air. The angle of deflection in a tunnel has been shown to vary with V/U_o , where V is the longitudinal ventilation velocity in the tunnel and U_o is the “centreline upward velocity in a calm open space”, that is the upward velocity of a similar fire plume in the open air. Investigations into this relationship are ongoing [43,44].

2.5 Types of fires

Although many different types of substance will burn, only liquid pool fires and solid objects will be considered in this discourse. Gaseous burning and the combustion of liquid droplets & solid dusts are not common in tunnel fires and are therefore outwith the scope of this thesis.

2.5.1 Liquid pool fires

Liquids tend to burn as “pools” with uniform horizontal surfaces (although “running liquid fires” have also been observed on non-horizontal surfaces or where a leak of fuel produces a flow, but these will not be considered here). Pool fires have been studied extensively in many ways over many years. Reviews of some comprehensive experimental test series are given by Hall [45] and by Drysdale [27]. They show that the burning rate of a pool fire (expressed in the earliest experiments as a “regression rate” R measured in mm/min) varies with the diameter of the pool for pools less than about 1m in diameter. At very small diameters (less than about 3cm), the flames are laminar and the rate of burning decreases as the diameter is increased. For pools with a

diameter larger than 1m, the flames are turbulent and the burning rate becomes independent of pool size. For intermediate sized pools “transitional” flame behaviour, between laminar and turbulent, is observed.

The burning rate (mass loss), and hence the heat release rate, of a pool fire is dependent on the heat transfer from the flames to the liquid fuel, as described by equation [2.1]:

$$\dot{m}'' = \frac{\dot{q}_s'' - \dot{q}_L''}{L_V} \text{ gm}^{-2}\text{s}^{-1}$$

Here, \dot{q}_s'' is the heat flux from the flame (and other heat sources) to the fuel and \dot{q}_L'' is the loss of heat to the pool rim (or walls), etc. L_V is the latent heat of evaporation of the fuel.

The different burning regimes for different sizes of pool can be explained in terms of the different mechanisms of heat transfer; in small pools the dominant heat transfer mechanism is conduction (through the pool rim), in large fires radiation dominates (the influence of the pool rim is not significant). Convection currents within the pool are also important heat transfer processes. In particularly narrow or shallow pools, the convective processes tend to be suppressed, which leads to a reduction in heat loss from the surface and hence an increased mass loss rate. For this reason, pool fires often exhibit a brief HRR peak as they near extinction.

In this thesis, few very small pool fires will be considered. Most of the pool fires discussed herein will be ‘large’ in diameter and turbulent in nature. Hence the most important factor in their burning behaviour is the radiation to the surface from the flames and the hot gas layer (which may accumulate below the ceiling in compartment or tunnel fires).

A simplified graph of (steady) burning rate vs. pool diameter is shown in Figure 2.01.

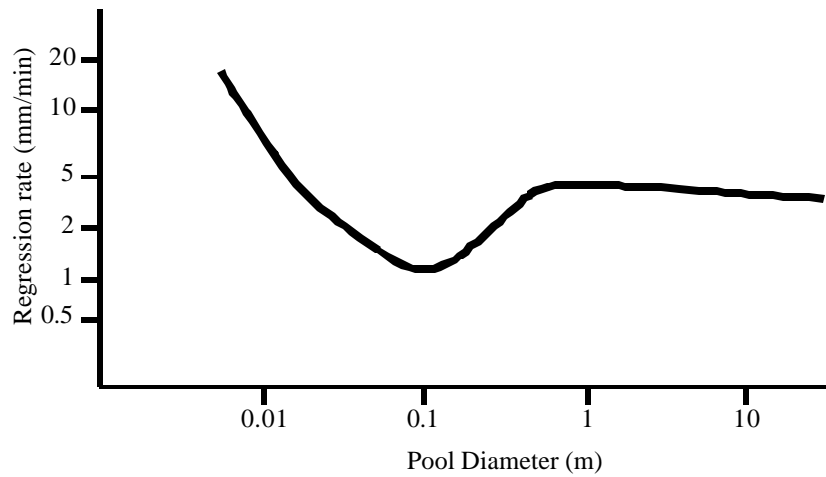


Figure 2.01 – Burning rate vs. pool diameter for a liquid pool fire

Zabetakis & Burgess [46] proposed that it was possible to predict the burning rate of pool fires (greater than 0.2m in diameter) using this equation:

$$\dot{m} = \dot{m}_{\infty} \left(1 - e^{-k\hat{a}D} \right) \quad [2.17]$$

where \dot{m}_{∞} is the limiting burning rate, k and \hat{a} are the extinction coefficient and the “mean beam length corrector” (which are constants for each type of fuel) and D is the pool diameter. Babrauskas [47] published \dot{m}_{∞} and $k\hat{a}$ data for a number of common liquid fuels. Some of these data are given in Table 2.1. The low values of \dot{m}_{∞} for methanol and ethanol are partly due to high values of L_v (the latent heat of vaporisation) and largely due to the lower emissivity of the flames from these fuels [48].

Using equations [2.2] & [2.17] and the data from Table 2.1 it is possible to estimate the heat release rate of a pool fire (larger than 0.2m in diameter) in the open air.

The rate of flame spread across the surface of a liquid fuel is dependent on the surface tension of the liquid [49] and this is in turn dependent on the temperature of the fuel itself. The rate of spread is also influenced by convection within the liquid, so flame spread across shallow pools tends to be slower than across deep pools due to the restriction of the convection currents [50]. However, the rate of flame spread across fuel pools is not of direct relevance in this study as, in most cases, the pool will be fully

involved within a matter of seconds. This thesis will only be concerned with fully established pool fires.

<i>Liquid fuel</i>	<i>Density (kgm^{-3})</i>	<i>\dot{m}_{∞} ($kgm^{-2}s^{-1}$)</i>	<i>$k\hat{a}$ (m^{-1})</i>
Liquid methane	415	0.078	1.1
Methanol	796	0.017	n/a
Ethanol	794	0.015	n/a
Heptane	675	0.101	1.1
Petrol	740	0.055	2.1
Kerosene	820	0.039	3.5
Crude oil	830-880	0.022-0.045	2.8

Table 2.1 – Data for calculating the burning rate of large pool fires from Babrauskas [47].

2.5.2 *Solid objects*

As noted at the start of the chapter, the burning of solid materials almost always requires the pyrolysis of the solid to give volatile fuel gases that leave the surface and burn in the flame. As this thesis is largely concerned with the macroscopic behaviour of solid objects on fire, the chemical reactions involved in this process will not be considered here. The macroscopic behaviour of a solid, say a sample of wooden sticks, may be determined using some form of calorimeter (e.g. the cone calorimeter, see [27]) and this sort of testing is usually sufficient to define the material properties without a detailed investigation of the chemical processes involved. While there are many forms of combustible solids, only synthetic polymers and wood will be considered here. The burning of wooden ‘cribs’ will be of importance later in this thesis and the burning behaviour of synthetic polymers is important when considering vehicle fires.

2.5.3 *Polymeric solids*

Unlike liquids, solids do not necessarily burn as a pool (although thermoplastics will tend to melt and form a pool); they may burn in any orientation. Generally, the heat required to produce volatiles, L_v (the “heat of gasification”), is much higher for solids than for liquids as chemical decomposition is involved. This means the surface

temperature of burning solids tends to be high ($>350^{\circ}\text{C}$) and this temperature may be further increased if the solid forms a char on burning. Charring on the surface of a fuel tends to hinder heat transfer into the solid and shields the unburned fuel from the flame.

In equation [2.2] a combustion efficiency factor, \div , was included to account for incomplete combustion of the fuel. Tewarson [51] suggests that \div may vary from 0.7 to 0.4 for solid polymeric substances, decreasing in the following order:

- Aliphatic (organic compounds composed primarily of carbon chains)
- Aliphatic/Aromatic
- Aromatic (organic compounds containing benzenoid rings)
- Highly halogenated species (often used as fire retardants)

Rasbash [52] observed that the heat release rate of a burning material is strongly dependent on the “combustibility ratio”, $\dot{A}H_c/L_v$. For solids this may vary from a value as low as about 3 (Red oak has a value of 2.96) to about 30 (for a rigid polystyrene foam with a value of 30.02), whereas liquid fuels tend to have combustibility ratios with higher values (heptane, for example, has a value of 92.83).

For vertical burning surfaces, the interaction between the surface and the flame is obviously very different to the interaction between a horizontal burning surface and the flame. The flame will cling to the surface so air is entrained from one side only. Orloff *et al.* [53] studied flame behaviour on thick vertical slabs of polymethylmethacrylate (PMMA) and observed that the emissive power of the flame increases with height and that the flame is laminar at its lower edge but quickly becomes turbulent with height as the volatiles from further up the surface mix with the plume. This behaviour is assumed to apply to other surfaces as well as PMMA [27]. Of course many polymeric surfaces will melt and flow and tend to form a pool at the base, this combination of horizontal and vertical burning will tend to produce vigorous burning which will create special problems in confined spaces. Downward facing horizontal surfaces tend not to burn in isolation and in situations where flames from other fire sources impinge on a combustible ceiling, the effect is only to extend the horizontal extent of the flames under the ceiling [41]. In “real life” the isolated burning of a single flat surface is a rare occurrence, fires will generally involve objects with multiple surfaces and cross-

radiation from surface to surface and localised build-ups of heat will greatly affect the rate of burning and rate of fire spread.

2.5.4 Wood

As the majority of “real life” fires in tunnels involve vehicles and liquid pools, this thesis will not go into great detail about the processes involved in the burning of wood. However, as several of the experimental tunnel fires that will be considered later involved the use of wooden “cribs” it is necessary to describe some of the burning properties of wood.

Two of the most important burning characteristics of wood are that it is non-isotropic and that it forms a char on burning. The non-isotropic nature means that its burning properties vary with the direction that the measurements are made. The production of a char means that the volatiles produced in burning are different at different stages of burning. Browne & Brenden [54] discovered that $\dot{A}H_c$ of the volatiles from Ponderosa pine was 11.0 kJg^{-1} at 10% weight loss of the wood but this increased to 14.2 kJg^{-1} at 60% weight loss.

For the purposes of this thesis, the burning of wooden cribs is the most important characteristic. A wooden crib is a pile of wooden sticks (generally square in cross-section) arranged in layers with the sticks in each layer being perpendicular to the sticks in the previous layer, see Figure 2.02. Cribs may be defined by the number of layers (N), the stick thickness (b) and the separation of the sticks in each layer (s). The length of the sticks is also of importance, but in all the early wooden crib tests the sticks used were ten times longer than they were thick [55,56], so this dimension is frequently assumed. Gross [55] observed two different burning regimes, which he described as “under-ventilated” and “well-ventilated”. In the former regime (corresponding to densely packed cribs) the rate of burning is dependent on the ratio A_v/A_s , where A_v is the open area of the vertical shafts (see Figure 2.02) and A_s is the total exposed surface area of the sticks. Gross defined the “porosity factor” of a wooden crib as follows:

$$\Phi = N^{0.5} b^{1.1} \left(\frac{A_v}{A_s} \right) \quad [2.18]$$

Gross compared this factor with the rate of burning (scaled with stick thickness) expressed as $Rb^{1.6}$, where R is the rate of burning expressed as a percentage per second. He found that $\ddot{O} \propto Rb^{1.6}$ when $\ddot{O} < 0.08$ (under-ventilated) and $Rb^{1.6}$ is approximately constant when $\ddot{O} > 0.1$ (well-ventilated). When $\ddot{O} > 0.4$ sustained burning is not possible. \ddot{O} is directly proportional to \dot{m}_{ac}/\dot{m} , where \dot{m}_{ac} is the mass flowrate of air through the vertical shafts and \dot{m} is the total rate of production of the volatiles.

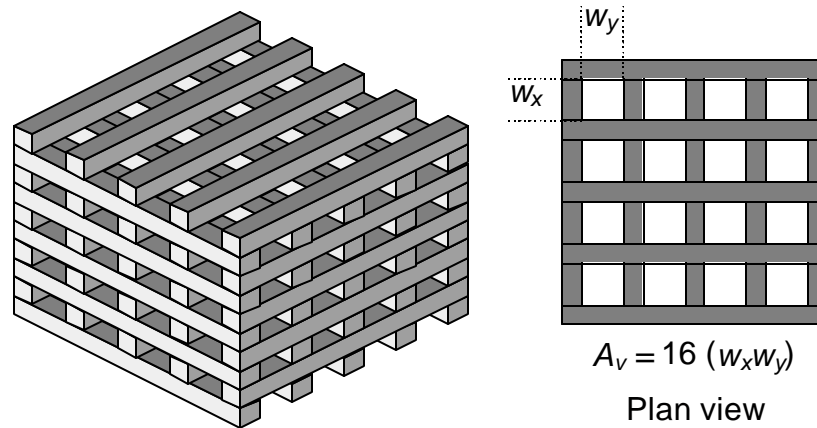


Figure 2.02 – A typical wooden crib.

2.5.5 Fire spread over solids

Unlike pools of liquid fuel, the rate of spread across (and through) solid objects will be considered in this study. While the timescale of a pool fire reaching full involvement is very short compared to the duration of the fire, this is not the case for fires involving solid objects, cars, cribs and HGVs. It is of interest (and indeed of importance) to investigate the effect of different ventilation scenarios on the rate of fire spread on vehicles etc.

In general, flame spread is most rapid when it is going up a vertical surface. Hirano *et al.* [57] found that the rate of fire spread down cardboard surfaces was approximately 0.0013ms^{-1} irrespective of the downward slope at angles greater than 30° below horizontal. They also found that the rate of spread increased rapidly as the downward angle was decreased from 30° to 0° (horizontal). Magee & McAlevy [59] carried out a similar study with upward slopes and found that the flame spread increased from 0.0036ms^{-1} at 0° to 0.0112ms^{-1} at 45° to over 0.046ms^{-1} at 90° (i.e. vertically upwards).

The principal reason for the vast difference in rate of spread is due to the entrainment of air into the flame; for downward and horizontal spread the air is entrained into the flame from the opposite direction to the flame spread (this is known as “counter-current spread”), so it tends to reduce the rate of spread. For upward flame spread the buoyancy of the flame generates “concurrent spread” which accelerates the rate of spread. The upward flame spread in the experiments using card is also influenced by the flow of hot gases on the underside of the card, this does not happen on thicker solid objects. In these instances the rate of fire spread up a combustible slope is not significantly enhanced until the slope is more than 15-20° [59]. Upward flame spread is also significantly enhanced if air entrainment from the side is restricted, as demonstrated by the fatal fire in the Kings Cross Underground station in 1987 [37] and subsequent modelling of the phenomenon [60]. The geometry of the object also influences fire spread over solid objects; fire spreads faster up a wide object than it does up a narrow object and also spreads faster along the edge of an object than it does across its surface [59].

Other factors that influence the rate of fire spread include the composition of the atmosphere (higher oxygen content causes faster flame spread), the temperature of the fuel (hotter surface causes faster flame spread), external heat fluxes (greater incident heat flux causes faster spread) and atmospheric pressure (higher pressure causes faster spread).

An imposed air movement (i.e. wind or a forced longitudinal airflow) will also have a significant effect on the burning rate. In general confluent air movement will enhance the rate of spread over a combustible surface. Freidman [61] observed that the rate of spread appears to increase exponentially up to a critical level at which extinction (or “blow-off”) will occur, but this phenomenon has not been adequately investigated. It is supposed that this occurs because the airflow tends to push the flame forward, towards the unburned surface, and thus the unburned fuel will be pre-heated to a greater degree. The wind may also enhance the burning behind the flame front which will also increase the pre-heating of the unburned fuel. Counter-current airflow may also cause an increase in flame spread; Magee & McAlevy [58] observed that imposed airflow enhanced the (counter-current) rate of flame spread on horizontal PMMA slabs at airflow velocities up to about 4-5ms⁻¹ while higher airflows reduced the rate of spread and ultimately extinguished the flame. Counter-current airflow will have two main

effects, (i) enhancing mixing (and therefore combustion) at the flame front, and (ii) cooling the unburned surface ahead of the flame. Clearly effect (i) dominates at low airflow velocities and effect (ii) dominates at higher airflow velocities.

The influence of airflow on fire spread will be considered further in Chapters 4 - 6.

2.5.6 *Vehicles*

The burning characteristics of vehicles are not easy to define, this is because vehicles are a combination of substances in complex geometrical relationships to each other. Mangs & Keski-Rahkonen [62] have studied the burning characteristics of passenger cars in the open. Their main observations are summarised as follows:

- Maximum heat release rate of a passenger car (in the open air) is ~1.5-2.0MW.
- HRR vs. time graphs exhibit several sharp peaks corresponding to the fire involving different parts of the car (e.g. engine, passenger compartment, petrol tank).
- A fire initially in the engine will spread to the passenger compartment in about 4-5 minutes.
- A fire initially in the passenger compartment will spread to the engine in about 11-12 minutes.
- The temperature inside the passenger compartment rises to post-flashover room fire temperatures.
- The temperature outside the car has short peaks of very high temperature (600-800°C) but is generally about 200-400°C.
- The radiation from a burning passenger car is sufficient to ignite a second passenger car nearby “at least if the window in the adjacent car is open”.
- The burning time of a car is about 40-60 minutes and the car continues to radiate heat for several hours afterwards (~50kW after four hours).

To date no studies of HGV fire behaviour in the open air have been carried out. Only one HGV fire test has been carried out in a tunnel and that will be described below, and more fully in Chapter 5 & appendix A. Other vehicle types including railway carriages and subway cars have been fire tested in a tunnel as part of the EUREKA test series, these will be described below.

2.6 Experimental research into tunnel fires

Up until the 1960s, fire research in tunnels had been largely concerned with fire safety in mine tunnels, so the main fire loads that had been considered were coal (on the coal face, in sacks, coal dust explosions etc.), wooden structures (e.g. wooden scaffolding supporting a mine tunnel ceiling) and conveyor belts (seemingly the source of several fires in mines). The consequences of vehicle fires had never really been considered. In the early 1960s many transport tunnels were being constructed, particularly in the Alps, so in order to better understand what might happen if there was a fire, experimental testing of fires in vehicle tunnels began.

2.6.1 *The Ofenegg tunnel fire experiments, 1965*

The primary tunnel fire safety concern in Switzerland in the early 1960s was what would happen if there was an accident involving a fuel tanker in one of their new road tunnels. To address this question, a series of fire tests were carried out in an abandoned railway tunnel, near Ofenegg, Switzerland in 1965 [63]. The tunnel was converted to allow for the testing of natural, longitudinal and semi-transverse ventilation systems by building a duct along one side of the tunnel. One end of the tunnel was blocked so semi-transverse ventilation ($25\text{m}^3\text{s}^{-1}\text{m}^{-1}$)^F could be simulated by having vents at 5m intervals along the length of the duct and longitudinal ventilation (1.7ms^{-1}) could be simulated by sealing these vents and having an opening between the duct and the main tunnel near to the blocked end of the tunnel. Three different sized pools of “aircraft quality petrol” were used in the tests, 6.6m^2 , 47.5m^2 and 95m^2 (containing 100l, 500l and 1000l of fuel respectively), each pool filled the width of the tunnel (3.8m). Data recorded included: visibility measurements, air temperatures, CO and O₂ concentrations, air velocities and pieces of hair, meat and wood were hung at various points along the tunnel to determine the effect of the heat from the fires. In all, 12 tests were carried out, the main observations being:

^F The units $\text{m}^3\text{s}^{-1}\text{m}^{-1}$ may seem slightly odd, but this is common when describing tunnel ventilation systems. A volumetric flow of air is supplied at periodic intervals along the length of the tunnel, so units of volumetric flow per metre of tunnel are used.

- Natural and semi-transversely ventilated fires burn slower than equivalent fires in the open air, due to oxygen depletion. This effect is greater with larger fires.
- Longitudinal ventilation can cause an increase in burning rate (compared to other fires in tunnels, not compared to burning in the open air).
- The velocity and thickness of the smoke layer is larger for larger fires (up to 11ms^{-1} and 4m for semi-transverse ventilation).
- Longitudinal ventilation can cause the smoke layer to fill the whole tunnel (loss of stratification).
- Maximum temperatures are achieved within 1-2 minutes from ignition.
- Survival is not possible within 30-40m of a large pool fire (with any ventilation configuration) and the chances of survival downstream of the fire are substantially reduced with longitudinal ventilation.
- Sprinklers can extinguish the fire but fuel vapours will remain and may re-ignite with devastating effects (airflow over 30ms^{-1} and damage to the tunnel structure).

A description of the tunnel and some of the experiments is given in Appendix A.

2.6.2 *The West Meon tunnel fire experiments*

In the early 70s some fire tests were carried out by the Fire Research Station (FRS – now “Fire & Risk Sciences”) in a disused railway tunnel near West Meon, Hampshire [64]. The tunnel was 480m long, 8m wide and 6m high. Few details of the tests are reported in the literature except that a number of cars were burned and the natural ventilation was a wind of about 2ms^{-1} . The main findings were:

- The smoke layer from the fire was up to 3m thick (i.e. the air was breathable at head height).
- “Observers were able to remain near the fire without any ill effects except headaches afterwards.”

2.6.3 *The Glasgow tunnel fire experiments, 1970*

Five fires were carried out in a 620m long, 7.6m wide, 5.2m high disused railway tunnel in Glasgow [65]. The fire load in each case was made up of 1, 2 or 4 trays of kerosene fuel, each tray ($1.2 \times 1.2\text{m}$) having an approximate thermal output of 2MW. Smoke

movements were recorded as were some temperature measurements. The main findings were:

- The smoke layer in most tests started out as being 1-2m thick but thickened with time. For the largest fire, the smoke layer reached a thickness of 3-4m after 10 minutes.
- The smoke layer advanced at about $1-1.5\text{ms}^{-1}$.
- A “plug” of smoke was formed at the end of the tunnel as it encountered the crosswind outside. This filled the entire height of the tunnel and tended to be drawn back into the tunnel by the fire-induced airflow.
- The air below the main smoke layer did not remain smoke free – some mixing occurred shortly after the fire started.

2.6.4 The Zwenberg tunnel fire experiments, 1976

In the early 1970s, the Austrian road network was being improved, and this involved the construction of many road tunnels between 5 and 13km long. As the Austrian authorities had no experience of fires in tunnels, they carried out 30 fire tests (25 of a 6.8m^2 petrol pool, 3 of a 13.6m^2 petrol pool, one of a 6.8m^2 diesel pool and one test with a mixed load of wood, car tyres and sawdust) in a 390m long abandoned railway tunnel in order to gain a better understanding of them [66]. This tunnel was modified in order to simulate natural, longitudinal, transverse and semi-transverse ventilation systems. The main findings were:

- Temperatures at the ceiling were very high (sometimes over 1200°C).
- “Higher” longitudinal air velocities destroyed thermal layering (stratification).
- With transverse ventilation, fans in the fire section should be set to maximum exhaust, while the power of fans supplying fresh air should be reduced by 20-30% to maintain stratification.
- The position of supply vents (above or below) is not crucial.
- For the smaller fires it was possible to extract all the plume gases over a tunnel length of approximately 260m with maximum extraction and minimum supply of fresh air.
- The tunnel lining and intermediate ceiling were not destroyed by the fires.

2.6.5 PWRI tunnel fire experiments, 1980

The Japanese Public Works Research Institute (PWRI) carried out 16 full scale fire tests in a 700m long fire gallery and 8 full scale fire tests in a 3.3km road tunnel. Fire loads tested included twelve petrol pools (10 tests using 4m² pools and 2 with 6m² pools), six passenger cars and six buses (one vehicle per test). The conditions (temperature, gas concentrations, smoke, etc.) in the gallery / tunnel were monitored during tests with natural and longitudinal ventilation [67]. The main observations were:

- Stratification of smoke was partially destroyed by longitudinal ventilation at 1ms⁻¹ and totally destroyed by longitudinal ventilation at 2ms⁻¹.
- The “heat generation speed” (heat release rate) of a fire increased at higher longitudinal ventilation velocities; for a petrol pool fire the HRR was 4MW at 1-2ms⁻¹ and 6MW at 4ms⁻¹. This effect is “more evident” for car fires.
- The temperature rise in the tunnel was significant only near to the fire source.
- None of the car, bus or pool fires were totally extinguished by the sprinklers, but the “heat generation speed” was reduced in each case.
- The sprinklers had an “adverse effect on the environment” by causing a reduction in smoke density near the ceiling and an increase in smoke density in the lower part of the tunnel.

2.6.6 Tunnel fire tests at VTT, 1985

As a precursor to the EUREKA project (see below), two “pilot” fire tests of wooden cribs were carried out in a “small” tunnel in Lappeenranta, south-eastern Finland [68]. The purpose of the tests was to investigate the effect of the fires on the tunnel lining and also to investigate fire spread across and between objects. The tunnel is 183m long, between 5.5 & 6.1m wide and between 4.3 & 5.0m high, ventilation was forced by two fans at one end of the tunnel. The main observations were:

- In test one (which involved a “mock-up” of a subway train – wooden cribs totalling 3.2m wide by 48.0m long) a constant rate of fire spread (6.6×10^{-4} ms⁻¹, ~1.8MW) was established after a brief ignition phase.

- In test two (which involved a line of eight “mock-ups” of passenger cars – wooden cribs $1.6 \times 1.6 \times 0.8\text{m}$ high, spaced 1.6m apart) no spread was observed between cribs.
- Identical cribs at opposing ends of the line (in test two) exhibited very different burning characteristics – the crib at the windward end of the line burned with almost twice the HRR of one at the other end.
- Since experiments of this scale are never fully reproducible, more than one experiment is needed to make far reaching conclusions of vehicle fires [69].
- Considerable spalling of rock takes place during fires in rough rock tunnels.
- Using the theoretical models available at the time, both tests were expected to reach flashover. Neither did.

2.6.7 *The EUREKA EU-499 “Firetun” test series, 1990-1992*

The tunnel fire test series with the largest scope was undoubtedly the EUREKA “firetun” test series, carried out between 1990 and 1992 by teams of fire researchers representing Austria, Finland, France, Germany, Italy, Norway, Sweden, Switzerland and the UK [70]. The majority of the fire tests (21) were carried out in an abandoned tunnel near Hammerfest, Norway in 1992, and involved fire loads such as cars, train carriages, wooden cribs, heptane pools, a “simulated truck load” and a HGV fully laden with a cargo of furniture. Other fire tests carried out as part of the series were wooden crib fire tests in a disused railway tunnel in Germany, wooden crib fire tests at VTT in Finland (see above) and a laboratory test of samples of tunnel lining. The objectives of the project were to provide information on:

- Fire phenomena
- Escape, rescue and fire-fighting possibilities
- The effect of the surrounding structure on the fire
- Reusing the structure (damage done, time required for redevelopment, etc.)
- Accumulation of theory (improving understanding of fire, modifying models, etc.)
- Formation, distribution and precipitation of contaminants

The Hammerfest tunnel is a 2.3km long mine tunnel with an irregular cross-section (very approximately square, varying from 30-40m²). During the fire tests various data types were recorded including mass loss, temperature, gas concentrations, smoke

density, airflow velocity, etc. These were all recorded at many points, near the fire load and distant from it (except the mass loss which was measured directly by load cells under the fire location). Unfortunately not all these data types were recorded in each experiment, for example in several of the wooden crib tests and one of the car fire tests, mass loss and gas concentration data were not recorded, so it is not possible to estimate the heat release rate of these fires. Many conclusions have been drawn from this test series, including:

- The influence of damage both to the vehicles and the tunnel lining, especially in the crown area, depends on the type of vehicle. The roof of those vehicles constructed of steel resisted the heat, whereas the roofs of the vehicles made of aluminium were completely destroyed at an early stage of the fire [71,72].
- The temperatures during most of the vehicle fires reached maximum values of 800-900°C. The temperature during the HGV test reached 1300°C. Temperatures decreased substantially within a short distance from the fire location. Temperatures are greater downwind than upwind [72].
- The railway carriages burned between 15 & 20MW. The HGV burned at over 100MW [72].
- A “small fire load” such as a single railway carriage may exhibit a HRR of 45MW [73].

(NB: The above two conclusions appear to contradict one another. This is partially due to the different methods of estimating the heat release rate of a fire in a tunnel and partially due to the different “agendas” of the two references; one was comparing HGV and railway carriage fires and concluding that the HGV fire was far more severe, whilst the other was warning the reader that even a “small fire load” can give rise to a very serious fire.)

- All road and rail vehicles registered a fast development in the first 10-15 minutes [72].
- Growth rates of vehicle fires varied from “medium” to “ultra fast” (see [74]) [75].
- Modern rail cars are more resistant to ignition than older carriages (due to the composition of the internal furnishings) [72].

- In naturally ventilated fire tests of railway carriages, the smoke density and CO concentration exceeded “acceptable” limits over 300m away from the fire location [76].
- To enable fire-fighters to get to the fire location, a “sheltered route” needs to be provided (e.g. the service tunnel in the Channel Tunnel) [76].
- The maximum concentration of polycyclic aromatic hydrocarbons (PAH) and other pollutants is found about 70-80m downwind of the fire location [77].
- Fire growth and burning pattern is strongly influenced by ventilation conditions [78].
- If a container or enclosure is not well sealed the prevailing ventilation can introduce sufficient leakage air for combustion to continue at a slow rate [78].
- The rate of burning can be significantly accelerated by a free supply of air [78].
- Controlled ventilation can be useful in smoke management [78].
- Longitudinal ventilation destroys stratification downwind of the fire [78].

Further details of some of the EUREKA tunnel fire tests are given in Appendix A.

2.6.8 *The Memorial Tunnel Fire Ventilation Test Program (MTFVTP), 1993-1995*

Although the scope of the EUREKA test series was larger than any other series, in terms of the range of fuel types and objectives, the MTFVTP was the largest tunnel fire test series to date in terms of actual scale. In all, 98 pool fire tests ranging in size from ~10MW to ~100MW were carried out in a disused 850m long two-lane road tunnel near Charlestown, West Virginia, USA [13]. The tunnel was modified to allow for the testing and comparison of natural, semi-transverse, fully transverse and longitudinal ventilation systems and their ability to control / extract smoke. Extensive arrays of temperature sensors, gas analysers, airflow sensors and smoke density measuring equipment were located throughout the tunnel, so there are extensive data from each test. The experiments were carried out by the Federal Highway Administration for the Boston Central Artery Tunnel project, and the objectives of the test series were:

- To develop a comprehensive database regarding temperature and smoke movement from full-scale fire ventilation tests which would permit a definitive comparative evaluation of the capabilities of transverse and longitudinal ventilation systems to manage smoke and heat in a fire emergency.

- To determine, under full-scale fire test conditions, the relative effectiveness of various ventilation system configurations, ventilation rates, and operating modes in the management of the spread of smoke and heat for tunnel fires of varying intensities.

The influence of the different ventilation strategies on the heat release rate of the fire was not considered. A systematic series of tests each with a single (different) airflow velocity was not carried out, instead the configurations of active ventilation fans were changed several times (in some instances, many times) during a test, so changes in the behaviour of the fires due to different ventilation strategies are not clear. The fires were all carried out using diesel fuel, which produces a lot of smoke and reduces the risk of explosion, but unfortunately has not been used in many other fire experiments, so comparison with other pool fire tests (both in and out of tunnels) is not easy. The main conclusions from the test series include:

Longitudinal ventilation

- Longitudinal ventilation using jet fans is highly effective in controlling smoke spread for fires up to 100MW. However, it is appropriate only for unidirectional tunnels.
- Longitudinal air velocity is dependent on the number of active fans and the thrust, not on the configuration of the fans.
- A 10MW fire tends to reduce the longitudinal airflow by 10%, a 100MW fire reduces it by 50-60%.
- Airflow velocities of 500 to 580 fpm ($2.5\text{-}3\text{ms}^{-1}$) are sufficient to prevent backlayering of smoke from 100MW pool fires in the Memorial Tunnel.

Transverse ventilation

- It is not sufficient to supply air in a tunnel fire situation, extraction is also necessary.
- Longitudinal airflow is a major factor in smoke control for transversely ventilated tunnels.
- Multiple-zone ventilation systems are better than single-zone ventilation systems at controlling smoke.
- Single point extraction openings (SPE) and oversized exhaust ports (OEP) significantly enhance the ability of a ventilation system to control and extract smoke.

Smoke and heat movement

- The time taken for smoke to enter the “occupied zone” at positions distant from the fire location is dependent on the height and geometry of the tunnel ceiling.
- Significant reduction of visibility occurs more quickly than debilitating heat.

Further details of some of the tests are given in Appendix A.

2.6.9 Tests in operational tunnels

The majority of the tunnel fire tests described above were carried out in abandoned or disused tunnels. This has the advantage of allowing the testing of very large scale fires which may destroy the tunnel lining and fittings (e.g. the “100MW” pool fire tests in the Memorial tunnel), but the majority of these fire tests (except in the Memorial tunnel) have the disadvantage that the test tunnel was significantly smaller than most operational tunnels, especially two or three lane road tunnels. It would be particularly valuable if tunnel fire experiments could be carried out in real vehicle tunnels, but this is generally unrealistic for large scale fires. However, some small scale fires (car and pool fires) have been carried out in new and operational road tunnels, generally in order to test the capabilities of the ventilation system or as a fire-fighting exercise [79,80]. Some details of tests carried out in French road tunnels are in the public domain, these include:

Des Monts Tunnel

The tunnel is a twin tube, twin lane tunnel 850m long, it has a cross-section of about 80m², the ventilation system is longitudinal. The fire load tested in 1988 was a van, with hay bundles, tyres and petrol ignited to start the fire. Conclusions include [79]:

- The fire size was approximately 2MW (at 1.3ms⁻¹ ventilation velocity).
- Temperatures in the vicinity of the fire did not exceed 80°C.
- The temperature quickly decreased when the ventilation was started.
- Other vehicles can easily overtake a burning car.

Nogent-Sur-Marne Covered Trench

The tunnel is a twin tube, three lane tunnel 1.1km long, the ventilation system is partially transverse. Smoke tests and a car fire test were carried out in 1988/89. Conclusions include [79]:

- The smoke remained stratified with natural ventilation. With the ventilation set to exhaust, part of the tunnel was kept smoke free, but 100m from the fire location the whole tunnel was filled with smoke.
- The wind induced airflow in the tunnel dominated the exhaust ventilation in one test, the partially transverse system was unable to extract the smoke.
- When the wind induced airflow was blocked (one end of the tunnel was physically blocked) the partially transverse ventilation system was better able to remove smoke.
- An air or water curtain in the tunnel may be able to minimise wind induced airflow.

Frejus Tunnel

Many tests have been carried out in this twin lane, 13km long tunnel on the border of Italy and France, generally for training of emergency personnel and testing of ventilation & communications systems [79].

FFF Tunnel

The tunnel is a twin tube, twin lane motorway tunnel, 750m long. The ventilation system is longitudinal. In 1990, shortly before the tunnel was due to be opened, a passenger car was burned in the tunnel to test the ventilation system. Conclusions include [79]:

- Maximum fan operation results in a ventilation velocity of 8ms^{-1} , this is sufficient to prevent backlayering.
- Smoke was transferred from the tube containing the fire to the other tube. Steps were taken to prevent this in future incidents.

Monaco Branch Tunnel

The tunnel is a single tube, bi-directional, three lane tunnel, 1.5km long. The tunnel has a slope of 5.5% and the ventilation system is partially transverse. The tests were carried out in 1992 shortly before the tunnel was due to open. One wood fire test and six car fire tests were carried out, primarily to investigate the capabilities of the ventilation system. Conclusions include [80]:

- Smoke removing equipment is useful as conditions were substantially worse when it was not used.
- The ventilation system was able to control the smoke when the wind induced airflow was low, when the wind induced airflow was about $1\text{-}2\text{ms}^{-1}$ the smoke reached the tunnel portals.
- In every test one side of the fire location was always kept smoke free, this will help fire fighting activities.
- Supply of fresh air (via wall jets) causes a loss of stratification.

Grand Mare Tunnel, Rouen

The tunnel is a twin tube, twin lane tunnel, 1.5km long. The ventilation is longitudinal and, in the tube the tests were carried out in, opposes the natural airflow induced by the chimney effect of the sloping tunnel. Three pool fire tests were carried out, corresponding to approximate sizes of 5, 10 and 20MW. Conclusions include [80]:

- The smoke from a 20MW fire can be controlled by longitudinal ventilation (4ms^{-1}).
- The flames flattened by the airflow caused some damage to the carriageway downstream of the fire.
- The HRR of the “10MW” fire was slightly higher than expected, the HRR of the other two tests was slightly lower than expected.

The overall lessons learned from all these fire tests include [79]:

- A car fire in a tunnel is not very big. It is possible to pass the fire location on foot or by car.
- Increased knowledge of smoke behaviour in various configurations.
- Some quantitative data on temperature and smoke movement.
- Cold smoke tests are not representative of real fires.
- Experience gained by the tunnel operators and emergency services.

2.7 Experimental testing on a smaller scale

Fire tests involving full size fires in full size tunnels are enormously expensive. The EUREKA “Firetun” test series cost about U.S.\$10,000,000 and the MTFVTP cost in excess of U.S.\$40,000,000 [26]. These high costs seriously limit the number of full size experimental tests that are possible. To date, full scale tests have not been able to answer many fundamental questions about the behaviour of fire and smoke in tunnels.

In order to be able to answer these questions at an affordable price, and sometimes to model a specific tunnel design, reduced scale and small scale experiments have been carried out.

In order for reduced or small scale experiments to be in any way useful, there must be a well defined *similarity* between the scale model and the full scale case of interest. If there is a strong similarity then a scale model can be used to investigate specific aspects of the behaviour of the fire or smoke, if the similarity is not so strong then the behaviour of the fire can only provide information in general terms. In order to scale between reality and a scale model with a strong similarity, it is necessary to consider the gas flow at and around the fire.

Earlier in the chapter the *Froude number* was used to classify fire type (see equation [2.14]):

$$Fr = \frac{U^2}{gL}$$

where U is the velocity of the gases, g is the acceleration due to gravity and L is a characteristic dimension of the system. Other non-dimensional numbers are also used to classify flow behaviour, including the *Reynolds number*:

$$Re = \frac{UL}{\nu} \quad [2.19]$$

(where ν is the viscosity), the *Richardson number*:

$$Ri = \frac{gL}{U^2} \frac{\Delta\rho}{\rho} \quad [2.20]$$

(where \tilde{n} is the density of the plume gases and $\tilde{A}\tilde{n}$ is the difference between this and the density of the surrounding air) and the *Grashof number*:

$$Gr = g \frac{L^3}{\nu^2} \frac{\Delta\rho}{\rho} \quad [2.21]$$

which is essentially a combination of the Reynolds and Richardson numbers. Ideally each of these numbers should be the same in the scale-model as in reality. In reality however, this is not possible and models are usually scaled assuming conservation of the Froude number only. This is a reasonable assumption to make for all but the smallest scale models as variations in the Reynolds number are not particularly significant for turbulent flows.

As noted earlier in the chapter, the Froude number is proportional to \dot{q}^2/L^5 , this means that, for example, a model fire which is half the scale of a full size tunnel will have a heat release rate 0.177 times that of the full scale fire ($0.5^{5/2} = 0.177$). In a similar way the ventilation velocity in the scale model scales as $L^{1/2}$, so a full scale airflow velocity of 2ms^{-1} will be modelled by a half scale airflow velocity of 1.4ms^{-1} . The temperature of the fire will be the same at test scale and full scale [81].

Reduced scale fire test series tend not to be as high profile as full scale test series and the data and results from these series are not always in the public domain. Some reduced scale test series which are relevant to this study include:

2.7.1 Pool fire tests at the Londonderry Occupational Safety Centre, Australia

A series of five kerosene pool fire tests was carried out in a 130m long, 5.4m wide by 2.4m high “mine roadway” tunnel near Londonderry, NSW, Australia [82,83]. The Longitudinal ventilation in the tunnel was maintained by two exhaust fans at one end of the tunnel, with a rectangular grid for “flow straightening” near the other end of the tunnel. Three tests were carried out using a 1m diameter pool with ventilation velocities ranging from minimal (0.5ms^{-1}) to 2ms^{-1} , tests were also carried out using 0.57 and 2m diameter pools. An extensive array of thermocouples and airflow probes was arranged around the fire and mass loss was measured by load cells under the pool tray. Two video cameras were also used to record the experiments. The experiments were carried out to test a numerical model^G. Some of the observations from the study include:

^G When experiments are carried out to test a numerical model, the process is frequently referred to as “validation”. This term has often been criticised as being misleading as

- Increasing the ventilation from 0.5 to 2.0ms^{-1} caused a 25% decrease in HRR of the 1m diameter fire.
- This was probably due to the fact that less of the plume was above the fuel surface at higher air velocities.
- The mass loss rate of larger fires was proportionately higher than that of smaller fires (subject to ventilation velocities about 0.9ms^{-1}).
- There was significant backlayering at 0.85ms^{-1} , but this was “arrested” by a 2ms^{-1} airflow.

2.7.2 *Reduced scale fire tests in the HSL test tunnel, Buxton, UK*

A series of nine fire tests involving wooden crib and kerosene pool fires contained within a “mock-up” of a Eurotunnel HGV shuttle carriage were carried out in the test tunnel at the Health & Safety Laboratory (HSL) near Buxton in 1993 [81,84]. The tunnel is 366m long and 5.6m^2 in cross-section. It is constructed of concrete and arch shaped; with a maximum height of 2.44m at the centre of the tunnel and a maximum width of 2.75m near the floor. The tunnel walls and ceiling were fireproofed in the vicinity of the fire location with mineral fibre sheeting. Longitudinal ventilation in the tunnel was supplied by up to three fans housed at one end of the tunnel. Measurements of the temperature, the airflow velocity, the smoke density, the heat flux, the gas concentrations and the mass loss of the fire load were recorded during each^H test, these data were gathered primarily for testing of computational fluid dynamics (CFD) model results (see below). The conclusions from the study include:

- The fires produced small but measurable effects on the ventilation rate.
- Many of the fires, particularly the larger ones, showed elements of ventilation control.
- Temperatures near the ceiling reached 1000°C in some tests.

the process does not actually make the model “valid”. To avoid confusion, the word “testing” will generally be used in this thesis.

^H Except test 7, due to instrument failure

- Backlayering of smoke was prevented at ventilation rates above 1.25ms^{-1} , was controlled¹ at ventilation rates between 0.75 and 1.25ms^{-1} and was not controlled at lower ventilation rates.
- There was no clear relationship between the critical velocity required to prevent backlayering and the heat output of the fire.
- The air velocity required to prevent any backlayering was less than predicted by existing theories.
- The reduced scale data can be extrapolated to tunnels of different scales using Froude scaling.

Further details of some of these tests are presented in Appendix A.

2.7.3 Test series carried out by the Swedish National Testing and Research Institute (SP)

A series of 18 fire tests were carried out in a 11m long fire gallery at SP (Sveriges Provnings) in Sweden in 1995. The gallery is 1.08m wide by 1.2m high and is equipped with extensive measuring equipment and natural or longitudinal ventilation [85]. The pool fire tests were carried out using heptane (11), methanol (2) and xylene (5) as fuels. Two sizes of square fuel pans were used; 0.09m^2 and 0.16m^2 . The tests were primarily carried out to investigate the effects of under-ventilation on the HRR of a fire. Comparable fire tests were also carried out in the open air. The following observations were made:

- Restricting the airflow caused a decrease in HRR but not a significant increase in CO production.
- Despite attempts to make the fires under-ventilated, it was not possible to do so.
- The mass burning rate (and hence the HRR) was much higher in the tunnel than in the open for heptane and xylene fuel pools.
- The mass burning rate for methanol fires was slightly lower in the tunnel than in the open air.
- Burning rate decreases with increasing wind velocity for heptane & xylene fuel pools.

¹ i.e. a *stationary* hot gas layer was formed upstream of the fire location.

- With restricted airflow, the flames (from heptane pools) tended to be deflected by about 30-45°, with unrestricted airflow the flames were deflected almost horizontally at the fuel pan and did not reach the ceiling until about 1.2m from the fire location (corresponding to approximate airflow velocities of 0.4 and 0.7ms⁻¹ respectively).

2.7.4 Test series carried out by the Swedish Defence Agency (FOA)

A series of 24 fire tests were carried out in a 100m long “blasted rock tunnel”, approximately 3m wide by 3m high. The tunnel was open to the air at one end and had a large chimney at the other. There was no mechanical ventilation system installed in the tunnel, but different ventilation rates were achieved by restricting the inflow of air in some tests and using two different fire locations within the tunnel. The experiments included fire tests of heptane pools (12), methanol pools (2), kerosene pools^J (2), polystyrene cups in cardboard boxes (2), wooden cribs (3), heptane pools contained within a dummy vehicle (2) and a car [86]. Although the tests were primarily carried out to provide experimental data for testing of CFD codes, the following conclusions were made:

- All fire tests show some correlation between the degree of ventilation and the heat release rate of the fire, this effect is more apparent for solid fire loads than for liquid pools.
- Measurements of optical density and gas concentrations indicate that there is a correlation, however a parameter of the fuel must be included.
- In a confined space the heat release rate of a small car may reach 4MW for a short time [87].

2.8 Laboratory scale experiments

In addition to these reduced scale test series, there have also been a number of laboratory scale tests of fires in “tunnels.” While the results from these tests can give some information on the behaviour of larger scale fires, the *similarity* of lab scale experiments to full scale fires is not good. Froude scaling criteria may not apply to fires

^J Occasionally incorrectly referred to in the report as “diesel” pools

in tunnels smaller than about 1m in diameter [81], and small scale pool fires may behave substantially differently from their full scale counterparts. For example, a pool of a hydrocarbon fuel will exhibit “transitional” (laminar-turbulent) flame behaviour if its diameter is less than about 1m, whereas larger pools will exhibit fully turbulent flame behaviour (see section on “pool fires” earlier in the chapter). However, these laboratory scale experiments can yield useful results and help us to understand some features of tunnel fire dynamics better. In particular, these laboratory scale models can give valuable information on smoke behaviour in tunnels at a fraction of the cost of full scale experiments. Also it is possible to observe *trends* in the behaviour of laboratory scale experimental series which may be relevant to full scale fires, even if the quantitative data are not scalable. These test series include:

2.8.1 *A scale model to investigate smoke movement in the Paris Metro (1991)*

A laboratory scale Pyrex “tunnel” 3m in length was used to investigate some aspects of smoke movement and backlayering for the Paris Metro tunnel system [88]. The apparatus was semi-circular in aspect and 30cm in diameter, the fire source was a porous burner 2cm in diameter with a variable rotameter regulating the fuel flow, the ventilation was obtained using an extraction fan at one end of the apparatus and ventilation flows of up to 25cm s^{-1} could be attained. Smoke movements were recorded using lasers, video cameras and photography. Temperatures and airflow were recorded inside the tunnel. Conclusions from the test series include:

- Some backlayering will occur in the Paris Metro tunnels in the event of a fire if the usual ventilation velocity of $\sim 1.5\text{ms}^{-1}$ is used.
- In the absence of forced ventilation (natural airflow at about $0.2\text{-}0.4\text{ms}^{-1}$) the smoke from a fire is likely to remain stratified, so a smoke-free layer will exist near to the floor.
- The behaviour of smoke entering a station from a tunnel was also modelled.

2.8.2 *A wind tunnel study to investigate the influence of ventilation on pool fires (1995)*

Many pool fire experiments were carried out in a $0.3 \times 0.3 \times 21.6\text{m}$ long wind tunnel at the Japanese fire research institute, to investigate burning rate, ceiling temperature and

backlayering in a number of different experimental configurations [89]. To investigate the influence of longitudinal ventilation on burning rate for pool fires, 31 methanol pools (of 10, 15, 20 & 25cm diameters) were tested at a range of ventilation rates from 0.08 to 1.03ms⁻¹, five pools of n-heptane (all 15cm diameter) were also tested with ventilation rates ranging from 0.43 to 1.3ms⁻¹. To investigate the phenomenon of backlayering many tests were carried out using different sizes of methanol pools, different ventilation rates and different tunnel slopes. Conclusions from this study include:

- Burning rates of liquid pools in tunnels depend on the airflow velocity.
- The burning rate of a pool fire in a tunnel is higher than the burning rate of a similar fire in the open air, the burning rate tends towards the open air burning rate as ventilation rate is increased.
- The ceiling temperature of the tunnel fire is inversely proportional to wind velocity.
- Some pool fires reach a steady rate of burning, in others the rate increases with time. The airflow velocity is the deciding factor in this.
- The relationship between critical velocity and heat output rate is almost linear.
- When backlayering is long (twenty times tunnel height) the backlayering length is only weakly dependent on the slope of the tunnel (up to 10°) or the fire size, it can be expressed by a non dimensional parameter. When backlayering is short it is dependent on both fire size and tunnel angle.

2.8.3 Critical velocity experiments in a laboratory scale model of the HSL tunnel (1997)

A series of fire tests was carried out in a 1/10 scale model of the HSL tunnel described above (section 2.7.2). The apparatus was mounted in such a way that different tunnel slopes (up to 10°) could be tested. The fire source used in the test series was a propane burner, able to produce heat release rates of 2.8-14.1kW. When scaled to “full size” dimensions of a 5m diameter tunnel this corresponds to HRRs between 5 and 30MW. Longitudinal airflow was produced using compressed air at one end of the apparatus [21]. The main conclusion from these tests was:

- The effect of slope on the critical velocity required to control smoke is modest.

The same apparatus was modified to study the influence of tunnel geometry on critical velocity [21]. Burner fire experiments were carried out in the apparatus as described, then the tunnel section was replaced with a new section of different aspect (250mm × 250mm) and the test series was repeated. Then the tunnel section was again replaced with another new section of different aspect (500mm × 250mm) and the test series was repeated. The results from the three series were compared. Conclusions include:

- The critical velocity required to control smoke varies with the mean hydraulic diameter of a tunnel (ratio of 4 times the tunnel cross-sectional area to the tunnel perimeter).
- A universal formula for critical velocity may be possible (subject to further work).

2.8.4 *A small scale model for CFD model testing (1997)*

Tests have been carried out in a lab scale “tunnel” at Turin Polytechnic University, primarily for the testing of CFD models [90]. The apparatus is modular in design so different lengths of tunnel may be tested, but the configuration described in the literature was 1.0m long, 0.1m high and 0.2m wide. The tunnel is constructed of concrete but has a ceramic-glass wall on one side for observation and recording purposes. Ventilation ducts along the top of the tunnel can simulate transverse ventilation and fans at one end can drive longitudinal ventilation as well. The fire source can be either a fuel pool or a gas burner. A naturally ventilated petrol pool fire test is presented in the literature. No conclusions are presented from the experimental work, but the advantages and limitations of the CFD model are presented.

There have been other tunnel fire test series carried out at a laboratory scale. Recently Megret *et al.* [91] described a new lab scale apparatus to study smoke control in tunnels, although no experimental results have been published to date. Other research centres are undoubtedly continuing to investigate tunnel fire phenomena at a laboratory scale, and will do so in the future. The few lab scale studies that have been presented here demonstrate the sort of conclusions that can and can't be drawn from very small scale experimental tests. Most of the small scale (and some of the larger scale) experiments have been carried out in parallel to numerical or computational studies, and it is to these computer models that we now turn.

2.9 Summary of experimental observations

While the conclusions from some of the studies described above appear to contradict the conclusions from some of the others, there are several aspects of tunnel fire behaviour which have been observed in different experimental test series. These are summarised below:

Smoke

- Fires in tunnels produce thick smoke layers which advance faster than walking speed.
- Smoke stratification is destroyed by longitudinal ventilation.
- Smoke stratification is destroyed if sprinklers are used.
- Smoke does not remain stratified even in naturally ventilated tunnels.
- There is a significant reduction in visibility before the onset of debilitating heat.

Heat release rate

- Naturally and semi-transversely ventilated (pool) fires burn slower than those in the open air.
- Burning rate is enhanced by longitudinal ventilation. This is more evident in vehicle fires.
- The burning rate of some pool fires is reduced by increased longitudinal ventilation.
- All vehicle fires exhibit a 'fast' rate of fire development.
- The heat release rate of car fires in tunnels may be significantly larger than in the open air.

Temperature

- High temperatures (often above 1000°C) are common in tunnel fires.
- High temperatures are only evident in the immediate vicinity of car fires. In most instances it is possible to pass (or get close to) a car fire.
- High temperatures may cause explosive 'spalling' of the tunnel lining.

2.10 Computational modelling of fires in tunnels

Many of the results of the fire tests described above, from laboratory scale through to full scale, have been used to build up a mathematical description of the processes involved in tunnel fires. The majority of equations presented in this chapter have been derived from empirical observations of experimental fire tests. These equations have been used over many years to try to predict some aspects of fire behaviour under certain circumstances. During the past two decades computer technology has advanced to the point where it is now possible to run a fire model which can perform millions of mathematical calculations every second and thus it is possible for exceedingly complex predictions to be made in a matter of hours using current computer models.

Even the most complex of today's computer fire models rely on assumptions about the fire and the behaviour of the fire. Fires are frequently still modelled as being merely sources of heat and smoke and many models do not predict the development or maximum size of the fire, they require these factors to be input by the user. Assumptions such as these do not mean that these models are not useful, but they do mean that the results from these models should be used with caution and that the models themselves need to be operated by users who understand the implications of the assumptions and the limitations of the models [92].

2.10.1 Computational Fluid Dynamics

The most common fire models in use today are based on the principles of computational fluid dynamics (CFD) [93]. These models generally solve equations of the form:

$$\frac{\partial}{\partial t}(r\rho\phi) + \text{div}(r\rho\vec{v}\phi - r\Gamma_{\phi}\text{grad}\phi) = rS_{\phi} \quad [2.21]$$

where r is the phase volume fraction (which cancels out throughout), $S_{\mathbf{f}}$ is the source term, \vec{v} is the velocity vector, t is time, \tilde{n} is density, \mathbf{f} is the dependent variable (for example, when calculating for temperature, T is substituted for \mathbf{f} throughout) and $\tilde{A}_{\mathbf{f}}$ is the diffusion coefficient. Essentially this equation represents:

$$\left\{ \begin{array}{l} \text{Rate of} \\ \text{increase of } \mathbf{f} \\ \text{in fluid} \\ \text{element} \end{array} \right\} + \left\{ \begin{array}{l} \text{Rate of} \\ \text{flow of } \mathbf{f} \\ \text{out of fluid} \\ \text{element} \end{array} \right\} - \left\{ \begin{array}{l} \text{Rate of} \\ \text{increase of} \\ \mathbf{f} \text{ due to} \\ \text{diffusion} \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of} \\ \text{increase of} \\ \mathbf{f} \text{ due to} \\ \text{sources} \end{array} \right\} \quad [2.21a]^K$$

These equations are solved numerically by integrating over a control volume. Generally a CFD simulation will contain thousands of control volumes^L which make up the whole volume of interest (e.g. a tunnel or an enclosure) over a control volume.

However, it should be noted that the underlying assumptions of the models remain the same, however complex the models are. In recent years there has been a trend in CFD publications not to state the assumptions put into the model at the start, only to present the results; usually in an attractive and colourful manner. Without knowledge of the assumptions, the results of the study are of little use to anybody.

An in-depth discussion of CFD is outwith the scope of this thesis, however the results of this study will hopefully be of use to CFD modellers. It is intended that the predicted relationships between longitudinal ventilation velocity & fire size and between tunnel geometry & fire size will help CFD modellers to develop more realistic sub-models of fire growth and maximum fire size for use in their tunnel fire simulations.

2.10.2 Non-CFD fire models

CFD models are not the only fire models in use today, a significant reduction in computation time can be achieved if the model considers only a small number of control volumes rather than thousands. These models may give results which appear, at first glance, to be less complex and (we might assume) therefore less reliable. They frequently will also give results which are less visually appealing (rarely rendered as three dimensional images in full colour), but this does not mean that the results are less useful. Indeed, consider the two CFD simulations shown in Figure 2.03, the pictorial rendering of the data might make the upper fire look more severe than the lower one, but this is not the case; the data in each case are exactly the same, the only difference is in the colours used to render the data. Pictorial representations of computer model data may be misleading, and should be interpreted with caution.

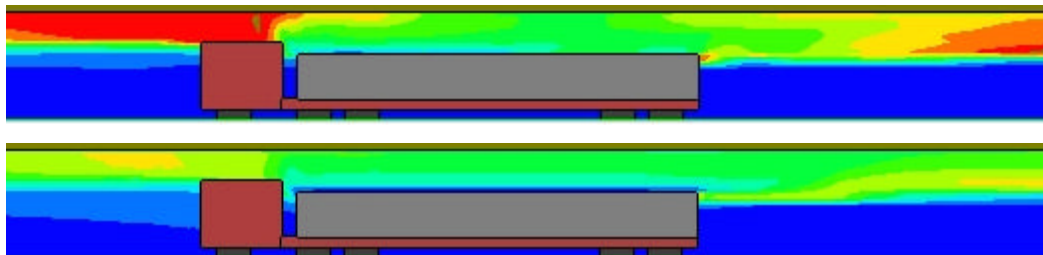


Figure 2.03 – Two pictorial renderings of CFD fire data.

The most common form of non-CFD fire models are known as “zone models.” These models generally split each compartment of interest into two control volumes or “zones”. Perhaps the most widely used zone model is CFAST [96]. The model considers a number of compartments in the form of rectangular prisms, connected to each other (and the outside air) by horizontal or vertical openings. Each compartment contains two layers with homogeneous properties; the upper layer represents the combustion gases and the lower layer represents the ambient air. Counting the mass, internal energy, density temperature, etc. for each layer results in a total of eleven variables for each compartment, four of which are independent of the others. The program solves a set of differential equations (derived from conservation laws) and predicts two layer temperature values, one layer volume and the pressure. As with some of the CFD models, the fire behaviour is predetermined by the user, although the combustion rate can be modulated according to the availability of oxygen.

One of the assumptions of CFAST is that no mixing of the layers occurs within each compartment, only at the openings between them. Assumptions about the heat transfer between the gas layers and the walls and ceiling are also made. The model assumes an initially small (but non-zero for mathematical reasons) upper layer and calculates the growth of this layer as the fire progresses. Production of CO, CO₂, water vapour and other combustion products can also be modelled.

CFAST has been adapted to study fire development in tunnels. For example, the main modifications in the TUFISI (TUNnel FIRE Simulation) adaptation are as a result of the observations that the energy loss along the tunnel and the mixing of the layers would be largely dependent on the number of “compartments” the tunnel was split up into, which is clearly not a realistic situation [97]. Instead the mixing in each “compartment” is modelled as a function of the Richardson number and the friction losses are modelled as a function of tunnel roughness and tunnel length.

The results of zone modelling of tunnel fires have compared favourably with real experimental data. For example:

TUFISI “is capable of predicting the temperature, smoke layer height and the concentrations of various combustion products with sufficient accuracy to be used for

the preliminary design of tunnel ventilation systems in order to control the movement of fire induced hot combustion gases and to provide escape routes free of smoke” [97].

The simplified approach of zone models also means that the models are not computationally intensive – zone model calculations for a simulation of one of the Ofenegg tunnel fire experiments carried out by Altinakar *et al.* [97] took fifteen minutes on a personal computer, whereas CFD simulations of the same fire carried out by Biollay & Chasse [98] took nine days on a Sun workstation.

Another notable non-CFD model which describes tunnel fire behaviour is the non-linear model of fire spread in a tunnel (FIRE-SPRINT) developed by Beard [99-102]. This model considers just a single control volume, see Figure 2.04. By solving the differential equations of energy and mass for the control volume, the model predicts the conditions necessary for the system to “jump” from one stable state to a higher stable state. In the context of the model this jump is interpreted as the flashover-like spread of fire from a single object to a neighbouring object. For illustrative purposes calculations based on fire spreading between two HGV objects in the Channel Tunnel have been presented (e.g. [100]).

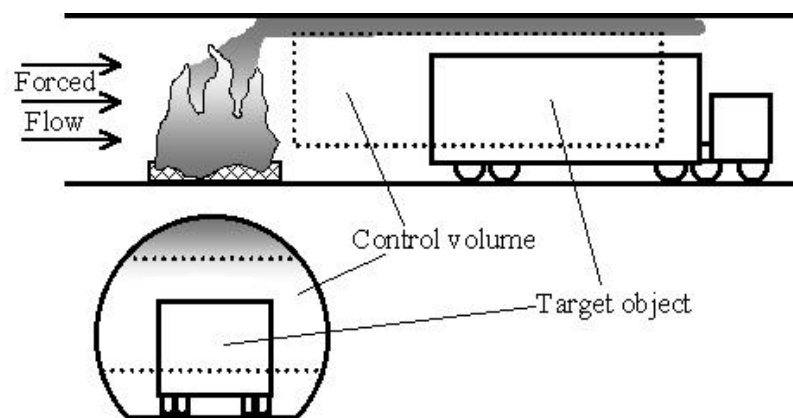


Figure 2.04 – The control volume considered by the FIRE-SPRINT (A2) model [100].

Of course a model describing fire does not necessarily have to perform numerical solutions of differential equations in a number of control volumes. A model is essentially just a mathematical description of some observed (or hypothesised) phenomenon. In all of the models discussed above the results produced by the model are deterministic, that is, a certain set of input variables will always produce the same

results. Real fires however are not like that: two seemingly identical wooden cribs may burn in significantly different manners under seemingly identical conditions. It may be that it is more appropriate to model certain aspects of fire behaviour in a non-deterministic manner.

Non-deterministic modelling of fire (or any other phenomenon) includes the mathematics of probability in its calculations. Using a probabilistic approach it is possible to model the apparent “randomness” of fire and fire related phenomena. Part of this thesis will concern itself with an investigation into the probabilistic relationship between fire size and longitudinal ventilation in a tunnel. Before this investigation is presented it is necessary at this point to include an introduction to probability and a discussion of some probabilistic tools.

Chapter 3. Introduction to Probability & Bayes' Theorem

3.1 Introduction

We saw in the last chapter how the majority of fire models are deterministic in nature, yet fire does not always behave in a deterministic manner. Fire is a random phenomenon and the study of random phenomena is called probability. In order to understand the methodology used to study fire as a random process in this project, it is necessary to define concepts such as *probability*, *likelihood*, *inference*, *conditional probability* at this stage. The following is based on a text book by Lindley [103] unless otherwise noted.

Most phenomena studied by science are deterministic in nature, *if A then B*, and it is possible to describe these processes in mathematical terms. When randomness is present in a system *A* may sometimes cause *B*, but sometimes cause *C* instead. Nevertheless, these random processes are able to be described mathematically.

If A_i always causes B_i , and no two of the B_i are the same, then it is a simple *inductive* process to infer that if B_i is observed then A_i must have been the cause. But if A_i can sometimes cause B_i and sometimes B_j , then the cause of B_j may be either A_i or A_j and the induction is not complete. It becomes necessary to introduce probability in order to make inductive statements precise. A spinning coin will eventually fall on one of its faces, but it is not generally possible to successfully predict which face will be uppermost when the coin comes to rest. Even if the initial conditions of the coin, its spin and the surface on which it is spinning were exactly defined so that it would, in theory, be possible to predict the exposed face, it would not usually be useful to do so. However, using probability it is possible to make precise statements about the outcome of spinning a coin and so it is possible to deduce other results. For example it is possible to calculate how long one can expect to go on repeatedly spinning the coin until the number of times it comes to rest on each face are equal; or how many heads one can expect to get after ten spins. This is a matter of mathematical *deduction*. To go in the reverse direction, from the results of the spinning coin tests to determine whether the coin is fair (i.e. equally likely to fall on its head as its tail), is an *inductive* process and is a problem typical of statistics.

3.2 The concept of a frequency limit

Consider a situation in which A can either cause an event B to occur or not, so that the situation is not deterministic. We say A either produces B or not- B , which we will denote \bar{B} . In many situations it is possible to repeat A and observe B or \bar{B} . It is an empirical fact that often, as the number, n , of repetitions increases, the ratio of the number, m , of times B occurs to the total number of repetitions becomes stable and appears to tend to a limit. Each repetition is termed a trial, the occurrence of B is a *success* (and of \bar{B} , a *failure*) and the ratio m/n the *success ratio*. This empirical observation can be expressed by saying that $\lim_{n \rightarrow \infty} (m/n)$ exists. The limiting number is the empirical value of the *probability of B given A* , which is written $P(B/A)$. Any probability is a function of two arguments which are separated by a vertical line; the first is the event being considered, the second describes the conditions under which it is being considered and is called the *conditioning event*, or simply the *condition*. Here, the event “the occurrence of B ” is being considered under condition A .

It is important to note that the conditioning event A is just as relevant to the probability as the event B . Consider the spinning coin again, event B is the coin falling with its head uppermost. If the coin is a newly minted one, the probability will be about $1/2$, but if the coin is badly bent or has a lump of chewing gum stuck on one face, the probability of B may be far from $1/2$. It is easy to produce apparent paradoxes by failing to mention the conditioning event.

3.3 The axioms of probability

Consider a sample space, \mathbf{A} , consisting of points, a , called *elementary events*. An *event* is a collection or a *set* of elementary events and is denoted by a capital letter A, B, C, \dots , with suffixes A_1, A_2, \dots , where necessary. If a belongs to A we write $a \in A$. Selection of a particular a is referred to by saying “ a has occurred.” If $a \in A$ and a has occurred we say that A has occurred. If A and B are two events the set of a such that both $a \in A$ and $a \in B$ is denoted by AB . If AB has occurred then both A and B have occurred, and conversely. If $\{A_n\}$ is a sequence of events, the set of a which belong to at least one A_n is denoted by $\sum_n A_n$. If $\sum_n A_n$ has occurred then at least one A_n has occurred, and conversely. The members of the sequence are *exclusive given C*, if whenever C has occurred no two of them can occur together, that is $A_m A_n C$ is the empty set whenever $m \neq n$. If the conditioning event C is \mathbf{A} , the sample space, then, in this last definition, (and similar ones) the words “given \mathbf{A} ” are omitted. If $\sum_n A_n = \mathbf{A}$, that is, if every a belongs to at least one A_n , then $\{A_n\}$ is said to be *exhaustive*. Two events, A and B , are said to be *independent given C* if $P(AB|C) = P(A|C)P(B|C)$. This is a special case of the following important definition:

The events, finite or infinite, of a sequence $\{A_n\}$ are *independent given B* if, for any finite collection of them, say $A_{n_1}, A_{n_2}, \dots, A_{n_k}$, the equation:

$$P(A_{n_1} A_{n_2} \dots A_{n_k} | B) = P(A_{n_1}|B) P(A_{n_2}|B) \dots P(A_{n_k}|B) \quad [3.1]$$

holds. $A_{n_1} A_{n_2} \dots A_{n_k}$ denotes the event which occurs if and only if all the events $A_{n_1}, A_{n_2}, \dots, A_{n_k}$ occur: it is an extension of the notation AB used earlier. Again, if $B = \mathbf{A}$ we sometimes omit reference to the conditioning event and speak of the events being independent, writing $P(A_{n_1}|\mathbf{A}) = P(A_{n_1})$, etc.

For certain pairs of events, A and B , a real number $P(A/B)$ is defined and called the *probability* of A given B . These numbers satisfy the following axioms:

1. $0 \leq P(A/B) \leq 1$ and $P(A/A) = 1$

2. If the events in $\{A_n\}$ are mutually exclusive given B then

$$P\left(\sum_n A_n | B\right) = \sum_n P(A_n | B)$$

3. $P(C/AB)P(A/B) = P(AC/B)$

The whole structure of probability theory is derived from these three simple axioms.

3.4 Various theorems including “Bayes’ Theorem”

The second axiom of probability is often called the *addition law* of probabilities. Similarly the independence condition is often referred to as the *multiplication law* of probabilities. Notice that the addition law only holds for mutually exclusive events and that the multiplication law only holds for independent events. From these axioms other simple, but useful, results may be deduced. In what follows, $P(A|A)$ will be written $P(A)$. Notice that if $B = A$ the third axiom may be expressed as $P(C/A)P(A) = P(AC)$.

Theorem 1.

$$P(A/B) = P(AB/B)$$

This follows from the third axiom which says that $P(AB/B) = P(A/BB)P(B/B)$ which equals $P(A/B)$ since $BB = B$ and $P(B/B) = 1$ by the first axiom.

Theorem 2.

$$\text{If } A \text{ implies } B, P(A/B)P(B) = P(A)$$

This follows from the third axiom with the condition that $AB = A$.

Theorem 3.

$$\text{If } A \text{ implies } B, P(A) \leq P(B)$$

This follows from theorem 2 and the first axiom.

Theorem 4 (Generalised addition law).

If $\{A_n\}$ are exclusive and exhaustive and B is any event, then

$$P(B) = \sum_n P(B | A_n)P(A_n)$$

From the third axiom it follows that each term on the right-hand side is $P(BA_n)$. Since the $\{A_n\}$ are exclusive and exhaustive the $\{BA_n\}$ are exclusive and $\sum_n A_n B = B$. The result follows from the addition law.

Theorem 5.

If $P(B)$ does not vanish then
$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

This follows directly from the third axiom.

Theorem 6 (Bayes' Theorem).

If $\{A_n\}$ is a sequence of events and B is any other event with $P(B) > 0$, then
$$P(A_n | B) \propto P(B | A_n)P(A_n)$$

This follows from theorem 5 substituting A_n for A . The constant of proportionality is $P(B)^{-1}$. It follows from this that if, in addition, the $\{A_n\}$ are exclusive and exhaustive then:

$$P(A_n | B) = \frac{P(B | A_n)P(A_n)}{\sum_i P(B | A_i)P(A_i)} \tag{3.2}$$

This is immediate on rewriting $P(B)$ as a summation by the generalised addition law (theorem 4). This is the form of Bayes' Theorem that will be used in much of this study.

Theorem 7.

If $\{A_n\}$ are exclusive and not all $P(A_n) = 0$, and B is any event, then

$$P\left(B \left| \sum_n A_n \right.\right) = \frac{\sum_n P(B | A_n)P(A_n)}{\sum_n P(A_n)}$$

The left hand side is
$$\frac{P\left(B \left| \sum_n A_n \right.\right)}{P\left(\sum_n A_n\right)} = \frac{\sum_n P(BA_n)}{\sum_n P(A_n)}$$
 on application of the addition

law to numerator and denominator which is valid since $\{A_n\}$ and hence $\{BA_n\}$ are exclusive. The result follows since $P(BA_n) = P(B|A_n)P(A_n)$.

Theorem 8 (Generalised multiplication law).

If A_1, A_2, \dots, A_n are any events and the events A_1, A_2, \dots, A_{n-1} have non-zero probability, then $P(A_1A_2\dots A_n) = P(A_1)P(A_2/A_1)P(A_3/A_1A_2)\dots P(A_n/A_1A_2\dots A_{n-1})$.

The result is immediate by repeated use of axiom 3.

Proofs of all these theorems and examples of their use may be found in many books on probability (e.g. [103]).

3.5 Thomas Bayes (1702-1761)

Theorem 6, above, has been named “Bayes’ Theorem” after the 18th century cleric and mathematician who appears to have been the first person to have derived and used this particularly useful probabilistic theorem.

Little is actually known about Thomas Bayes, indeed the year of his birth is even in question. All that is known (from his gravestone in Bunhill Cemetery, Moorgate, London) is that he was 59 when he died on 7th April 1761 [104]. Aside from that, and occasional references to him in the Edinburgh University archives^M all that is known about him are a few anecdotal stories about his time as a Presbyterian preacher and the handful of letters and papers of his which were published, mostly after his death [104].

In the 1730s there was some debate concerning Sir Isaac Newton’s work on fluxions with some church leaders attacking the work on metaphysical grounds. A strong defence of Newton’s work entitled “*An Introduction to the Doctrine of Fluxions, and Defense of the Mathematicians against the Objections of The Analyst, so far as they are designed to affect their general Methods of Reasoning*” was circulated in 1736 [105]. The tract was published anonymously but has always been attributed to Thomas Bayes. It appears to have been on the basis of this tract that Bayes was elected to fellowship of the Royal Society in 1742.

^M Bayes appears to have studied theology at Edinburgh University from 1719 (he also attended classes in logic and Roman history amongst other things); he was licensed as a preacher, but did not graduate and was not ordained at Edinburgh.

In 1764 & 1765 three articles were published in “*Philosophical Transactions*”, the first, a “*Letter from the late Reverend Mr. Thomas Bayes, F.R.S. to John Canton, M.A. & F.R.S.*” [106] was a short note dealing with divergent series, the second was “*An Essay towards solving a Problem in the Doctrine of Chances. By the late Rev. Mr. Bayes, F.R.S. communicated by Mr. Price, in a letter to John Canton, A.M. F.R.S.*” [107] and the third was “*A Demonstration of the Second Rule in the Essay towards the Solution of a Problem in the Doctrine of Chances*” [108]. It was the second of these publications which contained the derivation of “Bayes’ Theorem” and changed the science of probability forever. Thomas Bayes also left several notebooks containing various philosophical and mathematical writings. Excerpts from these have been reproduced in some accounts of Bayes’ life and writings [104].

Although it is clear from the introduction to Bayes’ essay, written by Richard Price, that Bayes himself had written an introduction, the content of the original introduction was not reproduced in “*Philosophical Transactions*” and has thus been lost to posterity. Bayes intention in the essay was however noted in the letter from Price accompanying the essay, where the following problem was posed:

“to find out a method by which we might judge concerning the probability that an event has to happen, in given circumstances, upon supposition that we know nothing concerning it but that, under the same circumstances, it has happened a certain number of times, and failed a certain other number of times.” [107]

However, the condition that the event of concern should take place “under the same circumstances” as previous events appears to have been introduced by Price as it is not present in the essay. Also the meaning of the phrase “judge concerning the probability” is uncertain; did Bayes intend that a specific value be attached to the probability of an event or merely that a (possibly vague) inference about the probability should be made? Scholars favour the latter interpretation; that Bayes did not intend specific numerical values of probability [109].

In the essay Bayes “thought fit to begin his work with a brief demonstration of the general laws of chance” not only to save the reader the trouble of looking elsewhere for them but because he “did not know whither to refer him for a clear demonstration of them” [107]. Bayes’ definition of probability:

“the probability of any event is the ratio between the value at which an expectation depending on the happening of the event ought to be computed, and the value of the thing expected upon its happening” [107]

is slightly unusual, indeed Bayes appears to use the words “chance” and “probability” in the same manner [110]. Another slightly unusual belief held by Bayes is that the failure of an event is the same thing as the “happening of its contrary” (Bayes’ own terminology) [107], e.g. that the failure to obtain a head in a coin toss is the same thing as obtaining a tail (this discounts the small, but non-zero, probability that the coin will land on its edge); this has implications as to whether degrees of belief are additive, but will not be considered further here. It also should be noted that Bayes emphasises that the happening or failure of the same event in different trials is in fact the same thing as the happening or failure of different independent events [107], which may support de Finetti’s [111] view that the idea of “repeated trials” is meaningless for subjective probability.

Bayes’ own summary of the problem addressed in the essay appears to have been:

“Given the number of times in which an unknown event has happened and failed: Required the chance that the probability of its happening in a single trial lies somewhere between any two degrees of probability that can be named” [107].

Which confines the problem to information about a “degree of belief” not about an arbitrary sort of parameter, although Bayes’ theorem has been used in both ways in the years since then. Savage [110] expresses the belief (based on Price’s introduction) that Bayes was aware of both types of use of “Bayes’ theorem” although he appears to have confined his own use to “degrees of belief”. This implies that Bayes’ theorem was used by others during his lifetime – before the publication of the essay.

In the introduction to the essay, Price says that Bayes saw clearly how to solve his problem if an initial (prior) distribution of probability were given and that Bayes thought there was good (but not perfect) reason to postulate a uniform prior distribution. This assumption is generally known as “Bayes’ Postulate”. Some scholars hold that

Bayes' uncertainty about the validity of his postulate may well have been the reason why he never published the essay during his lifetime [112]. As Price published Bayes' essay with no comment on this uncertainty, it would appear that he did not share Bayes' doubts.

Price declares Bayes' method to be central to the philosophy of induction and therefore to the "argument taken from final causes for the existence of the Deity" [107], this is because

"it shows us, with distinctness and precision, in every case of any particular order or recurrency of events, what reason there is to think that such recurrency or order is derived from stable causes or regulations in nature, and not from any of the irregularities of chance."

In other words, every recurrent event in nature (e.g. the sun rising in the morning) causes us to increase our degree of belief in the existence of a creator God. However, theological questions like this are outside the scope of this thesis; this study has applied Bayes' theorem to solve a more down to earth problem.

3.6 Bayes' Theorem

In modern notation^N, Bayes' theorem is either expressed in its discrete form:

$$P(A_n | B) = \frac{P(B | A_n)P(A_n)}{\sum_i P(B | A_i)P(A_i)} \quad [3.2]$$

or in its continuous form:

$$P(A | B) = \frac{P(B | A)P(A)}{\int P(B | A)P(A)dA} \quad [3.3]$$

^N The notation used in Bayes' essay in the 18th century is somewhat different to that used today.

In conventional notation, $P(A)$ is referred to as the *prior* probability of A , $P(B/A)$ is the *likelihood* of B given A and $P(A/B)$ is the *posterior* probability, that is the probability of A refined in the light of observation B . Thus it is possible to refine estimates of the probability of occurrence of some event A if information regarding the conditional probability of some other event B given A is known.

For example, suppose one has a coin. It is not known how fair the coin is. Consider the three hypotheses that (a) the coin is fair (hypothesis A_1), (b) the coin is biased towards heads (A_2) and (c) the coin is biased towards tails (A_3). Suppose that one's *prior* estimate of probability is that there is an 80% chance that the coin is fair and a 10% chance that the coin is biased to one side or the other (i.e. $P(A_1) = 0.8$, $P(A_2) = P(A_3) = 0.1$). Event B_1 is a trial in which the coin is spun three times, each time it lands with the head uppermost. Clearly $P(B_1/A_2) > P(B_1/A_1) > P(B_1/A_3)$, thus using Bayes' theorem revised values of the probability of A_n can be determined (if the likelihoods are given specified or relative values). Further B_n trials will enable the probability to be further refined and so on.

This is of course a trivial example, there is no clear need to use Bayes' theorem in this instance as the probability of A_n may be determined by a quick and simple series of tests. A more appropriate use of Bayes' theorem is in medical diagnosis. Suppose there is a disease which is found in 0.01% of the population and that there is a symptom which will be present in 99% of cases of the disease. On observing the symptom a doctor may decide that the patient has the disease, but Bayes' theorem shows us that this might not be the case:

Example

Let A be the disease and B be the symptom. $P(A_{yes}/B)$ is the probability of a patient with the symptom also having the disease, so:

$$P(A_{yes} | B) = \frac{P(B | A_{yes})P(A_{yes})}{\sum_i P(B | A_i)P(A_i)}$$

$$P(A_{yes} | B) = \frac{P(B | A_{yes})P(A_{yes})}{P(B | A_{yes})P(A_{yes}) + P(B | A_{no})P(A_{no})}$$

$$P(A_{yes} / B) = \frac{0.99 \times 0.0001}{0.99 \times 0.0001 + P(B / A_{no}) \times 0.9999}$$

Suppose the probability of having the symptom without the disease is 1%, then

$$P(A_{yes} / B) = \frac{1}{102}$$

That is only one person in 102 having the symptom will actually have the disease. Furthermore using similar calculations it can also be shown that one person in 98991 who does not have the symptom will have the disease.

In this study Bayes' theorem will be used to estimate (a) the influence of longitudinal ventilation and (b) the influence of tunnel geometry on fire size for vehicle, fuel pool and wooden crib fires in tunnels. The results of the small number of experimental fire tests that have been carried out in tunnels will be used as evidence to increase (or decrease) our "degrees of belief" in various hypotheses relating to these influences. The prior probability distribution functions will be devised (i) based on the estimates of a panel of experts in the fields of fire safety engineering and fire fighting, and (ii) based on Bayes' postulate of a uniform prior probability function.

3.7 Other methods of density estimation

In the study on the influence of longitudinal ventilation on fire size, Bayes' theorem will be used to estimate the probability distribution of an unknown variable, k . However, Bayes' theorem isn't the only method of estimating a probability distribution, others include the "kernel" and "nearest neighbour" methods and the "naïve" estimator. These methods will be briefly described here.

3.7.1 The kernel method

The probability distribution generated by the kernel method can be considered to be the sum of a series of "bumps" with the bumps being centred on each of the data points or experimental observations. An example is shown in Figure 3.01.

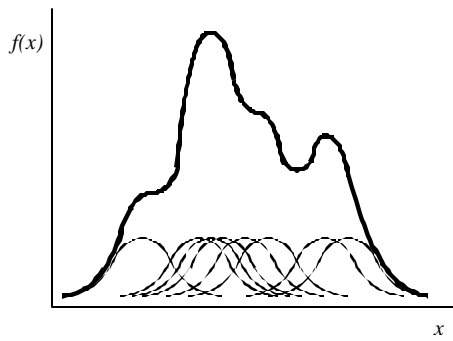


Figure 3.01 – an example of the kernel method of density estimation

The shape of the overall density function is dependent on the kernel function (the shape of each individual bump) and the “window width” (the width of each bump). In real life usage the kernel method has been shown to perform well with data sets of fifty or more points [113] although it tends to produce spurious noise on the tail of long-tailed distributions [114].

3.7.2 *The naïve estimator*

The naïve estimator is one of the simplest methods of probability density estimation. For a random variable X , with a density function f , then:

$$f(x) = \lim_{h \rightarrow 0} \frac{1}{2h} P(x-h < X < x+h)$$

For any given h , $P(x-h < X < x+h)$ can be estimated by the proportion of the sample falling in the interval $(x-h, x+h)$. So a natural estimator \hat{f} of the density is given by choosing a small number h and setting

$$\hat{f}(x) = \frac{1}{2hn} [\text{no. of } X_1, \dots, X_n \text{ falling in the interval}]$$

This is the naïve estimator. To illustrate the use of the naïve estimator, suppose a weight function w is defined as:

$$w(x) = \begin{cases} 1/2 & \text{if } |x| < 1 \\ 0 & \text{otherwise} \end{cases}$$

The naïve estimator may then be written:

$$\hat{f}(x) = \frac{1}{n} \sum_{i=1}^n \frac{1}{h} w\left(\frac{x - X_i}{h}\right)$$

It follows from this that the estimate is constructed by placing a “box” of width $2h$ and height $(2nh)^{-1}$ on each data point or experimental observation and then summing all the boxes. It is clear that this method needs a fairly large number of data points in order to yield a meaningful probability distribution.

3.7.3 *The nearest neighbour method*

The nearest neighbour method is similar to the naïve estimator method in that the estimated probability distribution is formed by considering a number of boxes containing the data points. However, unlike the naïve estimator method, the boxes used in the nearest neighbour method are not of fixed width, but rather the value of the probability function at a given point is inversely proportional to the size of the box needed to contain a specified number of data points. To illustrate this, consider the distance $d(x,y)$ between two points on a line to be $|x-y|$ and for each t define

$$d_1(t) \quad d_2(t) \quad \dots \quad d_n(t)$$

to be the distances, arranged in ascending order, from t to the data points of the sample. The k^{th} *nearest neighbour density estimate* is then defined by

$$\hat{f}(t) = \frac{(k-1)}{2nd_k(t)}$$

Again it is clear that a significant number of data points are needed in order to produce a reasonable estimate of a probability distribution.

3.7.4 *Other estimators*

While these methods of density estimation are common in statistical analysis they are not the only methods in use. Other techniques such as “orthogonal series” and “maximum penalised likelihood” estimators are used, but as with the kernel, naïve and nearest neighbour techniques, they all require a significant number of data points to produce a reasonably well defined probability distribution. When considering the

question of fire behaviour in tunnels, there are only a handful of experimental observations to use, not enough to use any of these density estimation techniques. The Bayesian method on the other hand is able to estimate a probability distribution using only a single experimental observation if there is some form of prior probability distribution to start with. These other methods of density estimation will not be considered further in this study. For further information on density estimation, the reader is directed to Silverman's book [114] on the subject.

Chapter 4. Description of the first problem: Longitudinal ventilation and tunnel fires

4.1 Introduction

The first problem to be considered in this study may be summed up by the following question:

What effect does forced longitudinal ventilation have on fire size for fires in tunnels?

In Chapter 1 it was noted that this question had not been considered until recent times. Previously the main issue of interest was along the lines of “What effect does fire have on ventilation velocity in tunnels?”

Historically, the main purpose of ventilation systems in vehicle tunnels, subway systems and mines was to provide reasonably pollution-free air to all parts of the underground tunnel network. The presence of a fire in one part of a tunnel network may affect the ventilation airflow in other parts of the network, because the fire will have a localised “throttling” effect on the airflow; this may prevent fresh air reaching some parts of the tunnel network. For this reason, most of the early investigations into the interaction of fire with ventilation systems were carried out by ventilation engineers trying to ensure that fresh air would reach all parts of their tunnel network in a fire situation. What effect the ventilation system would have on the behaviour of the fire itself was never considered.

Fire requires three things: fuel, heat and oxygen. Change the quantity of any of these factors and the fire behaviour will change accordingly. Water is used to extinguish fires because it will cool the fire (remove heat) and also may block the flow of oxygen to the fuel. Carbon dioxide can be used to extinguish fires as it can block the oxygen flow; it may also have a cooling effect. In some situations it is even possible to extinguish a fire by blowing air on it, so long as the cooling effect is more significant than the effect of

the extra oxygen. However, in many situations, blowing on the fire will enhance the burning as the fire will get a greater supply of oxygen.

So one of the considerations when attempting to answer the main question is: will the cooling effect of tunnel ventilation systems dominate the enflaming effect of the additional oxygen?

Another important consideration is whether or not the airflow will cause the fire to spread to unburned fuel faster than it would have done. If the fire grows in area faster with applied ventilation then it will probably grow significantly faster in heat release as well.

Understanding the influence of ventilation on fire in tunnels is essential if an acceptable level of fire safety in tunnels is to be achieved. If the emergency ventilation strategies currently in use could have an enflaming effect on a fire occurring in a tunnel, then it is important to determine the scenarios which will lead to a more serious fire and try to find alternative emergency procedures which will tend to mitigate rather than enflame the fire.

Once the question of the influence of ventilation on fire size has been asked, the next task is to find a way to answer it. Clearly the best way of answering such a question would be to carry out a large number of fire tests in tunnels, using identical fire loads and varying the ventilation conditions between tests, or varying the fire load whilst using identical ventilation conditions. To date, such a comprehensive test series has not been carried out. However, there have been a number of experimental fire tests carried out in a variety of tunnels which may be able to provide some information on the relationship between fire size and ventilation conditions. If these nuggets of information could be combined in a systematic manner, the overall picture would hopefully reveal some information on the nature of the relationship. This overall picture would still be like an incomplete jigsaw in many respects, but it would reveal far more of the picture than any individual jigsaw piece, and as more information becomes available in the future, more pieces of the jigsaw may be added so the picture may become clearer.

The first stage in this process is identifying all the experimental fire test data that are available.

4.2 Survey of the available data

To be able to estimate the influence of longitudinal ventilation on a fire in a tunnel, the ideal situation would be to be able to compare experimental data from a fire test in a tunnel subject to forced longitudinal ventilation with data from an identical fire test in the same tunnel subject to natural ventilation. In reality, this is not possible due to the paucity of data. In this study similar fire tests in similar tunnels, one with forced longitudinal ventilation and one with natural ventilation are compared. The sources of experimental tunnel fire data that were available for the study are summarised in Table 4.1.

<i>Fire load</i>	<i>Tunnel</i>	<i>Tunnel size</i>	<i>Ventilation</i>	<i>HRR</i>	<i>Reference</i>
HGV	EUREKA	30m ²	Forced	~130MW	[70]
“truck load”	EUREKA	30m ²	Natural	~16MW	[70]
Car	EUREKA	30m ²	Natural	~6MW	[70]
Wooden cribs	EUREKA	30m ²	Natural & forced	~10 / 26MW	[70]
“HGV simulation”	HSE	5.7m ²	Forced	~10MW	[81]
Wooden crib	HSE	5.7m ²	Forced	~1.4MW	[84]
Car	Des Monts	80m ²	Forced	~2MW	[79]
Wooden cribs	FOA	9m ²	Natural	~1MW	[86]
Car	FOA	9m ²	Natural	~4MW	[86]
Pool fire series	Ofenegg	23m ²	Natural & forced	~10 – 50MW	[63]
Pool fire series	Memorial	56m ²	Various	~10-100MW	[13]
Pool fire series	EUREKA	30m ²	Various	~2 / 4MW	[70]
Pool fire series	Japanese laboratory	0.09m ²	Forced (various)	10 – 60kW	[89]
Pool fire series	Australian mine tunnel	13m ²	Forced (various)	1.4 – 1.8MW	[82]

Table 4.1 – Sources of experimental tunnel fire data

Data from each fire test with forced ventilation can be compared with data from equivalent fire tests with natural ventilation, to determine the approximate influence of forced ventilation for each forced ventilation test. For the reduced scale tests, HRR and ventilation velocity values can be scaled up to “full size” using Froude scaling laws.

Some observers have questioned the decision to rely on only experimental data in this study when there are many data from CFD fire models available. However, these CFD data are based on a number of assumptions that may not be appropriate for this study. Also the CFD models themselves do not predict the HRR of the fire, only the smoke and temperatures around a fire of (usually) predetermined HRR. The HRR of a CFD fire in a tunnel subject to a forced longitudinal airflow will usually be the same as the HRR of a CFD fire in a tunnel not subject to any forced airflow. This is inconsistent with experimental observations (see figure 4.01 for example) and so CFD data have not been used in this study. It is hoped that the results from studies such as this will be considered by those building new CFD models, so that the fire models of the future may include effects such as the influence of longitudinal ventilation on fire size in tunnels.

4.3 Description of the methodology

4.3.1 Definition of the variable k

If there were a relationship between fire size and ventilation velocity in tunnels, it would be desirable to express this relationship in terms of a simple function:

$$k = f(v) \quad [4.1]$$

where k is the variable used to describe the effect of the ventilation on fire size, and v is the ventilation velocity. It is reasonable to suppose that increasing the ventilation rate will increase (or decrease) the absolute heat release rate of the fire by a multiplicative factor, which will be considered to be the unknown variable k . In this study k (the “heat release rate coefficient”) is defined by:

$$k = \frac{\dot{q}_{vent}}{\dot{q}_{nat}} \quad [4.2]$$

where \dot{q}_{vent} is the HRR of a fire in a tunnel with forced ventilation and \dot{q}_{nat} is the HRR of a similar fire in a similar tunnel with natural ventilation. By considering the coefficient k , rather than the absolute HRR of a fire, factors such as the composition and chemical nature of the fuel do not need to be considered. Thus if $k = 1.5$ for a car fire in a certain tunnel with a 2ms^{-1} airflow, then a small car, which would be expected to burn at 2MW in a tunnel with natural ventilation, would probably burn at about 3MW whereas a larger car, which might burn at 5MW in a naturally ventilated tunnel, would be expected to burn at about 7.5MW. This assumes the k value for a larger car to be the same as for a smaller car.

4.3.2 *Determining values of k for experimental fire tests*

Experimental data from tunnel fire experiments with natural ventilation and longitudinal ventilation have been collected. By comparing data from experiments with longitudinal ventilation with data from similar experiments with natural ventilation it is possible to determine values of k for each specific fire load at a particular ventilation velocity in a specific tunnel.

For example, two fire tests were carried out in the EUREKA fire test series in a tunnel near Hammerfest, Norway with identical wooden cribs: one test was carried out with natural ventilation, the other test with longitudinal ventilation at 2.2ms^{-1} [70]. The naturally ventilated fire test exhibited a maximum HRR of just under 10MW after about 18 minutes, the longitudinally ventilated fire test exhibited a maximum HRR of about 27MW after about 19 minutes. Comparing these tests gives a k value of about 2.8 for a wooden crib fire in the Hammerfest tunnel at 2.2ms^{-1} , see figure 4.01.

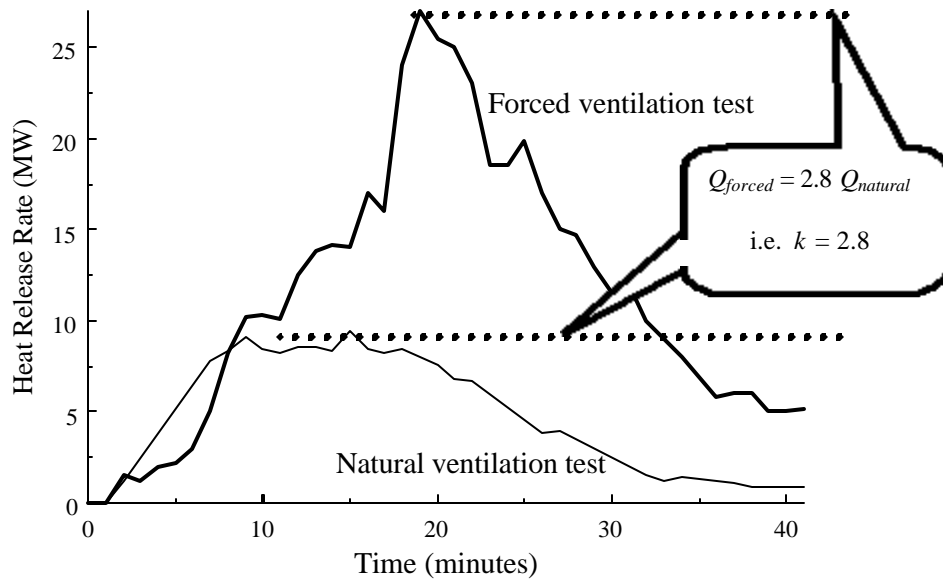


Figure 4.01 – Graphs of the HRR of a wooden crib fire in the Hammerfest tunnel with natural ventilation and forced ventilation at 2.2ms^{-1} .

It is also possible to estimate k values for tunnel fire experiments where there is not an identical fire test with different ventilation conditions. For example, some wooden crib experiments were carried out with natural ventilation in a “blasted rock tunnel” in Sweden [86] and a wooden crib test was carried out using forced ventilation at 1.7ms^{-1} ^o in the HSE test tunnel, UK [84]. Although there are a number of differences between these tests in terms of tunnel shape and the porosity of the cribs, a value of k can still be estimated by comparing the experimental data, see figure 4.02. As the discussion will show later on, estimates such as this are still of great value when the problem is considered in a Bayesian manner.

In some of the fire experiments carried out in the EUREKA test series, the ventilation was changed part way through the test [70,115], which enables values of k to be directly calculated from the HRR data from a single test. However, this can only be done if the ventilation change causes an increase in HRR; if the ventilation change causes a reduction in HRR then the value of k determined in this manner would probably be significantly under-estimated due to the radiation from the thick hot gas layer (which was produced by the fire in its higher HRR phase) enhancing the HRR of the fire.

^o Scaled from $1/3$ scale to “full size”, see Chapter 2 for details of “Froude scaling.”

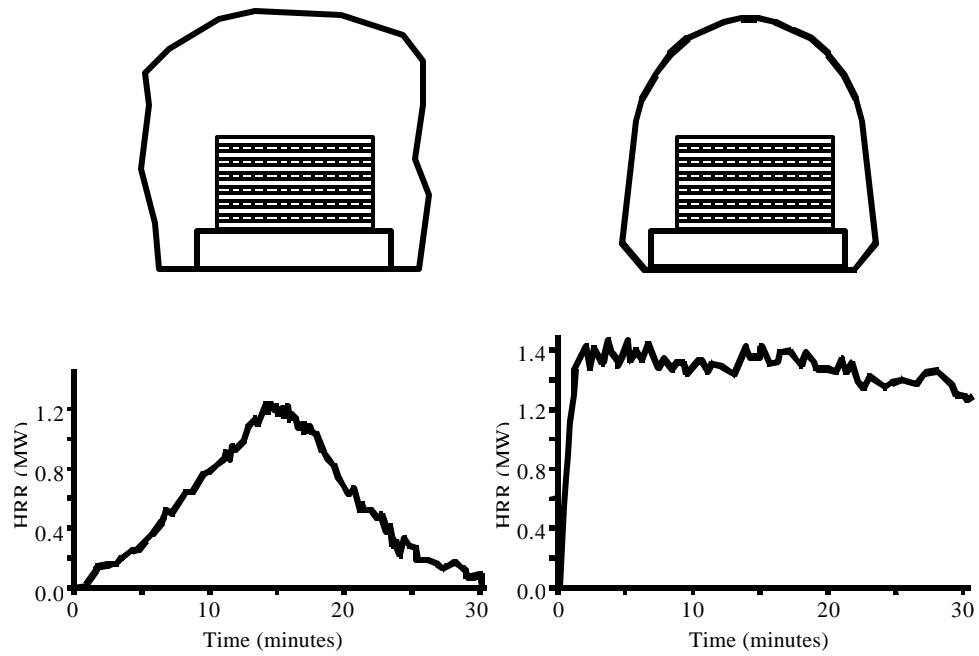


Figure 4.02 – Comparison of the naturally ventilated wooden crib fire test in the “blasted rock tunnel” and the longitudinally ventilated wooden crib fire test in the HSE tunnel.

If sufficient experimental data were available, it would be possible to determine the variation of k with ventilation velocity for a particular fire type in a specific tunnel geometry, simply by calculating the value of k for each piece of experimental evidence and plotting the data appropriately. However, the amount of data available (see Table 4.1) is insufficient for that sort of analysis. Faced with such a lack of data, we turn to Bayes’ Theorem in order to estimate the function $k = f(v)$.

Chapter 5. Application of Bayes' Theorem to the first problem

5.1 Initial Considerations

For any specified tunnel and ventilation velocity, k is essentially a random variable with unknown value. Any problem concerning an unknown variable and a small number of pieces of evidence is ideally suited for solution using Bayes' Theorem. If a prior probability distribution can be found or constructed for the value of k at a given ventilation rate, and a piece of experimental evidence (i.e. the value of k for a particular experimental tunnel fire) is available, then, using Bayes' theorem (equation [3.2]), it is possible to obtain a posterior probability distribution. This process may be repeated using each piece of experimental evidence to further refine the probability distribution and ultimately (given sufficient pieces of experimental evidence) reveal the "real" distribution of k values for the specified tunnel and ventilation velocity.

The first question that must be addressed is whether the problem is more suited to solution using the continuous or discrete form of Bayes' Theorem. A continuous approach would have the benefits of giving a solution which would give a well defined probability for any range of k values, but is limited by the assumptions regarding the shape of the probability function. If the probability distribution considered is not a 'normal' distribution (or one of a very small number of other useable distributions), the equations relating to the distribution become very complex after only two or three 'updates'. It is further complicated by the conceptual difficulties of defining a likelihood function for each piece of evidence (which would have to be conjugate to the prior distribution). A discrete approach has the benefits of having to make no assumptions about the shape of the probability distribution and a conceptually easier task of estimating likelihood. However it is limited by the choice of the discrete ranges that k is broken down into.

For the purposes of this study it was decided that the discrete approach was more appropriate. Not only does this remove the conceptual problems associated with estimating a continuous likelihood function for each piece of evidence (each of which

would have to be justifiable), but it also does not restrict the possible shapes of the probability function.

Using the discrete methodology it is necessary to split up the span of all possible values of k into a number of discrete ranges. If the number of ranges is too small then the results will be useless. If the number of ranges is too large then the allocation of specific likelihood values for each range may be unjustifiable. From a quick study of the evidence available, the span of possible values of k seems substantially different for a HGV fire than for a pool fire, so the discretisation of the span will be different for each of the cases considered. These different discretisations will be discussed in turn as each case is described.

The following are needed in order to determine the *posterior* probability distribution of k :

1. Specification of the type of fire, e.g. a HGV, a car, a fuel pool
2. Specification of the tunnel shape and size
3. A specified ventilation velocity
4. A *prior* probability distribution of k for the specified tunnel and ventilation velocity
5. The *likelihood* of at least one piece of experimental evidence (preferably several)

These will be considered in turn.

5.1.1 *Types of fires*

Vehicles that pass through tunnels come in all shapes and sizes, however experimental fire testing of vehicles in tunnels has not yet covered the whole range of vehicle sizes, so it was decided to consider only passenger cars and heavy goods vehicles (HGVs) in this study. It is also likely that fuel pools may form as the result of incidents in tunnels and that these may burn as pool fires. Three different sizes of pool fire will be considered to cover the whole range of possible scenarios. As each type of fire load is different and may respond differently to forced ventilation, each of these cases will be considered separately.

5.1.2 The tunnels of interest

In the UK and France there has been much debate about the safety and use of “semi-open” carriages to carry HGVs through the Channel Tunnel. This has meant that much of the research into the fire behaviour of HGVs has been carried out in single lane tunnels which are in some way comparable to the geometry of the Channel Tunnel. For this reason it was decided to determine the distribution of k for HGV fires in a tunnel the size and shape of the Channel Tunnel, see Figure 5.01a.

Conversely, a significant number of pool fire experiments have been carried out in wider, two-lane road tunnels, so it was decided that it would be of interest to determine k values for a typical two-lane road tunnel geometry, see Figure 5.01b. The tunnel shape and size are based on the “Standard 505” tunnel, with a 9.7m wide base and a maximum ceiling height of 6.4m, giving an overall cross-sectional area of approximately 50m² [116].

Tunnels for cars seem to come in many shapes and sizes, so a range of different tunnel sizes were chosen for the case of car fires, see Figure 5.02. This will be discussed fully later.

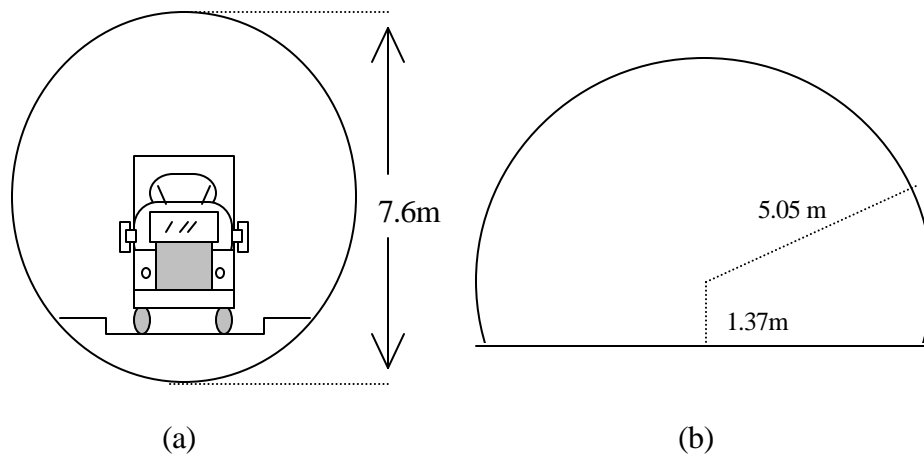


Figure 5.01 – The tunnel specifications for (a) the HGV fire study, and (b) the pool fire study

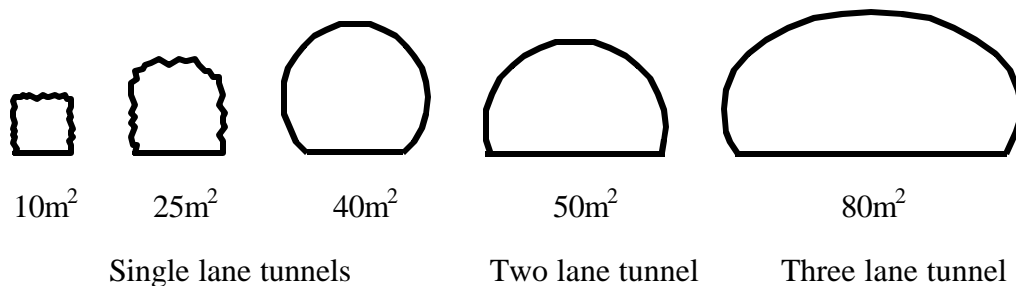


Figure 5.02 – The various tunnel specifications for the car fire study.

5.1.3 The ventilation velocities of interest

Tunnel ventilation systems generally deliver longitudinal ventilation velocities between 2 and 6ms⁻¹. It was decided to investigate the probability distributions of k for each case at only four different ventilation velocities; at 2, 4, 6ms⁻¹ and the slightly more extreme case of 10ms⁻¹, this should be sufficient to give a reasonable picture of the variation of k with ventilation velocity. Unfortunately car fire tests in tunnels have not been carried out across a range of different ventilation velocities, so it was decided to investigate the probability distribution of k for a car fire in a tunnel with a ventilation velocity of 1.5ms⁻¹ only.

5.1.4 The prior probability distribution

As the central question of this part of the thesis has never really been considered before, certainly not in a probabilistic manner, there is no type of prior probability distribution available to be used in this study. It was decided that the prior probability distribution functions for this study should be representative of “expert opinion” and to this end a panel of experts in the fields of fire safety engineering, fire dynamics and fire fighting was organised.

The panel members were:

- ◆ The late H.L. Malhotra – Fire consultant; he was involved with the EUREKA tunnel fire test series, amongst other things.
- ◆ Dr Martin Shipp – Head of “Centre for Fire Safety in Transport”, Fire & Risk Sciences (FRS), BRE
- ◆ Mr Stewart Miles – Senior Project Engineer, BRE; involved in CFD modelling of MTFVTP tests.

- ◆ Mr Richard Chitty – Senior Fire Consultant, Fire & Risk Sciences, BRE
- ◆ Dr Graham Atkinson – Member of “Fire & Explosions Group”, HSE; has carried out experimental fires in tunnels.
- ◆ Mr Jeremy Beech – Chief Fire Officer, Kent Fire Brigade (now retired); was involved in the operation to extinguish the Channel Tunnel fire (1996); close links with Eurotunnel.
- ◆ Prof. Dougal Drysdale – Professor of Fire Safety Engineering, Edinburgh University; a world leader in fire dynamics.
- ◆ Dr George Grant – Fire consultant; was involved with the EUREKA HGV fire test; has carried out experimental tunnel fire experiments for Eurotunnel. Currently employed by Halcrow.
- ◆ Dr Alan Beard – Reader, Heriot-Watt University; an expert in fire safety, his specialities include modelling of flashover in room fires and modelling of fire spread in tunnels.

For each case (HGV fires, pool fires, car fires), each panel member was independently asked to estimate various factors relating to fire size and k for vehicle and pool fires in specific tunnel situations subject to various ventilation velocities. These estimates were combined, using a “kernel-like” method (see Chapter 3), to give the prior distribution functions used in this study. Further details of this process, as it relates to each case, will be given later.

5.1.5 The likelihood of a particular piece of experimental evidence

The way that a piece of experimental evidence is used to refine the probability distribution is by evaluating the “likelihood” of that particular experimental result given the hypothesis one wants to test.

For example, suppose one has a prior probability distribution for k for a wooden crib fire in a certain tunnel at 2ms^{-1} . An appropriate piece of experimental evidence is the EUREKA wooden crib test, carried out at 2.2ms^{-1} (see Figure 4.01). Comparing experimental data from that test with data from a similar test using natural ventilation gives a k value of 2.8. Suppose we are considering the

probabilities that $k = 1.5, 2.0, 2.5, 3.0$ or 3.5 for a wooden crib fire in the tunnel of interest. The question one must ask oneself is of the form:

“How likely is it that this experiment would have happened, in the way it did (in the EUREKA tunnel at 2.2ms^{-1}), if $k = 2.5 (\pm 0.25)$ for a wooden crib fire in the tunnel of interest at 2ms^{-1} ?”

If the tunnel of interest is similar to the EUREKA tunnel then it is clear that this is quite likely, similarly it is quite likely that it would have happened if $k = 3.0$. It is less likely if $k = 2.0$ or 3.5 and probably even less likely if $k = 1.5$. So in this instance the likelihood values are: $L(E/k = 1.5) = \text{low}$, $L(E/k = 2.0) = \text{medium}$, $L(E/k = 2.5) = \text{high}$, $L(E/k = 3.0) = \text{high}$ and $L(E/k = 3.5) = \text{medium}$, where E is the piece of experimental evidence.

The likelihood values produced in this manner can then be used in conjunction with the prior probabilities to determine the posterior probabilities using Bayes' theorem.

If the tunnel of interest is substantially different to the tunnel in which the experimental test was carried out, the process is much the same although the allocation of likelihood values becomes conceptually more difficult. These conceptual difficulties can be overcome by classifying likelihoods with labels such as “high”, “medium” and “low” rather than trying to allocate specific numerical values. High, medium and low can be given numerical values in a particular ratio; in this study ratios of 10:5:1, 4:2:1, 3:2:1 and 4:3:2 have been used, the merits and disadvantages of each ratio will be discussed in later chapters. Generally, if there is similarity between the tunnel of interest and the experimental tunnel, the likelihood distribution has been assumed to be fairly narrow, whereas if there is less similarity the likelihood distribution has been assumed to be broad.

5.2 The first case: The HGV fire in a tunnel

For the case of a HGV fire in a tunnel there are two important questions:

1. How does longitudinal ventilation affect the spread of the fire during the growth phase of the fire? and
2. How does longitudinal ventilation affect the heat release rate of a fully involved HGV fire?

The answer to the former question may have serious implications for the use of emergency tunnel ventilation systems once a fire is detected (e.g. if the emergency ventilation strategy in a particular tunnel would cause the fire to spread up to five times faster than the normal operational ventilation would, should the emergency ventilation strategy be used for a HGV fire?). The answer to the latter question may have implications for the ventilation strategy used when the fire fighters arrive on the scene (e.g. if reducing the ventilation velocity will reduce the heat release rate, this may help the fire fighting operations).

These two questions have been considered separately.

5.3 HGV fire in the growth phase

The actual rate of spread of fire across the load is not recorded in any of the experimental tests that may be considered to be relevant to the case of a HGV fire, so some other way of describing fire spread needs to be used. It is reasonable to assume that the increase in heat release rate with time during the growth phase of a fire is an indication of the rate of spread of the fire, so if the heat release rate coefficient k is calculated at any given point in time during the growth phase, rather than at maximum HRR, it will be a reasonable indication of the rate of fire spread at test velocity compared to natural ventilation. That is:

$$k_{growth} = \frac{\dot{q}_{vent}(\text{at time } t_g)}{\dot{q}_{nat}(\text{at time } t_g)} \quad [5.1]$$

where t_g is any time during the growth phase of the fire.

5.3.1 Choice of discrete k_{growth} ranges

Comparing the rate of fire growth on the EUREKA HGV experiment (ventilation at 6ms^{-1}) with the rate of growth for the simulated truck load (natural ventilation) suggests that k_{growth} could have a value in excess of twenty under some circumstances. Ideally the span of possible k_{growth} values should be discretised into a small but not too small number of ranges, perhaps between five and ten. If the span of values from 1 to 40 was split up in this manner, each range would itself span between 4 and 8 k_{growth} values. This sort of discretisation would have no resolution at low values of k_{growth} ; the difference between $k_{growth} = 1$ and $k_{growth} = 4$ could be very important. In order to keep some resolution at low values of k_{growth} it was decided to discretise the span of possible values into ranges of $2^n - 2^{n+1}$. This gives eight k_{growth} ranges of:

$$\frac{1}{2}, 1, 1, 2, 2, 4, 4, 8, 8, 16, 16, 32, 32, 64 \text{ and } 64+$$

It is assumed that k_{growth} for a HGV fire will not be less than 0.5 or greater than 128 under any conditions.

5.3.2 Building the prior probability distributions

Each of the experts was asked to consider a HGV loaded with furniture in a tunnel. The HGV considered is similar to the one used in the EUREKA fire test [70] (see also Appendix A), the tunnel of interest is similar in size and shape to the Channel Tunnel (see Figure 5.01a). It is assumed that a fire breaks out at the front of the trailer and grows until it involves the whole vehicle. Under natural ventilation conditions the fire

grows from 1MW to 5MW in time t_g . The experts were then asked to consider a similar vehicle in a similar tunnel with forced longitudinal ventilation at 2, 4, 6 and 10ms⁻¹, and were asked to estimate the probability distribution for the HRR of the fire at time t_g after the fire was 1MW in size, for each of these ventilation velocities. A sample estimate sheet is shown in Figure 5.03, below.

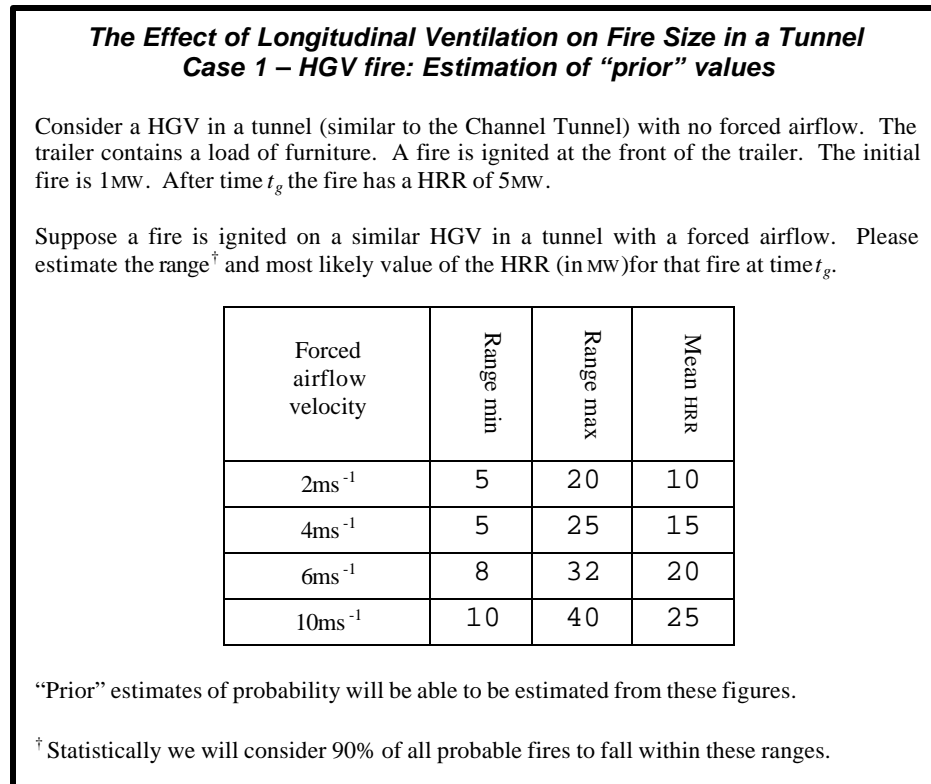


Figure 5.03 – A sample estimate sheet

In this chapter, and in the discussion that follows, the experts will not be named in conjunction with their opinions. It will be shown that some of the experts’ estimates are at odds with the evidence and bear little similarity to the, hopefully realistic, results of this Bayesian study. As it is not intended to tarnish the reputations of any of the experts in this thesis, care will be taken to ensure that none of the estimates can be linked with any of the names of the experts.

The experts were asked for their estimates before the discrete ranges had been decided upon. They were asked to estimate a span of HRR values (from which the k_{growth} values could be derived) and a peak value for each ventilation velocity. These estimates do not

therefore fall naturally into the discretised ranges. Their estimates of probability were split into the discrete ranges before they were combined.

Only one of the experts considered the possibility that k_{growth} could be less than one with a 2ms^{-1} airflow. Most of the rest of the group gave very high estimates of probability in the 1-2 range and some probability in the 2-4 range, with only one expert allocating any probability in the 4-8 and 8-16 ranges. For a 4ms^{-1} ventilation velocity the spread of estimates was similar, the same expert was the only person to allocate any probability in the 0.5-1 range, the other expert was the only person to allocate any probability in the 8-16 range and the others allocated the highest probability in the 1-2 range. Two experts allocated probability in the 4-8 range this time. At 6ms^{-1} , nobody allocated any probability in the 0.5-1 range, one expert allocated a very high probability in the 8-16 range with the rest of the group being split into two; half allocating high probability in the 1-2 range and the other half allocating high probability in the 2-4 range. At 10ms^{-1} , a different expert allocated quite a high probability in the 0.5-1 range, while another expert allocated high probability in the 8-16 and 16-32 ranges. The rest of the group estimated high probabilities in the 1-2, 2-4 and 4-8 ranges.

Clearly one expert expected that a small ventilation velocity might have a cooling effect on a fire whereas a high ventilation velocity might have an enflaming effect. Another expert appears to expect the opposite; that small ventilation velocities will have an enflaming effect but higher ventilation velocities will have a cooling effect. Yet another expert expects that a small ventilation velocity will have a strong enflaming effect and that this influence will increase with increasing ventilation velocity.

On average the expectation of the experts was that the HRR would probably be between 1 and 4 times greater (with a higher probability of k_{growth} being in the 1-2 range than the 2-4 range) at time t_g after the fire was 1MW for all the ventilation velocities considered. The probability functions were combined using a kernel-like estimator to give the prior probability distribution used in this part of the study. This was done by adding the individual probability estimates together and smoothing the combined estimate slightly (at 6ms^{-1} for example, there was a low probability of k_{growth} being in the 4-8 range compared to both the 2-4 and 8-16 ranges, this doesn't seem likely so the probability

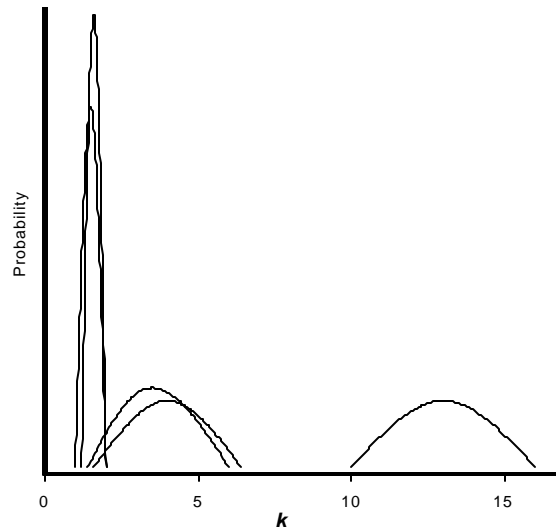
was “spread” between these ranges slightly to balance things out). In cases where none of the experts had allocated any probability in a particular range, the range was still given a nominally small probability as a prior estimate of zero probability will always yield a posterior probability of zero using Bayes’ Theorem. An example of the derivation of a prior probability distribution is shown in Scheme 5á, overleaf. The prior probability distribution, overlaid with a representation of some of the experts’ individual estimates, is shown in Figure 5.04.

Example: derivation of prior distribution for k_{growth} at $6ms^{-1}$

Expert estimates:

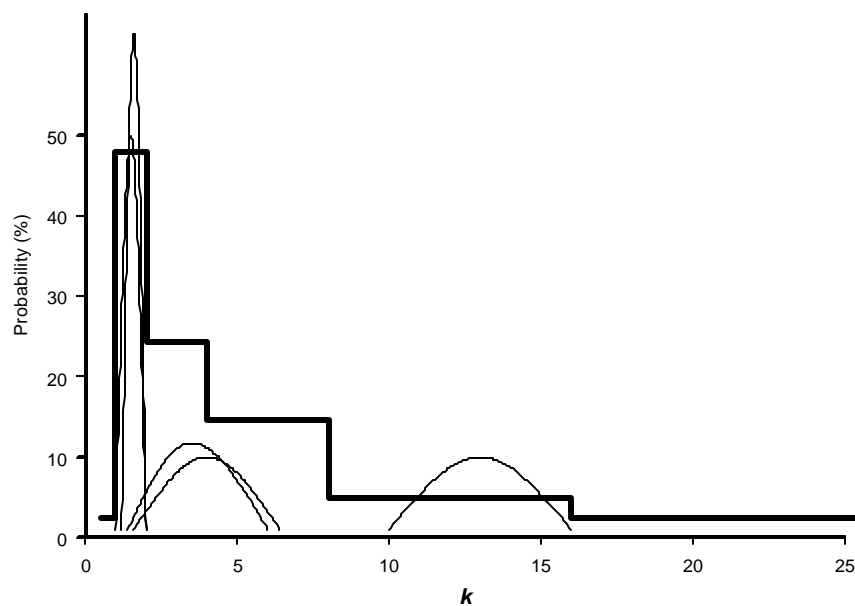
	k_{min}	k_{max}	k_{mean}
Expert A:	1.0	2.0	1.5
Expert B:	1.2	2.0	1.6
Expert C:	1.4	6.0	3.0
Expert D:	10.0	16.0	13.0
Expert E:	1.6	6.4	4.0

These data can be plotted as shown:
(the curves shown are only approximations of the probability distributions)



Assuming the areas under each curve represent the same amount of probability, it is a relatively straightforward process to approximately calculate that part of the area under each curve which falls into each of the k ranges of interest; 0.5-1, 1-2, 2-4, 4-8, 8-16, 16-32, 32-64, 64+. For example about half of the probability estimated by expert E falls into the 4-8 range (assuming the mean is approximately the 50th percentile) and most of the remainder (approximately 30-35%) falls into the 2-4 range, whereas the entire estimates of probability made by experts A & B fall in the 1-2 range.

These amounts were calculated for each curve and range, summed and normalised to give a total probability equivalent to 100%. In this instance some of the probability from the 8-16 range was transferred to the 4-8 range to give a more balanced distribution. Although none of the experts allocated any probability in the 0.5-1, 16-32, 32-64 and 64+ ranges, these were allocated nominally small amounts of probability. The prior probability distribution derived in this way is shown below:



Scheme 5á – The derivation of a prior probability distribution.

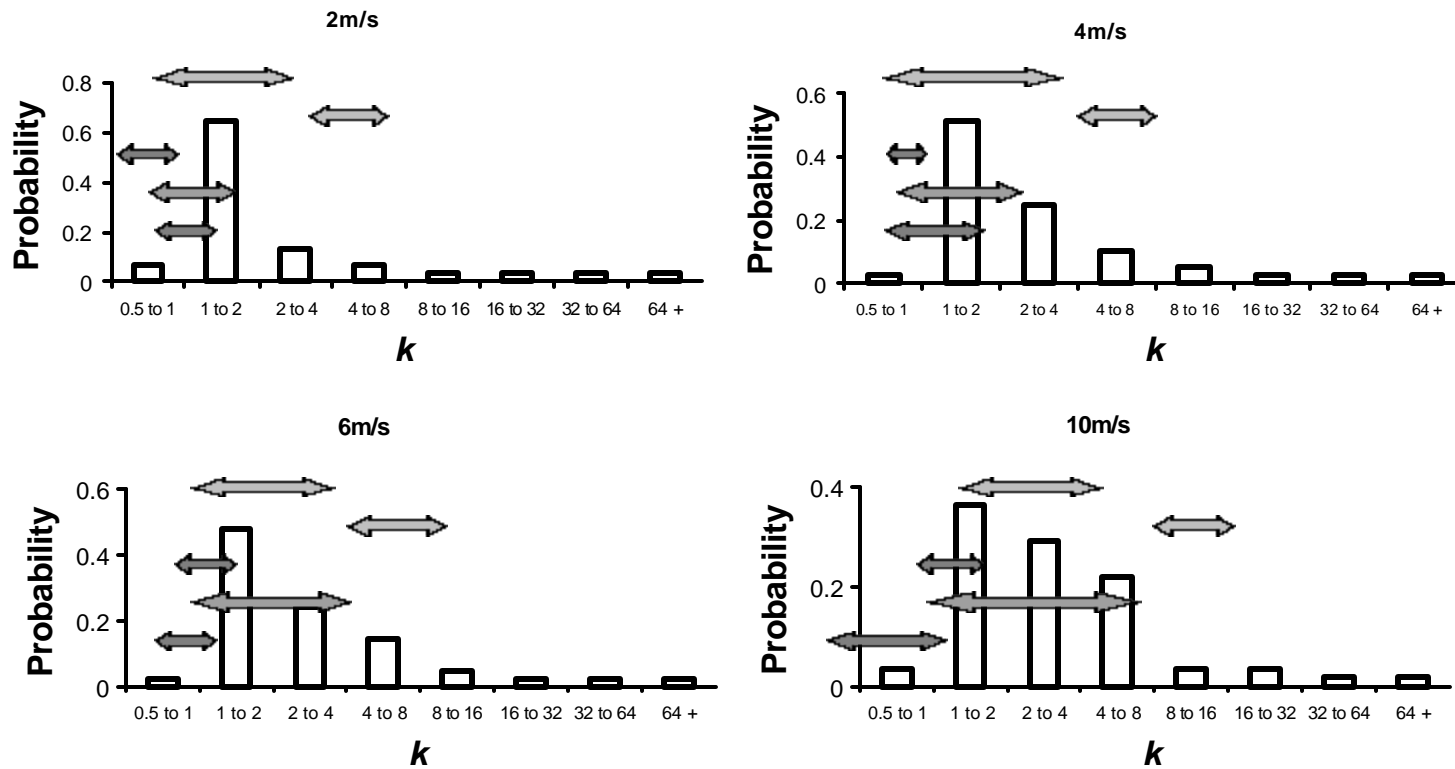


Figure 5.04 –The prior probability function for a HGV fire in the growth phase, some expert estimates are overlaid to show the diversity within expert opinion^P.

^P Each double-headed arrow represents the span between the maximum and minimum estimates of one expert. Similarly shaded arrows will not necessarily represent the same expert's estimates in other figures.

5.3.3 *The available evidence*

In order to determine the influence of longitudinal ventilation on a HGV fire in the growth phase, experimental data from fire tests of HGVs and HGV-like fire loads in tunnels with both natural and forced ventilation needs to be considered. The following experimental tests were considered to be relevant to this case:

1. *The EUREKA HGV fire test in the Hammerfest tunnel*

This is the only experimental fire test of a real HGV that has been carried out to date (there have been no experimental fire tests of HGVs outside of tunnels). The Hammerfest tunnel has been described already (section 2.6.7). The HGV used in the test was a fairly typical model comprised of a Leyland-DAF model “95” cab (3.96m long, 3.1m high and 1.5m wide) and a 12.2m long, 2.4m wide, 4.0m high trailer (the actual trailer was 2.5m high, sitting 1.5m above the ground at the highest point) filled with wooden framed furniture. The HGV created a tunnel blockage of about 42%, that is, the cross-sectional area of the HGV trailer was 42% of the cross-sectional area of the tunnel. In the initial stages of the fire the ventilation in the tunnel was longitudinal at 6ms^{-1} (equivalent to 6.9ms^{-1} in the Channel Tunnel). The fire was started in the cab and the doors were closed, the fire grew inside the cab for about ten minutes before the windscreen cracked and the fire spread to the trailer. Once the fire reached the trailer it grew in intensity from about 10MW to well over 100MW in under two minutes. For the purposes of this study, this rapid growth is considered to be the “growth phase” of the fire.

2. *The EUREKA simulated truck load test in the Hammerfest tunnel*

Due to the enormous expense of carrying out vehicle fires in tunnels, a second HGV test under different ventilation conditions was not carried out in the Hammerfest tunnel. Instead a mixed fire load, similar in width to the HGV, was burned under natural ventilation conditions. The “simulated truck load” (0.8m wide, 5.4m long, 2.4m high) consisted of wooden cribs, HGV tyres and other plastic materials. In this test the fire grew fairly steadily to a maximum HRR of about 16MW after 10 minutes.

3. The EUREKA wooden crib tests in the Hammerfest tunnel

Two virtually identical wooden crib fire tests were carried out in the Hammerfest tunnel, one with forced longitudinal ventilation at 2.2ms^{-1} (equivalent to 2.5ms^{-1} in the Channel Tunnel) and one with natural ventilation. Although the cribs were not of comparable dimensions to a HGV, they were large enough to give some information regarding the initial stages of growth of a large HGV-like fire. The cribs may be considered as if they were at the front of a larger load onto which the fire would spread after it had spread across the cribs. The HRR of the forced ventilation test grew at a slightly faster rate than that of the natural ventilation test.

4. Simulation of HGV fire in the HSE tunnel

A reduced scale fire test was carried out in the dust explosions gallery at the Health & Safety Laboratory, Buxton UK. The test was designed to model some of the features of the Hammerfest HGV test. The fire object was a mock-up of a Eurotunnel HGV carrier and HGV containing a fuel tray filled with kerosene. The ventilation in the initial stages of the fire was 3.7ms^{-1} , equivalent to 6.4ms^{-1} when scaled to full scale (equivalent to the Channel Tunnel dimensions). An example of the Froude scaling calculations is shown in Scheme 5â, overleaf. Although the geometry of the fuel load was that of a solid object, much of the fuel itself was liquid, so the behaviour of the fire may be substantially different to that of a real HGV – this will be discussed later in the chapter. The fire in this test grew to a full scale equivalent of 156MW in 5 minutes.

5. Wooden crib test in the HSE tunnel

A wooden crib fire test was also carried out in the dust explosions gallery at HSL. The ventilation velocity throughout the fire test was 1.1ms^{-1} which is equivalent to 2ms^{-1} at full scale. When scaled to full scale (Channel Tunnel) the fire load is equivalent to a very large wooden crib, or possibly a HGV-like object. The fire grew to a full scale equivalent of 22MW in 2 minutes.

6. FOA wooden crib tests in the “blasted rock tunnel”

Several wooden crib fire tests were also carried out in a small “blasted rock tunnel” (BRT) in Sweden. These were all carried out with natural ventilation. When scaled to

full scale (Channel Tunnel) the cribs may be considered to represent a HGV-like object. These tests may be used to compare with the HSE wooden crib fire test in order to estimate k for that case.

Further details of all these tests are given in Appendix A. From these experimental data, four pieces of “evidence” can be derived for our study:

- A. EUREKA HGV test with forced ventilation compared to naturally ventilated “simulated truck load.”
- B. EUREKA wooden crib test with forced ventilation compared to naturally ventilated one.
- C. HSE HGV “simulation” test with forced ventilation compared to EUREKA “simulated truck load.”
- D. HSE wooden crib test with forced ventilation compared to BRT naturally ventilated wooden crib tests.

Example: Froude scaling calculations.

Reduced scale tunnel: HSE fire gallery, Buxton, UK. Arched shape, 2.52m high, 5.6m² cross-section.

Full scale tunnel: Similar to the Channel Tunnel. Circular shape, 7.6m diameter, ~40m² cross-section.

Assuming the height / diameter of the tunnel to be the characteristic dimension, the reduced scale tunnel is approximately $1/3$ of the scale of the full scale tunnel.

Ventilation velocity scales with the square root of the length scale: $v \propto \sqrt{L}$

Heat release rate scales with the length scale raised to the $5/2$: $\dot{q} \propto (L)^{5/2}$

Hence, for the HSE “simulation” test, where the HRR was 10MW with a forced airflow of 3.7ms⁻¹, the full scale equivalents are:

$$v_{full} = \frac{v_{reduced}}{\sqrt{L}} = \frac{3.7}{\sqrt{1/3}} = 6.4 \text{ms}^{-1} \quad \text{and} \quad \dot{q}_{full} = \frac{\dot{q}_{reduced}}{(L)^{5/2}} = \frac{10}{(1/3)^{5/2}} = 156 \text{MW}$$

Scheme 5â – An example of Froude scaling calculations

5.3.4 The likelihood of each piece of evidence

For comparison, each of the reduced scale test data were scaled up to an equivalent size to the Channel Tunnel using Froude scaling criteria. Each forced ventilation test was then compared to the equivalent natural ventilation test to gain an approximate value of k_{growth} for that test, at the test airflow velocity. Estimates of the likelihood functions for each forced ventilation test were then made for each of the four ventilation velocities.

The original intention of the project was to have each of the experts estimate the likelihood distributions for each of the pieces of evidence as well as making estimates of the prior probability distribution. However, after this was tried with a few of the experts, it became clear that they regarded all experimental evidence as support for their own prior expectations. Thus, the expert who estimated that k_{growth} would have a mean value of 13 (at 6ms^{-1}) gave a high estimate of likelihood to the 8-16 range for the Hammerfest HGV test (compared to the naturally ventilated simulated truck load test), whereas the expert who estimated that k_{growth} would have a mean value of 1.5 (at 6ms^{-1}) gave a high estimate of likelihood to the 1-2 range based on exactly the same evidence. In the end the author of this thesis estimated the likelihood distributions as he had not been part of the expert group and so was the only person involved who was able to make impartial estimates.

In the discussion that follows, all estimates of “likelihood” relate to the case of a tunnel similar in size and shape to the Channel Tunnel. The likelihood estimates were as follows:

A. In the initial stages of the HGV fire test, the ventilation velocity was 6ms^{-1} (equivalent to 6.9ms^{-1} in the Channel Tunnel). The fire in this case was ignited in the cab, not at the front of the trailer, and so the HRR of the fire was between 10 and 15MW when the fire spread to the trailer. However the fire then grew to well over 100MW in under two minutes, which is substantially faster than the growth of any of the natural ventilation tests. Comparing the rate of increase of HRR of the HGV test with the naturally ventilated tests suggests a k_{growth} value of about 25, possibly much greater, for a HGV in the Hammerfest tunnel with a forced ventilation

velocity of 6ms^{-1} (the HRR of the HGV test grew from $\sim 20\text{MW}$ to $\sim 100\text{MW}$ in just 90s after the fire spread to the trailer; this increase of $\sim 50\text{MWmin}^{-1}$ is more than 25 times greater than the maximum increase of $\sim 1.7\text{MWmin}^{-1}$ observed in the ‘simulated truck load’ test, which went from 4MW to 14MW in about 360s). For forced ventilation rates of 6 and 10ms^{-1} (in the tunnel of interest, i.e. similar to the Channel Tunnel) a “high” likelihood has therefore been given for k_{growth} values in the 16-32 range, whereas for ventilation rates of 2 and 4ms^{-1} , a “high” likelihood has been given for k_{growth} values in the 8-16 range. “Medium” and “low” likelihood values are allocated around these ranges in accordance with the amount of uncertainty (as the test was carried out at 6ms^{-1} , the estimated likelihood function for 2ms^{-1} has more uncertainty than for 4ms^{-1}). The likelihood “distributions” for the EUREKA HGV test are shown in Figure 5.05.

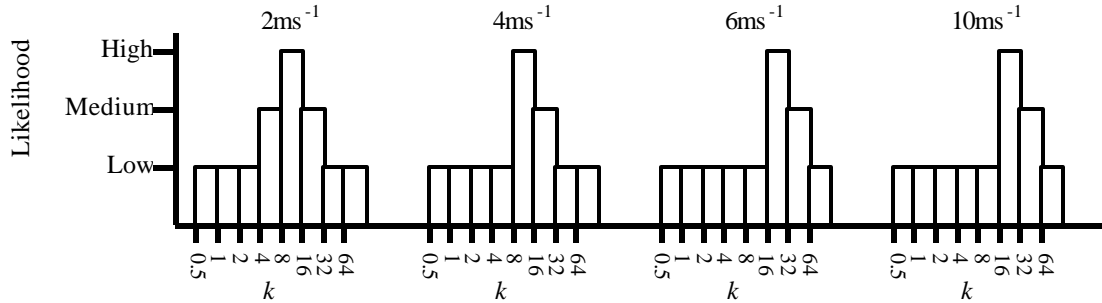


Figure 5.05 – The likelihood distributions for the EUREKA HGV test at 2, 4, 6 and 10ms^{-1} (see footnote^Q below)

B. The wooden crib test was carried out in the Hammerfest tunnel with a forced ventilation velocity of 2.9ms^{-1} (equivalent to 3.3ms^{-1} in the Channel Tunnel). Data from this test (HRR scaled up to Channel Tunnel dimensions) were compared with data from the naturally ventilated wooden crib test in that tunnel and with naturally ventilated crib tests in the BRT (also scaled up to Channel Tunnel dimensions). Figure 4.01 compares the HRR – time graphs of the naturally ventilated wooden

^Q When interpreting the likelihood graphs in this thesis, the reader should bear in mind that all estimates of likelihood are made for discrete ranges of k . The graphs should not be interpreted as giving any indication of the value of likelihood at precise values of k . For example, the only bar with high likelihood at 2ms^{-1} on Figure 5.05 represents the k range from 8 to 16, it does not mean that likelihood is very high at the precise values $k = 8$ or $k = 16$. This applies to all likelihood graphs in this thesis.

crib fire test in the Hammerfest tunnel with the forced ventilation test. It is clear from those graphs that the gradient of the graph in the initial stages of the fire is significantly steeper for the test with forced ventilation than it is for the test with natural ventilation. At its greatest rate of increase of HRR in the early stages of the fire, the HRR of the naturally ventilated fire grew by about 6.5MW in a five minute time period (2 to 7 minutes after ignition; 1.30MWmin^{-1}). The HRR of the forced ventilation test grew by about 8.2MW in the same time period at its greatest rate of increase (4 to 9 minutes after ignition; 1.64MWmin^{-1}). Thus k_{growth} appears to be about $(1.64/1.30)^{1.64} \approx 1.3$ for this wooden crib with a forced ventilation velocity of about 3ms^{-1} , based on this comparison. In order to compare the HRR – time graphs of the Hammerfest wooden crib test with the naturally ventilated wooden crib tests in carried out in the BRT, the HRR data from these tests were scaled up to the same size as the Hammerfest tests using Froude scaling techniques. Comparing the gradients of the graphs in the initial stages of the fire suggests a k_{growth} value for the Hammerfest crib test of about 1.7, compared with BRT test 13, and of about 1.3 compared with BRT tests 14 and 22. Thus k_{growth} is taken to be about 1.3 - 1.7 for the Hammerfest wooden crib test with a ventilation velocity of about 3ms^{-1} . A high likelihood has therefore been allocated for k_{growth} ranges 1-2 and 2-4 at 2 and 4ms^{-1} . Medium likelihoods have been given for ranges 0.5-1 and 4-8 at 2 and 4ms^{-1} and for all ranges from 1-8 for 6 and 10ms^{-1} ventilation rates. All other ranges have been allocated a low likelihood. The likelihood distributions for the EUREKA crib fire test are shown in Figure 5.06.

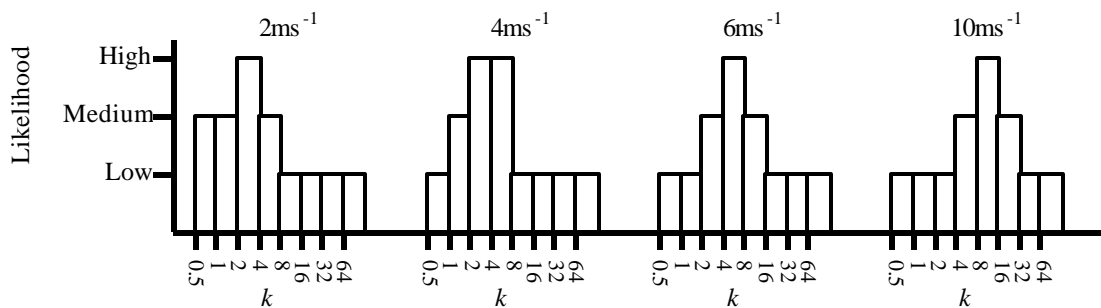


Figure 5.06 – The likelihood distributions for the EUREKA wooden crib test at 2, 4, 6 and 10ms^{-1}

C. The HGV simulation test carried out in the HSE tunnel was a $1/3$ scale model of a Eurotunnel carriage and HGV. The initial ventilation velocity was equivalent to 6.4ms^{-1} at full scale. Comparing data from this fire test with data from all the

naturally ventilated tests suggests a k_{growth} value of above 25 for a ventilation velocity of about 6ms^{-1} during the growth phase (in the Channel Tunnel geometry), although it must be noted that the development of the fire in the fuel pan in this test would be significantly different from the development of a fire in a wooden crib or a real vehicle, so these observations should be used with caution. A high likelihood has been allocated to k_{growth} range 16-32 at 4, 6 & 10ms^{-1} and to k_{growth} range 8-16 at 2ms^{-1} . Medium likelihoods have been allocated to the 4-8 range at 2 & 4ms^{-1} , to the 8-16 range at 4, 6 & 10ms^{-1} , to the 16-32 range at 2ms^{-1} and to the 32-64 range at 4, 6 & 10ms^{-1} . All other ranges have been allocated a low likelihood. Results will be discussed both using and discounting this test. The likelihood distributions for this test are shown in Figure 5.07.

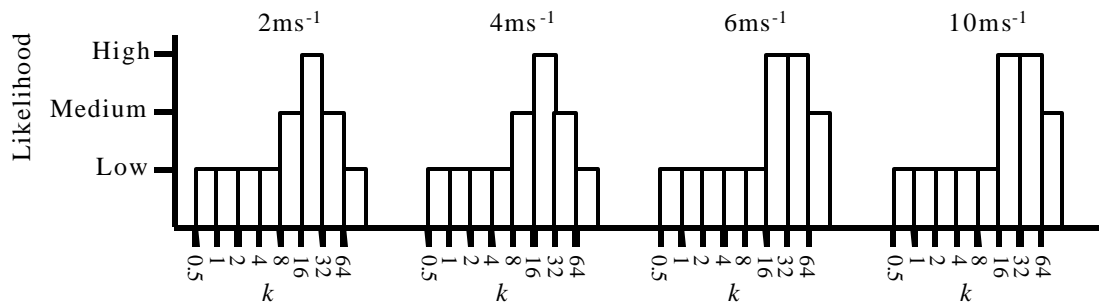


Figure 5.07 – The likelihood distributions for the HSE HGVS simulation test at 2, 4, 6 and 10ms^{-1}

D. The wooden crib test carried out in the HSE tunnel at $\frac{1}{3}$ scale had a ventilation velocity equivalent to 2.0ms^{-1} at Channel Tunnel scale. Comparing data from this test with data from all the naturally ventilated wooden crib tests (Hammerfest and BRT tests 13, 14 & 22, all scaled up to Channel Tunnel dimensions using Froude scaling techniques) suggests a k_{growth} value of between 8 and 20 for the initial stages of the fire with a 2ms^{-1} airflow. A high likelihood has therefore been allocated to k_{growth} range 8-16 for a 2ms^{-1} forced airflow, and to k_{growth} range 16-32 for all other airflow velocities. Medium likelihoods have been allocated to the ranges on either side of the highs and all other ranges have been allocated a low likelihood. These likelihood distributions are shown in Figure 5.08.

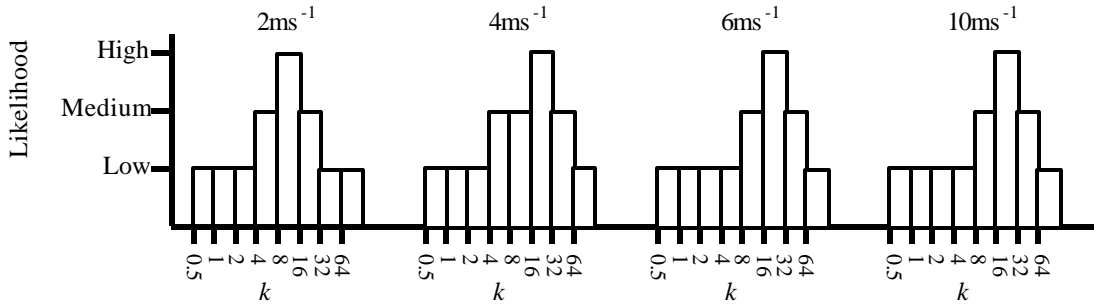


Figure 5.08 – The likelihood distributions for the HSE wooden crib fire test at 2, 4, 6 and 10ms⁻¹

5.3.5 Calculations

The prior probability distributions, based on the estimates of the expert panel, were refined using Bayes' theorem with the likelihood values allocated for the four pieces of experimental evidence described above. An example of the calculations is shown in scheme 5ã, overleaf.

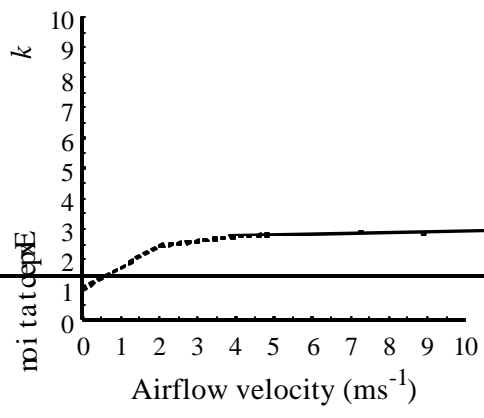
The posterior probability distributions are shown in Figure 5.10. The expectation of k_{growth} for each case was calculated using the Bayesian estimator:

$$E(k_{growth}) = \sum k_i P(k_{growth} = k_i / E_J) \quad [5.2]$$

Given that the k_{growth} ranges are not uniform in their spans, it is necessary to calculate the expectation of n , where $k = 2^n$, first and from that calculate $E(k)$. For the ranges considered, $n_1 = -0.5 \pm 0.5$, $n_2 = 0.5 \pm 0.5$, ..., $n_8 = 6.5 \pm 0.5$.

$$E(n) = \sum n_i P(n = n_i / E_J) \quad [5.3]$$

The variation of the expectation of k with ventilation velocity is shown in figure 5.09.



Example: Bayesian calculations for HGV fire in a tunnel (similar to the Channel Tunnel) with a forced ventilation velocity of 6ms^{-1} .

Prior probability distribution:

k_{growth} range:	0.5-1	1-2	2-4	4-8	8-16	16-32	32-64	64+
Probability:	0.024	0.48	0.243	0.146	0.048	0.024	0.024	0.024

(see Scheme 5á)

Likelihood \underline{A} : Low Low Low Low Low High Med Low

(see Figure 5.05)

(assuming Low = 1, Med = 2 and High = 4; this will be discussed fully in section 6.8)

Bayes' theorem can be expressed as:

$$P(k_{growth} = k / E) = \frac{P(E / k_{growth} = k)P(k_{growth} = k)}{\sum_i P(E / k_{growth} = k_i)P(k_{growth} = k_i)} \quad (\text{from equation [3.2]})$$

where $P(E / k_{growth} = k)$ is the likelihood of the evidence, E , and $P(k_{growth} = k)$ is the prior estimate of probability.

There are eight equations, one for each of the k_{growth} ranges: (see overleaf)

Thus:
$$P(k_{growth}=0.5-1/E_{\underline{A}}) = \frac{(1) \times (0.024)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.024}{1.109} = 0.022$$

and
$$P(k_{growth}=1-2/E_{\underline{A}}) = \frac{(1) \times (0.480)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.480}{1.109} = 0.433$$

and
$$P(k_{growth}=2-4/E_{\underline{A}}) = \frac{(1) \times (0.243)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.243}{1.109} = 0.219$$

and
$$P(k_{growth}=4-8/E_{\underline{A}}) = \frac{(1) \times (0.146)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.146}{1.109} = 0.131$$

and
$$P(k_{growth}=8-16/E_{\underline{A}}) = \frac{(1) \times (0.048)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.048}{1.109} = 0.043$$

and
$$P(k_{growth}=16-32/E_{\underline{A}}) = \frac{(4) \times (0.024)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.096}{1.109} = 0.087$$

and
$$P(k_{growth}=32-64/E_{\underline{A}}) = \frac{(2) \times (0.024)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.048}{1.109} = 0.043$$

and finally
$$P(k_{growth}=64+/E_{\underline{A}}) = \frac{(1) \times (0.024)}{(1 \times 0.024) + (1 \times 0.480) + (1 \times 0.243) + (1 \times 0.146) + (1 \times 0.048) + (4 \times 0.024) + (2 \times 0.024) + (1 \times 0.024)} = \frac{0.024}{1.109} = 0.022$$

Scheme 5ã – Page 2 of 3 – Bayesian calculations^R

^R The likelihood values used here have not been converted into probabilities for reasons of clarity. Technically, the likelihood values used in Bayesian equations do not need to be probabilities as they occur on the top and bottom of all equations and, essentially, normalise themselves.

Posteriors A: 0.022 0.433 0.219 0.131 0.043 0.087 0.043 0.022

These posterior values were then used as prior values for the next Bayesian update using evidence B:

Likelihood B: Low Low Med High Med Low Low Low

to give:

Posteriors B: 0.013 0.261 0.265 0.318 0.052 0.052 0.026 0.013

Again, these posterior values were then used as prior values for the third update using evidence C:

Likelihood C: Low Low Low Low Low High High Med

to give:

Posteriors C: 0.010 0.209 0.212 0.255 0.042 0.167 0.084 0.021

Finally, these posterior values were then used as prior values for the fourth update using evidence D:

Likelihood D: Low Low Low Low Med High Med Low

to give:

Posteriors D: 0.007 0.129 0.130 0.156 0.051 0.411 0.103 0.013

Thus, after four updates, it is estimated that there is a 41.1% probability of k_{growth} falling into the range 16-32, etc.

To calculate the expectation of k_{growth} , equation [5.3] was used:

$$E(n) = \sum n_i P(n = n_i / E_J) \quad \text{where } n_1 = -0.5, n_2 = 0.5, \dots, n_8 = 6.5$$

Thus:
$$E(n) = (-0.5 \times 0.007) + (0.5 \times 0.129) + (1.5 \times 0.130) + (2.5 \times 0.156) + (3.5 \times 0.051) + (4.5 \times 0.411) + (5.5 \times 0.103) + (6.5 \times 0.013) = 3.325$$

Hence: $E(k_{growth}) = 10$, that is k_{growth} (at 6ms^{-1}) is *expected* to fall into the 8-16 range.

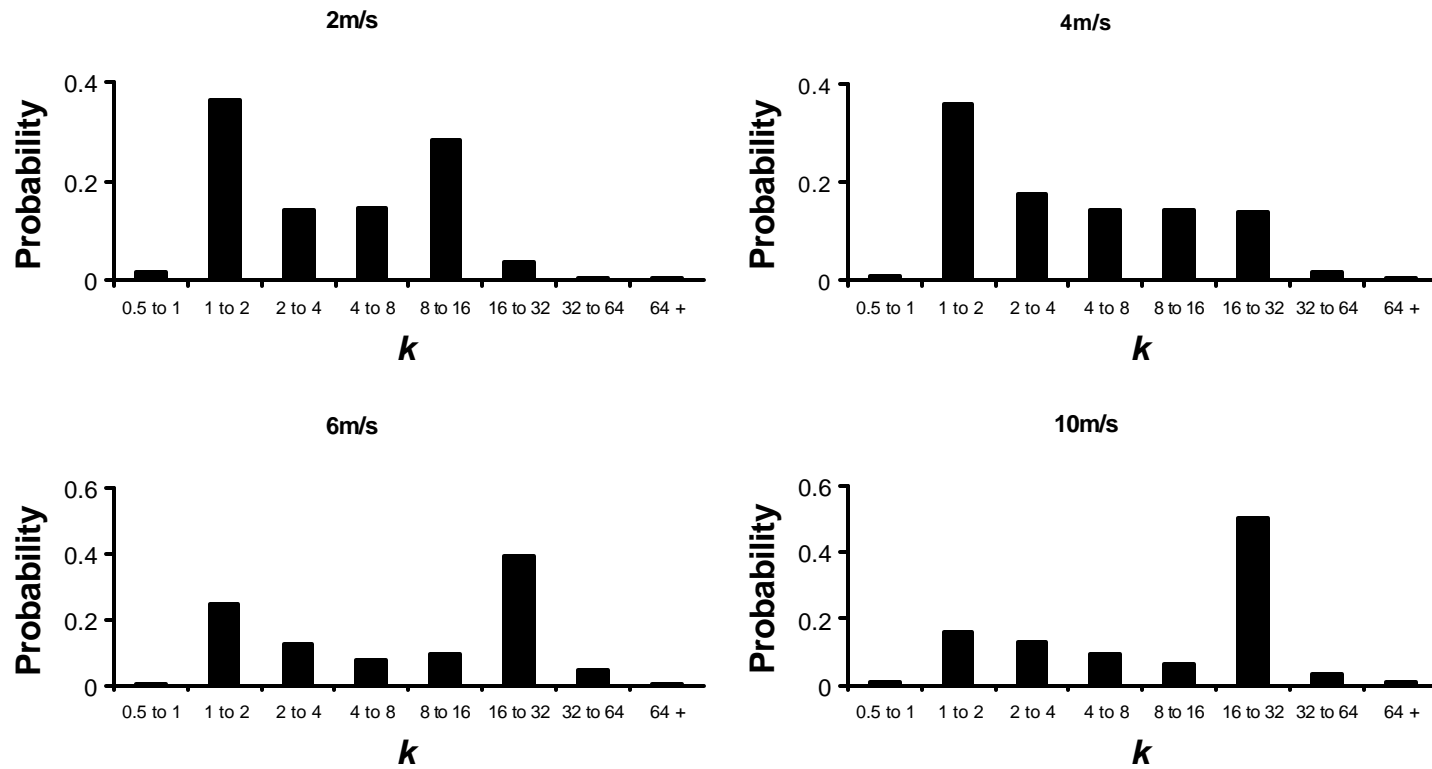


Figure 5.10 – The posterior probability distributions of k at 2, 4, 6 and 10ms^{-1} after four refinements

5.4 HGV fire at maximum heat release rate

The experts were asked to consider the same HGV fires, one with natural ventilation and one with forced ventilation, once the fires became fully involved. They were asked to estimate values of k at the maximum heat release rate (k_{peak}). Once again, the experts were asked for their estimates before the discretisation was finalised. Their estimates have once again been split up into the same k ranges as used in the k_{growth} case.

The spread of expert opinion was somewhat larger in this instance than it had been with the k_{growth} case. At 2ms^{-1} the majority of experts allocated most of the probability within the 1-2 range. Once again, only one expert allocated a low probability in the 0.5-1 range and only one expert allocated any probability within the 4-8 and 8-16 ranges. At 4ms^{-1} , while one expert allocated all his probability in the 4-8 and 8-16 ranges, the rest of the group was split, half allocating the highest probability in the 1-2 range and the other half allocating the highest probability in the 2-4 range. At 6ms^{-1} and 10ms^{-1} the pattern was mostly the same as at 4ms^{-1} except that the expert who estimated high k values gave a very high probability in the 8-16 range at 6 and 10ms^{-1} and in the 16-32 range at 10ms^{-1} , while one of the others gave a reasonably high estimate in the 4-8 range at both ventilation velocities. One expert predicted a k value of 1.0 at all four ventilation values; that is, he did not expect any change in the peak heat release rate of a HGV fire whatever the ventilation rate.

On average the expectation of the experts was that the HRR would probably be between 2 and 4 times greater for all four ventilation velocities. Once again, a prior probability distribution was built for each of the four ventilation velocities from these estimates. The prior probability distribution used in the study, overlaid with a representation of some of the experts' estimates, is shown in figure 5.11.

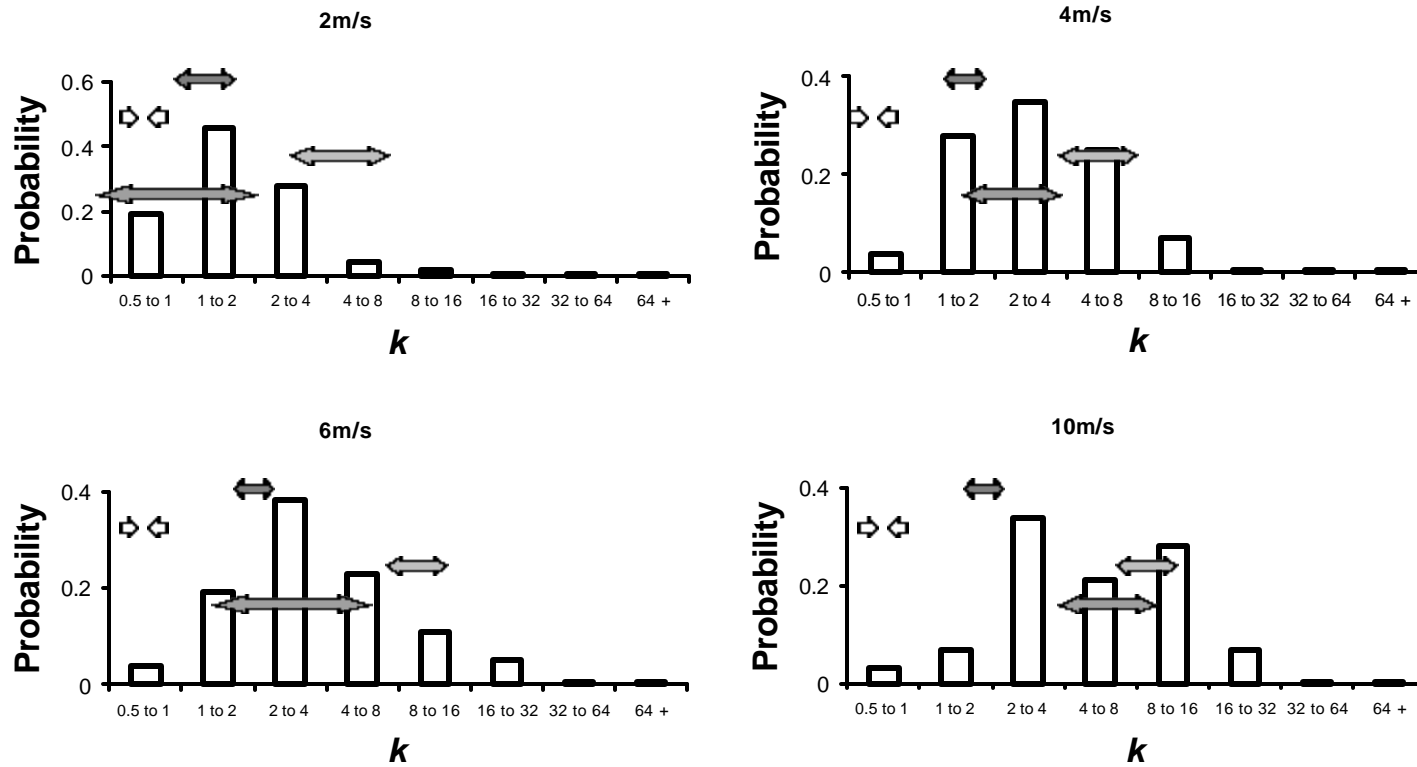


Figure 5.11 – The prior probability functions for a fully involved HGV fire, some expert estimates are overlaid to show the diversity within expert opinion.

5.4.1 The available evidence

With the exception of the EUREKA wooden crib fire tests, which were considered to be too small, all the fire tests considered in the previous part of the study were considered to be relevant to the case of the fully involved HGV fire. These were:

A. The EUREKA HGV fire test in the Hammerfest tunnel

The HGV fire test reached a maximum HRR of about 120-130MW with a forced longitudinal ventilation velocity of 6ms^{-1} (equivalent to 6.9ms^{-1} in the Channel Tunnel). Then the ventilation was switched off causing a dramatic reduction in HRR; it should be noted that the HRR of the fire may not have reached its maximum value when the ventilation was switched off. When the ventilation was re-started at 2.9ms^{-1} (equivalent to 3.3ms^{-1} in the Channel Tunnel) two minutes later, the HRR rose to about 130MW once more before levelling off at about 120MW.

B. The EUREKA simulated truck load test in the Hammerfest tunnel

As noted earlier the simulated truck load test reached a maximum HRR of about 16MW with natural ventilation.

C. Simulation of HGV fire in the HSE tunnel

After the initial growth phase of the fire, the ventilation was maintained at a full scale (Channel Tunnel) equivalent of 6.4ms^{-1} for 10 minutes, in which time the HRR was approximately equivalent to 156MW at full scale. Then the ventilation was reduced to the full scale equivalent of 2.5ms^{-1} for 10 minutes, during which time the HRR was equivalent to 115MW at full scale. Finally the ventilation was reduced to the equivalent of 1.7ms^{-1} and the HRR dropped to the equivalent of 67MW.

D. Wooden crib test in the HSE tunnel

The ventilation in this test was maintained at 1.1ms^{-1} , equivalent to a full scale (Channel Tunnel) velocity of 2ms^{-1} . The HRR reached a peak equivalent to 25MW and stayed at approximately 20-25MW for the majority of the test.

E. FOA wooden crib tests in the “blasted rock tunnel”

The HRR of these naturally ventilated tests reached maximum values equivalent to approximately 12MW (test 13) and 10MW (test 22).

These experiments give three pieces of “evidence”:

- A. EUREKA HGV test compared with EUREKA simulated truck load
- B. HSE HGV simulation test compared with EUREKA simulated truck load
- C. HSE wooden crib fire test compared with FOA wooden crib tests

5.4.2 The likelihood of the evidence

Once again all the data were scaled up to the scale of the Channel Tunnel and were compared to each other. The likelihood distributions were calculated as follows:

A. The airflow velocity during the Hammerfest HGV test was reduced from 6.0ms^{-1} to 2.9ms^{-1} (equivalent to 6.9ms^{-1} and 3.3ms^{-1}) once the fire had engulfed the entire vehicle. Comparing the maximum HRR of the fire at each of these ventilation velocities with the HRR of the simulated truck load, gives k values of approximately 7-10 and 8-9 at 6 and 3ms^{-1} respectively. High likelihood values have therefore been allocated to the 8-16 range for 4, 6 & 10ms^{-1} and to the 4-8 range for 2ms^{-1} . Medium likelihoods have been allocated to the 4-8 range at 4, 6 & 10ms^{-1} , to the 16-32 range at 6 and 10ms^{-1} and to the 2-4 and 8-16 ranges at 2ms^{-1} . All other ranges have been allocated a low likelihood. The likelihood distributions for this test are shown in figure 5.12.

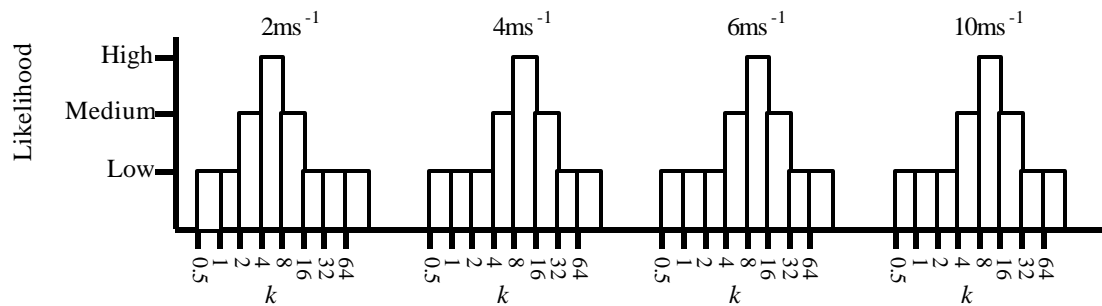


Figure 5.12 – The likelihood distributions for the EUREKA HGV test at 2, 4, 6 and 10ms^{-1}

B. A constant ventilation velocity, equivalent to 2ms^{-1} at full scale, was maintained during the wooden crib test in the HSE tunnel. Comparing the HRR data from this test with data from the naturally ventilated wooden crib tests in the BRT suggests a k value of approximately 2 at 2ms^{-1} . High likelihoods have therefore been given to the 1-2 and 2-4 ranges at 2ms^{-1} and to the 2-4 range at 4ms^{-1} . Medium likelihoods have been allocated to the 1-2 and 4-8 ranges at 4ms^{-1} . All other ranges have been allocated a low likelihood.

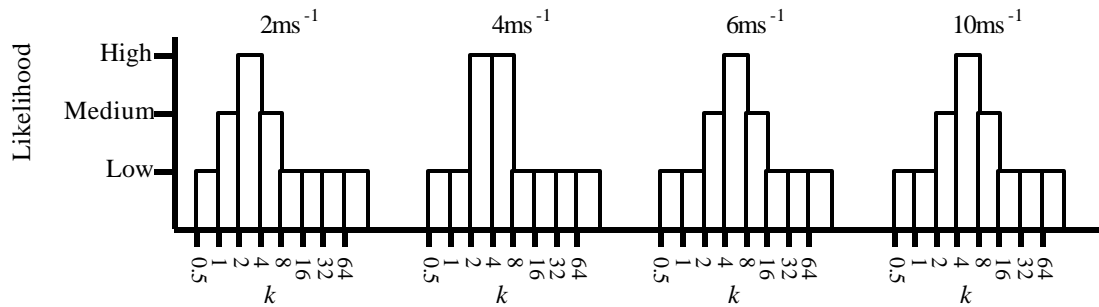


Figure 5.13 – The likelihood distributions for the HSE wooden crib test at 2, 4, 6 and 10ms⁻¹

C. During the HSE simulation test, the airflow velocity was reduced from a full scale equivalent of 6.4ms⁻¹ to 2.5ms⁻¹ and again to 1.7ms⁻¹. Comparing these HRR data with the naturally ventilated tests suggests *k* values of approximately 13, 9.5 & 5.4 for each of those ventilation velocities. High likelihood values have therefore been allocated to the 4-8 range at 2 and 4ms⁻¹, to the 8-16 range at 4, 6 and 10ms⁻¹ and to the 16-32 range at 10ms⁻¹. Medium likelihoods have been allocated to the 4-8 range at 6 and 10ms⁻¹, to the 8-16 range at 2ms⁻¹ and to the 16-32 range at 6ms⁻¹.

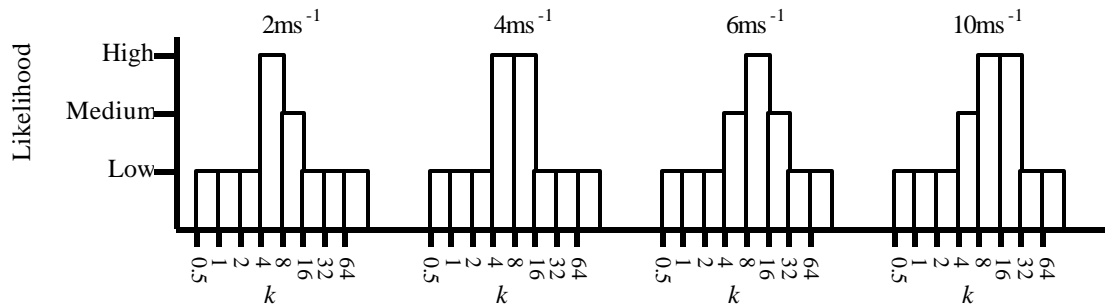


Figure 5.14 – The likelihood distributions for the HSE simulation test at 2, 4, 6 and 10ms⁻¹

5.4.3 Results

The prior probability distributions, based on the estimates of the expert panel, were again refined using Bayes' theorem with the likelihood values allocated for the four pieces of experimental evidence described above. The posterior probability distributions are shown in figure 5.15.

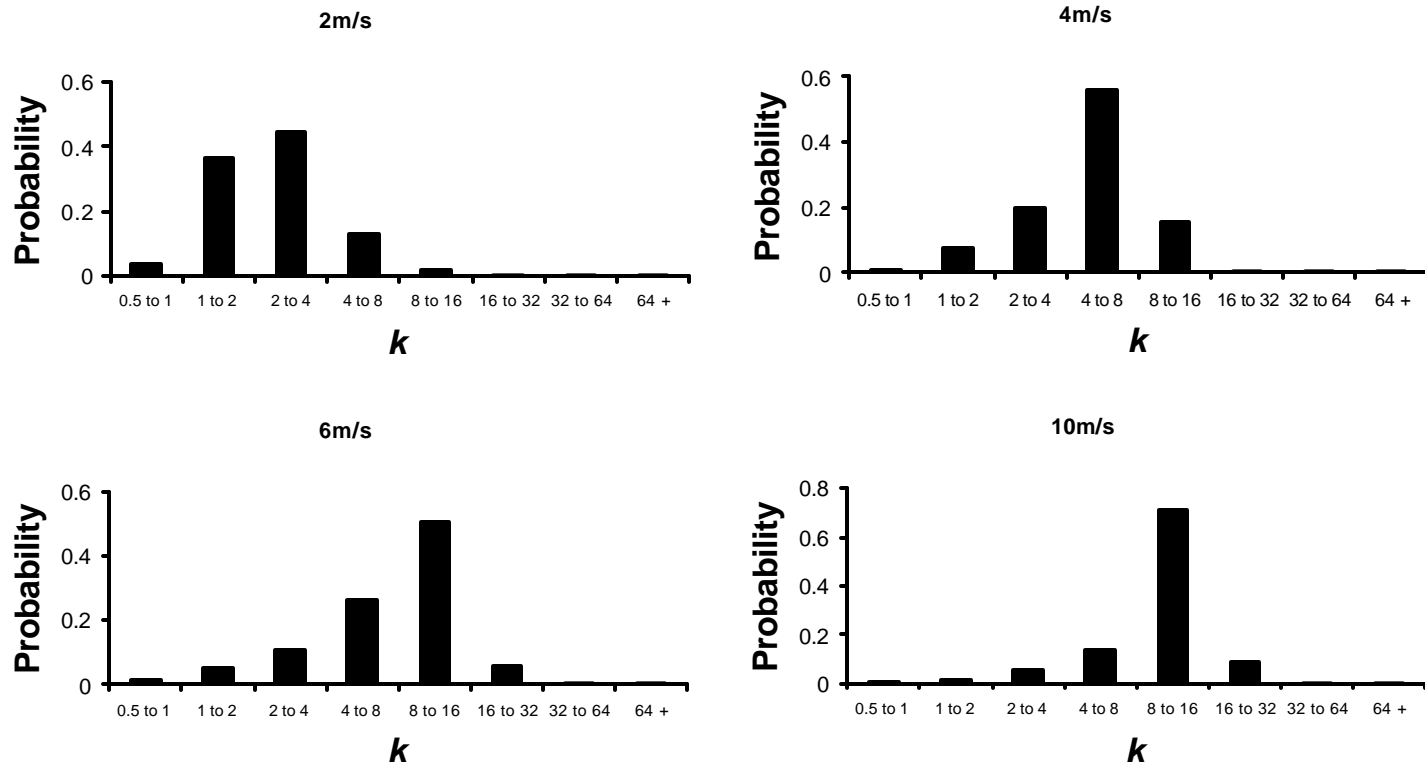
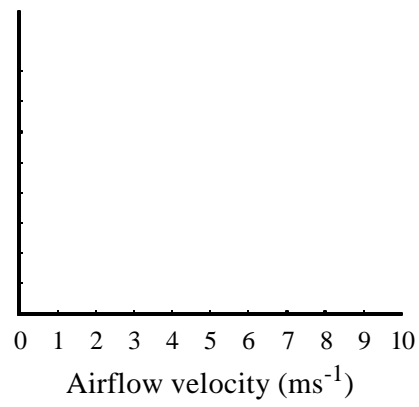


Figure 5.15 – The posterior probability distributions of k at 2, 4, 6 and 10ms⁻¹ after four refinements

The expectation of k for each case was calculated using equation [5.3] (for method see Scheme 5ã). The variation of the expectation of k with ventilation velocity is shown in figure 5.16.



5.5 The second case: pool fires in tunnels

Fuel pools or fuel spills may be virtually any size and it is reasonable to assume that the response to ventilation of fires involving these different sized pools will probably vary with size and shape. In order to take account of these variations, three different pool configurations have been considered, these are:

- (i) a pool that is short, compared to the tunnel width, in the direction of the tunnel airflow. For example a small rectangular pool, the width of the tunnel but only 1m long ($\sim 10\text{m}^2$)
- (ii) a pool that is about as long, in the direction of the tunnel airflow, as half the tunnel width. For example a square pool, half as wide as the tunnel ($\sim 25\text{m}^2$)
- (iii) a pool that is as long, in the direction of the tunnel airflow, as the tunnel is wide. For example a large rectangular pool, the width of the tunnel and over 10m long ($\sim 100\text{m}^2$).

The three example pool sizes are shown in figure 5.17.

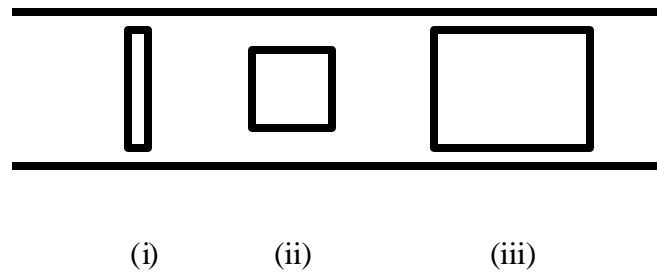


Figure 5.17 – The three example pool fire sizes

5.5.1 Choice of discrete k ranges

After examining the experimental data it seemed extremely unlikely that a pool fire would be reduced to less than half its HRR, or enhanced to as much as twice its HRR by any of the ventilation velocities considered in this study. Thus, the k ranges used in the HGV part of this study are not applicable to the case of pool fires. Instead, it was decided to discretise the span of possible k values into nine equally sized ranges:

0.4 ± 0.1 , 0.6 ± 0.1 , 0.8 ± 0.1 , 1.0 ± 0.1 , 1.2 ± 0.1 , 1.4 ± 0.1 , 1.6 ± 0.1 , 1.8 ± 0.1 and 2.0 ± 0.1

It is assumed that k for a pool fire will not be less than 0.3 or greater than 2.1 under any conditions.

5.5.2 Building the prior probability distributions

The experts were asked to consider the three example pool fire cases shown in figure 5.17. Each expert was asked to estimate the average, maximum and minimum percentage increase or decrease in HRR for a pool fire of each size, subjected to 2, 4, 6 or 10ms⁻¹, compared to natural ventilation, in the tunnel of interest (see Figure 5.01). The experts were asked to estimate in terms of percentages as it was clear (from discussions with the experts) that they found this conceptually easier than estimating in terms of k as they had in the earlier HGV case. A sample extract from one of the questionnaire forms is shown in Figure 5.18, below.

The Effect of Longitudinal Ventilation on Fire Size in a Tunnel
Case 2 – Pool fires: Estimation of “prior” values

Consider a pool fire in a tunnel with no forced airflow. At its peak, the HRR reaches a value of Q_{peak} .

Suppose a similar pool fire is burning in a tunnel with a forced airflow. Please estimate the minimum, mean and maximum deviations from Q_{peak} .

Velocity	(i) Medium sized, square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	10 % increase / decrease	20 % increase / decrease	30 % increase / decrease
4ms ⁻¹	10 % increase / decrease	0 % increase / decrease	10 % increase / decrease
6ms ⁻¹	10 % increase / decrease	20 % increase / decrease	30 % increase / decrease
10ms ⁻¹	10 % increase / decrease	30 % increase / decrease	50 % increase / decrease

“Prior” estimates of probability will be able to be estimated from these figures.

Statistically we will consider 90% of all probable fires to fall between the minimum and maximum values.

Figure 5.18 – A sample estimate sheet

As with the HGV case, there was little similarity amongst the experts’ estimates. Two of the group members predicted very small variations in k , with their maximum and minimum k values being within 5% of their estimated mean value, whereas others predicted much larger spans of k . One expert predicted that high velocity airflow could

reduce a large pool fire by as much as 80% whereas another expert predicted a maximum *increase* of 1200% for the same case. Most of the experts were agreed that ventilation would not have as extreme an effect on a pool fire as on a HGV fire.

On average the experts expected that k for a small pool fire would be about 1.0 to 1.2 at 2ms^{-1} , 1.0 at 4ms^{-1} , 0.8 at 6ms^{-1} and about 0.6 to 0.8 at 10ms^{-1} . For a medium pool fire they expected k would be about 1.0 to 1.2 at 2ms^{-1} , 0.8 to 1.0 at 4ms^{-1} , 0.8 to 1.0 at 6ms^{-1} and about 0.8 at 10ms^{-1} .

In the case of the large pool fire there was a clear split in opinion amongst the group: half the group expected that ventilation above 4ms^{-1} would cause a reduction in HRR whereas the other half expected that ventilation at these velocities would cause an increase in HRR. This division of opinion will be discussed in the next chapter. Considering these differences of opinion, the average expert expectations of k for a large pool fire, subject to a 2ms^{-1} ventilation, were about 1.0 to 1.4. They were 0.8 to 1.0 *and* 1.6 to 1.8 at 4ms^{-1} , 0.8 *and* 1.8 at 6ms^{-1} and 0.6 *and* 2.0 at 10ms^{-1} . The prior probabilities for each of the three different pool fire sizes are shown in figures 5.19, 5.20 and 5.21. Some of the experts' individual estimates are overlaid to show the diversity of expert opinion.

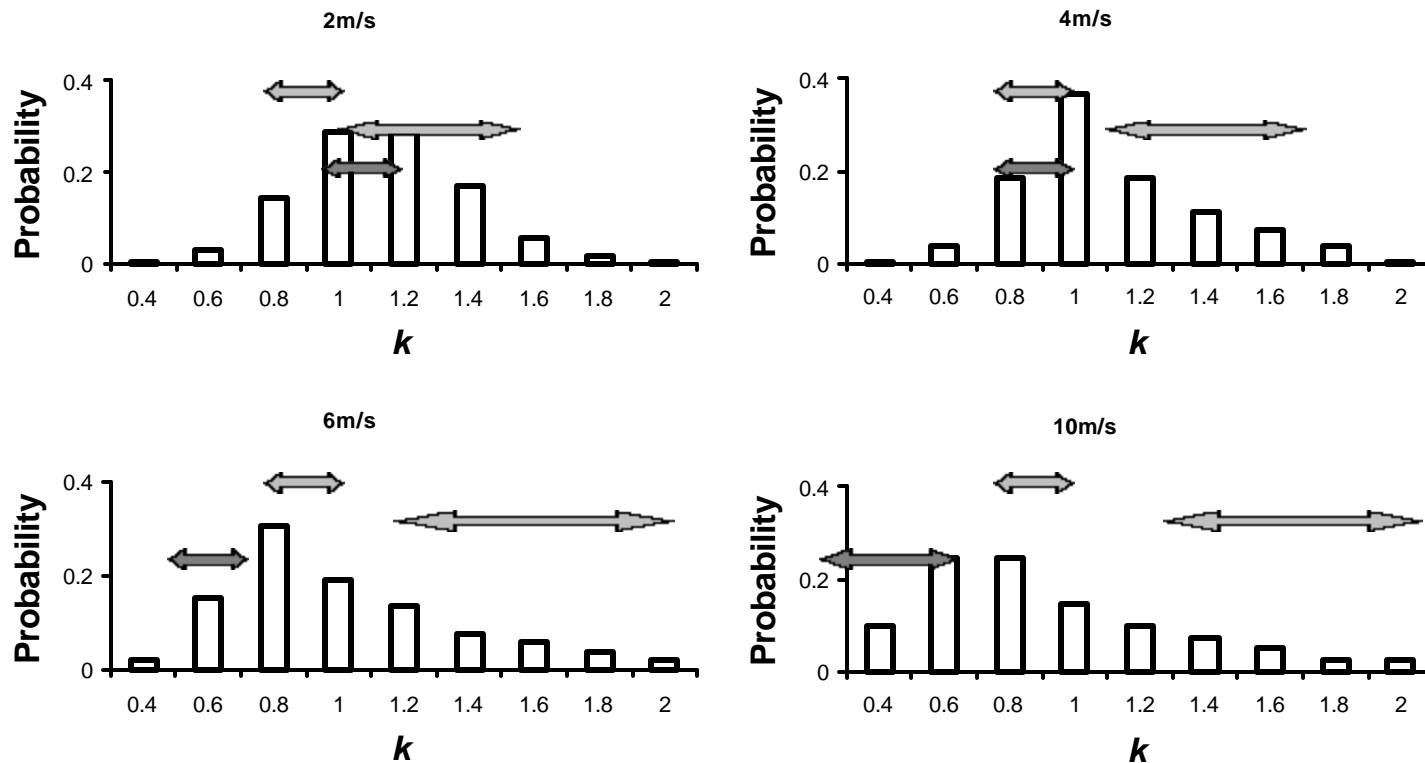


Figure 5.19 – The prior probability distributions for a small pool fire, some expert estimates are overlaid^S.

^S Similarly shaded arrows will not necessarily represent the same expert's estimates in other figures. The vertical positioning of the arrows does not signify anything.

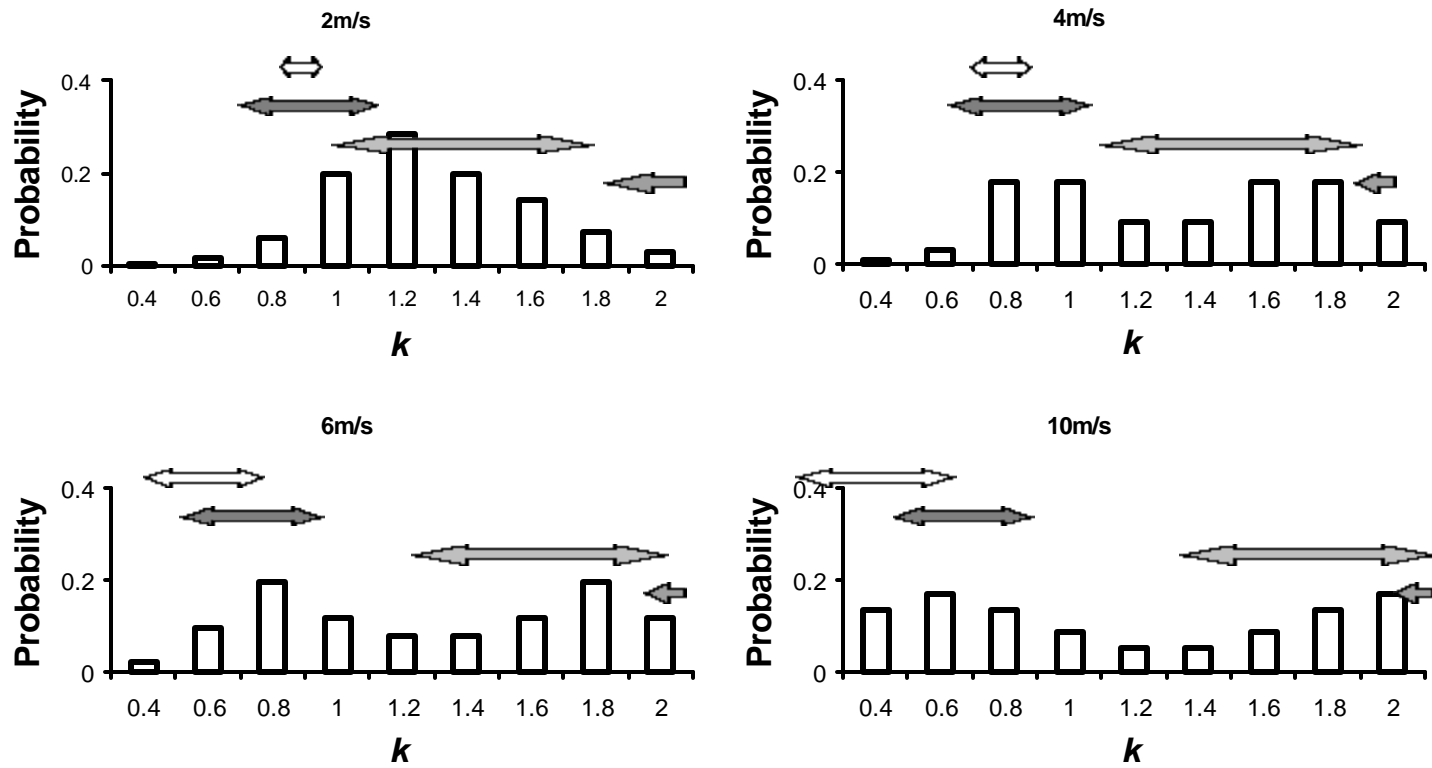


Figure 5.21 – The prior probability distributions for a large pool fire, some expert estimates are overlaid.

5.5.3 *The available evidence*

Heat release rate data from tunnel fires are rare but the majority of data that do exist are for tests involving pool fires. Only experimental reports that detail the HRR of pool fires under a range of ventilation conditions have been used to refine the estimates.

5.6 **The small pool fire**

5.6.1 *The evidence*

For the case of the small rectangular pool fire ($\sim 10\text{m}^2$) the following experimental tests were used as evidence:

1. Full scale pool fire tests in Ofenegg tunnel (two tests)

Two petrol pool fire tests, that are relevant to this case, were carried out during the Ofenegg fire test series. The same fuel pool size was used in both tests (1.7m long by 3.8m wide, 100l of fuel) but one test was carried out with a longitudinal airflow of 1.7ms^{-1} while the other was carried out with natural ventilation. Although HRR data were not recorded during these tests, it was recorded that the fuel in the naturally ventilated test was consumed in about $\frac{3}{4}$ of the time taken for the fuel in the longitudinally ventilated test to be consumed. This allows us to estimate that the HRR of the longitudinally ventilated fire was about 25% lower than the HRR of the naturally ventilated test.

2. Full scale “10MW” pool fire tests in Memorial tunnel

Three diesel pool fire tests were carried out using the smallest fuel pan, 3.66m wide by 1.22m long^T, in each test the ventilation was varied several times as the configuration of

^T The “10MW” fuel pan was 48 square feet according to the test report. The actual dimensions are not recorded but, from examination of the diagrams in the report, the small pool is assumed to be 12 feet by 4 feet (3.66m by 1.22m).

jet fans was changed. The ventilation velocities used in these tests ranged from negligible up to about 15ms^{-1} . No test was carried out with natural ventilation but there were occasions during each test when the forced airflow was negligible, so the heat release rate corresponding to these times of low airflow was used to estimate q_{nat} for each test.

3. Full scale tests in Hammerfest tunnel

Two small heptane pool fire tests, that are relevant to this case, were carried out in the Hammerfest tunnel. Both tests involved a circular pool, 1m^2 in area. In the first test the fire was started with natural ventilation, but a 1ms^{-1} forced ventilation was switched on after an hour. In the second test the ventilation was at 1.5ms^{-1} at the start of the test and was increased to 2ms^{-1} after 45 minutes.

Further details of all these tests are given in Appendix A. From these experimental data, six pieces of “evidence” can be derived for our study:

- A. The Ofenegg pool fires
- B. Memorial fire test 605
- C. Memorial fire test 606a
- D. Memorial fire test 617a
- E. Hammerfest pool fire test H11
- F. Hammerfest pool fire test H21

5.6.2 The likelihood of each piece of evidence

Although these tests were all carried out at “full scale”, the size of these tunnels is still different from the size of the hypothetical “standard” tunnel considered in this section, so Froude scaling has again been used to determine the approximate equivalent airflow velocities in the hypothetical tunnel.

In the discussion that follows, all estimates of “likelihood” relate to the case of the hypothetical two lane tunnel based on the dimensions of the “Standard 505” tunnel (see section 5.1.2). The likelihood estimates were as follows:

- A. Determination of k for the Ofenegg tunnel tests is simple, one test was carried out with natural ventilation and one test with forced ventilation at a fixed velocity, equivalent to about 2ms^{-1} in the full scale tunnel of interest. From these tests it appears likely that k is approximately 0.75 for a small pool fire subject to forced ventilation with a velocity near 2ms^{-1} . As these tests give little information about the effect of ventilation velocities other than 2ms^{-1} , no k values were allocated a high likelihood for any of the higher ventilation velocities.

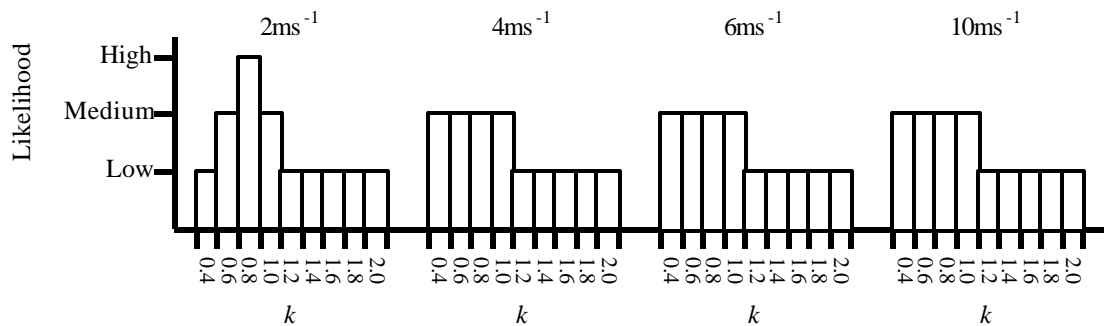


Figure 5.22 – The likelihood distributions for the Ofenegg pool fire tests at 2, 4, 6 and 10ms^{-1}

- B. Determining values of k for the Memorial tunnel tests is not as straightforward, in each of the three fire tests the ventilation velocity was varied throughout the test, so estimates of k have been made by comparing the HRR when the forced ventilation was minimal with when it was approximately 2, 4, 6 or 10ms^{-1} (the

scales of the Memorial tunnel and the tunnel of interest are approximately the same). Memorial test 605 showed a clear increase in k at 4 and 10 ms^{-1} , a significant reduction in k at 6 ms^{-1} and no particular variation at 2 ms^{-1} , so likelihood values have been chosen accordingly. It may appear unlikely that the ventilation at 6 ms^{-1} would have the opposite effect to ventilation at 4 and 10 ms^{-1} , but it would be “unBayesian” to modify or discount this evidence just because it doesn’t seem to make sense at first glance.

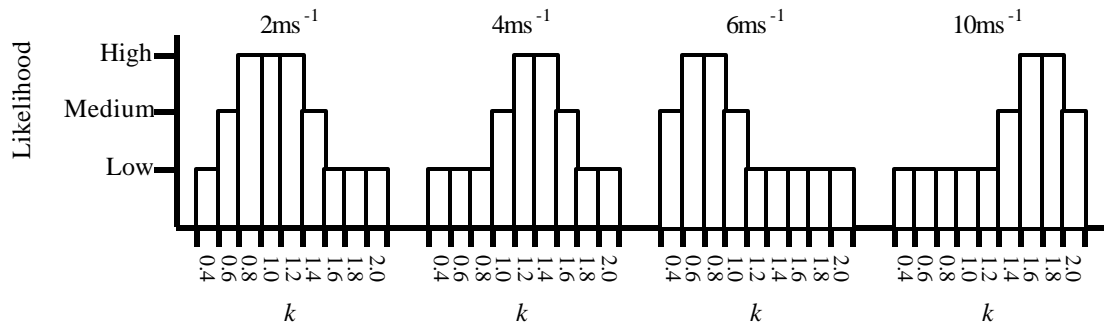


Figure 5.23 – The likelihood distributions for Memorial pool fire test 605 at 2, 4, 6 and 10 ms^{-1}

C. Test 606a showed a small increase in k at 4 ms^{-1} and a small reduction at a ventilation rate of 2 ms^{-1} .

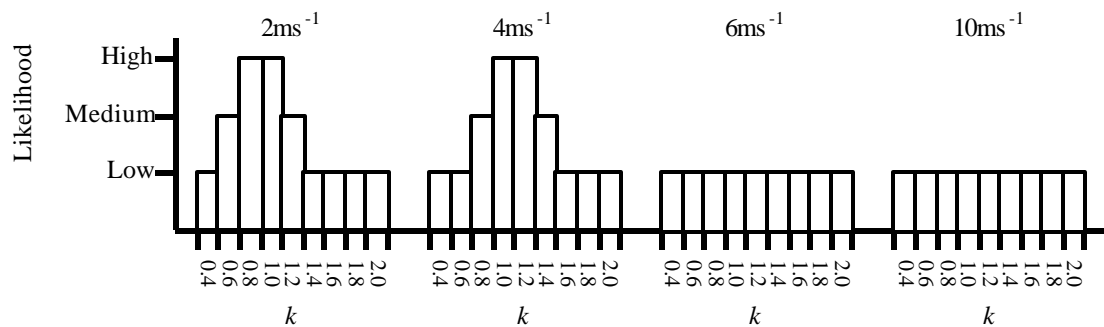


Figure 5.24 – The likelihood distributions for Memorial pool fire test 606a at 2, 4, 6 and 10 ms^{-1}

D. In test 617a the HRR of the fire was slightly enhanced on one occasion by a forced airflow of 4 ms^{-1} but was slightly diminished by forced airflow of the same magnitude at a different time in the test. Forced ventilation at 6 ms^{-1} had a similar effect, exhibiting both an increase and a decrease in k at different times

during the test. This test showed no significant variation in HRR at 2ms^{-1} . The likelihood values were chosen to reflect these variations.

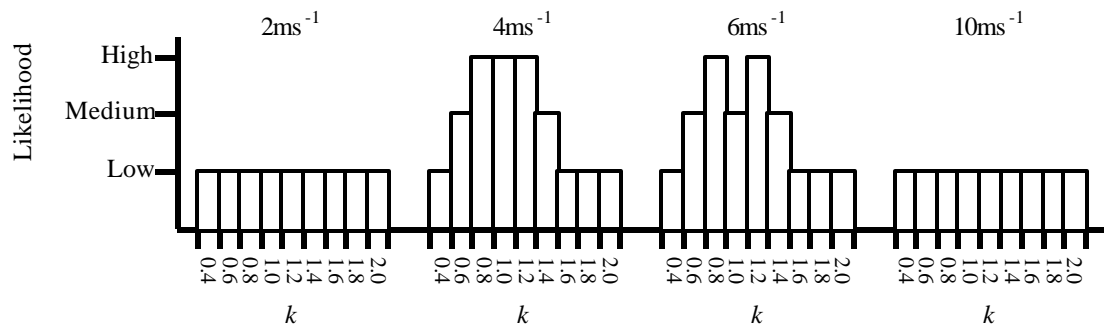


Figure 5.25 – The likelihood distributions for Memorial pool fire test 617a at 2, 4, 6 and 10ms^{-1}

E. In Hammerfest test H11, low forced ventilation was switched on midway through the test; there was no significant variation of HRR, so k is assumed to be close to 1.0 for 2ms^{-1} (in the tunnel of interest). This test does not give any information for higher airflow velocities.

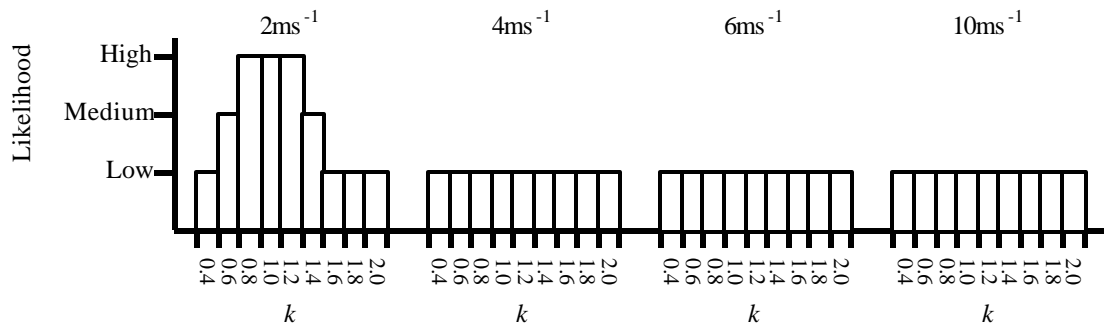


Figure 5.26 – The likelihood distribution for Hammerfest pool fire test H11 at 2, 4, 6 and 10ms^{-1}

F. In test H21 a forced airflow of 2ms^{-1} was switched on midway through the test (this corresponds to a full scale ventilation rate of slightly higher than 2ms^{-1}), and the HRR increased by about 20%, so k is assumed to be about 1.2 for 2ms^{-1} (in the tunnel of interest) in this instance. This test does not give any information for higher airflow velocities.

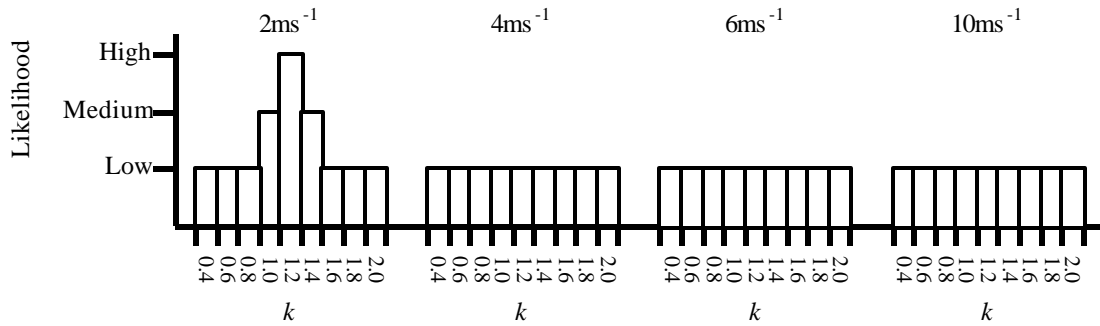


Figure 5.27 – The likelihood distributions for Hammerfest pool fire test H21 at 2, 4, 6 and 10ms⁻¹

5.6.3 Calculations

The prior probability distributions, based on the expert estimates, were refined using Bayes' Theorem with the six likelihood distributions described above. The posterior probability distributions are shown in figure 5.29. The expectation of k for each ventilation velocity was calculated (using equation [5.2]). The variation of the expectation of k with ventilation velocity is shown in figure 5.28.

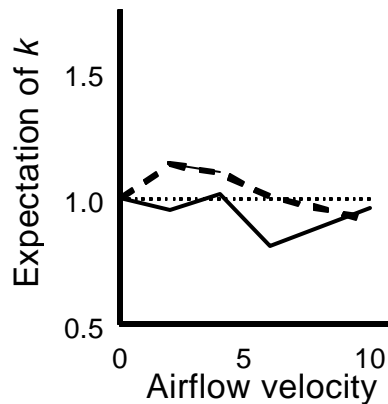


Figure 5.28 – The variation of the expectation of k with ventilation velocity for a small pool fire in the tunnel of interest (see figure 5.01b). The solid line represents the expectation based on the posterior probability distributions, the broken line represents the expectation based on the experts' prior estimates.

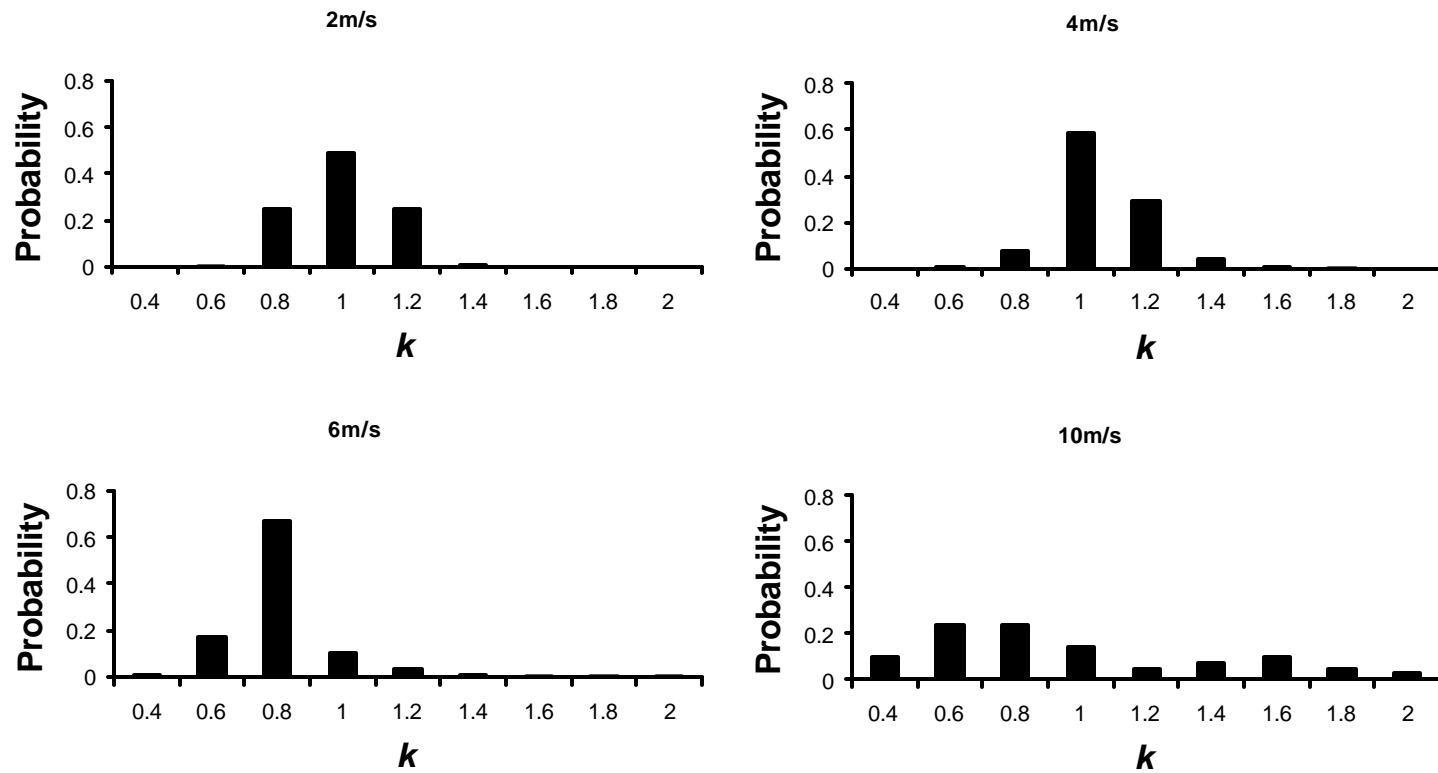


Figure 5.29 – The posterior probability distributions of k for a small pool fire (in the tunnel of interest) at 2, 4, 6 and 10ms⁻¹ after six refinements

5.7 The medium pool fire

5.7.1 The evidence

The following experimental tests were used as evidence for this case:

1. Medium scale kerosene pool fire tests in mine roadway tunnel

A number of pool fire experiments were carried out at the Londonderry Occupational Safety Centre, Australia. Of these, three tests were carried out using the same size pool but with different ventilation velocities of 0.5, 0.85 and 2.0ms⁻¹. No natural ventilation test was carried out. It was observed that the HRR of the fire was decreased with increasing ventilation velocity. The HRR of the 2ms⁻¹ test was 25% less than the HRR of the 0.5ms⁻¹ test.

2. Small scale heptane pool fire tests in wind tunnel

Five heptane pool fire tests were carried out using a circular pool, half the width of the tunnel, in the Japanese lab scale wind tunnel. The ventilation velocities in these tests varied from 0.43ms⁻¹ to 1.3ms⁻¹, this is equivalent to ventilation velocities of 2.15ms⁻¹ to 6.50ms⁻¹ in the tunnel of interest. As with the previous evidence, it was observed that increasing the ventilation velocity brought about a decrease in HRR; the HRR at the highest ventilation velocity was $\frac{1}{3}$ the HRR of the test with the lowest ventilation velocity.

3. Small scale methanol pool fire tests in wind tunnel

A large number of tests were carried out in the Japanese lab scale tunnel using methanol fuel. These used a number of different sizes of pool and a range of ventilation velocities. In each case it was observed that increasing the ventilation rate brought about a decrease in HRR; this effect was more significant with the larger pool sizes.

4. Full scale heptane pool fire test in Hammerfest tunnel (test H32)

One pool fire test was carried out using a 3m² pool in the Hammerfest tunnel. The forced ventilation rate was increased from 1.5ms⁻¹ to 3ms⁻¹ 45 minutes into the test. There was a slight reduction in HRR (11MW to 10MW) associated with this change in ventilation conditions.

None of the experimental tests used in this part of the study were carried out with natural ventilation, so exact values of k for each test with forced ventilation cannot be calculated, however trends in the variation of k can be observed, and thus approximate values of k can be predicted for each piece of evidence.

Further details of all these tests are given in Appendix 1. From these experimental data, six pieces of “evidence” can be derived for our study:

- A. The three kerosene tests carried out in the Australian mine roadway
- B. The five heptane tests carried out in the Japanese lab tunnel
- C. The 25cm methanol pool size tests carried out in the Japanese lab tunnel
- D. The 20cm methanol pool size tests carried out in the Japanese lab tunnel
- E. The 15cm methanol pool size tests carried out in the Japanese lab tunnel
- F. The heptane test carried out in the Hammerfest tunnel

5.7.2 The likelihood of the evidence

All the experiments used as evidence in this part of the study were carried out at a smaller scale than the tunnel of interest. All of the experimental data have therefore been scaled up to the scale of the tunnel of interest using Froude scaling criteria before being used as evidence. As before, all estimates of “likelihood” referred to below relate to the case of the hypothetical two lane tunnel based on the dimensions of the “Standard 505” tunnel (see section 5.1.2). The likelihood estimates were as follows:

- A. The three mine roadway experiments were considered as one piece of “evidence” for the likelihood calculations. Although there was no natural ventilation test in this series, it is clear that increasing the ventilation velocity from a very low forced ventilation rate causes a reduction in the HRR of the pool fire. A further increase causes a further reduction. Clearly there is a low likelihood that k will have a value at or above 1.0 for any of the four ventilation velocities considered in this study. It also appears likely that the value of k will decrease with increasing ventilation velocity.

The tunnel used for these experiments was much wider than it was high. This poses a slight problem when trying to apply Froude scaling rules; is the “characteristic dimension” of the tunnel its width (5.4m), its height (2.4m), its mean hydraulic diameter^U (3.3m) or some other dimension? Depending on which of these dimensions is chosen to scale up to “full scale” (10.1m wide, 6.4m high, 7.6m \bar{H}), the HRR of the fire tests can vary by more than a factor of two^V. When scaling this test up to full scale, the mean hydraulic diameter was chosen as this has been found to be the best dimension for Froude scaling when estimating the critical velocity (i.e. the airflow velocity required to prevent

^U Denoted \bar{H} , defined by $\bar{H} = \frac{4A}{P}$, where A and P are the cross-sectional area and perimeter of the tunnel, respectively.

^V The full scale HRRs calculated using the height of the tunnel as the characteristic dimension are 2.4 times greater than those calculated using the width of the tunnel. Values calculated using \bar{H} as the characteristic dimension are 1.7 times greater than those calculated using the width of the tunnel.

backlayering) in tunnel fire situations [21]. Using these scaling criteria, the HRR from these tests are multiplied by a factor of 8.05 to scale up to full scale, while the ventilation velocities are multiplied by a factor of 1.52.

The data from the three tests in this series show that the HRR of the pool fire subject to the full scale equivalent of a 3.04ms^{-1} airflow is 20% less than the HRR of a pool fire subject to a ventilation airflow equivalent to 0.76ms^{-1} . It is also clear that the HRR of a pool fire tends to be reduced as the ventilation velocity is increased. Thus it seems reasonable to expect that a 2ms^{-1} airflow in the tunnel of interest would reduce the HRR of a naturally ventilated pool fire by about 20%, a 4ms^{-1} airflow would reduce the HRR by slightly more than this and that 6 and 10ms^{-1} airflows would reduce the HRR further. The likelihood values for this test have been chosen to reflect these observations, see Figure 5.30.

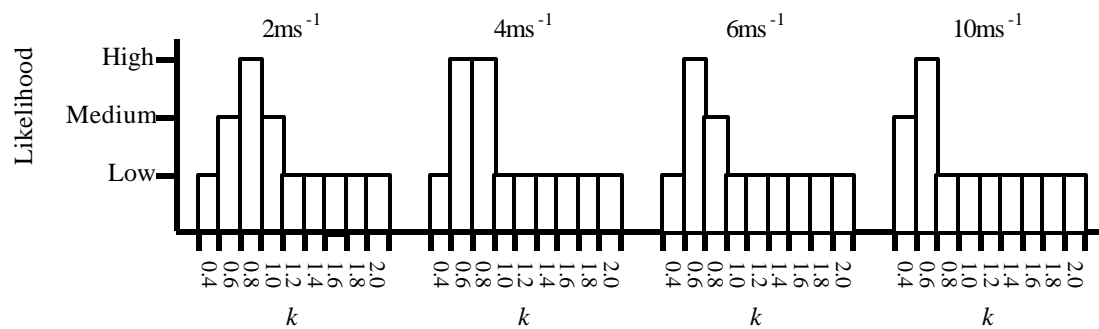


Figure 5.30 - The likelihood distributions for the mine tunnel pool fire tests at 2, 4, 6 and 10ms^{-1}

B. The five heptane pool fire tests were considered as a single piece of evidence. Again it is clear that increasing ventilation causes a decrease in k . The ventilation velocities covered by this test series range from the full scale equivalent of 2.15ms^{-1} to 6.5ms^{-1} . The HRR of a pool fire subject to the equivalent of a 6.5ms^{-1} airflow was 40% smaller than the HRR subject to 2.15ms^{-1} . Thus, it is estimated that a forced airflow of about 2ms^{-1} would cause a slight reduction in HRR and that pool fires subject to airflows of 4, 6 and 10ms^{-1} would tend to exhibit progressively smaller HRRs; the HRR of a pool fire

subject to an airflow of 6ms^{-1} would be expected to be about 60% smaller than that of a naturally ventilated pool fire. The likelihood values have been chosen accordingly, see Figure 5.31.

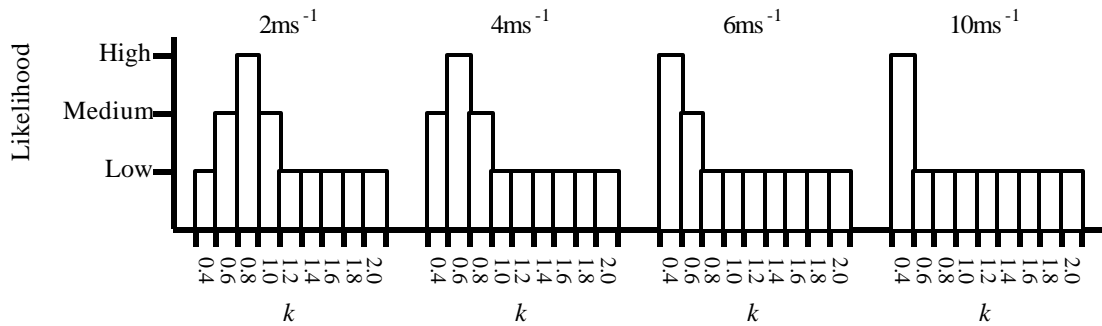


Figure 5.31 - The likelihood distributions for the heptane pool fire tests at 2, 4, 6 and 10ms^{-1}

C. The methanol pool fire tests used different sizes of pool, so these have been considered as three pieces of evidence. The first piece of evidence consists of the series of tests carried out with the 25cm pool: 83% of the width of the tunnel. Once again it is apparent that increasing the ventilation rate causes a decrease in the HRR, so it appears unlikely that k will have a value greater than or equal to 1.0 at any ventilation rate. The HRR of a pool fire subject to a ventilation rate equivalent to 1.0ms^{-1} at full scale was 45% smaller than the HRR of a pool fire subject to a ventilation rate of 0.4ms^{-1} , while there was little difference between the HRRs of the pool fires subject to ventilation velocities ranging from 1.65ms^{-1} up to 5.0ms^{-1} . Thus the likelihood of $k = 0.6$ is estimated to be high at 2ms^{-1} and it is estimated that k will be further reduced slightly at higher ventilation rates. The estimates of likelihood for this evidence are shown in figure 5.32.

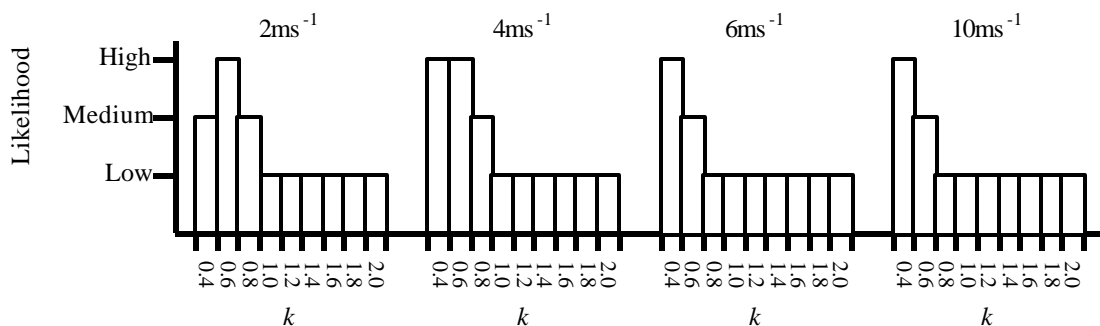


Figure 5.32 - The likelihood distributions for the 25cm methanol pool fire tests at 2, 4, 6 and 10ms^{-1}

D. A series of tests was also carried out with a 20cm pool, 66% of the width of the tunnel. Yet again it is apparent that increasing the ventilation rate caused a decrease in HRR, but the effect was not as significant as in the previous piece of evidence, the likelihood values shown in figure 5.33 reflect these observations.

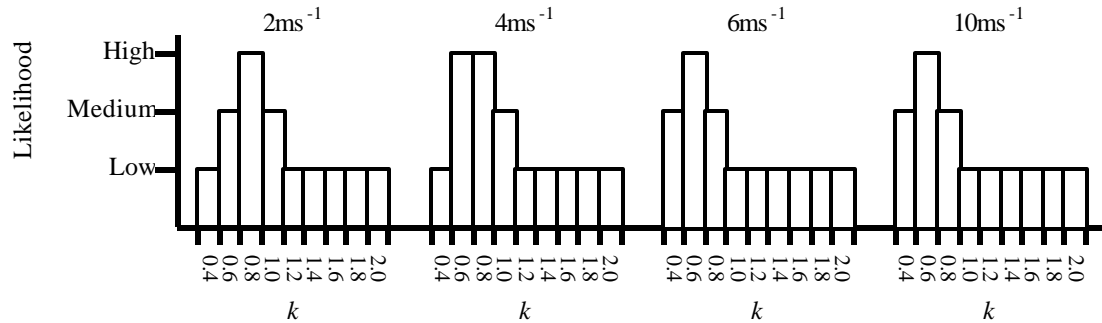


Figure 5.33 - The likelihood distributions for the 20cm methanol pool fire tests at 2, 4, 6 and 10ms⁻¹

E. A series of tests was also carried out with a 15cm pool, 50% of the width of the tunnel. Once again it was apparent that increasing the ventilation rate caused a decrease in HRR, but the effect was again not as significant as in the previous two pieces of evidence. As the range of ventilation velocities covered by this test series was quite limited (equivalent to 0.45ms⁻¹ to 2.15ms⁻¹), no “high” likelihood values have been allocated for this test series, instead the values have been chosen such that there is a medium likelihood of the fire being unchanged or reduced slightly in HRR by the influence of ventilation and there is low likelihood of the fire being increased in HRR. These likelihood values are shown in figure 5.34.

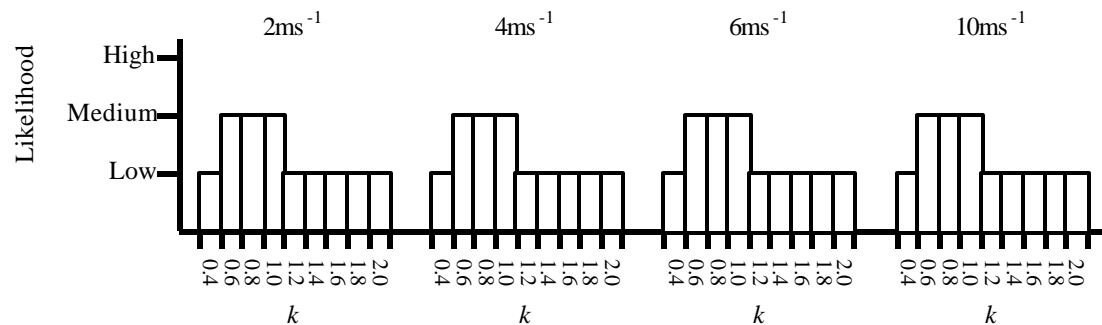


Figure 5.34 - The likelihood distributions for the 15cm methanol pool fire tests at 2, 4, 6 and 10ms⁻¹

It is interesting to note that in each of the three test series involving methanol pools (used as evidence C, D and E, above) it is clear that k tended towards a constant value as ventilation was increased. In each case, the limiting HRR appears to be similar to the HRR of a similar fire in the open air.

F. The ventilation rate for the pool fire test at Hammerfest was increased from 1.5ms^{-1} to 3.0ms^{-1} forty five minutes into the test (corresponding to ventilation velocities of 1.7ms^{-1} and 3.4ms^{-1} in the tunnel of interest). The heat release rate of the fire was observed to drop by about 10%. Clearly k is likely to be slightly less than 1.0 for ventilation rates between 2 and 4ms^{-1} in the tunnel of interest. This test does not give any information for higher ventilation rates so uniform likelihood distributions have been used for 6 and 10ms^{-1} .

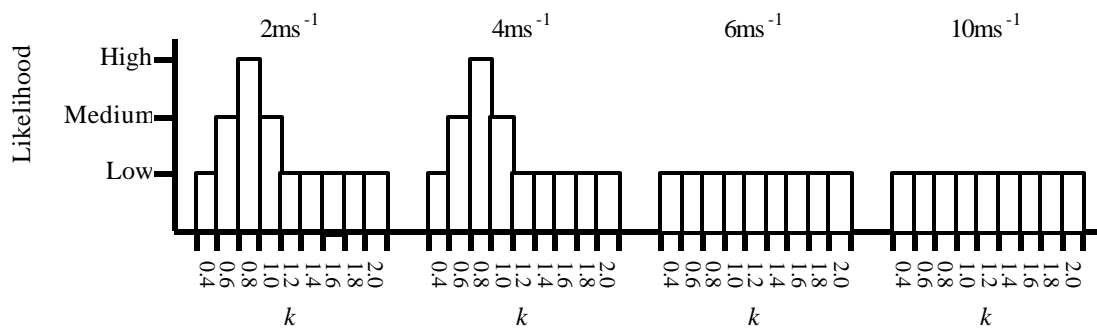


Figure 5.35 - The likelihood distributions for the Hammerfest pool fire test H32 at 2, 4, 6 and 10ms^{-1}

5.7.3 Calculations

The prior probability distributions, based on the expert estimates, were refined using Bayes' Theorem with the six likelihood distributions described above. The posterior probability distributions are shown in figure 5.37. The expectation of k for each ventilation velocity was calculated. The variation of the expectation of k with ventilation velocity is shown in figure 5.36.

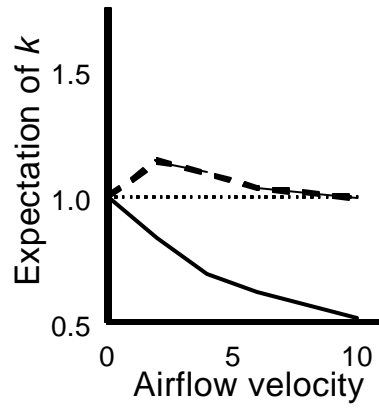


Figure 5.36 – The variation of the expectation of k with ventilation velocity for a medium pool fire in the tunnel of interest (see figure 5.01b). The solid line represents the expectation based on the posterior probability distributions, the broken line represents the expectation based on the experts' prior estimates

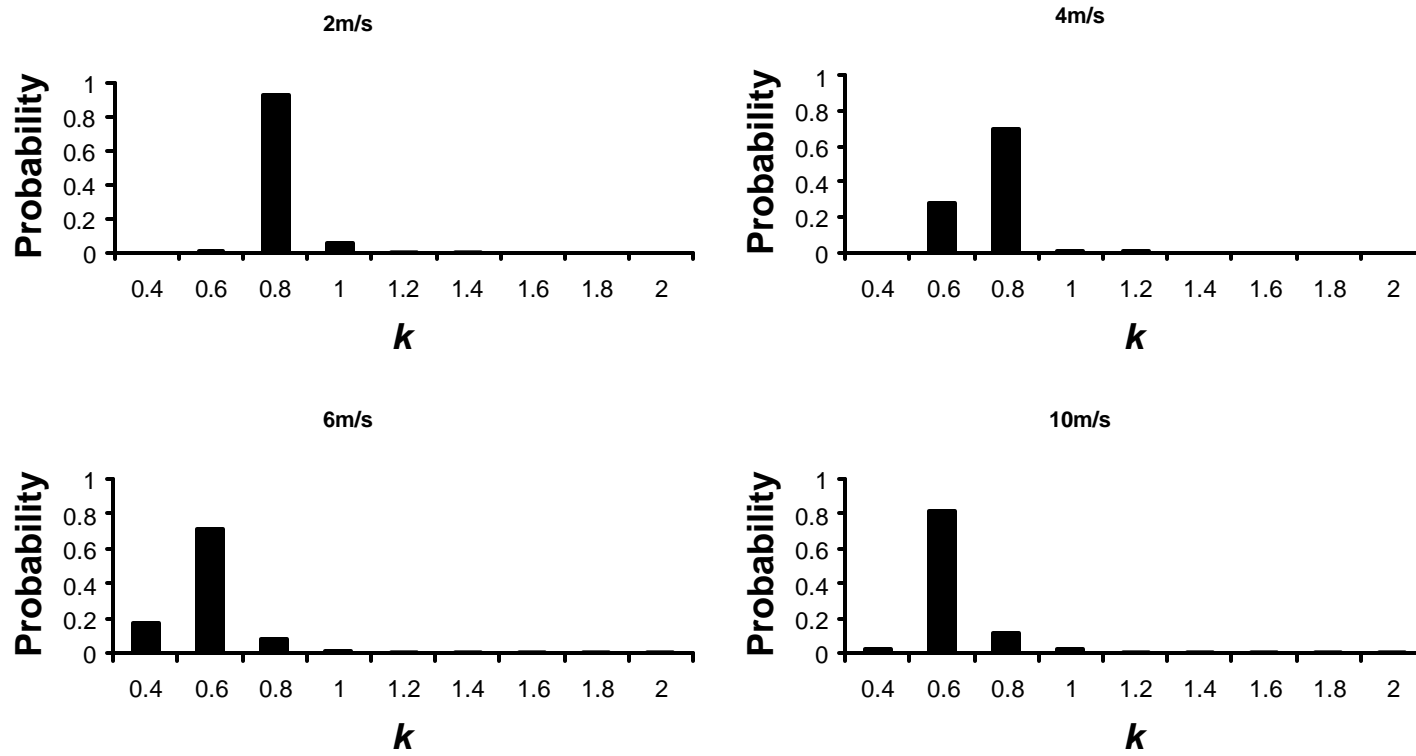


Figure 5.37 – The posterior probability distributions of k for a medium pool fire in a tunnel at 2, 4, 6 and 10ms⁻¹ after six refinements

5.8 The large pool fire

5.8.1 The evidence

For the case of the large rectangular pool fire (~100m²) the following experimental tests were used as evidence:

1. Full scale pool fire tests in Ofenegg tunnel (two tests)

Two petrol pool fire tests, that are relevant to this case, were carried out during the Ofenegg fire test series. The same fuel pool size was used in both tests (12.5m long by 3.8m wide, 500l of fuel) but one test was carried out with a longitudinal airflow of 1.7ms⁻¹ while the other was carried out with natural ventilation. Although HRR data were not recorded during these tests, it was recorded that the fuel in the longitudinally ventilated test was consumed in about $\frac{2}{3}$ of the time taken for the fuel in the naturally ventilated test to be consumed. This allows us to estimate that the HRR of the longitudinally ventilated fire was about 50% higher than the HRR of the naturally ventilated test.

2. Full scale “50MW” pool fire tests in Memorial tunnel

Five diesel pool fire tests were carried out using the largest fuel pan, 3.66m wide by 6.2m long^W, in four of the tests the ventilation was varied several times as the configuration of jet fans was changed. One test was carried out with natural ventilation.

3. Full scale “100MW” pool fire tests in Memorial tunnel

Three diesel pool fire tests were carried out using a combination of fuel pans, totalling 3.66m wide by 12.4m long, nominally 100MW. In each test the ventilation was varied several times as the configuration of jet fans was changed. No test was carried out with

^W The “50MW” fuel pan was 240 square feet according to the test report. The actual dimensions are not recorded but, from examination of the diagrams in the report, the small pool is assumed to be 12 feet wide by 20 feet long (3.66m by 6.2m).

natural ventilation but there were occasions during each test when the forced airflow was negligible, so values of k can be estimated for each test.

Further details of all these tests are given in Appendix A. From these experimental data, nine pieces of “evidence” can be derived for our study:

- A. The Ofenegg pool fires
- B. Memorial fire test 610
- C. Memorial fire test 611
- D. Memorial fire test 612b
- E. Memorial fire test 622b
- F. Memorial fire test 624b
- G. Memorial fire test 615b
- H. Memorial fire test 621a
- I. Memorial fire test 625b

5.8.2 The likelihood of the evidence

In the discussion that follows, all estimates of “likelihood” relate to the case of the hypothetical two lane tunnel based on the dimensions of the “Standard 505” tunnel (see section 5.1.2). The likelihood estimates were as follows:

A. Determination of k for the Ofenegg tunnel tests is simple, one test was carried out with natural ventilation and one test with forced ventilation at a fixed velocity (corresponding to 2.1ms^{-1} in the tunnel of interest). From these tests it appears likely that k is approximately 1.5 for a forced ventilation velocity near 2ms^{-1} . As these tests give little information about the effect of ventilation velocities other than 2ms^{-1} , no k values were allocated a high likelihood for any of the higher ventilation velocities. However, as the 2ms^{-1} airflow had a significant enflaming effect, it was assumed that all other ventilation rates would also have an enflaming effect.

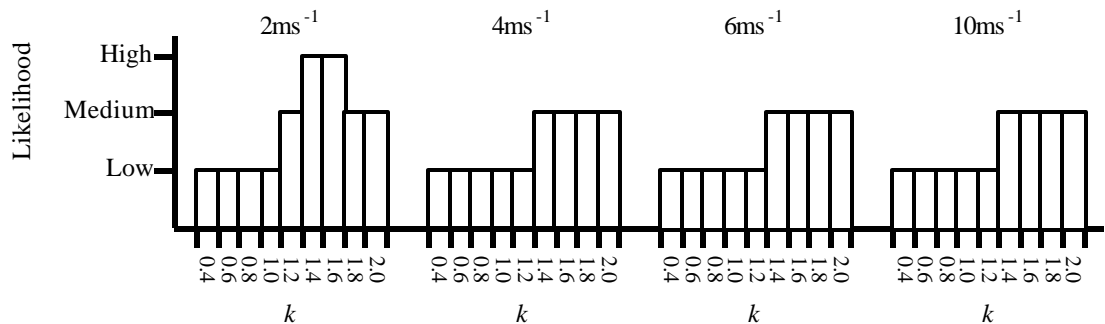


Figure 5.38 – The likelihood distributions for the large Ofenegg pool fire tests at 2, 4, 6 and 10ms^{-1}

B-F. A “50MW” fire test with natural ventilation was carried out in the Memorial tunnel, so this has been used for direct comparison with the tests with forced ventilation and accurate estimates of k have been made for each of the different ventilation velocities (the scales of the Memorial tunnel and the tunnel of interest are approximately the same). The ventilation velocity for tests 610, 612b and 624b was approximately 4ms^{-1} throughout each test, and the most likely values of k were approximately 1.2, 1.0 and 1.0 respectively. In tests 611 and 622b the ventilation was varied from 4ms^{-1} to 6ms^{-1} and k exhibited likely

values of approximately 1.0 & 1.2 in test 611 and 1.2 & 1.4 in test 622b. The likelihood distributions for these tests are shown in figures 5.39 to 5.43.

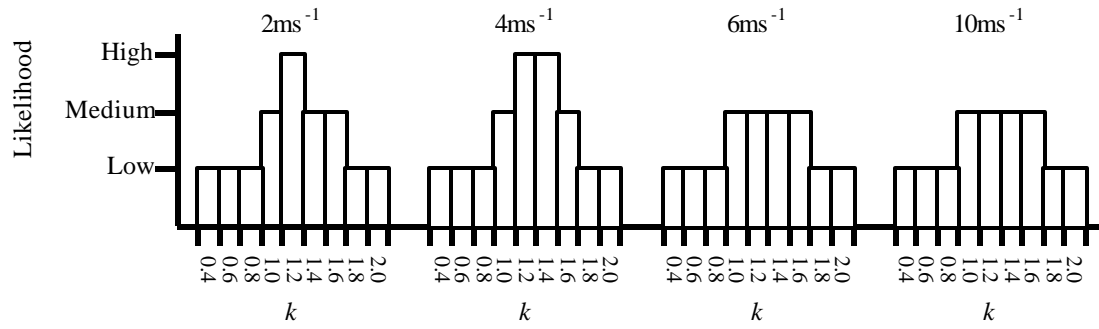


Figure 5.39 – The likelihood distributions for Memorial pool fire test 610 at 2, 4, 6 and 10ms⁻¹

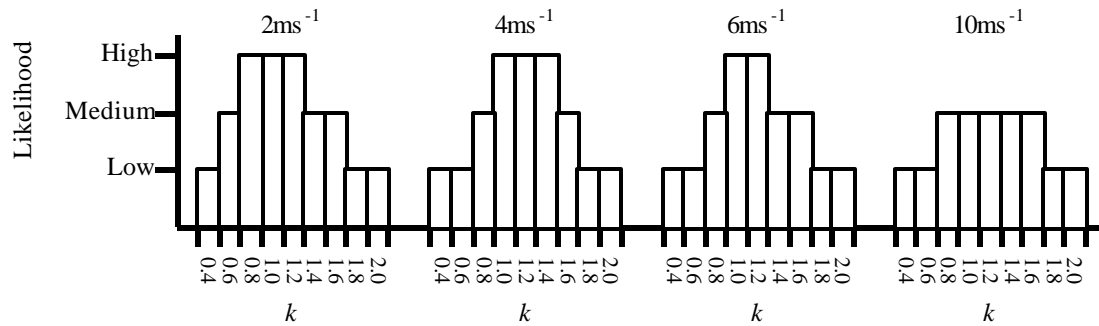


Figure 5.40 – The likelihood distributions for Memorial pool fire test 611 at 2, 4, 6 and 10ms⁻¹

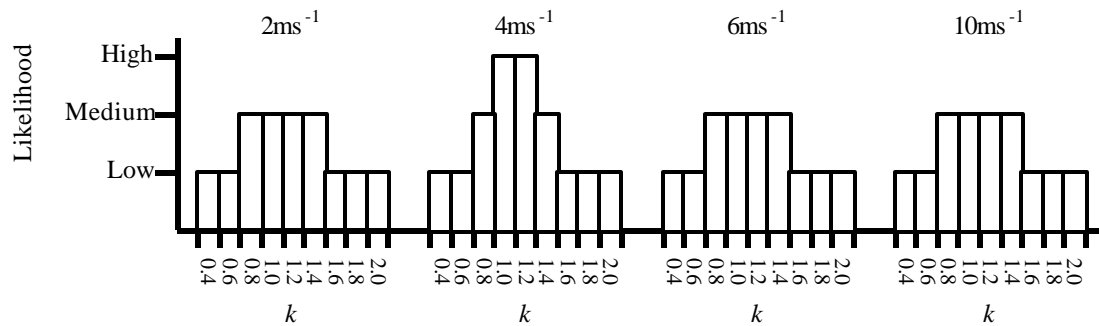


Figure 5.41 – The likelihood distributions for Memorial pool fire test 612b at 2, 4, 6 and 10ms⁻¹

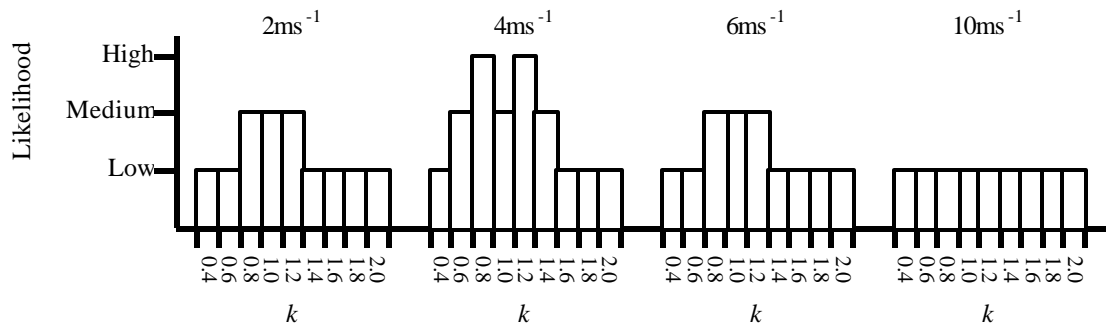


Figure 5.42 – The likelihood distributions for Memorial pool fire test 622b at 2, 4, 6 and 10ms⁻¹

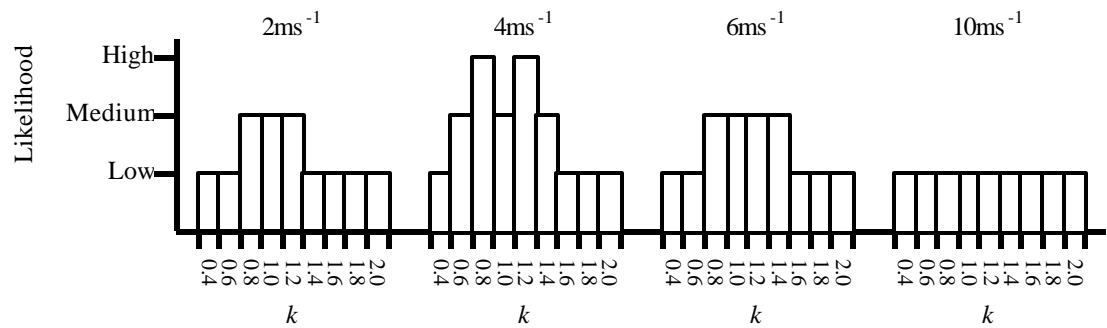


Figure 5.43 – The likelihood distributions for Memorial pool fire test 624b at 2, 4, 6 and 10ms⁻¹

There was no naturally ventilated “100MW” test carried out in the Memorial Tunnel, but estimates of likelihood have again been made, by comparing the HRR at times when the ventilation was close to zero (in practice, when it was less than 1ms⁻¹) with the HRR at times when the ventilation was at higher velocities. From an examination of the data it seems unlikely that any of these fires would have exhibited a HRR as high as 100MW under natural ventilation conditions.

- G. In test 615b, the ventilation rate was maintained at about 3-4ms⁻¹ for most of the test, however there were two instances when the ventilation was reduced to zero (and the ventilation direction was reversed), in each of these instances the HRR of the fire reduced significantly as the ventilation reduced and increased again as the ventilation increased. It is therefore assumed that *k* exhibited a value over 1 for all ventilation velocities. Furthermore, it can be observed that the HRR was

slightly higher with a forced ventilation velocity of 4ms^{-1} than with 3ms^{-1} , implying that k increases with increasing ventilation velocity. The likelihood distributions for this test are shown in figure 5.44.

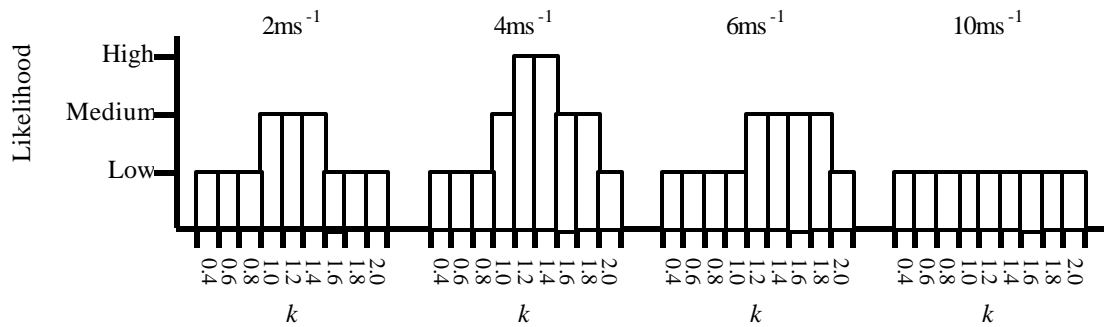


Figure 5.44 – The likelihood distributions for Memorial pool fire test 615b at 2, 4, 6 and 10ms^{-1}

H. In test 621a the ventilation rate varied between 3 and 5ms^{-1} for most of the test. By comparison with HRR data from test 615b when the ventilation rate was close to zero k appears to be over 1 for most of test 621a although the values of k corresponding to ventilation velocities around 4ms^{-1} vary from about 1.0 to 1.4. The pool fire exhibited its highest HRR when the ventilation reached its highest velocity (slightly below 6ms^{-1}) so it is assumed that k may be significantly above 1 at 6ms^{-1} . The likelihood distributions for this test are shown in figure 5.45.

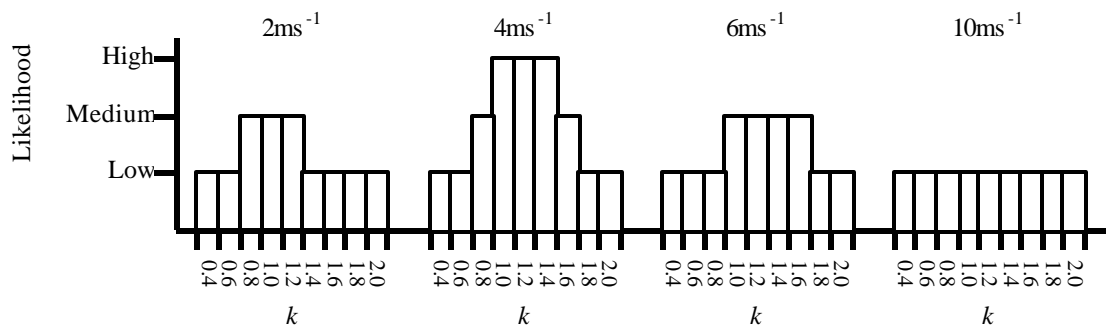


Figure 5.45 – The likelihood distributions for Memorial pool fire test 621a at 2, 4, 6 and 10ms^{-1}

I. Except in the initial stages of test 625b, where a high ventilation rate was used, the ventilation velocity was about $3\text{-}4\text{ms}^{-1}$ throughout the test. Once again (by comparison with HRR data from test 615b when the ventilation rate was close to zero), k appears to be greater than 1 for most of the test. Again, higher ventilation velocities seemed to correspond to higher HRRs, so k is assumed to increase with increasing ventilation rates. The likelihood distributions for this test are shown in figure 5.46.

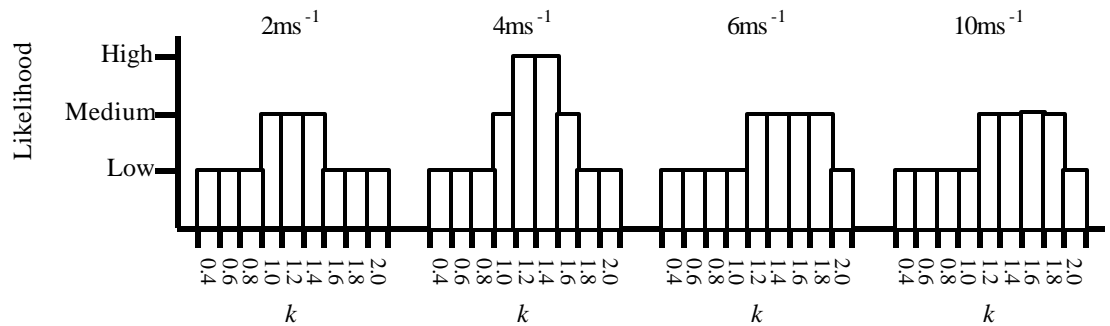


Figure 5.46 – The likelihood distributions for Memorial pool fire test 625b at 2, 4, 6 and 10ms^{-1}

5.8.3 Calculations

The prior probability distributions, based on the expert estimates, were refined using Bayes' Theorem with the nine likelihood distributions described above. The posterior probability distributions are shown in figure 5.48. The expectation of k for each ventilation velocity was calculated. The variation of the expectation of k with ventilation velocity is shown in figure 5.47.

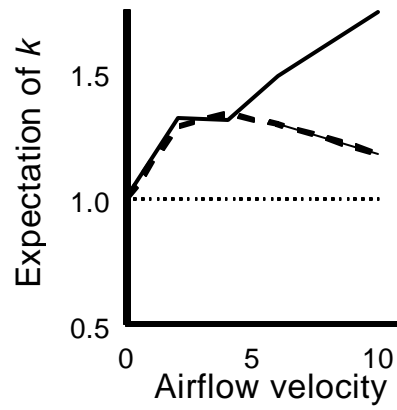


Figure 5.47 – The variation of the expectation of k with ventilation velocity for a large pool fire in the tunnel of interest (see figure 5.01b). The solid line represents the expectation based on the posterior probability distributions, the broken line represents the expectation based on the experts' prior estimates.

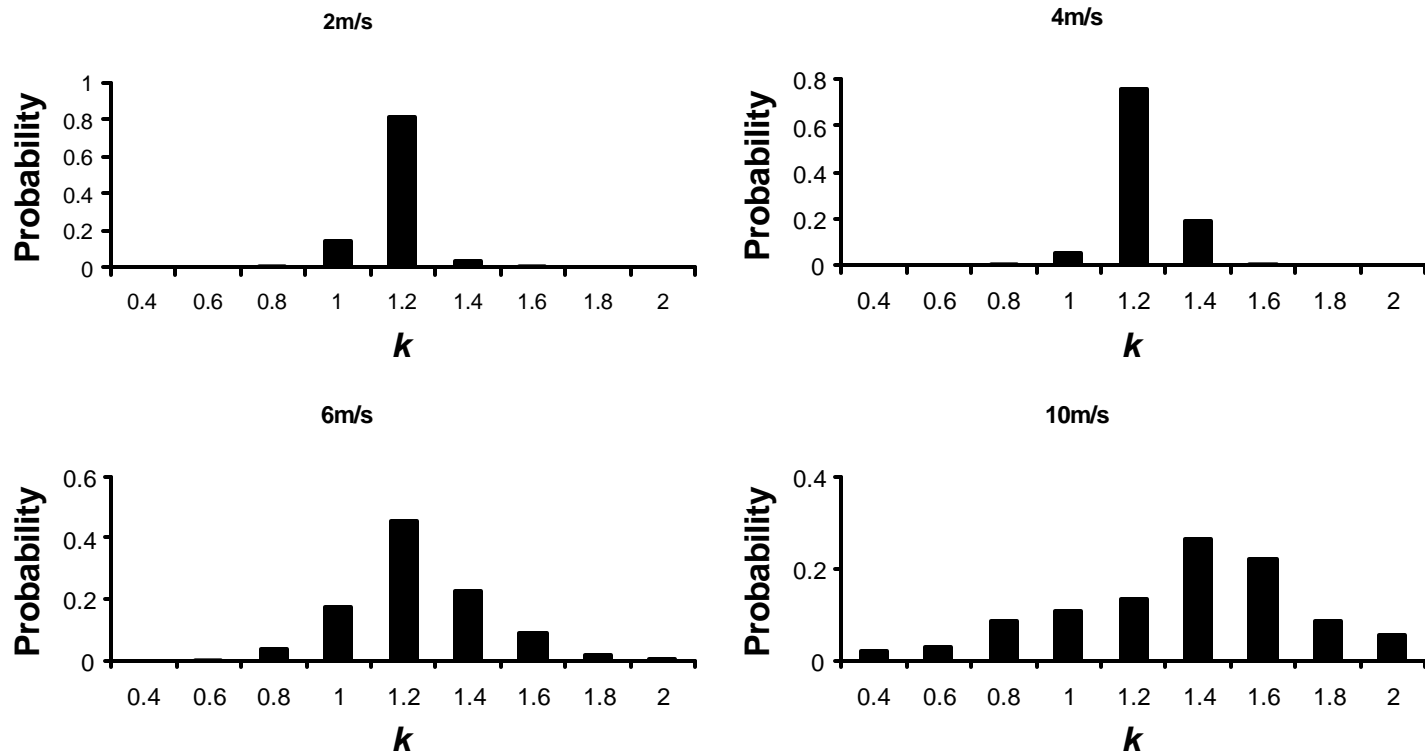


Figure 5.48 – The posterior probability distributions of k at 2, 4, 6 and 10ms^{-1} after nine refinements

5.9 The third case: car fires in tunnels

5.9.1 *Opening remarks*

When this research was carried out, in 1998-2000, there had been very few well documented car fire tests in tunnels. Furthermore, virtually all of these car fire tests had been carried out under natural ventilation conditions, making it almost impossible to attempt to predict the influence of ventilation on k for car fires in tunnels. However, it was decided that it was of value to try and estimate k for car fires with what little evidence was available, in the hope that more experimental car fire tests would be carried out in the future, and that the estimates made during this study would therefore be able to be updated and refined as more data became available.

Since then a number of car fire tests have indeed been carried out in tunnels, both with natural and forced ventilation. Sadly (for the purposes of this study) the heat release rates of these car fire tests have not been recorded; in general the tests have been carried out as demonstrations of some tunnel protection product, e.g. tunnel lining systems and sprinkler/deluge systems.

Faced with only a handful of useful car fire tests in tunnels, this part of the study had to rely on data from wooden crib fires in tunnels as well. It is likely that there will be a number of significant differences between the burning behaviour of a car and the burning behaviour of a wooden crib, but until more car fire data become available, it will have to do.

5.9.2 *Choice of discrete k ranges*

From an examination of the handful of data that exist, it was predicted that k for a car fire is unlikely to have a value less than 0.5 or greater than 3.5, so it was decided to discretise the span of possible values into:

0.5±0.25, 1.0±0.25, 1.5±0.25, 2.0±0.25, 2.5±0.25, 3.0±0.25 and 3.5±0.25

5.9.3 Building the prior probability distribution

Unlike the previous cases, the experts were not given a single tunnel configuration to consider; real and experimental car fires have occurred across the whole range of tunnel shapes and sizes. In an attempt to see if there was any variation of fire behaviour with tunnel size, the experts were asked to make estimates for a number of different tunnel shapes and sizes, ranging from the very small (10m² cross-section, similar to the blasted rock tunnel used by FOA/SP for their fire tests [86]) to the very large (80m² cross-section, three lane tunnel based on the dimensions of the Vallvidera tunnel, Italy). They were also asked to make estimates for two different sizes of car; a “mini” car (e.g. a Citroën Saxo or a Rover Metro) and a “people carrier” (e.g. a Renault Espace). As the estimation procedure had involved some conceptual difficulties for the experts in the previous cases, in this instance they were asked to make their predictions in terms of absolute heat release rates.





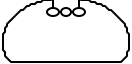
The Effect of Longitudinal Ventilation on Fire Size in a Tunnel																		
Case 3 – Car fire: Estimation of “prior” values																		
Case:	3a			3b			3c			3d			3e					
Area:	10m ²			25m ²			40m ²			50m ²			80m ²					
Lanes:	One			One			One			Two			Three					
Tunnel:																		
Please enter HRR values (in MW) and time (in minutes) for:	Min			Mean			Max			Min			Mean			Max		
	“Mini” car	HRR	Natural vent.	5	6	7	4	5	6	4	5	6	4	5	6	4	5	6
Forced 1.5ms ⁻¹			5	6	7	4	5	6	4	5	6	4	5	6	4	5	6	
Time		Natural vent.	8	1	1	8	1	1	8	1	1	1	1	1	1	1	1	
		Forced 1.5ms ⁻¹	8	0	2	8	0	2	8	1	1	1	1	1	1	1	1	
“Family” car	HRR	Natural vent.	6	8	1	6	7.	9	6	7.	9	6	7.	9	6	7.	9	
		Forced 1.5ms ⁻¹	6	8	1	6	7.	9	6	7.	9	6	7.	9	6	7.	9	
	Time	Natural vent.	1	1	2	1	1	2	1	2	1	2	1	2	1	2	1	
		Forced 1.5ms ⁻¹	0	5	0	0	5	0	0	5	0	0	5	0	0	5	0	

Figure 5.49 – A sample estimate sheet

In general it was found that the experts expected that the absolute heat release rate of a car fire in a tunnel would be greater in a smaller tunnel than a larger tunnel, but that the influence of ventilation would be proportionately the same.

For example, one expert predicted a car fire to have a HRR of 3MW in the smallest tunnel, under natural ventilation conditions, and that this would be increased to 4.5MW with a 4ms^{-1} forced ventilation velocity. They also predicted that a car fire would be 2MW in the 50m^2 two lane tunnel under natural ventilation conditions and 3MW under 4ms^{-1} forced ventilation. That is, the absolute HRR of the fires are different in different tunnels but k remains the same; $k = 1.5$ at 4ms^{-1} in this instance.

The experts predicted the same kind of behaviour for different sizes of car; although the absolute HRR of a “people carrier” is substantially larger than the absolute HRR of a “mini” car, they predicted that k would be about the same for both types of car.

At present there are not enough data to confirm or deny this predicted behaviour, for this study it is assumed that these trends in the predictions are true; that the variation of k with ventilation velocity is not significantly influenced by tunnel size or car type, even though the absolute HRR of the fire will be influenced by these factors. The influence of tunnel size and shape on the absolute HRR of vehicle fires will be discussed in Chapters 7 to 9 of this thesis.

Unlike the HGV fire and pool fire cases, there was not much disagreement within the expert group regarding the expected values of k for a car fire in a tunnel. As noted earlier, there are no well documented car fire experiments at higher ventilation velocities, so this study only considered one forced ventilation rate, 1.5ms^{-1} . The prior probability distribution was constructed by averaging the experts’ estimates, see figure 5.50.

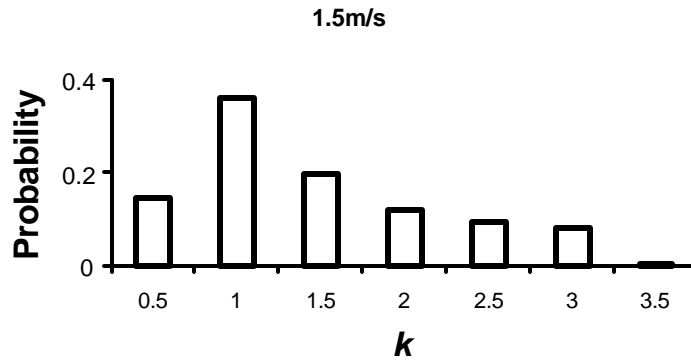


Figure 5.50 – The prior probability distribution for a car fire in a tunnel at 1.5ms^{-1}

5.9.4 Growth rates of car fires

As with the HGV case, it would be of great interest to know something about the influence of longitudinal ventilation on the rate of growth in the initial stages of the fire. Unfortunately there are insufficient well documented experimental data to tackle this question in the same way as in the HGV case. However, in order to gain some understanding of this influence it was decided to investigate the time taken for the fire to grow from ignition to its maximum heat release rate; obviously the shorter the time, the faster the growth rate. To this end the variable k_{time} was used, defined by:

$$t_{vent} = k_{time} t_{nat} \quad [5.4]$$

where t_{vent} is the time from ignition to peak HRR with forced ventilation and t_{nat} is the time from ignition to peak HRR with natural ventilation. The experts were asked to make estimates relating to the timescale of the fire. Once again there was general agreement among the experts; that a car fire subject to 1.5ms^{-1} longitudinal airflow would probably reach maximum HRR in 80% of the time taken for a naturally ventilated car fire to reach its maximum HRR, i.e. $k_{time} = 0.8$. It was decided to discretise the span of possible k_{time} values into eleven equally sized ranges:

$$0.5 \pm 0.05, 0.6 \pm 0.05, 0.7 \pm 0.05, \dots \text{ and } 1.5 \pm 0.05$$

The prior distribution of k_{time} is shown in figure 5.51.

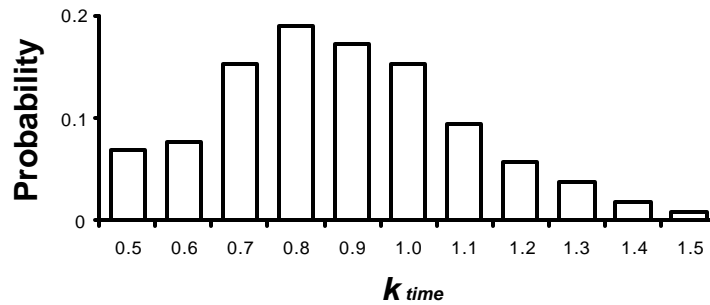


Figure 5.51 – The prior probability distribution of k_{time} for a car fire at 1.5ms^{-1}

5.9.5 The available evidence

The following experimental tests were used as evidence for the car fire case:

1. Car fire test in the Hammerfest tunnel

Heat release rate data were recorded during the fire test involving a Renault Espace people carrier in the Hammerfest tunnel. The fire reached a peak HRR of 6MW under natural ventilation conditions, but reduced to a steady HRR of about 2MW after a few minutes.

2. Car fire test in the Des Monts Tunnel

The only recorded car fire test with forced ventilation was carried out in the Des Monts Tunnel in France, with a longitudinal ventilation velocity of 1.3ms^{-1} . The only details reported about that fire were that the maximum HRR, recorded 4 minutes after ignition, was approximately 2MW.

3. Car fire test in a “blasted rock tunnel”

A Fiat 127 was burned under natural ventilation conditions in the “blasted rock tunnel” used by FOA. The fire achieved a peak HRR of about 4MW and the car burned out very quickly.

4.

D. The Hammerfest wooden crib tests compared to each other

5.9.6 *The likelihood of each piece of evidence: for k and k_{time} calculations*

In comparing fire tests in substantially different tunnels, e.g. the Fiat 127 in the 9m² blasted rock tunnel with the car fire in the 50m² Des Monts tunnel, the differences in absolute HRR were taken into account in accordance with the estimates of the experts. This will be discussed in more detail below.

A. The car fire in the Des Monts tunnel exhibited a peak HRR of 2MW, while the car fires in the Hammerfest tunnel and the blasted rock tunnel exhibited peak HRRs of about 6MW and 4MW respectively. If differences in car size and tunnel size were *not* taken into consideration, this would lead to a k value of about 0.3-0.5 for a car in the Des Monts tunnel with a longitudinal ventilation velocity of 1.3ms⁻¹. However, the Espace car burned in the Hammerfest tunnel was significantly larger than the car burned in the Des Monts tunnel, while the Fiat 127 burned in the BRT was significantly smaller; taking these differences in size into consideration would lead to estimates of k in the range 0.4-0.5 (assuming the absolute HRRs of the Espace and the Fiat would be 50% larger and 25% smaller, respectively, than the HRR of the Des Monts car).

Furthermore, the Hammerfest tunnel is substantially smaller than the Des Monts tunnel and the BRT is smaller still; these differences in size need to be accounted for as well. It is not appropriate to simply scale the data using Froude scaling as this would involve scaling up the size of the vehicle as well as the tunnel; a 5m wide Fiat 127 is incomparable to a standard sized car! At the time this part of the study was carried out, the influence of tunnel geometry on HRR (see Chapters 7-9) had not been investigated, so these changes in HRR were estimated in accordance with the estimates of the experts.

The experts predicted that the absolute HRR of a car fire in both the blasted rock and Hammerfest tunnels would be up to 33% larger than the HRR of a car fire in a tunnel the size of the Des Monts tunnel. Based on these predictions, the

Espace and the Fiat 127 would be expected to have peak HRRs of about 4.5MW and 3.0MW, respectively, in the Des Monts tunnel. Taking the differences in vehicle size into consideration gives peak HRRs of approximately 2.25MW (i.e. 50% of 4.5MW) for the Hammerfest test and 3.75MW (i.e. 125% of 3.0MW) for the BRT test. Comparing these values with the observed HRR in the Des Monts tunnel suggests a k value of about 0.6 when compared to the BRT test and 0.9 when compared to the Hammerfest test. However, on reflection, it seemed unlikely that a small Fiat 127 would burn with a HRR as high as 3MW in a fairly large tunnel, so this value was assumed to be unreliable and was not used.

Thus, by comparing the HRR of the Renault Espace (adjusted for tunnel size and vehicle size) with the estimate of HRR for the van in the Des Monts tunnel, a k value of approximately one at maximum heat release, can be estimated for a car subject to a forced ventilation velocity of 1.3ms^{-1} . It is assumed that there is little difference in k between 1.3ms^{-1} and 1.5ms^{-1} , therefore a high likelihood value has been allocated to the k value of 1.0 and low likelihoods to all other values. The timescale of this fire does not seem to be significantly faster or slower than the naturally ventilated fire tests, hence high likelihood values were allocated to the k_{time} values of 0.9, 1.0 and 1.1, medium to 0.8 and 1.2 and low at all other values.

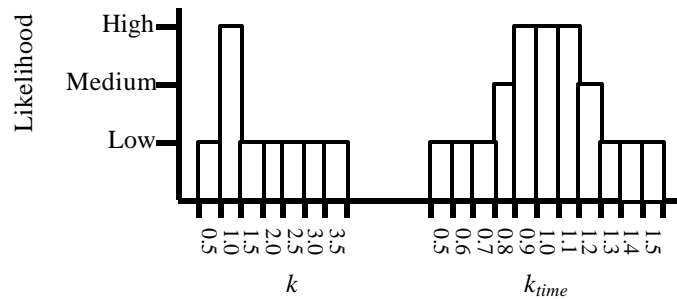


Figure 5.52 – The likelihood distributions for k and k_{time} for the Des Monts car fire test at 1.5ms^{-1}

It is interesting to note that the predictions of the experts concerning the influence of tunnel geometry on HRR do *not* correlate with the results of the study on HRR and tunnel geometry which was carried out a year later (see Chapters 7-9). From the new results it would be expected that the peak HRR of the fire in the BRT would be about

3-5 times greater^x than in the Des Monts tunnel and the HRR in the Hammerfest tunnel would be about 2 times greater than in the Des Monts tunnel. So, with hindsight, the estimate of the HRR of the Espace (adjusted for vehicle size (50%) and tunnel size (50%)) would be about 1.5MW and the estimate of the HRR of the Fiat 127 (adjusted for vehicle size (125%) and tunnel size (33 or 20%)) would be between 1.0 and 1.6MW. Hence it appears that k should have a value between 1.25 and 2.0 in this instance.

B. The wooden cribs in the Finnish tunnel were approximately 17% of the height of the tunnel and 27% of the width of the tunnel. The cribs in the BRT were 17% of the height of the tunnel and 23% of the width of the tunnel. Thus, it is appropriate to use Froude scaling to compare the HRR data from these tests. When the data from the BRT tests are scaled up to the size of the Finnish tunnel, the peak HRRs are 4.4 and 3.6MW ($\bar{H}_{BRT} \approx 3$ and $\bar{H}_{Finnish} \approx 5.2$ thus the HRR data are scaled by a factor of $(5.2/3.0)^{3/2} = 3.95$). Comparing these HRR data with the data from the first wooden crib test in the VTT tunnel (peak HRR just below 4MW) suggests a k value of about one, possibly just under. Thus a high likelihood value has been allocated to the k value 1.0, a medium value to 0.5 and low values to all other values of k for the initial fire. The growth rate of this fire seems to have been significantly slower than the naturally ventilated fire tests, hence high likelihood values were allocated to the k_{time} values of 1.4 and 1.5, medium to 1.1, 1.2 and 1.3 and low at all other values.

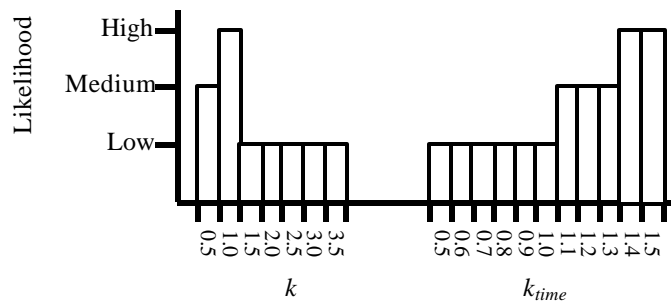


Figure 5.53 – The likelihood distributions for k and k_{time} for the initial VTT wooden crib test at 1.5ms^{-1}

^x The Fiat 127 fire test was significantly under ventilated, hence the HRR enhancement due to the tunnel ($\phi = 3.5$) was significantly less than its theoretical maximum value ($\phi = 6.2$).

C. Comparing the later crib fire test in the VTT tunnel (peak HRR = 2MW) with the blasted rock tunnel crib fire tests (scaled up HRR of 4.4 and 3.6MW) suggests a k value of significantly less than one. Thus a high likelihood value has been allocated to the k value 0.5, a medium value to 1.0 and low values to all other values of k for the later crib fires. The growth rate of this fire seems to have been slightly slower than the naturally ventilated fire tests, hence high likelihood values were allocated to the k_{time} values of 1.0 to 1.4, medium to 0.9 and 1.5 and low at all other values.

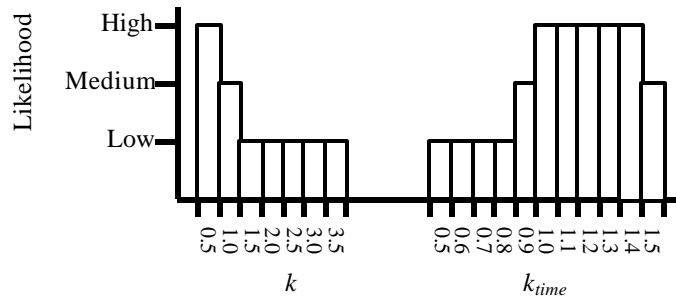


Figure 5.54 – The likelihood distributions for k and k_{time} for the later VTT wooden crib test at 1.5ms^{-1}

D. Comparing the HRR data from the two Hammerfest wooden crib tests suggests a k value of 2.8 for a forced airflow near 3.0ms^{-1} . As the velocity of interest is 1.5ms^{-1} , high likelihood values have been allocated to k values of 1.5 and 2.0, medium to 1.0 and 2.5 and low to all other values. The timescale of this fire does not seem to be significantly faster or slower than the naturally ventilated fire tests, hence high likelihood values were allocated to the k_{time} values of 0.9, 1.0 and 1.1, medium to 0.8 and 1.2 and low at all other values.

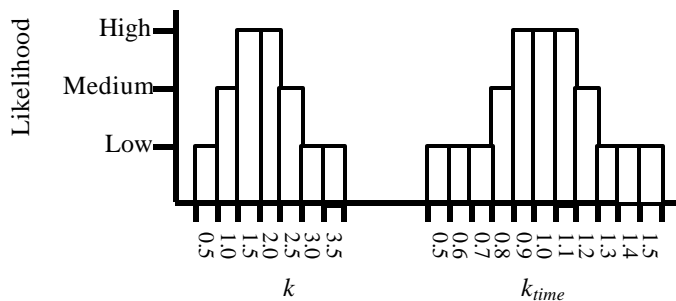


Figure 5.55 – The likelihood distributions for k and k_{time} for the Hammerfest wooden crib tests at 1.5ms^{-1}

5.9.7 Calculations

The prior probability distributions, based on the expert estimates, were refined using Bayes' Theorem with each of the likelihood distributions described above. The posterior probability distributions of k and k_{time} are shown in figures 5.56 and 5.57. The expectation of k at 1.5ms^{-1} was calculated to be very near to one. A graph of the variation of the expectation of k with increasing evidence is shown in figure 5.58.

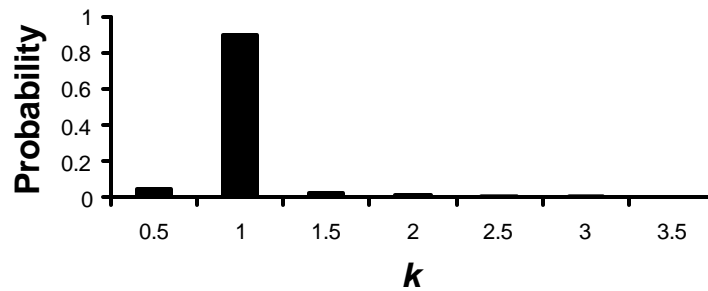


Figure 5.56 – The posterior probability distribution of k at 1.5ms^{-1} after four refinements

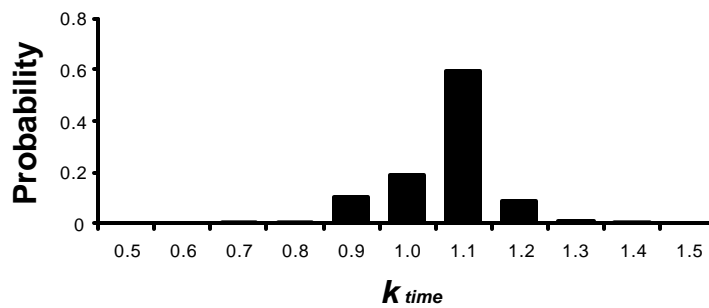


Figure 5.57 – The posterior probability distribution of k_{time} at 1.5ms^{-1} after four refinements

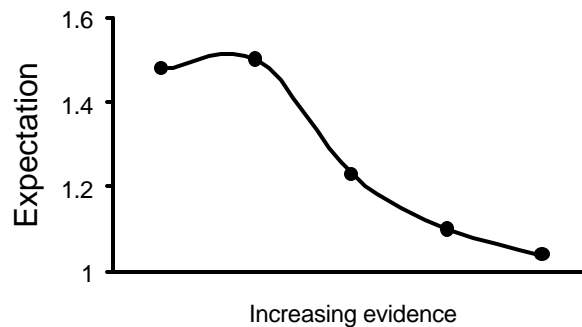


Figure 5.58 – The variation of the expectation of k with increasing evidence.

Chapter 6. Discussion of the first problem

6.1 Opening comments

Although fire safety in tunnels has become an important issue in the past decade, there are still many large gaps in our understanding of fire behaviour in tunnels; the effect of ventilation systems on fire development and size is only one of many poorly understood aspects of fires in tunnels.

Clearly the best way to fully understand influences like these would be to perform an extensive series of fire tests in a variety of tunnels, and it is hoped that such a study will be carried out at some time in the future. In the meantime, it is important to try to learn as much as possible from all the experimental results that are available, and to implement changes in practice where applicable.

At present there is no generally accepted consensus regarding the design or operation of ventilation systems for vehicle tunnels in the event of a fire. Where standards or recommendations do exist [22], they are largely based on individual judgement or experience and not on experimental results [117]. One of the most widely used tools for designing ventilation systems in tunnels (and tunnel networks) is the Subway Environment Simulation (SES) model [17,202,203]. The SES is a one-dimensional model which uses Froude number modelling to predict the ventilation conditions under which backlayering (see Section 1.2.1 and Figure 1.04) will be prevented in the considered scenario. The SES calculates the critical velocity for a user prescribed 'design fire' and takes no account of the influence of ventilation on fire size.

One of the issues highlighted by this study is the diversity of opinion amongst fire safety experts – very few of the experts expected the ventilation to have as dramatic an effect on the HRR of a HGV fire as the experimental evidence suggests, especially in the growth phase. It is clear that, if an engineering decision has to be made based on estimates alone, the opinion of one or two experts may not be enough. A method of combining expert judgement with what little experimental evidence is available is not merely desirable, but essential if the level of safety in vehicle tunnels is to be increased.

6.2 The results

In general terms the results of this part of the study may be summed up by the following statements:

- Increasing the rate of forced ventilation would be expected to cause the heat release rate of a HGV fire in a tunnel to increase substantially, compared to natural ventilation.

At 2, 4, 6 and 10ms^{-1} a HGV fire would be expected to exhibit heat release rates of about 2.5, 5, 7.5 and 10 times that of a similar naturally ventilated fire.

- Increasing the rate of forced ventilation would be expected to cause the rate of growth of a HGV fire in a tunnel to increase substantially, compared to natural ventilation.

At any given time in the growth phase, with an airflow velocity of 2, 4, 6 or 10ms^{-1} , a HGV fire would be expected to exhibit a heat release rate of about 4, 6, 8 or 10 times that of a similar naturally ventilated fire at the same time.

- Increasing the rate of forced ventilation would be expected to cause the heat release rate of a small to medium sized pool fire to decrease significantly, compared to natural ventilation.

At most ventilation velocities a small pool fire would be expected to exhibit heat release rates similar to or slightly less than that of a similar naturally ventilated fire.

At 2, 4, 6 and 10ms^{-1} a medium pool fire would be expected to exhibit heat release rates about 15%, 30%, 40% and 50% less than a similar naturally ventilated fire.

- Increasing the rate of forced ventilation would be expected to cause the heat release rate of a large pool fire to increase significantly, compared to natural ventilation.

At 2, 4, 6 and 10ms^{-1} a large pool fire would be expected to exhibit heat release rates about 30%, 30%, 50% and 70% greater than a similar naturally ventilated fire.

- Increasing the rate of forced ventilation to 1.5ms^{-1} would be expected to have little effect on the heat release rate of a car fire in a tunnel, compared to natural ventilation. It may tend to slightly slow the rate of growth of the fire.

6.3 A comment on the experts' estimates: an alternative use of Bayes' Theorem

In this part of the thesis, the main use of Bayes' Theorem has been to refine a probability distribution based on "expert opinion" with experimental data. However, during this process it has been shown that there is no consensus of opinion amongst experts; some of the experts' estimates are nearer to reality than some of the other estimates. An alternative use of Bayes' Theorem could be to assess the reliability of each of the experts' estimates using the same experimental evidence.

For example, in the case of the large pool fire, half of the expert group believed that forced airflow velocities of 4ms^{-1} and above would cause the heat release rate of the fire to decrease, whereas the other half of the group believed that increasing ventilation would cause the fire to increase in severity. This could be viewed as two rival theories, Bayes' Theorem can be used to decide which is valid.

Suppose theorem one (T_1) is "increasing ventilation will cause a large pool fire to increase in severity" and theorem two (T_2) is the contrary. Both of these theorems are allocated equal probabilities in the first instance, i.e. $P(T_1) = P(T_2) = 50\%$. These "degrees of confidence" can then be refined using the experimental data. That is, Bayes' Theorem can be used to find the posterior probability by combining these prior probabilities with the likelihood of the evidence. This likelihood can be estimated by asking oneself a question along the lines of "would this experiment have happened in the way it did if theorem one was true?" or the contrary.

In the part of the study relating to the influence of ventilation on a large pool fire in a tunnel, it can be observed that the posterior probability distribution becomes more and more skewed towards high k values with each successive refinement, see figure 6.01. This is analogous to each successive refinement increasing our degree of confidence in theorem one, that increasing ventilation velocity will cause an increase in fire severity. Similarly, our confidence in theorem two is lessened as each piece of evidence is considered.

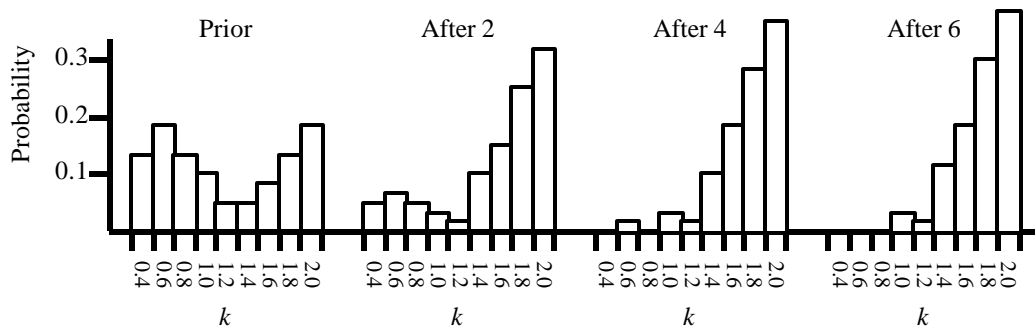


Figure 6.01 – The changes in the posterior probability distribution with increasing evidence

A similar methodology could be used to assess the value of estimates from individual experts. For example, consider the estimates of four of the experts regarding the case of a fully involved HGV fire:

Expert A (names have been withheld for obvious reasons) predicted that longitudinal ventilation would have no effect on fire size at any ventilation velocity ($k = 1$ at all ventilation rates).

Expert B predicted that a 2ms^{-1} ventilation rate would increase the heat release rate by a factor of 2, a 4ms^{-1} ventilation rate would have a k value of 4, a 6ms^{-1} ventilation rate would have a k value of 6 and a 10ms^{-1} ventilation rate would have a k value of 10.

Expert C predicted k values of 2, 3, 4 and 5 for ventilation rates of 2, 4, 6 & 10ms^{-1} .

Expert D predicted k values of 7, 10, 13 and 15 for the same ventilation rates.

Consider theorem A (T_A) to be “Expert A’s estimates are trustworthy”, theorem B (T_B) to be “Expert B’s estimates are trustworthy” and so on. We give all four theorems equal weighting in the first instance, i.e. $P(T_A) = P(T_B) = P(T_C) = P(T_D) = 25\%$ (if one or more of the experts were deemed more trustworthy in the first instance, the prior probability values could be weighted accordingly).

Now the likelihood of each experiment (e.g. $L(E|T_A)$) can be evaluated by asking oneself a question of the form “would this experiment have happened in the way it did if Expert A’s estimates were correct?” This has been done for the four experts described above:

The first experimental evidence (E_1) is the comparison of the Hammerfest HGV test with the Hammerfest simulated truck load. Comparing the HRR data from these tests gives k values of approximately 7-10 and 8-9 at 6 and 3ms^{-1} respectively. Clearly the likelihood of Expert A being correct is very small in this instance, whereas the experimental results are more consistent with Expert D’s estimates. Thus:

$$L(E_1|T_A) = \text{very small}, L(E_1|T_B) = \text{medium}, L(E_1|T_C) = \text{small and } L(E_1|T_D) = \text{high}$$

The second experimental evidence (E_2) is the comparison of the Buxton wooden crib test with naturally ventilated wooden crib tests. This suggests a k value of approximately 2 at 2ms^{-1} , thus:

$$L(E_2|T_A) = \text{medium}, L(E_2|T_B) = \text{high}, L(E_2|T_C) = \text{high and } L(E_2|T_D) = \text{small}$$

The third piece of experimental evidence (E_3) is the comparison of the Buxton simulation test with the naturally ventilated Hammerfest truck load test (taking differences in scale into consideration using Froude scaling). In this instance, forced ventilation rates of 6.3ms^{-1} , 2.5ms^{-1} and 1.7ms^{-1} corresponded to k values of approximately 13, 9.5 & 5.4, thus:

$$L(E_3|T_A) = \text{very small}, L(E_3|T_B) = \text{medium}, L(E_3|T_C) = \text{small and } L(E_3|T_D) = \text{high}$$

Repeatedly refining our degrees of confidence in the four theories, using Bayes’ Theorem together with the three sets of likelihood values (very small = 1, small = 2, medium = 3, high = 4), gives:

$$P(T_A|E_1,E_2,E_3) = 2\%, P(T_B|E_1,E_2,E_3) = 42\%, P(T_C|E_1,E_2,E_3) = 19\% \text{ and} \\ P(T_D|E_1,E_2,E_3) = 37\%$$

In other words, the estimates of Experts B and D are approximately twice as trustworthy as Expert C and twenty times more trustworthy than Expert A.

This method of using Bayes’ Theorem will be explored in more detail in Chapters 8 & 9 of this thesis.

6.4 The value of Bayes' theorem

The Bayesian method has much to offer in the field of fire safety engineering. The complexity of fire development makes the use of probabilistic methods necessary. Two ostensibly identical cases may produce fires which behave in widely different ways, and yet many of the fire models currently in use are deterministic in nature. Deterministic models may be valuable but they are not the sole answer, it is often better to consider a problem from a probabilistic viewpoint.

The Bayesian method has been used by statisticians for many years to aid decision making on the basis of limited information. It has been shown to be scientifically sound, adaptable to many different situations and it has even been claimed that it is the best way of making any decision. Indeed it has been claimed that we all subconsciously use Bayes-like reasoning when making everyday decisions [118]. In the attempt to address the first problem in this thesis, a Bayesian methodology has been used to refine estimates of probability with a diverse group of experimental data sets. The intention has been to come to an approximate understanding of the question of the effect of forced longitudinal ventilation on vehicle and pool fires in tunnels. It is part of the Bayesian understanding that the results presented in the previous chapter are not the definitive results, they are merely the current beliefs; as more experimental evidence becomes available these results will be further updated and refined, and so on.

The intention of this part of the study (Chapters 4-6) was to begin to build a systematic foundation on which future engineering judgements may be built. It may appear unwise to base any important decision on a hypothetical estimate refined by only a few sets of experimental data, but after consideration of future tunnel fire experiments it is hoped that these estimates may be refined to a useable resource and also give a clearer understanding of the behaviour of vehicle and pool fires in tunnels. At present it is hoped that these refined estimates are more realistic than expert judgement alone, having been refined using real experimental data. A similar Bayesian methodology may also be used with a specific case in mind; estimates can be sought for the particular tunnel size of interest and then these can be refined in a similar manner, yielding results that are specific to a particular tunnel configuration.

Of course, Bayes' theorem is not restricted to the question of fire development in tunnels. Any estimated probability distribution may be refined using only a single experimental observation using this method. Bayes' theorem has been used in a wide variety of contexts across the whole spread of engineering disciplines, from fire safety in nuclear plants [119] to pollution in water systems [120].

6.5 The meaning of the results

The purpose of the study was to estimate the probability distribution of the heat release rate coefficient, the random variable k , for hypothetical HGV, car and pool fires in tunnels with longitudinal ventilation. From the probability distributions produced it should be possible to estimate the sizes of vehicle fires in tunnels given the influence of forced longitudinal ventilation.

As there have been very few experimental fire tests on actual vehicles in tunnels, it is necessary to consider data from scale model fire tests and wooden crib fires in tunnels. Fires of these types may develop in significantly different ways to real vehicle fires, but as these provide most of the data that are available, they must be used until there are sufficient data from real vehicle fires.

6.5.1 HGV fires

In the case of HGV fire development, that is the study of k in the growth phase, data from a real HGV fire test, a reduced-scale simulation test and a number of crib fire tests were used. As noted earlier, the reduced scale simulation test was based around a liquid fuel pan. It is apparent from the previous chapter that fire development in fuel pools is very different to fire development involving solid fuel, especially in the growth phase, so the data from this test have been used with caution. However it should be noted that the fuel pool in the reduced scale simulation test was contained within a three dimensional "mock up" of a Channel Tunnel HGV carrier wagon, it was not exposed to the forced airflow directly. This means that several of the processes which determine the behaviour of a pool fire subject to longitudinal ventilation (e.g. cooling of the upwind part of the pool and "blow off" of fuel) might not apply in this instance, and hence the fuel may behave more like a solid fire source. Posterior distributions of k in the growth phase were calculated both with and without these data. As shown in figure

6.02, there are significant variations between the posterior distributions and expectations of k . Using the 4:2:1 ratio^Y, the posterior after three refinements (discounting the HGV “mock up” test) is significantly more dependent on the prior distribution than after four refinements (including the HGV “mock up” test). These variations are less significant if other likelihood ratios are used. Using, for example, the 10:5:1 ratio, the posterior after three refinements is not significantly dependent on the prior (see section 6.8 for details of sensitivity to the likelihood ratio).

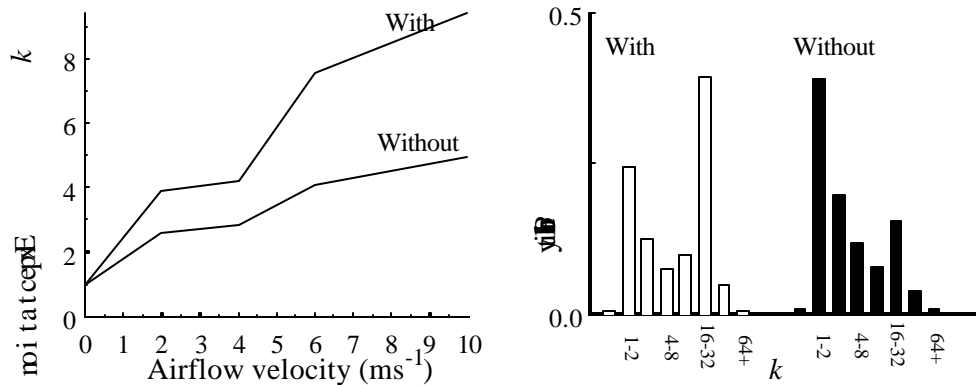


Figure 6.02 – The expectation of k and posterior probability distributions for a HGV fire in the growth phase both using and discounting the Buxton reduced scale simulation test data

The posterior distributions produced by the study suggest that k will increase dramatically with increasing ventilation velocity in the growth phase and for the fully involved fire. For each ventilation velocity considered in the study, the expected heat release rate of a HGV fire in the growth phase and at full involvement was several times larger than the average experts’ expectation (although two of the experts made estimates reasonably consistent with the results of the study, the rest did not).

In practical terms, the results of the study predict that a HGV fire in a tunnel subject to forced ventilation will release approximately 4, 5, 8 or 10 times more heat, at any given time within the growth phase, with ventilation rates of 2, 4, 6 or 10ms^{-1} than with natural ventilation.

^Y Throughout this thesis the high : medium : low ratio has been taken to be 4:2:1 in all Bayesian calculations unless explicitly stated otherwise.

The results of the study also predict that a fully involved HGV fire will release approximately 3, 5, 7 or 10 times more heat, at maximum heat release rate, with ventilation rates of 2, 4, 6 or 10ms⁻¹ than with natural ventilation.

What processes are dominant for HGV fires subject to a longitudinal airflow?

In Chapter 4 it was noted that there are a number of conflicting processes which could be dominating the behaviour of vehicle fires in tunnels subject to a forced airflow. From the results presented in the previous chapter it appears likely that those processes which tend to enhance the burning rate of a HGV fire dominate those processes which cool the fuel and hence slow the rate of burning.

For a fully involved HGV fire it is reasonable to conclude that increasing the ventilation rate tends to increase the rate of burning by bringing about a more efficient mixing of fuel and air at the fire location. It is possible that the applied ventilation is also able to force fresh air into those parts of the (three dimensional) fuel load that would not otherwise have access to fresh air, and hence would not burn until the outer parts of the load had been consumed. This would have a greatly enflaming effect as the effective burning area of the fire object would be considerably greater than under natural ventilation conditions.

These processes will also be active in the growth phase of the fire, but they will be supplemented by the additional effect of the ventilation “pushing” the fire towards the unburned fuel; increasing the rate of pre-heating and causing the fire to spread (and hence grow) at a greatly enhanced rate. Of course this effect would be reversed if the fire originated at the downwind end of the HGV, but at present there is insufficient experimental evidence to allow us to investigate this scenario adequately.

6.5.2 Pool fires

As noted earlier in the chapter, there was some diversity in opinion amongst the panel of experts regarding the effect of forced ventilation on the severity of a pool fire in a tunnel. For the small and medium sized pool fire cases, the majority opinion was that a small airflow velocity would cause a slight increase in HRR, but that faster airflow might slightly reduce the severity of the fire. However, all the evidence used for the case of the medium sized pool fire (see Table 4i, page 70) showed a significant reduction in severity for all airflow velocities tested, so the posterior probabilities predict a much smaller value of k than the experts do. It may be that there is a peak value of k , greater than 1.0, between 0 and 2ms^{-1} , but this cannot be predicted by the method used in this study; which only considers the value of k at 2, 4, 6 and 10ms^{-1} .

There was little experimental information available for the case of the small pool fire, and the few test results that have been used do not show similar trends in variation of HRR with forced ventilation. The Ofenegg tests [63] show a significant reduction in HRR with a forced velocity near 2ms^{-1} , whereas one Hammerfest test shows a slight increase in HRR under similar ventilation conditions and the other Hammerfest test shows no significant variation when the ventilation conditions are changed [70]. The three Memorial tests do not even show similar behaviour in response to forced ventilation under similar conditions [13]. However, each of these fire tests can still be used to refine the estimated prior probabilities, indeed it would be “unBayesian” to discount any of the pieces of evidence because it didn’t seem to fit with the rest of the evidence. It is expected that the irregularities in the posterior expectation graph, shown in figure 5.26, will be smoothed out as more data sets are considered in the future, and the probability distributions become less dependent on individual experiments.

For the case of the large pool fire there was no clear majority opinion, half the experts predicted an increase in severity with increasing airflow and half the experts predicted a decrease. However, all the evidence used for this case (see Table 4i, page 70) shows an increase in severity with increasing ventilation, so the posterior probability points to increasing values of k with increasing ventilation.

In practical terms these results mean that a small to medium sized pool fire will tend to be slightly enflamed by low airflow rates but the HRR would be expected to be reduced

by higher airflow velocities. In some cases the heat release rate may be reduced by as much as 50% at high airflow velocities. On the other hand, a large pool fire will tend to be enflamed by forced ventilation at all velocities. The heat release rate would be expected to increase as the ventilation rate is increased.

What processes are dominant for pool fires subject to a longitudinal airflow?

Clearly there are two different processes dominating the behaviour of large and small/medium pool fires subject to forced ventilation in tunnels. For small/medium pool fires it appears that small airflow rates may tend to enhance the burning rate by making the fuel vapour/air mix more efficiently and hence burn with a greater heat release rate. At higher airflow rates, the cooling effect of the ventilation tends to dominate and so the heat release rate is diminished.

This suggests that a small/medium pool fire in a tunnel, under natural ventilation conditions, is likely to burn slightly inefficiently; the mixing of fuel vapour and air is not quite optimum. However, applying a very small forced velocity airflow enables the fire to burn at maximum efficiency. Further increases of airflow cannot make the fire burn any more efficiently and so ventilation at higher velocities can only tend to decrease the rate of burning by cooling the fuel and blowing away the hot gases above the fuel surface; reducing the radiative feedback as a result.

Another factor which may influence the behaviour is the chemical nature of the fuel itself; the influence of ventilation on methanol pool fires appears to be greater than on other types of fuel [89]. In this study the medium sized pool fire case used several methanol pool fires as evidence and this may explain why the expectation of k (see figure 5.36) decreases dramatically with increasing ventilation velocity in this instance.

It is interesting to note that in Saito's experiments [89], the heat release rate of a pool fire in a tunnel appears to tend towards a lower limit as the ventilation rate is increased. From his results it appears that this lower limit corresponds to the heat release rate of a similar fire in the open air. That is, under natural and low velocity airflows a medium pool fire in a tunnel will tend to exhibit a heat release rate significantly higher than a similar pool fire would in the open air. The tunnel must somehow enhance the burning rate of the fire. Applying higher airflow velocities to such a fire only tends to

counteract this tunnel-enhancing effect. The nature of this tunnel-enhancing effect will be the subject of the study in Chapters 7-9.

For larger pool fires the influence of ventilation seems to have the opposite effect; increasing the ventilation velocity tends to increase the heat release rate. Considering the previous observations, it is clear that a large pool fire in a naturally ventilated tunnel is probably significantly starved of oxygen; the fire is ventilation controlled. Increasing the ventilation rate provides the fire with more oxygen, so the burning rate, and hence the heat release rate, is increased. Theoretically, there will come a point at which the fire becomes fuel controlled; when the ventilation rate is such that there is a stoichiometric balance between the amount of oxygen supplied and the production of the fuel vapours. Increasing the ventilation beyond this point will not enflame the fire further but cooling processes will begin to dominate, and so the heat release rate will tend to diminish. This turning point in the expectation of k graph is not predicted by the results presented here. Its position will undoubtedly vary with tunnel size, pool size and chemical nature and at present there are not enough experimental data to characterise this behaviour adequately.

6.5.3 *Car fires*

In the case of the car fire, data from forced ventilation fire tests involving wooden cribs and a car were compared with data from natural ventilation fire tests of cars and wooden cribs in tunnels. Because of the lack of data at higher ventilation velocities, k was only determined for a ventilation velocity of 1.5ms^{-1} . It is not expected that ventilation at this rate will have any significant influence on the heat release rate of a car fire in a tunnel, the rate of development of a car fire is expected to be slightly slower with forced ventilation (at 1.5ms^{-1}) than with natural ventilation.

What processes are dominant for car fires subject to a longitudinal airflow?

As the influence of forced ventilation on car fires has not been investigated at ventilation velocities other than at 1.5ms^{-1} it is not possible to deduce much about the processes that dominate the fire behaviour. Experimental car fire tests, both in and out of tunnels, have generally exhibited fairly low heat release rates with occasional transient peaks of high heat release. These peaks are generally attributed to crucial events in the fire development, e.g. the fire spreading to the fuel tank, the fire spreading to the engine compartment or the period of rapid burning due to fresh air entering the passenger compartment following the failure of the windscreen (which may produce behaviour similar to backdraught in building compartment fires) [62,70,121]. Due to the nature of these phenomena it seems reasonable to assume that the peaks of high heat release will not be significantly influenced by forced ventilation, so the severity of a car fire in a tunnel is more dependent on the characteristics of the car itself (e.g. fire resistance of the windows or fire protection of the fuel tank) and the point of origin of the fire, than on any influence of the forced ventilation. More experiments need to be carried out to confirm or refute this assumption.

6.6 The value of these results

The study set out to answer a simple question and has produced fairly simple results, a question that must be addressed is: are these results useful?

Tunnel fires are rare. The majority of fire fighters who work in areas near vehicle tunnels may have little or no experience of fighting such fires, and may not know what to expect in the event of such fires. Yet these fire fighters will probably have access to the controls of the tunnel ventilation systems in the event of a fire in a tunnel. Decisions on how to use the tunnel ventilation will be made. It is hoped that the results presented in this paper, together with results from other studies on tunnel fires, will enable the decision to be grounded in knowledge of fire behaviour, rather than just a “best guess.”

The primary concerns of the fire brigade are to help any people escape the fire to a place of safety and to control and extinguish the fire. Ventilation systems may be controlled in such a way as to blow all smoke produced by the fire to one side of the fire location. This will provide a smoke free escape route upwind of the fire location, but may also

significantly affect the size of the fire. This study has shown that, for a HGV fire in a tunnel, forced ventilation causes an increase in fire size. Increasing the ventilation velocity would be expected to cause the heat release rate of the fire to grow, possibly up to over 20 times larger. Without this knowledge it may seem reasonable to use the maximum possible ventilation to control the smoke, however, in the light of the results of this study, it would appear that the best solution would be to use the minimum ventilation velocity which is sufficient to control the smoke.

It has been shown that the size of fires on heavy goods vehicles can be greatly influenced by forced ventilation, it has also been shown that fires involving passenger cars are not significantly affected by forced ventilation. It has also been demonstrated that different sizes of pool fires in tunnels behave in different ways when forced ventilation is applied. Therefore it is clear that different ventilation strategies should be used when tackling different types of fires – ventilation should be kept to an absolute minimum if the fire involves a HGV or a large fuel spillage, whereas ventilation may be increased if the fire involves a passenger car or a smaller pool fire. Indeed, it has been shown that high ventilation rates would be expected to cause a decrease in fire size for smaller pool fires. Adopting the current recommendation of a 3ms^{-1} airflow velocity [22] in the event of any fire in a tunnel does not seem to be the most sensible option – if the fire type can be identified by the tunnel operators, the tunnel ventilation should be adjusted accordingly.

It is hoped that the simple results presented here will be easily remembered and therefore may be recalled when decisions need to be made when fighting real fires in tunnels.

6.7 The use of Bayes' theorem

The methodology used in this study was the discrete form of Bayes' theorem, it would also have been possible to use the continuous form of Bayes' theorem. In the continuous methodology, the random variable k is assumed to have a continuous probability distribution $P(k)$. Bayes' theorem is expressed as:

$$P(k | I) = \frac{L(I | k)P(k)}{\int L(I | k)P(k)dk} \quad \text{[from 3.3]}$$

where $P(k)$ is the prior probability function, $P(k|I)$ is the posterior probability function and $L(I|k)$ is the likelihood function of the evidence I .

A continuous approach has been used in studies such as that of Apostolakis & Kazarians [119], but was not used in this study due to the conceptual problems associated with evaluating a continuous likelihood function for each piece of evidence, and the necessary assumption that all the functions would be of a given distribution, e.g. a normal distribution. The combined expert estimates did not imply an obvious continuous distribution in any case.

The main reason Bayesian methods were chosen over other statistical methods is lack of data. In this study probabilities of k for various ventilation velocities have been estimated. Classically there is no method of estimating a probability distribution from as few data sets as were available. Also the data that were available came from a variety of tests in different tunnel configurations, again classically there is no way of using these together. The main advantage of Bayesian methods over classical estimation methods is the ability to incorporate expert judgement to compensate for lack of data. Bayesian methods also provide a simple way to refine estimates in the light of new evidence.

Some critics of this method would argue that these results are “all guesswork”, but by using Bayesian methods the experts estimates have been combined in a systematic way, which is scientifically justifiable, with all the available data. No *ad hoc* method of estimation can make such a claim. In their book “Scientific Reasoning” Howson and Urbach [118] contend that the Bayesian theory “is the only theory which is adequate to the task of placing inductive inference on a sound foundation.”

6.8 Sensitivity and uncertainties

Any calculation based on estimated values must be tested to determine how sensitive the final results are to variations in the estimates themselves. In this study the results are dependent on a number of estimated factors including the original prior probabilities and the ratio of high : medium : low likelihood used in the refining process. The sensitivity of results to both these factors must be considered.

6.8.1 Sensitivity of the results to likelihood ratio

The results presented in Chapter 5 were calculated using a likelihood ratio (high : medium : low) of 4:2:1. As it is important to test the sensitivity of the calculations to this ratio, the calculations have also been carried out using ratios of 10:5:1, 3:2:1 and 4:3:2. Graphs of the expectation of k in the growth phase and at maximum HRR for a HGV fire using each of these ratios are shown in figure 6.03. Selected posterior distributions are compared in figure 6.04. It can be seen that there are significant differences between the probability distributions with different likelihood ratios. Also, the expectation of k varies significantly depending on which likelihood ratio is used. In the growth phase of the fire, using the 10:5:1 ratio produces comparatively high values of the expectation of k . Although some preliminary results were published using this ratio [122] it appears that it may produce slightly exaggerated results.

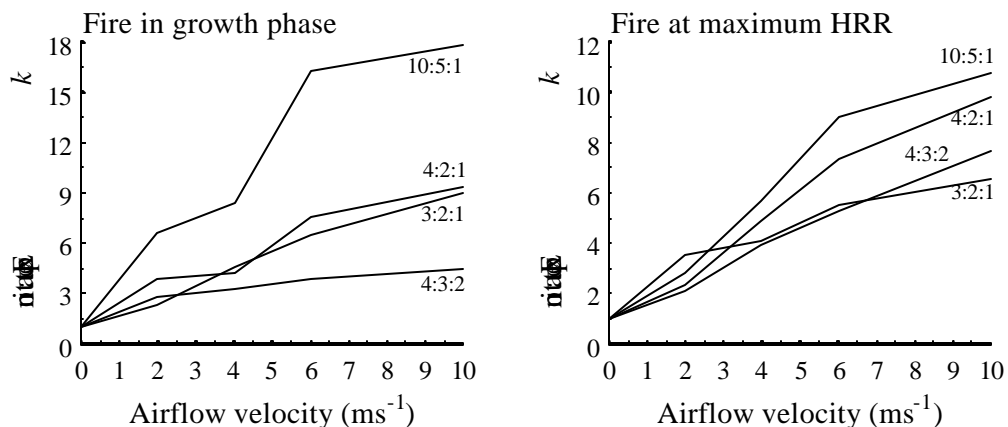


Figure 6.03 – The posterior expectation of k for a HGV fire using different likelihood ratios

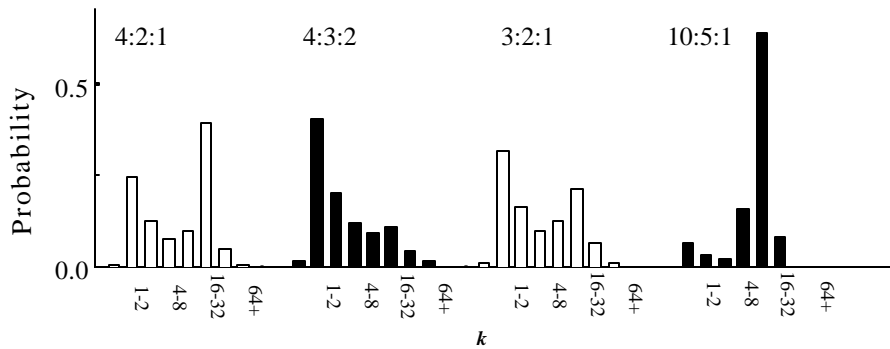


Figure 6.04 – Posterior probability distributions for a HGV fire in the growth phase at 6ms^{-1} using different likelihood ratios

In the pool fire cases, where there were many more pieces of evidence to refine the probability distribution with, the sensitivity to the likelihood ratio is much less than in the HGV case. As shown in figure 6.05, the variation in expectation of k at 2, 4 and 6ms^{-1} with likelihood ratio is not particularly significant.

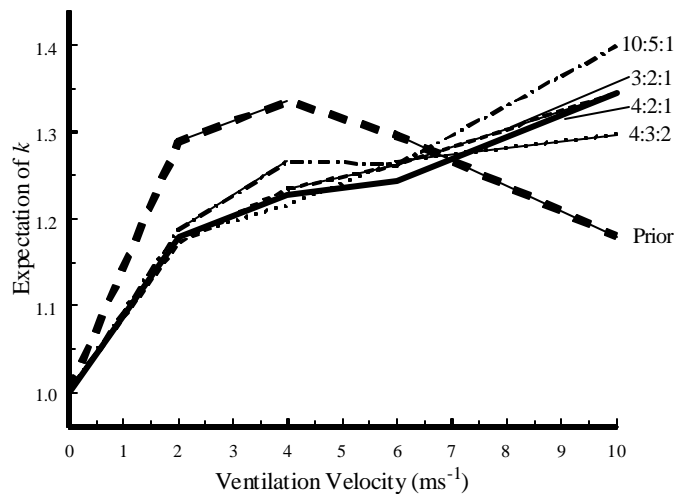


Figure 6.05 – The posterior expectation of k for a large pool fire using different likelihood ratios

The reason that the 10:5:1 ratio produces significantly exaggerated results in the HGV case but not in the case of a large pool fire is that this ratio gives more weight to the experimental evidence and less weight to the prior probabilities. Thus, even after only three pieces of evidence have been considered, the influence of the original expert prior distributions is virtually negligible. Conversely, the 4:3:2 ratio gives more weight to the

prior probabilities and less weight to the experimental evidence. Thus, after three pieces of evidence the posterior distributions and the expectations are still very much dependent on the original expert prior distributions. In the case of the large pool fire, nine pieces of evidence were considered and, as a result, the posterior probabilities are not significantly dependent on the expert prior distributions using any of the likelihood ratios, see below. Throughout this thesis the 4:2:1 ratio has been used as it was thought that this ratio provided a good balance between the weight of the evidence and the weight of the prior estimates.

6.8.2 Sensitivity to prior estimates

The sensitivity to the prior estimates is also of interest. To test this, the calculations were performed using a uniform prior, that is all ranges having equal probability in the first instance. Figure 6.06 compares the expectation of k for a HGV fire calculated using a uniform prior with that calculated using the estimated prior. Selected posterior HGV distributions are compared in figure 6.07. It can be seen that after four Bayesian refinements, the posterior probability distribution is still significantly dependent on the prior distribution. The expectation of k based on calculations using the expert prior is much smaller than using the uniform prior. When the likelihood ratio 10:5:1 was used in these calculations, the difference between the posterior distributions based on the expert and diffuse priors was insignificant. In the case of the large pool fire the situation is quite different. After nine refinements, the posterior probability distribution and the expectation of k are not significantly influenced by variations in the prior probability distribution, see figure 6.08.

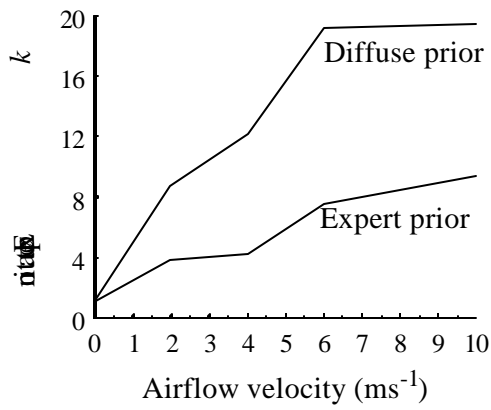


Figure 6.06 – The sensitivity of the expectation of k for a HGV fire in the growth phase to variations in the prior probability function (using the 4:2:1 likelihood ratio)

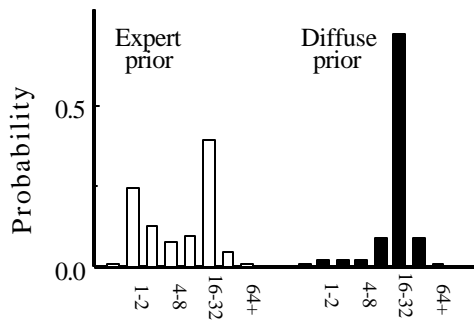


Figure 6.07 – Posterior probability distributions for a HGV fire in the growth phase at 6ms^{-1} using expert and diffuse prior probability functions (using the 4:2:1 likelihood ratio)

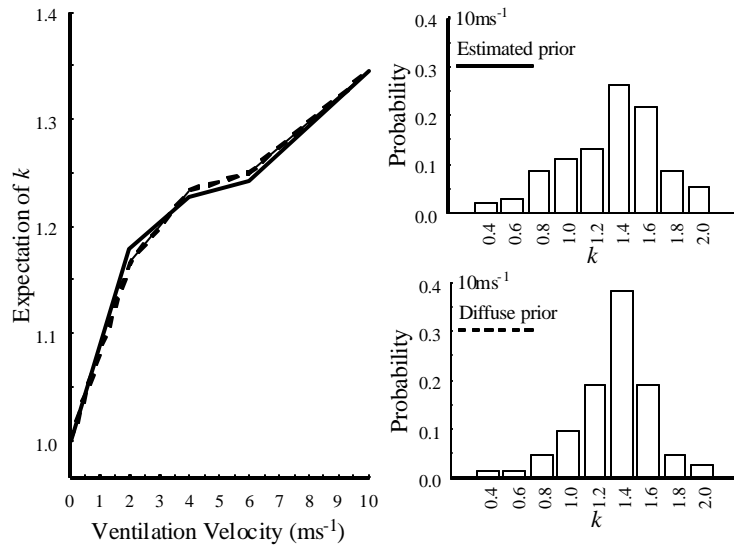


Figure 6.08 - The sensitivity of the expectation of k for a large pool fire to variations in the prior probability function. Also posterior probability distributions at 10ms^{-1} using the expert and diffuse prior probability functions (using the 4:2:1 likelihood ratio)

6.8.3 Uncertainty due to likelihood estimation

Due to the nature of the discrete Bayesian method used in this study there is also a degree of uncertainty introduced during the estimation of the likelihood of each piece of evidence. The influence of this uncertainty may best be seen by comparing the posterior distributions using the ratio 4:1:1 and the ratio 4:4:1 which may be considered to represent narrow and wide likelihood distribution functions. Selected posterior distribution functions and expectation graphs using these ratios are shown in figure 6.09. It can be observed that while the spread of the posterior distributions varies significantly, the expectation graphs show little variation. The wider likelihood functions tend to give slightly higher k values at low ventilation velocities, and lower k values high ventilation velocities, compared to values obtained using the 4:2:1 ratio. Whereas the narrow likelihood functions give slightly lower values at low ventilation velocities and slightly higher values at higher ventilation velocities. However the uncertainty introduced through this factor is small compared to other variations in the likelihood ratio.

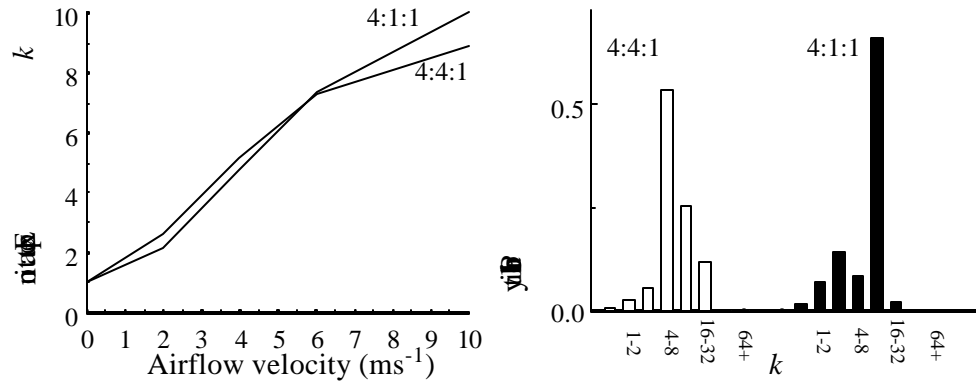


Figure 6.09 – The sensitivity of the expectation of k and posterior probability functions for a HGV fire in the growth phase (subject to forced ventilation at 6ms^{-1}) to variations in the likelihood function

6.8.4 Comment on the sensitivity analysis

It is clear from the above analysis that the uncertainties in the posterior probability distributions and calculated expectation values are highly dependent on the number of pieces of evidence considered.

Figure 6.03 shows that the expectation values of k for a HGV fire are quite sensitive to variations in the likelihood ratio used in the calculations. Figure 6.05, on the other hand, shows that the expectation values of k for a large pool fire are not as sensitive to the same variations. The reason for this is that only four pieces of evidence were considered for the HGV case (growth phase), whereas nine pieces of evidence were considered in the large pool fire case. A similar trend is observed when Figures 6.06 and 6.08 are compared; the results for the large pool fire case are much less sensitive to variations in the prior distribution than the results for the HGV fire case.

On the basis of this analysis it is expected that the uncertainties and errors in the estimates of posterior probability presented in this thesis will be reduced as they are updated in the future: as and when new evidence becomes available.

Chapter 7. Description of the second problem: Tunnel geometry and tunnel fires

7.1 Introduction

The second problem to be considered in this study may be summed up by the following question:

What effect does tunnel geometry have on fire size for fires in tunnels?

In 1965 a series of pool fire tests were carried out in the Ofenegg tunnel in Switzerland (see Chapter 2 and Appendix A for further details). Although the heat release rate of the fires was not directly measured, it was noticed that the burning times of the larger, naturally ventilated, fires were significantly longer than the burning times of the same amounts of fuel in the open air. This implies that the heat release rate of the fires in the tunnel was substantially smaller than the heat release rate of similar fires carried out in the open air.^Z This observation has been commented on in discussions about the test series, but an explanation for the phenomenon is not recorded [63].

Some pool fire tests were carried out in the fire gallery at INERIS in France as a precursor to the EUREKA fire test series. The heat release rate of these naturally ventilated pool fires was observed to be slightly higher than would be expected in the open air. This was commented on in the discussion of the tests and was attributed to “significant re-radiation from the heated walls” but was not quantified or discussed further [115].

^Z The burning time of the tests with forced ventilation was substantially shorter than tests in the open air and tests in the tunnel with natural ventilation. This was, presumably, due to the influence of the forced ventilation, see Chapters 4-6.

From these two examples it is apparent that the heat release rate of a fire can be influenced by simply *being* in a tunnel. In some cases the tunnel will cause a decrease in the HRR of a fire, whereas in other cases the tunnel may significantly enhance the HRR of a fire. Except in the above two examples, these effects have not been commented on in the literature relating to tunnel fires and tunnel fire experiments. However, the influence of a tunnel on HRR can be very significant. For example, a typical passenger car burns with a peak HRR of about 1.5-2MW in the open air [62] whereas a fire involving a small car (Fiat 127) in a small, naturally ventilated, tunnel exhibited a peak HRR of over 4MW [86]. One would expect a Fiat 127 fire in the open air to exhibit a HRR less than a typical car fire, so it would appear that the small tunnel was somehow responsible for enhancing the Fiat fire by at least a factor of two, possibly more.

7.2 The factors influencing HRR in a tunnel

7.2.1 Why might the tunnel cause the HRR to decrease?

In those cases where the HRR of a fire is decreased by being in a tunnel, the main reason will probably be that the geometry of the tunnel has restricted the flow of air to the fire location. This phenomenon is known as a “ventilation controlled fire” – the maximum HRR of the fire is limited, not by the properties of the object on fire, but by the amount of oxygen able to get to the fire object. In Chapter 2 (page 15) we saw that $\dot{A}H_{c,ox} = 13.1 \text{ kJg}^{-1}$ for most combustible liquids and solids, thus if the flow of oxygen to a fire is restricted, the maximum HRR of the fire will be restricted according to this relationship.

For example (1): if a vehicle is on fire in a tunnel with a 50m^2 cross-section and a 2ms^{-1} forced airflow (i.e. 2ms^{-1} is the average flow across the entire tunnel cross-section upstream of the fire), then from equation [2.7] the HRR of the fire cannot exceed $50 \times 2 \times 13.1 \times 0.21 \times 1000 \times 1 = 275100\text{kW}$ or 275MW due to the available oxygen.

For example (2): if a vehicle is on fire in a naturally ventilated tunnel with a 50m^2 cross-section, the maximum HRR of the fire is limited by the fire induced airflow. Suppose the smoke from the fire fills the upper half of the

tunnel and the fire induced airflow in the lower half of the tunnel is about 0.5ms^{-1} , then the maximum HRR of the fire is limited to $25 \times 0.5 \times 2^a \times 0.21 \times 13.1 \times 1000 \times 1 = 68775\text{kW}$ or 69MW .

To date, no study has adequately investigated the relationship between fire induced airflow and tunnel geometry.

7.2.2 Why might the tunnel cause the HRR to increase?

When a fire burns in the open air its heat release rate is largely dependent on the heat flux transferred from the flames and smoke plume back to the fuel. A large percentage of the heat produced in the flames and plume is dissipated into the surrounding air and transported away from the fire location, so only a relatively small amount of heat is transferred back to the fuel. In an enclosed space like a tunnel this is not the case. The tunnel ceiling prevents the fire plume from travelling upwards, so there tends to be an accumulation of hot gases above the fire location. These gases radiate much more heat back to the fire location than an upwardly mobile plume would. In addition to this, the fire and plume tend to heat up the tunnel walls and ceiling and these tend to radiate some heat back to the fire location in turn. These effects are far harder to quantify than the decrease in HRR due to oxygen depletion.

To date no study has adequately investigated the relationship between tunnel geometry and HRR enhancement.

7.2.3 The total influence

In most tunnel situations it is likely that both of these effects will influence the HRR of a fire; the geometry will enhance the HRR to a degree and the scarcity of oxygen may limit the maximum HRR of the fire. In different situations different influences will dominate. It is reasonable to assume that scarcity of oxygen will tend to dominate in those instances when the fire is large, relative to the tunnel. As with the first problem discussed in this thesis, it is useful to define a heat release rate coefficient to describe

^a Under natural ventilation conditions the airflow comes from both sides.

the influence of the tunnel geometry on the HRR. In this instance, we define ϕ according to the following relationship:

$$\phi = \frac{\dot{q}_{tunnel}}{\dot{q}_{open}} \quad [7.1]$$

where \dot{q}_{tunnel} is the HRR of a fire in a tunnel and \dot{q}_{open} is the HRR of a similar fire in the open air. For a given size of tunnel, it is reasonable that ϕ will vary with fire dimensions in a manner similar to the graph in figure 7.01, below.

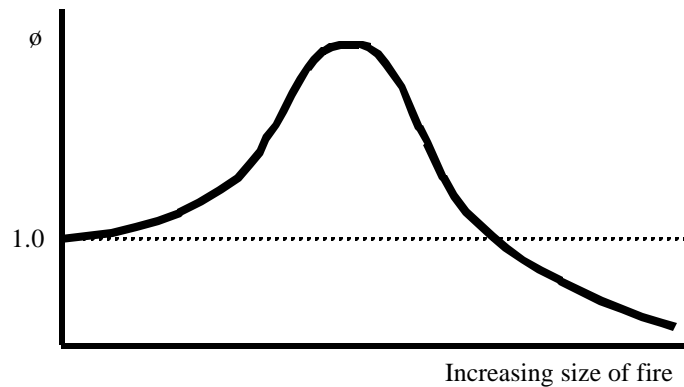


Figure 7.01 – The expected variation of ϕ with fire dimensions (tunnel size constant).

If the fire is very small compared to the tunnel, it is reasonable to assume that the heat release rate of the fire will be the same as the heat release rate of a similar fire in the open air, i.e. $\phi = 1.0$. If the fire is very large compared to the tunnel it is likely that the heat release rate will be limited by the (lack of) airflow and hence ϕ will be substantially less than one. In between these two extremes there will be a regime where the oxygen supply is not particularly limited and where the tunnel geometry will tend to enhance the heat release rate of the fire.

A similar relationship could be expected if the fire size was kept constant and the tunnel dimensions were varied, as shown in figure 7.02.

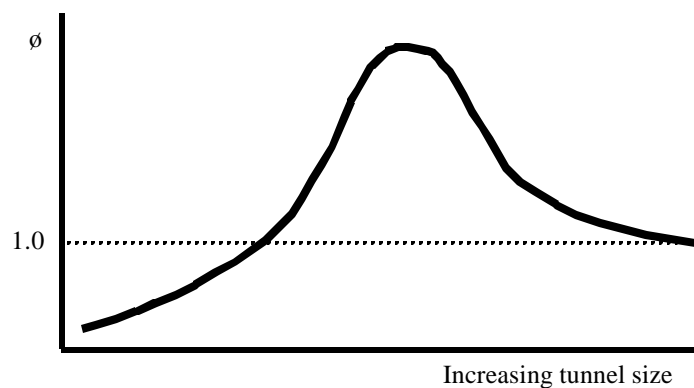


Figure 7.02 – The expected variation of ϕ with tunnel size (constant fire dimensions).

7.3 Survey of the available data

The majority of fire experiments carried out in tunnels world-wide have involved pool fires. There have been only a handful of fire tests involving vehicles or wooden cribs in tunnels, and even though there is a well documented fire test of a heavy goods vehicle (HGV) in a tunnel [123], there has been no similar test carried out in the open air, so there is no way of estimating the effect of the tunnel on the HRR of that test, or indeed for several of the other fire tests on vehicles in tunnels [70].

From an extensive literature study it was found that there are sufficient experimental data from car fires, wooden crib fires and pool fires, carried out in both naturally ventilated tunnels and the open air, for the purposes of this study.

7.3.1 Car fires

There have been two well documented car fire tests in tunnels which may be compared with car fire tests carried out in the open air. A Renault Espace was burned in the abandoned tunnel at Repparfjord as part of the EUREKA fire test series in 1992 and a Fiat 127 was burned as part of a series of tests carried out in a “blasted rock tunnel” in Sweden in 1997. A private van was also burned in the Des Monts tunnel in France in 1988, see Table 7.1. These data can be compared with HRR data from three cars burned in the open by VTT in Finland in 1993 (see Table 7.2) if differences in vehicle dimensions are taken into consideration. The Renault Espace was significantly larger than the three cars burned in the open air, so it is assumed that its HRR would also be

significantly larger than that of a regularly sized car; it was assumed that if an Espace was burned under the same conditions as the three open air cars its HRR would be approximately 50% greater than that of a regular sized car, i.e. 2.2 to 2.7 MW. Similarly, a Fiat 127 is significantly smaller than a regular car so its HRR is assumed to be 25% less than that of a regular car, i.e. about 1.2 to 1.4 MW. Thus, ϕ values of between 2 & 3 for the Renault Espace, about 3 for the Fiat 127 and just above 1 for the private van can be estimated.

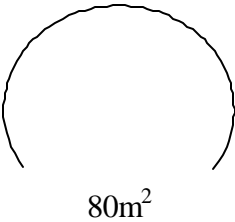
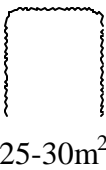

<i>Tunnel</i>	<i>Tunnel shape and size</i>	<i>Fire type</i>	<i>HRR</i>	<i>Reference</i>
Des Monts road tunnel France		Van	2.0MW (estimated)	[80]
Mine tunnel near Hammerfest, Norway		Renault Espace Car	6MW	[70]
Blasted rock tunnel used by FOA, Sweden		Fiat 127 Car	4MW	[86,87]

Table 7.1 – Car fire experiments in naturally ventilated tunnels

<i>Fire test centre</i>	<i>Fire type</i>	<i>HRR</i>	<i>Reference</i>
VTT, Finland	Ford Taunus	1.5MW	[62]
	Datsun 160J	1.7MW	
	Datsun 180B	1.8MW	

Table 7.2 – Car fire experiments in the open air

7.3.2 *Wooden crib fires*

A number of wooden crib fire tests have been carried out in tunnels, see Table 7.3. Data from these tests may be compared with data from the comprehensive study of wooden crib fire behaviour carried out by Gross [55]. Three wooden crib fire tests were carried out by FOA in Sweden in their “blasted rock tunnel” test series. A “free burning” fire test of a similar crib was also carried out at SP in Sweden (see Table 7.4). Of the three tests carried out in the tunnel, one had a significantly restricted air supply so it has not been considered in this study, the other two exhibited HRRs of 0.87MW and 1.12MW. The “free burning” (i.e. open air) test had a peak HRR of 0.81. This gives ϕ values of about 1.1 and 1.4 for the tunnel tests compared to the “free burning” test. Several wooden crib fire tests were carried out as part of the EUREKA test series, but only one test (designated W31) was with natural ventilation and during which HRR data were recorded, see Table 7.3. This test involved 5 piles of cribs (arranged in an unconventional manner) and had a peak HRR of 8MW, thus we can assume that each individual crib pile contributed 1.6MW to the total HRR. None of the wooden cribs tested by Gross were as large as the crib piles in the Hammerfest test, but cribs of identical composition (i.e. wood type, stick dimensions and porosity) were tested. The nearest comparable crib tested by Gross was about $\frac{1}{6}$ of the size of one of the Hammerfest crib piles and had a peak HRR of 0.2MW, thus it is assumed that if the crib had been six times larger, the HRR would have been 1.2MW. Hence, it is estimated that ϕ had a value of about 1.3 in this case.

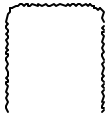

<i>Tunnel</i>	<i>Tunnel shape and size</i>	<i>Crib size</i>	<i>HRR</i>	<i>Reference</i>
Mine tunnel near Hammerfest, Norway	 25-30m ²	0.8 × 3.2 × 1.2m (test W31)	8MW	[70]
Blasted rock tunnel used by FOA, Sweden	 9m ²	0.7 × 0.7 × 0.53m (two tests)	0.87 & 1.12MW	[86]

Table 7.3 – Wooden crib fire experiments in naturally ventilated tunnels

<i>Fire test centre</i>	<i>Crib size</i>	<i>HRR</i>	<i>Reference</i>
SP, Sweden	0.7 × 0.7 × 0.53m	0.87MW	[86]
National Bureau of Standards, USA	Many	Various	[55]

Table 7.4 – Wooden crib fire experiments in the open air

7.3.3 Pool fires

A number of pool fire tests have been carried out in tunnels, mine tunnels and reduced scale model tunnels, see Table 7.5. For many of them a similar pool fire test carried out in the open air can be found. For others it is possible to estimate the burning rate or HRR of a large pool fire (defined as having a diameter greater than 0.2m) using the method and data described by Babrauskas [47]. The pool fire tests were carried out using a number of different fuels, which we will consider in turn.

Fire tests involving pools of methanol (CH₃OH) have been described in reports by the Fire Research Institute in Japan, and by SP and FOA in Sweden. The Japanese pool fire test series were carried out in a model tunnel 0.3m wide by 0.3m high and 21.6m long.

Using pools of 0.10, 0.15, 0.20 and 0.25m diameter the heat release rates of the fires, in the tunnel, with a low airflow velocity, were 1.2, 3.2, 7.5 and 23kW respectively. The same pools were tested in the open, giving heat release rates of 1.2, 3.0, 5.5 and 8.5kW respectively. Thus the ϕ values for these pool fires in a 0.3×0.3 m tunnel are approximately 1.0, 1.1, 1.4 and 2.7 respectively. Methanol pool fire tests in a model tunnel were also reported by SP. The tunnel in this instance was 1.08m wide by 1.20 m high and over 10m long. The pool itself was 0.4×0.4 m and was situated on a raised platform near one end of the tunnel. The natural airflow was restricted such that all smoke and combustion products would flow along the tunnel and through a hood calorimeter at the other end. The HRR of the fire test was 40kW which gives a ϕ value of 0.8 when compared to an open air test using the same pool. Two methanol pool fire tests were also carried out in a $3 \times 3 \times 100$ m “blasted rock tunnel” as described by FOA. The heat release rates of the naturally ventilated fire tests, both using a 2×1 m fuel tray, were 0.9MW, which gives an approximate ϕ value of 1.35 when compared to the predicted HRR of a similar pool fire in the open air.

Another commonly used fuel for pool fire tests is heptane (C_7H_{16}). Heptane pool fire tests in tunnels have been reported by SP and FOA in Sweden, The Japanese Fire Research Institute, INERIS in France and as part of the EUREKA test series carried out in Norway. The Japanese heptane pool fire test was carried out, at very low airflow velocity, in the same model tunnel as the methanol fire tests using a 0.15m diameter fire pool. This produced a HRR of 58kW which gives a ϕ value of approximately 4 when compared to the 14kW fire test using a pool of the same dimensions in the open air. Two heptane pool fire tests were carried out in the 1.08×1.2 m tunnel at SP, one with a 0.3×0.3 m pool and one with a 0.4×0.4 m pool. Comparing these tests to fire tests using the same pools in the open air suggests a ϕ of about 1.3 for the smaller pool and 2.2 for the larger one. Heptane pool fire tests were also carried out by FOA in the “blasted rock tunnel”. Two different sizes of pool were used; several tests were carried out with a 0.65×0.65 m pool and one test was carried out with a 0.8×0.8 m pool. Comparing these tests with estimated heat release rates for pools of those dimensions in the open air suggests ϕ values of 1.4 and 1.8. The Institut National de l’Environnement Industriel et des Risques (INERIS) carried out heptane pool fire tests in their own large scale gallery and in the EUREKA tunnel at Repparfjord. Circular pool fires of $1m^2$ (both tunnels) and $3m^2$ (EUREKA only) were tested. Comparing these tests with the predicted HRR of similar pools in the open air suggests a ϕ value of 1.8 for a $1m^2$ pool

in the 10m² INERIS gallery and ϕ values of 1.0 and 1.3 for 1m² and 3m² pools in the 25m² EUREKA tunnel.

Pool fires using fuel oils have also been reported, although reports are sometimes misleading: the words diesel, kerosene, fuel oil, aircraft fuel and petrol are occasionally interchanged in some reports causing some confusion and making it hard to compare tests. In 1965 several large pool fire tests were carried out in the Ofenegg tunnel in Switzerland. These were carried out using “aircraft quality petrol”^b. The fire tests involved a very large fire of 3.8 × 25m, an intermediate fire of 3.8 × 12.5m and a small one of 3.8 × 1.75m. Comparing these with estimated heat release rates for similar fires in the open air gives ϕ values of approximately 0.2, 0.4 and 1.2 respectively. A series of pool fire tests were also carried out at the Londonderry Occupational Safety Centre in Australia. The tunnel was a mine roadway 5.4m wide by 2.4m high and 130m long. Three kerosene pool fire tests were carried out with minimal ventilation velocity using circular pools with areas of 0.26m², 0.78m² & 3.14m². Comparing these tests with estimates of the HRR of similar pool fires in the open air suggests ϕ values of 3.5, 1.3 and 0.45 respectively. A kerosene pool fire test was also carried out in the “blasted rock tunnel” by FOA in Sweden^c. Using a 0.65 × 0.65m pool, the fire test exhibits a ϕ value of about 1.8.

By far the largest series of pool fire tests that has been carried out so far was the Memorial Tunnel Fire Ventilation Test Program (MTFVTP). Of the 98 tests carried out in that series, two were carried out with natural ventilation, one involving a rectangular pool of about 9m² and the other involving a combination of rectangular pools totalling 22m². The fuel used was “number 2 fuel oil” (i.e. diesel). Babrauskas does not quote data from diesel pool fire tests. However, the MTFVTP test report quotes data from fires involving diesel in the open air, although the source of the data is not given. Comparing the Memorial data with this gives ϕ values of slightly less than 1 for the smaller pool fire and approximately 0.8 for the larger pool fire.

^b Assumed here to be petrol, although petrol is not generally an aircraft fuel. If the fuel in question was kerosene then the ϕ values would be approximately 50% larger than those presented.

^c The report uses the words “kerosene” and “diesel” interchangeably. The fuel used was kerosene.

A $0.3 \times 0.3\text{m}$ pool fire test using xylene as a fuel was also carried out in the Swedish model tunnel. It exhibited a ϕ value of approximately 1.7, but as no other tests have been carried out using xylene, this cannot be compared with other tests to determine trends in fire behaviour in tunnels.


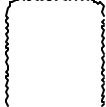






<i>Tunnel</i>	<i>Tunnel size</i>	<i>Pool fuel</i>	<i>Pool shape</i>	<i>Pool size</i>	ϕ	<i>Ref.</i>
Abandoned two lane road tunnel near Charleston, West Virginia, USA	 56m ²	Diesel	Rect	9m ² 22m ²	< 1 0.8	[13]
Abandoned mine tunnel near Hammerfest, Norway	 25-30m ²	Heptane	Circular	1m ² 3m ²	1.0 1.3	[70]
Abandoned railway tunnel at Ofeneegg, Switzerland	 23m ²	Petrol	Rect	6.65m ² 47.5m ² 95m ²	1.2 0.4 0.2	[63]
Mine roadway tunnel at Londonderry, Australia	 13m ²	Kerosene	Circular	0.26m ² 0.78m ² 3.14m ²	3.5 1.3 0.45	[82]
Large scale fire gallery at INERIS, France	 10m ²	Heptane	Circular	1.0 m ²	1.8	[115]
Blasted rock tunnel used by FOA, Sweden	 9m ²	Heptane	Square	0.42m ² , 0.64m ²	1.4 1.8	[86]
		Methanol	Rect	2.0m ² 0.09m ² ,	1.35 1.3	
Model scale tunnel at SP, Sweden	 1.3m ²	Heptane	Square	0.16m ²	2.2	[124]
		Xylene	Square	0.09m ²	1.7	
		Methanol	Square	0.16m ²	0.8	
Lab scale wind tunnel at Fire Research Institute, Japan	 0.09m ²	Heptane	Circular	0.018m ²	4	[89]
		Methanol	Circular	Various	1-3	

Table 7.5 – Pool fire experiments in naturally ventilated tunnels

<i>Fire test centre</i>	<i>Pool size</i>	<i>Fuel</i>	<i>HRR</i>	<i>References</i>
Several	Many	Many	Various	[55]
MTFVTP	3.66 × 1.22m	Diesel	10MW	[13,125]

Table 7.6 – Pool fire experiments in the open air

7.4 The relationship between ϕ and tunnel geometry

At first glance there does not appear to be any correlation between the dimensions of a fire and the value of ϕ . In the Japanese series of tests using methanol, ϕ appears to increase substantially as the pool dimensions are increased, while the tunnel dimensions remain unchanged. However, in the Australian series of tests using kerosene, ϕ decreases as the pool dimensions are increased, while the tunnel dimensions remain unchanged. These trends would appear to contradict each other. There appears to be no correlation between fire dimensions and ϕ . However, there are a number of factors which may explain the differences between these observations:

- (a) The shapes of the tunnels – the Australian tests were carried out in a tunnel more than twice as wide as it is high, the Japanese tests were carried out in a square tunnel.
- (b) The experimental scale – the scale of the Japanese test tunnel was much smaller than the other tests.
- (c) The nature of the fuel – methanol burns with a much lower heat release rate than kerosene, it also requires a much smaller amount of oxygen to burn stoichiometrically. Kerosene needs more than five times as much oxygen. Kerosene fires also produce many times more smoke than methanol fires.

As discussed above, it is probable that ϕ increases with fire dimensions up to a point, beyond which the fire does not have sufficient oxygen to burn completely. Larger fires would probably be starved of oxygen so that the heat release rate would be smaller than expected and would produce a decrease in ϕ as the fire dimensions were increased. It is possible that the Japanese methanol fire tests may all be in the “sufficient oxygen” part

of the curve, whereas the Australian kerosene tests may be on the downward “oxygen depleted” part.

In the previous section of this thesis, Bayes' Theorem was used to estimate the heat release rate coefficient k as a function of ventilation velocity: $k = f(v)$, all else remaining the same. It would be desirable to reduce the question of the relationship between ϕ and tunnel geometry to a similar function, $\phi = f(g_f)$, where g_f is some geometric factor. But which geometric factor has the most significant influence on ϕ ? In the next chapter, Bayes' Theorem is used to decide which geometric factor to use.

Chapter 8. Application of Bayes' Theorem to the second problem

8.1 Introduction

When applying Bayes Theorem to the first problem it was reasonable to assume that the heat release rate coefficient, k , was a random variable which could be expressed as a function of the ventilation velocity, v , given that other factors, especially fuel load and geometry, remain the same. In this instance the relationship is not so clear cut. The heat release rate coefficient, ϕ , may not be a simple function of a single variable; it is possible that it will vary with some combination of tunnel width, tunnel height, fire object width, fire object height and possibly other geometrical factors. It is not possible to alter a geometrical factor and leave all else remaining the same. Altering one geometrical factor, e.g. tunnel height, will alter other factors, e.g. the blockage ratio (ratio of object cross-section to tunnel cross-section). There are therefore a number of difficulties preventing the use of the same methodology to tackle this problem as was used for the first problem. That is, at the outset of the first problem it was clear that heat release rate would be influenced by variations in a single factor, that of ventilation, in this instance it is not clear which geometrical factor(s) will have any influence.

However, it is reasonable to assume that some geometrical factors will have more influence over the value of ϕ than others, all else remaining approximately the same. A more abstract use of Bayes' Theorem than was used for the first problem may be used to determine which variable (or variables) has the greatest influence over ϕ . Once this is determined it may then be a relatively straightforward task to determine the actual variation of ϕ with this variable.

8.2 The four hypotheses

From the literature review, it appears that ϕ may vary with (i) tunnel height, (ii) tunnel width or (iii) blockage ratio. Blockage ratio is defined as the ratio of the cross-sectional area of the fire object to the tunnel cross-sectional area. Another geometrical factor which is often significant in tunnel fire problems is the mean hydraulic diameter, \bar{H} , which is defined as the ratio of four times the tunnel cross-sectional area to the tunnel perimeter. It has been demonstrated that the critical velocity required to prevent backlayering from tunnel fires varies with \bar{H} and it is often used as the characteristic dimension of a tunnel for Froude scaling applications. It is conceivable that \bar{H} may have a significant influence on ϕ , so it will be considered as one of the variables of interest in this study.

From this we have four hypotheses:

- (i) that ϕ varies primarily with tunnel height (i.e. the distance from the fire object to the ceiling)
- (ii) that ϕ varies primarily with tunnel width (i.e. the distance from the fire object to the walls)
- (iii) that ϕ varies primarily with blockage ratio
- (iv) that ϕ varies primarily with \bar{H}

Variation in each is considered, keeping all else fixed as far as possible. Bayes' Theorem will be used to refine estimates of confidence in each of these four hypotheses using the evidence of experimental tests from the literature study.

8.3 Using Bayes' Theorem to decide amongst the hypotheses

As there was little "prior" evidence to support any one of these hypotheses at the outset, Bayes' postulate was used, that is each of the hypotheses were allocated equal prior probabilities, i.e. $P(E_1) = P(E_2) = P(E_3) = P(E_4)$. By estimating the likelihood of each piece of available experimental evidence, the probabilities of each of these hypotheses can be refined. In order to simplify the allocation of likelihood values for the evidence, each hypothesis will only be allocated a "high", "medium" or "low" likelihood, with values in the ratio 3:2:1. In this part of the study a piece of "evidence" will consist of a

set of experimental observations carried out in different tunnels or with different sizes of fire.

As the variation of ϕ with fire dimensions appears to go through two distinct phases, possibly associated with sufficient oxygen and oxygen depletion, these need to be considered separately. At present it does not appear that there are sufficient data to estimate the relationship between ϕ and tunnel geometry when there is insufficient oxygen.

From examining the experimental test reports, it seems likely that the following experimental fires in tunnels were not significantly starved of oxygen:

- Methanol and heptane fires in the Japanese model tunnel
- Heptane fires in the Swedish model tunnel
- Heptane and kerosene fires in the Swedish “blasted rock tunnel”
- Heptane pool fire in the INERIS fire gallery, France
- Heptane pool fires in the EUREKA tunnel, Norway
- Renault Espace fire test in the EUREKA tunnel, Norway
- Fiat 127 fire test in the “blasted rock tunnel”, Sweden
- Private van fire test in the Des Monts tunnel, France
- Crib fire tests in the “blasted rock tunnel”, Sweden
- Crib fire test in the EUREKA tunnel, Norway

8.3.1 Refining the probability estimates using Bayes' Theorem

The “prior” probabilities of each of the four hypotheses are shown in Figure 8.01.

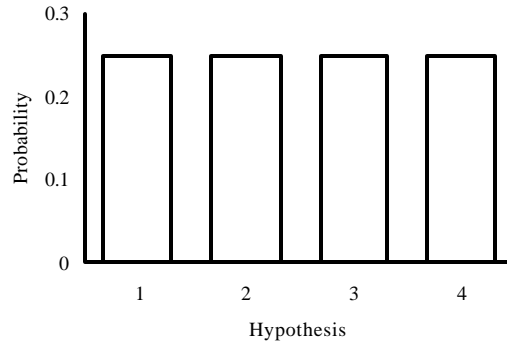


Figure 8.01 – The prior probabilities for each hypothesis

These are estimates of the probability of each hypothesis, that is, our degree of confidence in each hypothesis. They can be updated using Bayes' Theorem if any evidence is available. In this part of the study, the evidence used to update the probability estimates consists of sets of experimental data, taken from the list above, where there is some geometrical similarity between the tests, but where other geometrical factors vary.

The evidence used consists of the following sets:

A. Set of fire tests in the blasted rock tunnel

This set consists of data from the wooden crib and heptane pool fire tests in the blasted rock tunnel [86]. In this test series the tunnel dimensions (and hence the mean hydraulic diameter) and the distance from the fire load to the walls remain unchanged, while the blockage ratio and the distance from the fire load to the ceiling vary between tests.

B. Set of fire tests in the Japanese model tunnel

This set consists of data from a range of different sized heptane pool fire tests in a model tunnel [89]. The mean hydraulic diameter, distance from the fire to the ceiling and blockage ratio did not change in this test series, while the distance from the fire to the walls changed from test to test.

C. 1m² pool fire tests in different tunnels

This set of data considers identical pool fire tests carried out in two different tunnels; the Hammerfest tunnel and the fire gallery at INERIS [115]. The mean hydraulic diameter and the distance from the fire to the walls of the tunnel vary significantly between tests, the blockage ratio and the distance from the fire to the ceiling do not vary as much.

D. Set of car fires

This set consists of the three car fire tests. All of the geometrical variables vary between tests, some more than others.

E. Set of heptane pool fires in different tunnels

This set consists of data from the 0.09m² heptane pool fire in the Swedish model tunnel, the 0.64m² heptane pool fire in the blasted rock tunnel and the 1m² heptane pool fire in the INERIS gallery. These pool fires are all approximately $\frac{1}{3}$ of the width of their respective tunnels, so the distance to the walls, the distance to the ceiling and the blockage ratio do not vary significantly between tests.

F. Set of fire tests in the Hammerfest tunnel

This set consists of data from the car, crib and heptane pool fire tests in the Hammerfest tunnel. The mean hydraulic diameter remains unchanged between tests but the other three geometrical factors vary.

These data sets were used to update the estimates of probability as follows:

A. By considering the heptane pool ($\phi = 1.4$, see Table 7.5 and Section 7.3.3) and wooden crib ($\phi = 1.1$ and 1.4, see Table 7.3 and Section 7.3.2) fire tests in the blasted rock tunnel it can be observed that ϕ is much the same for the cribs as for the pool, and the “footprint” area of the fires is approximately the same. From this it can be observed that ϕ does not appear to vary when the distance to the ceiling and the blockage ratio are varied; the pool fire provided much less of a blockage than the crib, while the top of the crib was significantly closer to the tunnel ceiling than the pool. This lends support to hypothesis ii, undermines hypotheses i and iii and gives no information regarding hypothesis iv. Hence hypothesis ii is allocated a “high” likelihood, hypotheses i and iii are allocated “low” likelihoods and hypothesis iv is allocated a “medium” likelihood. The calculations for this case are shown in scheme 8á, overleaf. The likelihood of the evidence and the updated probability distribution are shown in Figure 8.02.

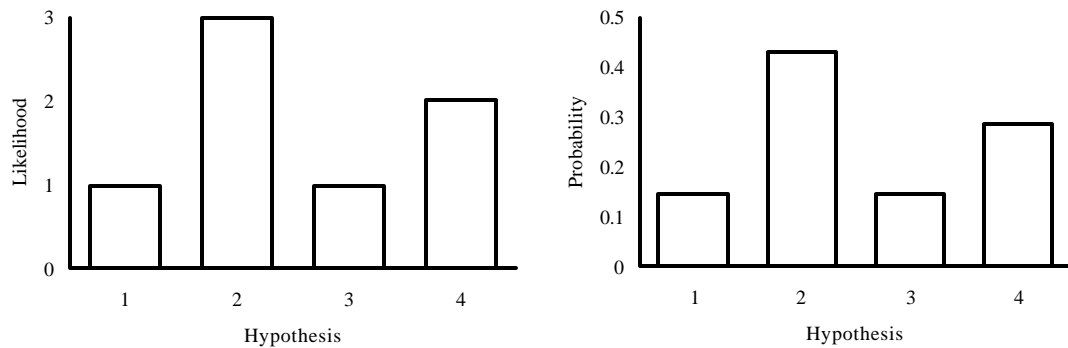


Figure 8.02 – The likelihood and posterior probability functions for the first refinement.

Example: Bayesian calculations when choosing amongst the four hypotheses.

Prior probability values:

Hypothesis:	i	ii	iii	iv
that ϕ varies with:	height	width	blockage	\bar{H}
Prior probability:	0.25	0.25	0.25	0.25
Likelihood A :	Low	High	Low	Medium

(assuming Low = 1, Medium = 2 and High = 3)

Bayes theorem can be expressed as:

$$P(H_i | E) = \frac{P(E | H_i)P(H_i)}{\sum_n P(E | H_n)P(H_n)} \quad (\text{from equation [3.2]})$$

where $P(E | H_i)$ is the likelihood of the evidence, E , and $P(H_i)$ is the prior estimate of probability.

There are four equations, one for each of the hypotheses:

$$P(H_i | E_A) = \frac{(1) \times (0.25)}{(1 \times 0.25) + (3 \times 0.25) + (1 \times 0.25) + (2 \times 0.25)} = \frac{0.25}{1.75} = 0.143$$

$$P(H_{ii} | E_A) = \frac{(3) \times (0.25)}{(1 \times 0.25) + (3 \times 0.25) + (1 \times 0.25) + (2 \times 0.25)} = \frac{0.75}{1.75} = 0.429$$

$$P(H_{iii} | E_A) = \frac{(1) \times (0.25)}{(1 \times 0.25) + (3 \times 0.25) + (1 \times 0.25) + (2 \times 0.25)} = \frac{0.25}{1.75} = 0.143$$

$$P(H_{iv} | E_A) = \frac{(2) \times (0.25)}{(1 \times 0.25) + (3 \times 0.25) + (1 \times 0.25) + (2 \times 0.25)} = \frac{0.50}{1.75} = 0.286$$

These posterior probability values are then used as the prior probabilities in the next update.

A. By considering all the Japanese methanol pool fire tests together it is observed that ϕ increases substantially as the fire dimensions are increased, despite the fact that the blockage ratio does not vary significantly and the distance to the ceiling does not change. This lends support to hypothesis ii, undermines hypotheses i and iii and gives no information regarding hypothesis iv. The calculations were carried out in the same way as in Scheme 5á except that the posterior values from the first update were used as the prior values for this update. The posterior values after the second update were:

$$P(H_i | E_B) = \frac{(1) \times (0.143)}{(1 \times 0.143) + (3 \times 0.429) + (1 \times 0.143) + (2 \times 0.286)} = \frac{0.143}{2.145} = 0.067$$

$$P(H_{ii} | E_B) = \frac{(3) \times (0.429)}{(1 \times 0.143) + (3 \times 0.429) + (1 \times 0.143) + (2 \times 0.286)} = \frac{1.287}{2.145} = 0.600$$

$$P(H_{iii} | E_B) = \frac{(1) \times (0.143)}{(1 \times 0.143) + (3 \times 0.429) + (1 \times 0.143) + (2 \times 0.286)} = \frac{0.143}{2.145} = 0.067$$

$$P(H_{iv} | E_B) = \frac{(2) \times (0.286)}{(1 \times 0.143) + (3 \times 0.429) + (1 \times 0.143) + (2 \times 0.286)} = \frac{0.572}{2.145} = 0.267$$

The likelihood of this evidence and the refined probability graph are shown in Figure 8.03.

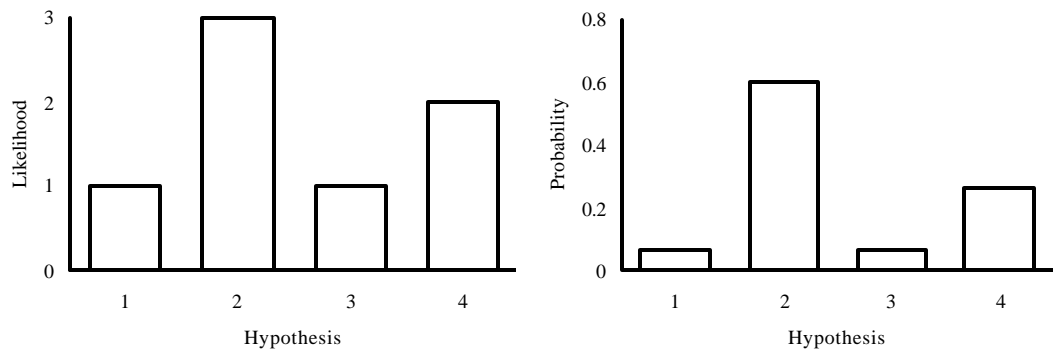


Figure 8.03 – The likelihood and posterior probability functions for the second refinement

A. Considering the 1m² heptane pool fire test in the INERIS gallery together with the 1m² heptane pool fire test in the EUREKA tunnel and the 0.64m² heptane pool fire in the blasted rock tunnel suggests that ϕ varies more with distance to walls than with \bar{h} . Hence hypothesis ii was allocated a high likelihood and hypothesis iv a low likelihood. No information is given for hypotheses i or iii so these were

allocated medium likelihoods. The calculations were done in the same manner as above. The likelihood of this evidence and the refined probability graph are shown in Figure 8.04.

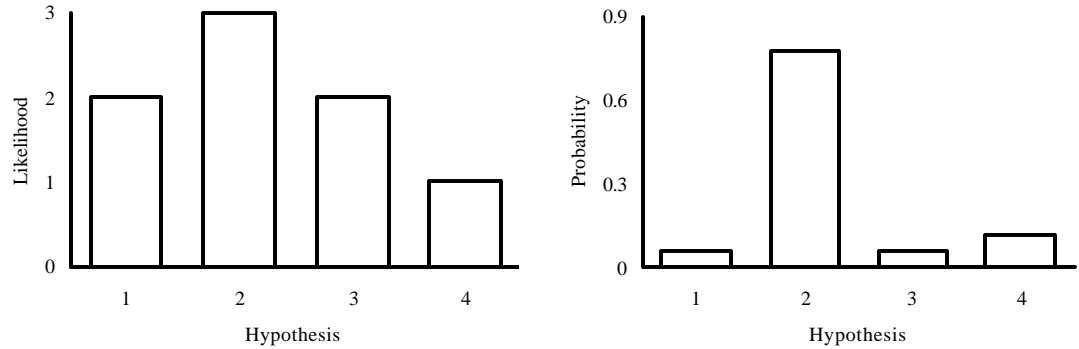


Figure 8.04 – The likelihood and posterior probability functions for the third refinement.

D. When all three car fire experiments were considered together, there was no clear support for any of the four hypotheses. However when considering the *relative* likelihoods of each of the four hypotheses, i and ii appear more *likely* than iii or iv; if ϕ was dependent on the blockage ratio one would have expected a greater difference in ϕ values between the Hammerfest and BRT tests, similarly one would have expected the variation to be greater if ϕ varied with \bar{H} . The likelihood of this evidence and the refined probability graph are shown in Figure 8.05.

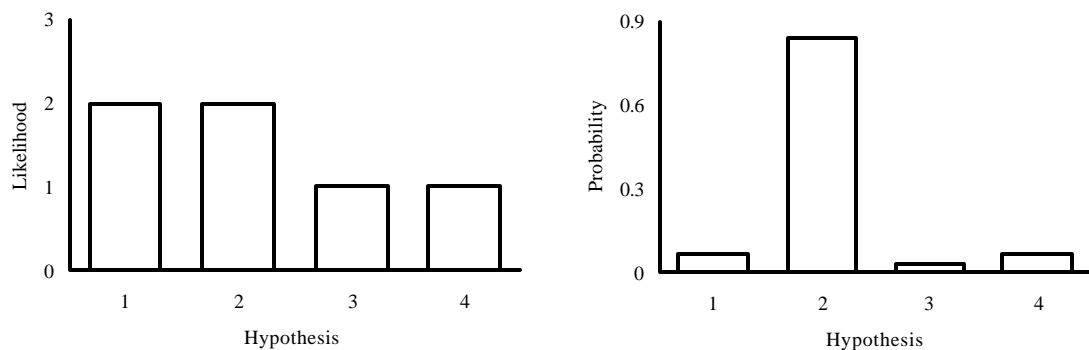


Figure 8.05 – The likelihood and posterior probability functions for the fourth refinement.

A. The 0.09m² heptane pool in the Swedish model tunnel, the 0.64m² heptane pool in the blasted rock tunnel and the 1m² heptane pool in the INERIS gallery are all approximately $\frac{1}{3}$ of the width of the tunnel. By considering them together it is clear that ϕ increases as the tunnel dimensions (both width and height) increase, so it seems most likely that ϕ varies principally with \bar{h} . The likelihood of this evidence and the refined probability graph are shown in Figure 8.06.

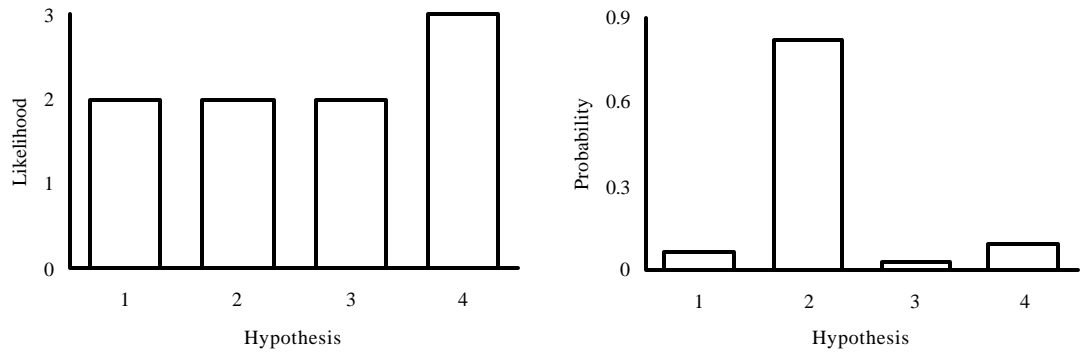


Figure 8.06 – The likelihood and posterior probability functions for the fifth refinement.

E. By considering the car, crib and pool fire tests carried out in the EUREKA tunnel together, it appears that blockage ratio is not greatly important, but that distance from the walls or ceiling may play a crucial role. No information is given regarding hypothesis iv. The likelihood of this evidence and the refined probability graph are shown in Figure 8.07.

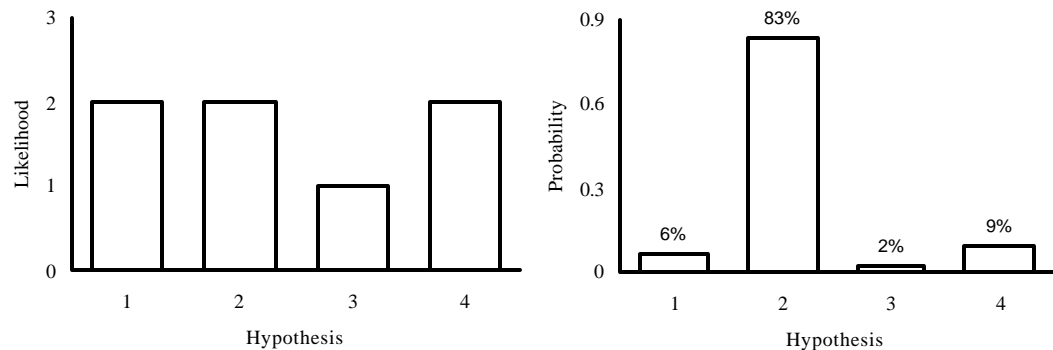


Figure 8.07 – The likelihood and posterior probability functions for the sixth refinement.

From this application of Bayes' theorem it appears that hypothesis ii is the most trustworthy, that the distance from the fire to the walls is the geometrical factor most

influential on ϕ . It is therefore assumed that ϕ may be regarded as being a simple function of w , the distance from the fire load to the walls of the tunnel, that is:

$$\phi = f(w) \quad [8.1]$$

This is, of course, a simplification of reality. Other geometrical factors may also have an influence on ϕ . However, by simplifying the problem to a single variable an approximate relationship may be established, which may then be elaborated on at a later date, adding complexity and accuracy to it by considering the influence of other geometrical factors. Other, non-geometrical, factors may also be important. The nature of the fuel, for example, also plays a crucial role; in the Swedish model tunnel, the fire test involving xylene exhibited a 30% higher value of ϕ than the heptane test using a pool of the same dimensions [124]. In the Japanese model tunnel the fire test using heptane exhibited a ϕ value over 250% higher than the methanol test using the same size pool [89].

8.3.2 Sensitivity to likelihood ratio

The above Bayesian calculations were carried out using a likelihood ratio of 3:2:1. In order to establish whether the ranking of hypotheses is sensitive to the choice of likelihood ratio, the calculations were repeated using three alternative ratios. The final posterior results (after six refinements) are shown in Table 8.1, below.

<i>Ratio</i>	<i>Hypothesis i</i>	<i>Hypothesis ii</i>	<i>Hypothesis iii</i>	<i>Hypothesis iv</i>
3:2:1	6%	83%	2%	9%
4:3:2	12%	66%	6%	16%
10:5:1	0.5%	99.0%	0.1%	0.4%
10:2:1	0.2%	98.8%	0.1%	0.9%

Table 8.1 – The posterior results calculated using different likelihood ratios.

From this analysis it is clear that Hypothesis *ii* is found to be the most trustworthy, irrespective of which likelihood ratio is used in the calculations. Furthermore, the ranking order of the hypotheses ($ii > iv > i > iii$) is not changed as the likelihood ratio is altered.

8.4 Estimating the relationship between ϕ and w

Having reduced the problem of tunnel geometry versus fire severity to merely finding the relationship between ϕ and w , the original intention of the study was to use a similar methodology to that used in Chapters 4-6 to estimate the relationship. However, estimating the relationship proved to be a much easier task than anticipated.

8.4.1 Plotting the data

w , the width geometry factor is a function of W_t , the width of the tunnel and W_f , the width of the fire object. Therefore all ϕ data were plotted on graphs against $W_t - W_f$, $(W_t - W_f) / W_t$ and W_f / W_t to see if any relationships were apparent. No simple relationships were apparent in the first two plots, but there appeared to be two distinct “arms” on the third graph. The plot of ϕ vs. W_f / W_t is shown in Figure 8.08.

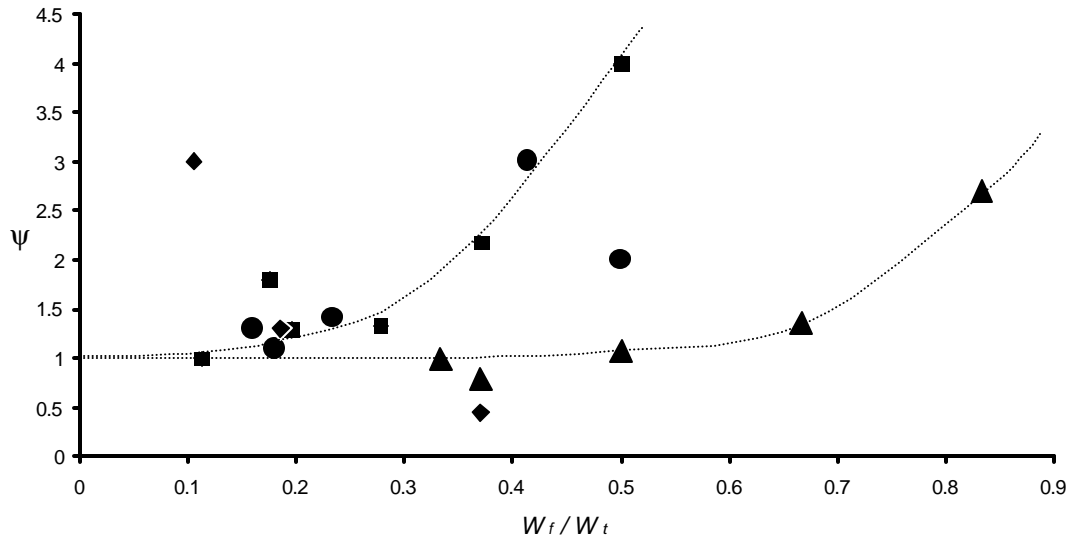


Figure 8.08 – Graph of all ϕ values against W_f / W_t . Heptane pool fire tests are indicated using ■, wooden crib and car fire tests are indicated using ●, ▲ represents the methanol pool fire tests and ◆ represents the kerosene pool fire tests from the Australian test series. The two observed relationships are indicated.

8.4.2 The anomalous behaviour of methanol pool fires

The lower arm on the graph in Figure 8.08 is comprised entirely of methanol pool fire tests. Methanol does not behave like most hydrocarbon fuels in many ways; these will be discussed in the next chapter. Here it is assumed that the relationship between ϕ and w for methanol fires is different from the relationship for most common fuels, so the data from methanol fires will be considered separately. The graph of ϕ vs. W_f / W_t for all data except methanol fires is shown in Figure 8.09.

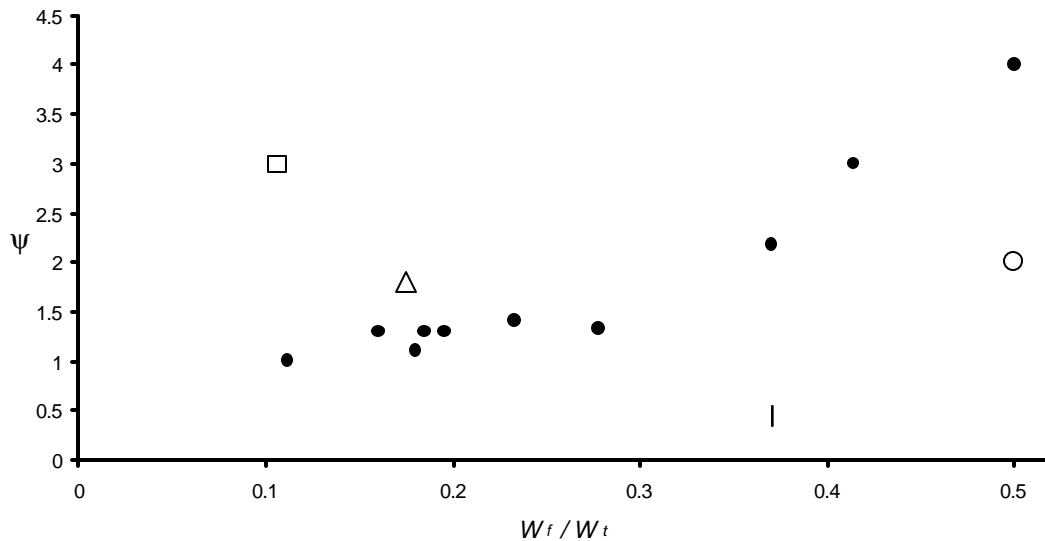


Figure 8.09 – Graph of all ϕ values against W_f / W_t except those from methanol pool fire tests. The outlying data points are indicated as follows: Car fire test in blasted rock tunnel, \circ ; Large kerosene pool fire test in Australian mine tunnel, \diamond ; Small kerosene pool fire test in Australian mine tunnel, \square ; Heptane pool fire test in INERIS fire gallery, Δ .

8.4.3 The other anomalous results

After discounting the methanol fire tests, there are still four experimental tests from the literature review which do not seem to fit with the trend in the other data points, these are:

1. The fire test of a Fiat 127 car in the blasted rock tunnel.
2. The fire test of a 1m^2 heptane pool in the INERIS fire gallery.
3. The largest kerosene pool fire test in the Australian mine tunnel.
4. The smallest kerosene pool fire test in the Australian mine tunnel.

Possible reasons for these discrepancies are:

1. There is a considerable size difference between the Fiat 127 and the cars that were burned in the open air. It may be that the open air heat release rate of a Fiat 127 would be considerably less than predicted and so ϕ would therefore be expected to have a greater value than depicted. It is also possible that the fire in this test was starved of oxygen due to the restricted ventilation conditions in the tunnel.
2. Unlike the rest of the tunnels considered in this study, the INERIS fire gallery has a concave ceiling. This may have the effect of “focussing” the re-radiated heat back

to the fire location (in the middle of the tunnel) and so the heat release rate may be enhanced more than it would be in a flat ceilinged tunnel. A concave ceiling would also mean that the hot gases in the fire plume would tend to accumulate more in the centre of the tunnel; in a flat ceilinged tunnel the gases would be expected to “spread out” across the whole tunnel width.

3. The ϕ value for this test is less than one, so oxygen depletion is clearly the dominant factor in the behaviour of this fire test.
4. The smallest fire test in the Australian mine tunnel is the only unexplainable anomaly. The test was substantially different from most of the others in the study in that there was a small (but possibly significant) forced airflow in the tunnel (0.5ms^{-1}), also the tunnel was considerably wider than it was high ($5.4\text{m} \times 2.4\text{m}$). However, it is not apparent why these two factors should combine to enhance the heat release rate of this fire by a factor of three.

8.4.4 *Estimating the relationship*

The anomalous nature of the data points numbered 1 and 3 above appears to have been due to oxygen depletion. As this part of the study is only concerned with estimating the relationship between ϕ and tunnel width when there is sufficient oxygen, these two points may justifiably be discarded at this point. The anomalous data point numbered 4 has also been discarded as it is clear that some factors, other than tunnel geometry alone, must have been at work to enhance the heat release rate of this fire to such an extent. Finally, on the understanding that the analysis which follows will only apply to tunnels with a flat ceiling, the anomalous data point numbered 2 has also been discarded.

The remaining data points appear to be related in an exponential or quadratic manner. Microsoft Excel was used to estimate this relationship using the “least squares” method. The relationship was found not to be exponential but polynomial in nature. The software predicted a relationship of:

$$\phi = 23.66\left(\frac{W_F}{W_T}\right)^3 - 0.53\left(\frac{W_F}{W_T}\right)^2 - 0.47\left(\frac{W_F}{W_T}\right) + 1 \quad [8.2]$$

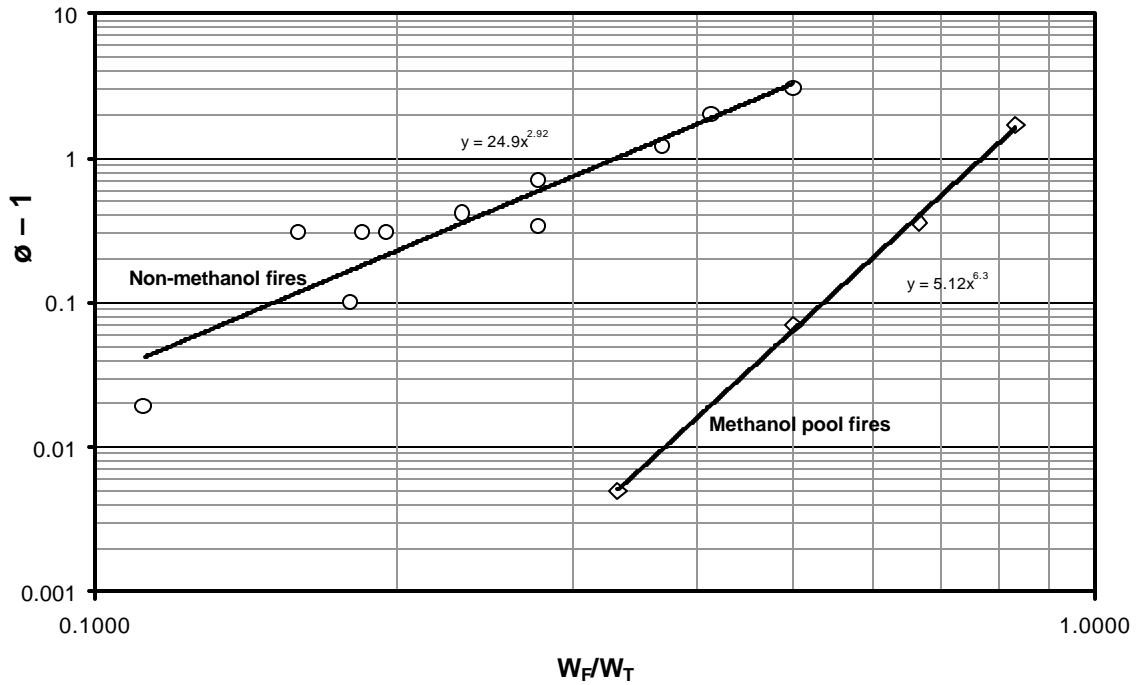


Figure 8.10 – Log-log graph of ϕ data.

The data points for methanol and the other fire tests were plotted on a log-log graph to demonstrate that the relationship for methanol is radically different to the relationship amongst the other data points, see Figure 8.10. The lines of best fit for these two different groups of lines are:

$$\psi = 24.9 \left(\frac{W_F}{W_T} \right)^{2.92} + 1 \quad [8.3]$$

for the non methanol fuels and

$$\psi = 5.12 \left(\frac{W_F}{W_T} \right)^{6.3} + 1 \quad [8.4]$$

for methanol pool fires.

Equations [8.2] and [8.3] are virtually indistinguishable from each other for the range of fire sizes considered. Considering the uncertainties involved in the data values (see next chapter), the relationship may be simplified to:

$$\phi = 24 \left(\frac{W_F}{W_T} \right)^3 + 1 \quad [8.5]$$

Equation [8.5] will be used as the relationship between ϕ and tunnel dimensions for all non-methanol fuels, for all practical purposes. This relationship is shown, overlaid on a graph of the remaining data points, in Figure 8.11. Whether or not the relationship holds for values of W_F/W_T greater than about 0.5 remains to be determined.

The relationship for methanol fuel is clearly very different but, as methanol fires pose little risk in tunnel fire scenarios, will not be considered further here.

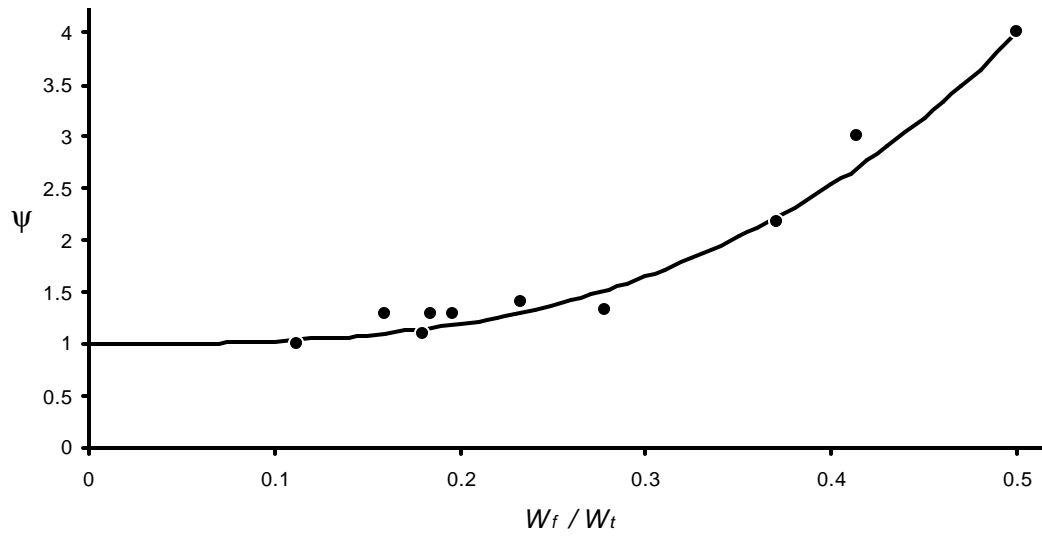


Figure 8.11 – Graph of ϕ against W_f / W_t . The trendline represents the graph

$$\phi = 24(W_F / W_T)^3 + 1$$

The relationship given in Equation [8.5] was compared to the numerical data to determine how well the proposed trendline fits the data. The calculations are shown in Scheme 8â. With all the anomalous points removed Equation [8.5] fits the remaining data points with a fit of $r = 0.989$ (where r is the coefficient of determination; $r = 1$ is a perfect fit). If the anomalous data from the fire test in the INERIS gallery (anomaly number 2 in Section 8.4.3) are not discarded then $r = 0.959$, which is still a very good fit. Even if one of the more extreme data points, for example the small kerosene pool fire in the mine tunnel (anomaly number 4), is included in the calculations, the fit is still reasonably good, with a value of $r = 0.757$.

An example calculation of r , the coefficient of determination.

For all data points excluding anomalies 1, 3 & 4 (see section 8.4.3):

<i>Test</i>	W_F/W_T	ϕ	<i>Trendline: Equation [8.5]</i>	<i>Difference between ϕ and trendline, squared</i>	<i>Difference between ϕ and average</i>
					0.2T6j -5.2f5-13

Chapter 9. Discussion of the second problem

9.1 Opening comments

Anyone reading the newspaper and magazine articles that followed any of the recent fire incidents in tunnels would probably notice that there appears to be a belief amongst the general public that vehicle fires in tunnels are in some way more severe than vehicle fires in the open air. This may be because of the perceived difficulties in escape from tunnels. Amongst many of those involved in tunnel fire safety however, the only hazard that appears to be considered as important in tunnel fire situations is smoke. Following a presentation of the results from the previous chapter, delivered at an international conference on tunnel safety, an internationally known and respected tunnel safety engineer commented that he would expect ϕ to have a value of less than one in *all* tunnel fire situations, in other words, he would expect any fire in a tunnel to be less severe than a similar fire in the open air. Other experts in the field have also expressed this opinion. However, as demonstrated by the results in the last chapter, this is not the case; many tunnel fires are significantly more severe (in terms of heat release rate) than similar fires in the open air.

Once again it is observed that there is much that even the leading experts in tunnel fire safety do not know and that much more research is necessary. As with the first problem addressed in this thesis, the full answer to the question of the influence of tunnel geometry on fire severity will only be found through an extensive series of experimental tests. The results presented here are not the definitive answer, merely a first attempt to try and quantify the relationship between tunnel geometry and fire severity.

9.2 The results

Some fires in tunnels burn with significantly higher heat release rates (HRR) than similar fires in the open air. The peak heat release rate of some fires in tunnels has been observed to be as much as four times greater than that of a similar fire in the open air.

In this study, a Bayesian methodology was used to predict which geometrical factor has the greatest influence over this degree of HRR enhancement. It has been shown that the distance from the tunnel walls to the fire object appears to have the greatest influence on HRR enhancement for fires in tunnels, all else remaining approximately the same.

It has been shown that heat release rate enhancement, tunnel width and fire width are approximately related according to the following equation:

$$\phi = 24 \left(\frac{W_F}{W_T} \right)^3 + 1 \quad \text{[from 8.3]}$$

where W_F is the width of the fire object, W_T is the width of the tunnel and ϕ is the ratio of heat release rate for a fire in a tunnel to heat release rate of a fire outside of a tunnel, thus:

$$\phi = \frac{\dot{q}_{tunnel}}{\dot{q}_{open}} \quad \text{[from 7.1]}$$

In practice, it may be useful to arrange these equations to give:

$$\dot{q}_{add} = 24 \dot{q}_{open} \left(\frac{W_F}{W_T} \right)^3 \quad \text{[9.1]}$$

where $\dot{q}_{add} = \dot{q}_{tunnel} - \dot{q}_{open}$, that is, the additional HRR due to the fire being in a tunnel.

9.3 What processes cause the heat release rate enhancement?

The heat release rate of a fire is determined by the rate of production of flammable gases from the fuel, which is in turn determined by the rate of heat transfer to the fuel itself. For liquid fuels the heat transferred to the fuel vaporises the fuel, whereas for most solid fuels, the heat pyrolyses the fuel into smaller gaseous components. In the open air, the heat transfer which governs the gasification of the fuel comes mostly from the fire plume; and only a small fraction of the heat produced in the plume is directed downward to the fuel.

If the heat release rate of a fire is enhanced due to being in a tunnel, this is because there is a greater heat feedback from the fire plume and the surroundings than there would be in the open air. This is because the upward movement of the fire plume is prevented by the tunnel ceiling, this leads to an accumulation of hot gases above the fire location which will radiate much more heat downwards than a buoyant plume in the open would. (Remember that radiation back to the fuel surface is the main process governing the heat release rate of a fire, see Section 2.5.1). These processes are illustrated in figure 9.01.

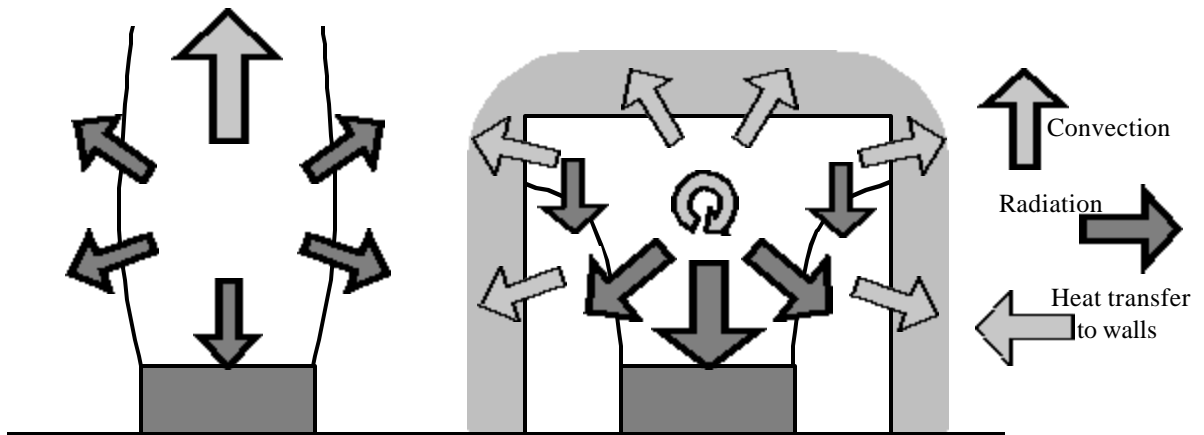


Figure 9.01 – Heat transfer processes in the open air and in a tunnel.

9.3.1 Tunnels with concave ceilings

It has been observed that the fire test in the study which was carried out in a tunnel with a significantly concave ceiling was enhanced to a greater degree than would be predicted by using the formula [8.5]. This may be due to one or both of the following reasons:

1. The shape of the ceiling may tend to focus the radiated heat toward the centre of the tunnel, where the fire object was located.
2. The shape of the ceiling means that there is a greater concentration of the hot gases in the centre of the tunnel, above the fire, than nearer the walls. In a rectangular aspect tunnel, the hot gases would be expected to be evenly distributed across the tunnel width.

These two scenarios are illustrated in figures 9.02 and 9.03 respectively.

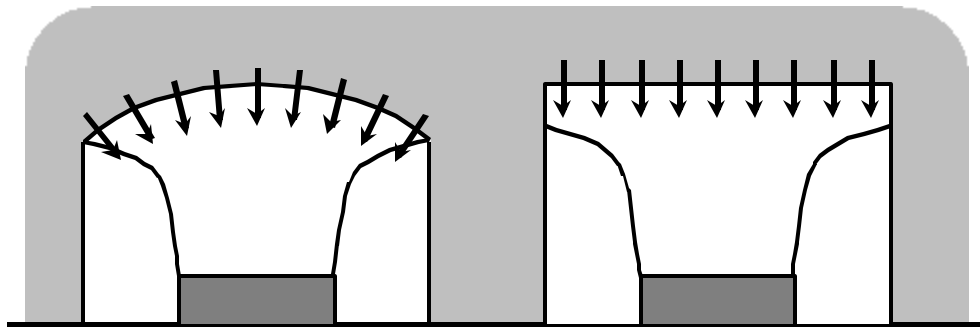


Figure 9.02 – Re-radiated heat from the tunnel ceiling for concave and flat ceilinged tunnels

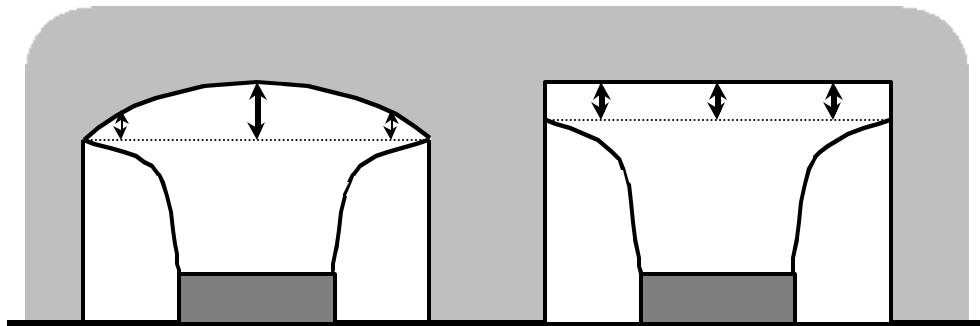


Figure 9.03 – The thickness of the hot gas layer in concave and flat ceilinged tunnels

9.3.2 Why is the enhancement greater in a narrower tunnel?

The Bayesian study predicts that, in general, the tunnel width has the greatest influence on the heat release rate enhancement. It is expected that this is in part due to the thickness of the hot gas layer above the fire location. All other factors being equal, the hot gas layer will be thicker in a narrow tunnel compared to a wide tunnel, hence there will be a greater amount of heat radiated down to the fire location in a narrower tunnel. This is illustrated in figure 9.04.

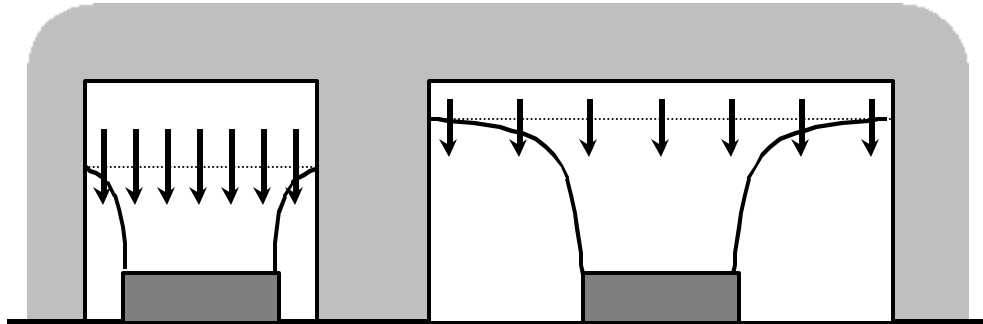


Figure 9.04 – Thickness of the hot gas layer in narrow and wide tunnels

9.4 Applicability of the formula

The formula presented here [8.5] is based on a number of experiments carried out in comparatively small tunnels. Also the majority of the experiments were carried out in tunnels that were approximately square in cross-section. Further study will be required to determine if this relationship holds for larger tunnels or tunnels which are significantly non-square in aspect.

Most of the tests used as the basis for this study involved fire loads which were generally as wide as they were long (i.e. having an approximately square or circular footprint). The biggest deviations from this were the fire test involving a Renault Espace car, which was approximately 2.3 times as long as it was wide, and the wooden crib fire tests in the Hammerfest tunnel, which were four times as long as they were wide. Because of this, it is not certain that this relationship will hold for vehicles or other fire loads that are significantly longer than they are wide, e.g. a typical HGV is five or six times longer than it is wide and the length : width ratio of train carriages may be greater than that.

However, until further evidence is presented, it is assumed that the formula approximates the relationship amongst tunnel width, fire object width and heat release rate enhancement for all types of fire load (excluding methanol fires) in naturally ventilated tunnels.

9.5 Use of Bayes' Theorem

In this part of the study, Bayes' Theorem was used in a more abstract way than in the earlier part. Instead of being used to estimate the probability distribution of a random variable directly, Bayes' Theorem was used to choose between four different hypotheses. A mathematical relationship was then inferred, based on the chosen hypothesis. Although little is known about what sort of use Bayes himself put his theorem to, it is generally believed that this sort of application, choosing between opposing hypotheses, was how Bayes intended the theorem to be used. Allocating equal probability to each of the hypotheses in the first instance is also consistent with what is known about Bayes' own use of the theorem; this is "Bayes' Postulate" (see Chapter 3). This sort of use of Bayes' Theorem has been used for centuries and is entirely justifiable in any situation where there are multiple hypotheses and at least a handful of relevant data. In scenarios like this, Bayes' Theorem offers a quick and easy method of simplifying a complex problem.

9.6 Errors & uncertainties

As with every problem in science and engineering, it is important to question the results of this study and attempt to describe the level of error or uncertainty in the results. The greatest uncertainties in this part of the project are probably to be found in the estimation of the ϕ values for each experimental tunnel fire. For some of the fire tests, there was a very good *similarity* between the fire loads in and out of the tunnel, e.g. the Japanese and Swedish pool fire tests; the same pool was used both in and out of the tunnel in both cases. In these cases the uncertainty in the value of ϕ may be as low as 5%. For other tests however, the fire loads were very different, e.g. the car fire experiments; the Renault Espace was considerably larger than any of the open air car fire tests, whereas the Fiat 127 was considerably smaller. In these cases the uncertainty in the value of ϕ may be high, perhaps as high as 30% or more.

The measurement of the heat release rate for any experimental fire is always an uncertain process. Even with state of the art measuring equipment, the calculations still involve some assumptions about the relationship between oxygen consumed and heat released; generally heat release rate is calculated assuming that 13.1MJ of heat are released for every kg of oxygen consumed, but there is at least a 5% uncertainty in this value.

In certain cases, the ϕ values have been estimated from mass loss data from tests carried out by the same researchers. In these cases, the errors in the values of ϕ are considerably less as recording the mass loss rate of a fire is far more accurate than estimating the heat release rate.

No two *similar* fires are exactly the same. If the value of ϕ for a specific case of interest turns out to be 2.08, it is unjustifiable to expect such a fire to be exactly 2.08 times greater in heat release rate than a similar fire in the open air. However, it is reasonable to expect a fire *approximately* twice the severity of a fire in the open air, and thus take appropriate precautions.

9.7 Methanol pool fires

The relationship expressed in equations [8.5] and [9.1] appears to be valid for a number of different types of fires in tunnels, but not for methanol pool fires. Methanol pool fires appear to follow the relationship given in Equation [8.5]. There are a few reasons why methanol may behave significantly differently to most other fuels:

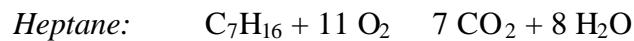
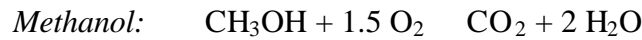
- *Heat of combustion*

The heat of combustion of methanol is 726 kJmol^{-1} (23 kJg^{-1}) which is substantially less than the heat of combustion of other common fuels, e.g. heptane: $H_C = 4817 \text{ kJmol}^{-1}$ (48 kJg^{-1}) and petrol $H_C = 4100 \text{ kJmol}^{-1}$ ($40\text{-}45 \text{ kJg}^{-1}$). From Babrauskas [47] it can be calculated that the heat release rate of a 3m diameter methanol pool fire (in the open air) would be about 2.4MW, whereas the heat release rates of similarly sized petrol and heptane pool fires would be about 17MW and 31MW, respectively. As it is likely that ϕ depends on the re-radiated heat from the hot gas layer and the tunnel lining, it is obvious that methanol will exhibit much lower

values of ϕ than these other fuels as the heat production (and hence the level of re-radiated heat) is between seven and thirteen times less than that of the other fuels.

- *Oxygen consumption*

It is also likely that a methanol pool fire will remain fuel controlled (that is, have more than enough oxygen to burn fully) under more restricted geometrical conditions than other common fuels. This can be seen if we compare the combustion reaction of methanol with that of heptane:



It can be seen that one mole of methanol requires 1.5 moles of oxygen to burn fully, whereas one mole of heptane requires eleven moles. Taking molecular weight and density into consideration, it can be calculated that one litre of methanol requires about 37 moles of oxygen (4m^3 of air at STP) to burn fully whereas one litre of heptane requires about 74 moles of oxygen (8m^3 of air at STP). In other words, methanol requires about half the amount of oxygen that other fuels, like heptane, need to burn.

- *Smoke production*

Another factor that sets methanol apart from most other common fuels is its smoke production. Methanol produces hardly any particulate smoke. It is expected that a significant factor contributing to the value of ϕ is the amount of heat radiated from the hot gas layer at the tunnel ceiling back down to the fire location. Much of the radiation from the upper gas layer is due to hot soot particles radiating their heat; if there are fewer particles, the radiation from the upper layer will be significantly less and hence ϕ will be less for methanol than for most other fuels.

These factors help to explain the anomalous behaviour of methanol pool fires. However, in reality it is unlikely that these factors will need to be taken into account; methanol is not a common fuel in transport tunnels and, considering its comparatively mild burning behaviour, it can be considered to pose little hazard in tunnel fire situations.

9.8 Combining geometry and ventilation effects

The first problem addressed in this thesis predicted the relationship between longitudinal ventilation and fire size in tunnels by using the heat release rate coefficient k defined by equation [4.2]:

$$k = \frac{\dot{q}_{vent}}{\dot{q}_{nat}}$$

where \dot{q}_{vent} is the HRR of a vehicle fire in a tunnel with forced ventilation and \dot{q}_{nat} is the HRR of a similar fire in a similar tunnel with natural ventilation. The second problem concerned the relationship between tunnel geometry and fire size in naturally ventilated tunnels. This was described using the coefficient ϕ defined by equation [7.1]:

$$\phi = \frac{\dot{q}_{tunnel}}{\dot{q}_{open}}$$

where \dot{q}_{tunnel} is the HRR of a fire in a naturally ventilated tunnel and \dot{q}_{open} is the HRR of a similar fire in the open air. Of course, for similar fire objects \dot{q}_{tunnel} and \dot{q}_{nat} are the same quantity, so it is possible to combine equations [4.2] and [7.1] to give:

$$\dot{q}_{vent} = k \phi \dot{q}_{open} \quad [9.2]$$

and hence, if the approximate HRR of a type of fire object in the open air is known, the HRR of such a fire in a tunnel can easily be estimated using the results presented in Chapters five and eight of this thesis.

However, it should be noted that the factor k , relating to the influence of ventilation on fire size, is only defined for very specific sizes of tunnel. The k values for HGV fires are only appropriate for single lane tunnels, approximately 7.6m wide. Similarly the values of k for pool fires are defined for two-lane tunnels, approximately 10m wide. Equation [9.2] cannot be used in situations which are significantly different from either of these two cases.

9.8.1 Some examples

For the purposes of making estimates of HRR in tunnels, it may be easier to present the probability distributions of k as percentile graphs as shown in figures 9.05, 9.06 and 9.07. For a given fire type and ventilation velocity it is easy to estimate a likely value of k from these graphs (that is, a value near to the expectation). This can be combined with a calculated value of ϕ and a known value of \dot{q}_{open} to estimate the HRR of such a fire in a tunnel. The derivation of these graphs is discussed below.

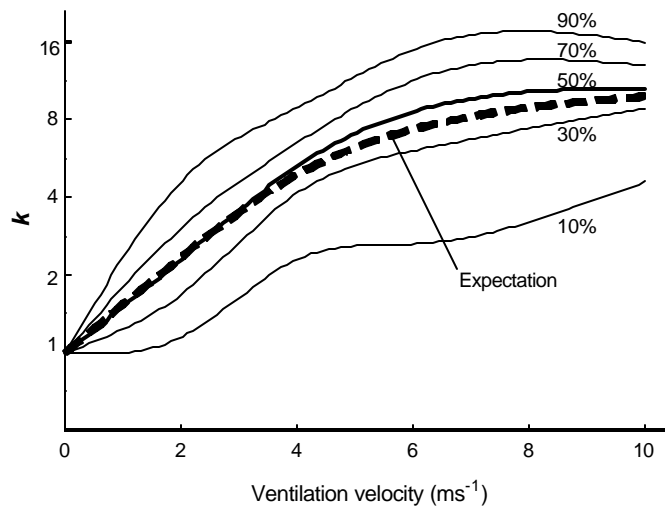


Figure 9.05 – Probability percentile graphs for a fully involved HGV fire in a single lane tunnel (approximately 7.6m wide)

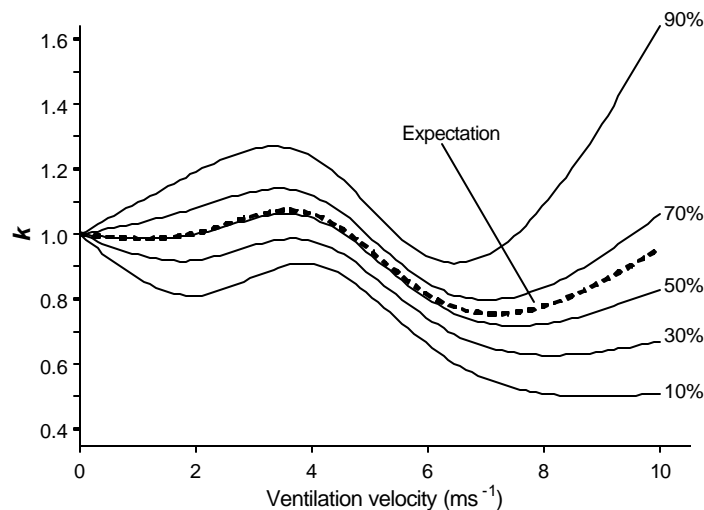


Figure 9.06 – Probability percentile graphs for a small / medium sized pool fire in a two lane tunnel (approximately 10m wide)

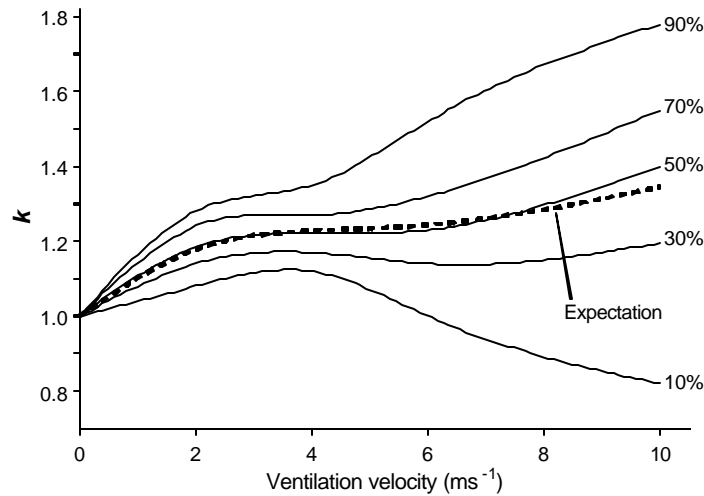


Figure 9.07 – Probability percentile graphs for a large pool fire in a two lane tunnel (approximately 10m wide)

Example 1. A 1m² heptane pool fire would be expected to have a HRR of about 3.0MW in the open air. If this fire were in a 9m wide tunnel (which would give a ϕ value of about 1.03 according to equation [8.5]) with a 6ms⁻¹ airflow (the expectation of k is about 0.8, from Figure 9.06) its expected HRR would be:

$$\dot{q}_{vent} = k \phi \dot{q}_{open} = 0.8 \times 1.03 \times 3.0 = 2.47\text{MW}$$

Example 2. A 2m wide truck might burn with a HRR of about 10MW in the open air. If this same vehicle were on fire in an 7m wide tunnel (which would give a ϕ value of about 1.6 according to equation [8.5]) with a 4ms⁻¹ airflow (the expectation of k is about 5, from Figure 9.05) its expected HRR would be:

$$\dot{q}_{vent} = k \phi \dot{q}_{open} = 5 \times 1.6 \times 10.0 = 80\text{MW}$$

It should be noted that while the values of ϕ appear to hold for fires in tunnels of all sizes, the values of k in the first part of the study were derived only for single lane tunnels (HGV fires) and twin lane tunnels (pool fires). It is likely that k values will not be as high (for a given airflow) in tunnels significantly larger than the archetypes considered by the study. In other words, it is likely that the mean value of k for a HGV fire in a three lane tunnel with a 4ms⁻¹ forced airflow will be less than five (the expected

value of k for a HGV in a single lane tunnel with a 4ms^{-1} forced airflow). This will be discussed in the concluding comments in the next chapter.

9.8.2 Derivation of the percentile graphs

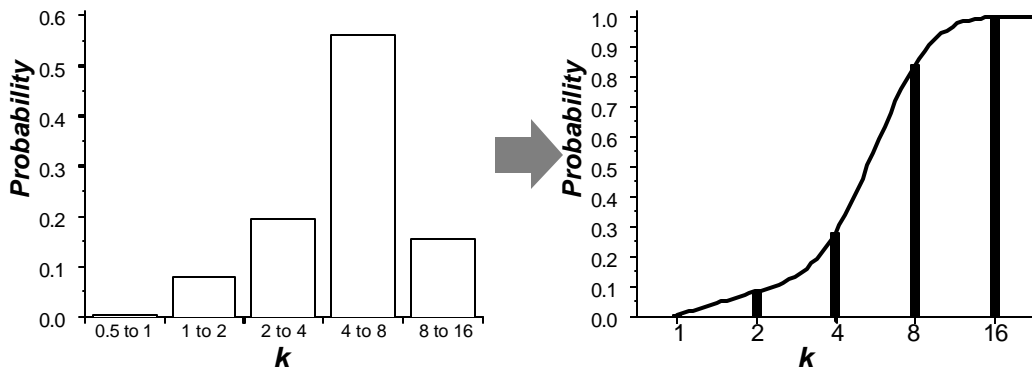
The percentile graphs presented in figures 9.05, 9.06 & 9.07 were conceived as a method of conveying the probabilistic nature of the results to a non-technical audience. They were devised as follows. First the posterior probability distributions were converted into cumulative distribution functions (c.d.f), such that the probability corresponding to the upper limit of the first k range ($k=1$ in the HGV case) was equal to the probability of the first range, the probability corresponding to the upper limit of the second k range ($k=2$ in the HGV case) was equal to the sum of the probabilities of the first two ranges, the probability corresponding to the upper limit of the third k range ($k=3$ in the HGV case) was equal to the sum of the probabilities of the first three ranges and so on, see scheme 9á-*i*.

The values of k corresponding to probabilities of 0.1, 0.3, 0.5, 0.7 and 0.9 were interpolated from these cumulative distribution functions, to give the k values of the 10th, 30th, 50th, 70th and 90th percentiles at the four ventilation velocities of interest (2, 4, 6 and 10ms^{-1}), see scheme 9á-*ii*.

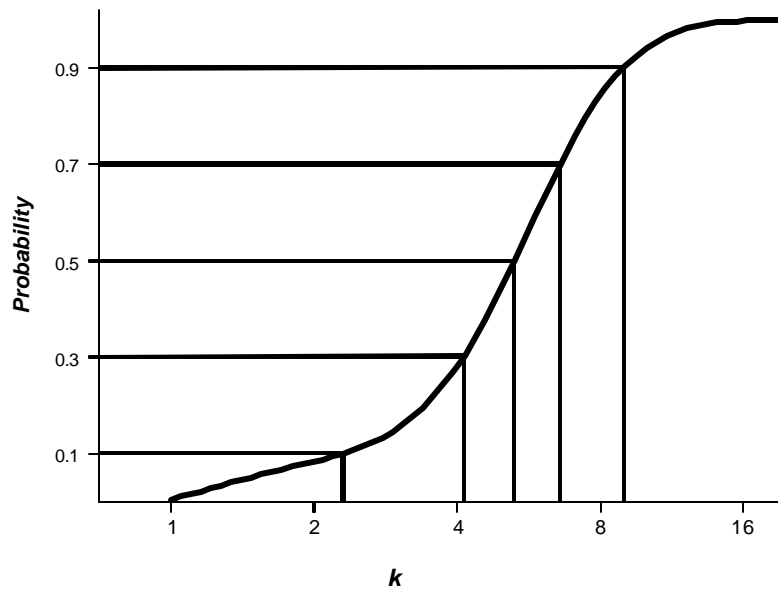
These graphs can be used to demonstrate the span of possible fire sizes under a given set of conditions. For example, in example 2 (on the previous page) it was calculated that a fire involving a truck under a given set of geometrical and ventilation conditions would be expected to be about 95MW. However, if we perform calculations for the 10th and 90th percentiles for those ventilation conditions (10th percentile of $k = 2.5$, 90th percentile of $k = 9$) we observe that the fire could have a peak HRR as low as 47MW or as high as 170MW.

Example: Calculation of percentile values of k for a fully involved HGV fire in a tunnel (at 4ms^{-1}).

Stage i – convert the probability distribution into a c.d.f.



Stage ii – obtain the values of k corresponding to the percentiles



Scheme 9á – Calculation of the percentile values

9.8.3 *An interesting observation*

It has been demonstrated that tunnel geometry can significantly enhance the heat release rate of a fire in a tunnel under certain conditions. It has also been demonstrated that applying ventilation to certain sizes of pool fires in a tunnel can significantly diminish the heat release rate of the fire. It is interesting to note that in the pool fire test series carried out by Saito *et al.* [89], the values of heat release rates of the pool fires were observed to tend towards a limiting value as the ventilation rate was increased. In every instance, this limiting value was very close to the heat release rate of the similar fire test carried out in the open air. From this observation it appears that the influence of ventilation on a pool fire in a tunnel may be simply to counteract the enhancing effect of re-radiation due to the tunnel geometry. In other words, given sufficient forced longitudinal ventilation, a pool fire in a tunnel is no more or less severe (in terms of HRR) than a similar fire in the open air. This is not the case for solid, three dimensional, fire loads as the interactions between the fire and forced ventilation are more complex.

Chapter 10. Concluding comments

10.1 Looking forwards: towards a bigger picture

In Chapters 4-6 the question of the influence of forced longitudinal ventilation on fire size (heat release rate) was examined. The results presented for HGV fires relate only to single lane tunnels. The results presented for pool fires relate only to two lane tunnels. At present it is assumed that the results presented for car fires are applicable to a range of tunnel sizes, but this needs testing. Clearly these results are only applicable to a small subset of all the tunnels in the world and care should therefore be taken not to attempt to extrapolate these results to apply to tunnels which they give no information about. More experimental data are needed before the bigger picture is clearly seen, that is, before the influence of longitudinal ventilation on fire size in *all* shapes and sizes of tunnels is understood.

A series of pool fire experiments (and a bus fire experiment) were carried out in a very large, three lane tunnel in Japan in 2002 [126-128]. One of the pool fire experiments was carried out with natural ventilation, one with forced ventilation at 2ms^{-1} and one with forced ventilation at 5ms^{-1} . Although there were slight variations in heat release rate amongst these tests (which may be attributed to the influence of ventilation), the magnitudes of these variations were considerably smaller than might be expected from the results of this study. Clearly ventilation has a much less significant influence in larger tunnels than in smaller tunnels. This is, of course, fairly obvious; as tunnel dimensions increase, so the influence of longitudinal ventilation on fire tends towards the influence of wind on fire in the open air (which is much less significant than the influence of ventilation in tunnels). What is not obvious, at present, is the relationship between ventilation and heat release rate in larger tunnels. It may be that scaling the heat release rates and ventilation velocities by preserving the Froude number is appropriate, but this has yet to be demonstrated. There is scope for much more investigation in this field of research.

10.2 Looking back: hindsight

With hindsight, perhaps it would have been better to have carried out this study investigating the influence of v^* on heat release rate, where v^* is some form of “non-dimensional ventilation velocity” related to the size of the tunnel, rather than v , the actual ventilation velocity, itself. This would certainly be of benefit when considering the influence of ventilation on HRR for pool fires (where the different sizes of pools were characterised as “small”, “medium” or “large” in relation to the size of the tunnel), but it is questionable whether it would be appropriate for the HGV and car fire cases (where the size of the vehicle was not measured in relation to the tunnel). This needs more research.

Looking back it appears that it might have been better to have carried out the two parts of the study simultaneously rather than one after the other. As we have observed, the relationship between longitudinal ventilation and fire size is itself influenced by the tunnel geometry. If the two projects had been carried out at the same time it is possible that the final results might have been appropriate to a larger set of tunnel configurations. However, this was not possible due to the way that the projects were funded (see acknowledgements), also the second project was not conceived until part-way through the first project.

10.3 Looking back: criticism

Some of the results presented in Chapter 5 and some of the discussion from Chapter 6 formed the basis for a paper which was submitted to the Fire Safety Journal in 2000 [130]. That paper concerned itself only with the vehicle fires; the pool fires part of this study was published elsewhere [131]. The referees appointed by the journal made a number of comments and criticism of the research and its conclusions. Some of these will be considered in this section. One of the questions raised during the assessment of this thesis will also be addressed here.

10.3.1 “Why didn’t you use data from the Memorial Tunnel fires for the HGV case?”

This comment was made by one of the referees. Unusually, the referee identified himself and a correspondence was entered into to discuss this issue. His main point was that the vast majority of tunnel fire data comes from pool fire tests (and from the Memorial Series in particular) and by not using these data the HGV case was somehow incomplete and unjustifiable. After a lengthy debate the referee accepted that pool fires and HGV fires behave in very different ways and so the use of the Memorial data in the HGV case was not appropriate.

10.3.2 “You can’t use the data from the Buxton simulation test as it was basically a pool fire”

This issue has been dealt with in section 6.5.1.

10.3.3 “What about the porosity of the wooden cribs?”

At the time the research was carried out I did not know very much about wooden cribs. The wooden cribs were taken to be “comparable” to cars in that they were similar in size and fire load. Subsequent research (see Chapters 7-9) has lead me to a greater understanding of the processes involved in crib fire burning, particularly the role of the “porosity” of the cribs: the burning rate and maximum heat release rate of a crib can be controlled by varying the size of the channels (“pores”) between the sticks. Two cribs of identical weight and overall dimensions can be made to burn with significantly different heat release rates. This was not taken into consideration during this project. However, the cribs used as evidence in this study were built to be comparable in certain ways to car fires in tunnels, so I have used the results of others in good faith and assume that the experimentalists knew more about crib burning dynamics than I did.

10.3.4 “How can you discard data points from the ϕ graph that were used in the selection of the geometrical factor?”

This question was raised during the assessment of this thesis. In Sections 8.4.2 and 8.4.3 the data from a number of experiments were discarded before the relationship between ϕ and tunnel width was estimated. However, these experiments were used in

the earlier part of the project which used Bayesian methods to choose which geometrical factor has the greatest influence over ϕ , see Section 8.3. These experiments were considered as parts of evidence \underline{C} , \underline{D} and \underline{E} . It is notable that these three sets of evidence gave much *less* clear support of any of the hypotheses than the other three sets of evidence considered. Had these sets not been considered, Hypothesis ii (that ϕ varies primarily with tunnel width), would still have been chosen as most likely. Indeed, had these three sets of evidence not been considered, our confidence in Hypothesis iv (that ϕ varies with \bar{H}) would have been even lower. Thus it is clear that the use of these experimental data did not bias the results of the study in any way.

10.4 Looking forwards: future research

It has often been found that research projects like these two tend to raise as many new questions as they answer. This has been the case in this research as well, indeed the question addressed by the second project (Chapters 7-9) was itself raised by the first project. Other questions raised by the research include:

- *What are the geometrical conditions at which oxygen depletion begins to dominate?*
In Chapters 7-9 the question of the influence of geometry on fire size was studied. A relationship was proposed which appears to hold when W_f/W_t is less than about 0.5, i.e. when the fire object is less than approximately half the width of the tunnel. However, the conditions determining the point at which this relationship no longer holds, that is when the scarcity of oxygen begins to significantly influence the fire behaviour, have not been determined. Also the relationship between ϕ and tunnel geometry beyond this point needs to be determined.
- *What is the total effect of ventilation and geometry on fire spread in tunnels?*
The issue of fire spread between vehicles in a tunnel with longitudinal ventilation has already been addressed in research carried out by Beard *et al.* [99-102]. The model FIRE-SPRINT A3 predicts the critical rate of heat release necessary to bring about fire spread from a fire to an adjacent object (e.g. a HGV) by remote ignition. Using the model it has been demonstrated that the critical HRR value tends to increase with increasing ventilation. This thesis has shown that increasing ventilation tends to increase the HRR of a HGV fire. A question of interest is therefore whether the increase in HRR due to ventilation is larger than the increase

in critical HRR necessary to bring about fire spread to an adjacent vehicle; in other words does increasing the ventilation velocity in a tunnel make spread to an adjacent vehicle more or less likely? Preliminary investigation into this question [129] suggests that, in a tunnel similar in size and shape to the Channel Tunnel, increasing ventilation velocity will tend to reduce the likelihood of the fire spreading to an adjacent vehicle. However, this does not consider the possibility of flame impingement. Research into this question is ongoing.

10.5 Closing summary

This study has used Bayes' Theorem to estimate two aspects of fire behaviour in tunnels:

- The influence of longitudinal ventilation on heat release rate
- The influence of tunnel geometry on heat release rate

The main findings are summarised here:

HGV fires in tunnels

It is expected that longitudinal ventilation will have an enflaming effect on HGV fires in tunnels. For HGV fires in single lane tunnels (approximately 7.6m wide) it is *expected* that:

- A 2ms^{-1} forced airflow will enhance the HRR by a factor of about 4 in the growth phase and 2 at full involvement.
- A 4ms^{-1} airflow will enhance the HRR by 6 and 5.
- A 6ms^{-1} airflow will enhance the HRR by 8 and 7.
- A 10ms^{-1} airflow will enhance the HRR by 9 and 10.

Large pool fires in tunnels

It is expected that longitudinal ventilation will generally have an enflaming effect on large pool fires in tunnels. For such fires in two-lane tunnels (approximately 10m wide) it is *expected* that:

- Forced airflows between 2ms^{-1} and 4ms^{-1} will increase the HRR by about 30%.
- A 6ms^{-1} airflow will increase the HRR by about 50%.
- A 10ms^{-1} airflow will increase the HRR by about 70%.

Medium sized pool fires in tunnels

It is expected that longitudinal ventilation will generally have a diminishing effect on medium sized pool fires in tunnels. For such fires in two-lane tunnels (approximately 10m wide) it is *expected* that:

- A 2ms^{-1} airflow will decrease the HRR by about 15%.
- A 4ms^{-1} airflow will decrease the HRR by about 30%.
- A 6ms^{-1} airflow will decrease the HRR by about 40%.
- A 10ms^{-1} airflow will decrease the HRR by about 50%.

However, it is noted that these results are dependent on experimental fires involving methanol fuel, and may not be representative of the fire behaviour of pools of other fuels.

Small pool fires in tunnels

It is expected that longitudinal ventilation will tend to have a slight enhancing effect on small pool fires in tunnels at low ventilation velocities (below 5ms^{-1}) but that it may have a slight diminishing effect at higher ventilation velocities. For such fires in two-lane tunnels (approximately 10m wide) it is *expected* that:

- A 2ms^{-1} airflow will increase the HRR by about 15%.
- A 4ms^{-1} airflow will increase the HRR by about 10%.
- A 6ms^{-1} airflow will decrease the HRR by a small amount.
- A 10ms^{-1} airflow will decrease the HRR by about 10%.

Car fires in tunnels

It is expected that longitudinal ventilation (at low velocity) will not have a significant effect on the HRR of car fires in tunnels.

The influence of tunnel geometry on fire size

It has been observed that, if a naturally ventilated fire in a tunnel has sufficient oxygen to burn, the HRR of the fire will be enhanced (compared to a fire in the open air, up to a maximum enhancement of about four times) according to the proximity of the fire to the tunnel walls. The following relationship has been proposed:

$$\frac{\dot{Q}_{\text{tunnel}}}{\dot{Q}_{\text{open}}} = \phi = 24 \left(\frac{W_F}{W_T} \right)^3 + 1 \quad \text{[from 7.1 and 8.3]}$$

where \dot{Q}_{tunnel} and \dot{Q}_{open} are the heat release rates of fires in and out of a tunnel, respectively, W_F is the width of the fire object and W_T is the width of the tunnel. It is proposed that this relationship holds for most vehicles and pool fires in tunnels, up to about half the width of the tunnel. It may slightly under-predict the enhancement in tunnels with a concave ceiling. The relationship does not hold for methanol pool fires.

Appendix A. Summaries of all experimental fire tests used as “evidence” in this thesis

This appendix presents a summary of the experimental set-up and results for all fire tests used as “evidence” in this thesis. Experiments will be described in the order cited, not in chronological or alphabetical order.

A.1 Experiments relevant to the HGV fire case (see Chapters 4 & 5)

Fire tests in a disused mine tunnel near Hammerfest, Norway, 1992

The “EUREKA” series of tests were carried out in a disused mine tunnel at Repparfjord, near Hammerfest, Norway [70]. The tunnel has a rough rock lining and an approximate horseshoe aspect. It varies in height from 4.8 to 6.0m and in width from 5.3 to 7.0m. On average the cross-sectional area is 34m². The tunnel is 2.3km long, running approximately north to south, terminating at a near vertical shaft. Temperature, airflow velocity, smoke density and heat release rate measurements were made at a number of locations along the length of the tunnel. Longitudinal ventilation was supplied using two fans inside the mouth of the tunnel. A removable wall at the entrance of the tunnel was also used in some tests to control the airflow. The tunnel layout is shown in Figure A.01.

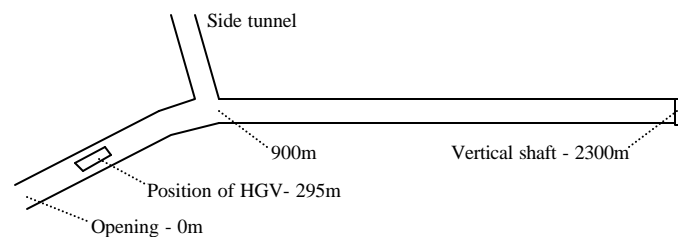


Figure A.01 – The layout of the Repparfjord tunnel.

EUREKA HGV fire test

In this test a HGV (fuelled with diesel, loaded with 2 tonnes of furniture covered by a tarpaulin) was set on fire 295m from the end of the tunnel [123]. Initially the fan (positioned 92m away from the vehicle) delivered an airflow velocity of $\sim 6\text{ms}^{-1}$. Once the fire was well established the fan was switched off for 3 minutes and the airflow reduced to about 0.5ms^{-1} . The fan was then restarted at a lower speed giving an airflow of $\sim 2.9\text{ms}^{-1}$. To date, this has been the only fire test of a HGV carried out under experimental conditions (in a tunnel or in the open air). The experimental configuration is shown in Figure A.02. The test was intended to simulate fire conditions on a HGV carrier wagon in the Channel Tunnel. In order to produce a situation more like that of a Channel Tunnel carrier wagon, a blockage was placed in the tunnel, upstream of the HGV location, to simulate the locomotive / amenity coach.

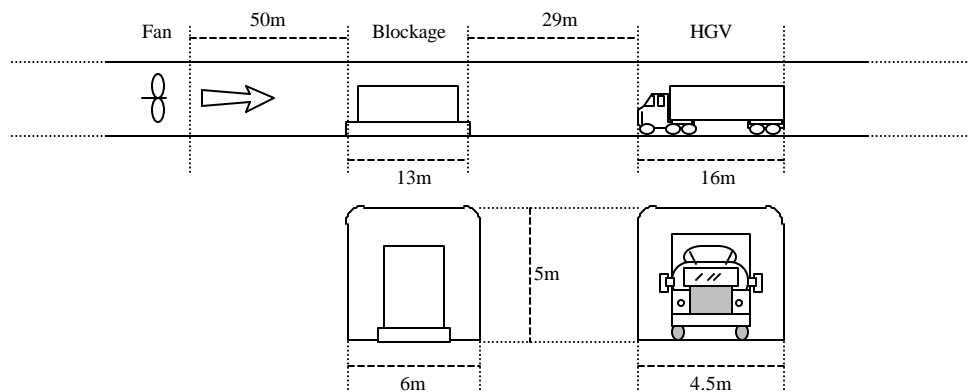


Figure A.02 – The positioning of the HGV within the tunnel.

The Heat Release Rate (HRR) was calculated from CO / CO₂ levels at 22 and 92m downstream of the vehicle [132]. The HRR values presented may well be smaller than the actual values, different calculation methods gave different results, the results presented are based on the calculations of the Unit of Fire Safety, Edinburgh University [133]. The development of HRR and airspeed velocity with time are shown graphically in Figure A.03.

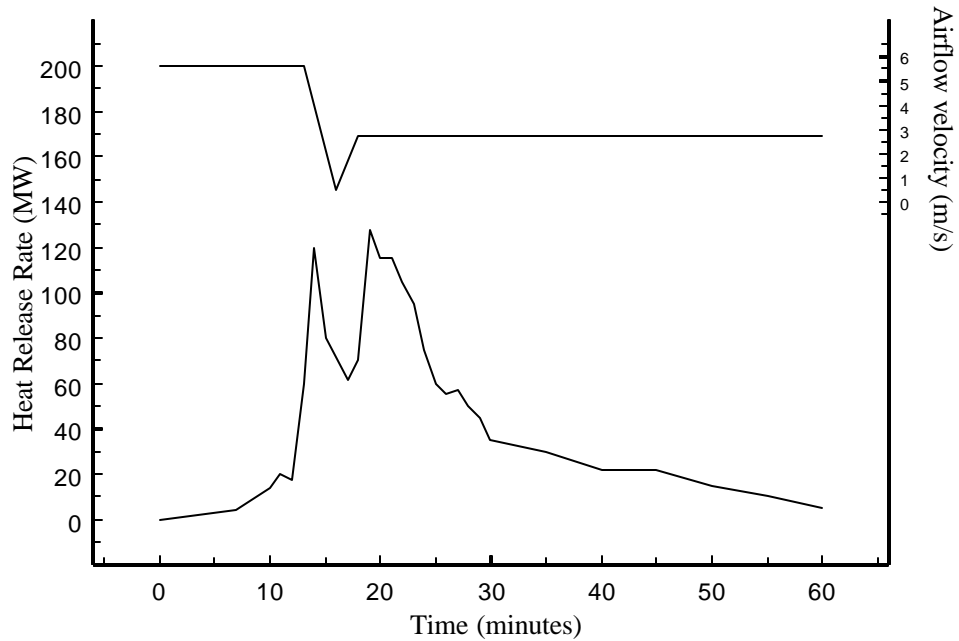


Figure A.03 – The HRR development and airflow velocity during the EUREKA HGV fire test

Sequence of events:

1. Small crib in cab ignited	time = 0:00	HRR = small	$v = 6.0\text{ms}^{-1}$
2. Cab side window breaks	time = 2:30	HRR = 2MW	
3. Cab windscreen breaks	time = 9:00	HRR = 10MW	
4. Burning spreads outside cab	time = 10:00	HRR = 15MW	
5. Signs of furniture on fire	time = 12:00	HRR = 20MW	
6. Ventilation stopped	time = 13:30	HRR = 100MW	$v = 6.0\text{ms}^{-1}$
7. Trailer contents fully involved	time = 14:00	HRR = 120MW	$v = \text{reducing}$
8. Fan restarted	time = 16:30	HRR = 60MW	$v = 0.5\text{ms}^{-1}$
9. Fire increases intensity	time = 20:00	HRR = 128MW	$v = 2.9\text{ms}^{-1}$
10. Noticeable reduction in fire severity	time = 30:00	HRR = 40MW	
11. Fire virtually extinguished	time = 60:00	HRR = small	

The HRR reached a magnitude of about 120 MW after 13.5 minutes from ignition, when the ventilation was switched off. It is not known whether the HRR would have continued to increase if the forced ventilation had been left on for longer. When the airflow dropped to 0.5ms^{-1} , the HRR dropped to about 60 MW. After the airflow was increased to 2.9ms^{-1} , the HRR reached another maximum of about 128 MW.

EUREKA “simulated truck load” fire test

In this test a 2212kg load of densely packed wood cribs mixed with 310kg of plastic, topped with 332kg of rubber tyres (supposedly the equivalent size and fire load of a HGV) was set on fire 295m from the end of the tunnel. The removable wall was placed at the entrance to the tunnel, restricting the natural airflow velocity to about 0.5ms^{-1} , this was maintained throughout the test. The heat release rate values were calculated from measurements of airflow velocity, O_2 concentration and CO / CO_2 concentration across the whole cross-section of the tunnel at 27m before and 34m after the fire load.

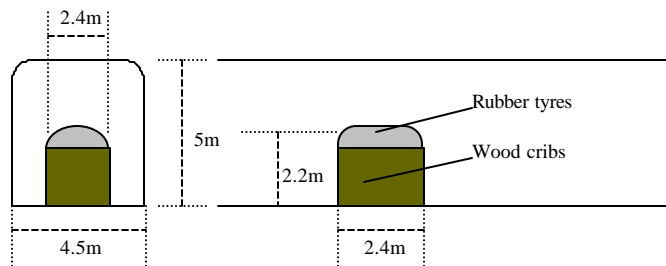


Figure A.04 – The layout of the fire load in the “simulated truck load” test.

The fire increased in severity to a peak of 15MW after ten minutes. After a few minutes the HRR dropped slightly to between 10 and 12 MW where it remained until most of the fuel was used up. A graph of the HRR against time is shown in Figure A.05.

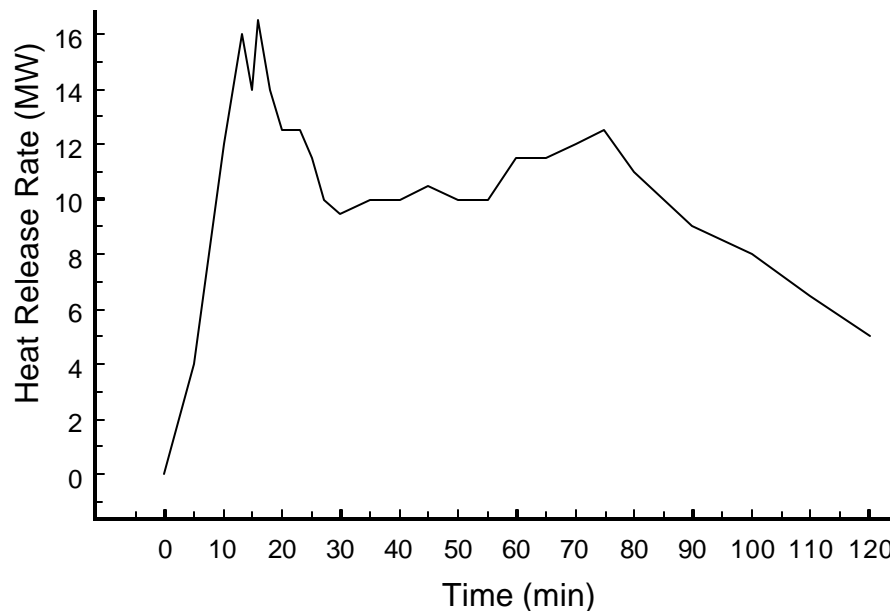


Figure A.05 – HRR development for the naturally ventilated “truck load” fire test

EUREKA wooden crib fire tests

Two tests were carried out with identical crib configurations, one with forced ventilation and one with natural ventilation. In each of these tests a pile of wooden cribs was burned. The fire load in both tests covered an area of $0.8\text{m} \times 3.2\text{m}$. Each crib was made of $40\text{mm} \times 40\text{mm} \times 0.8\text{m}$ sticks of pine. The cribs were arranged as follows: three piles of wooden cribs ($0.8\text{m} \times 0.8\text{m} \times 3$ cribs high) were placed on 0.5m high concrete blocks. The crib piles were 0.4m apart. The next layer consisted of two piles of cribs (2 cribs high) which were placed centrally across the gaps in the lower layer. On top of this, three piles of cribs (3 cribs high) were placed directly above the cribs in the bottom layer, some spacers were used to support the edges of the cribs at the ends. Overall the fire load was 2.4m high and consisted of 950kg of wood. The arrangement of the fuel is shown in Figure A.06.

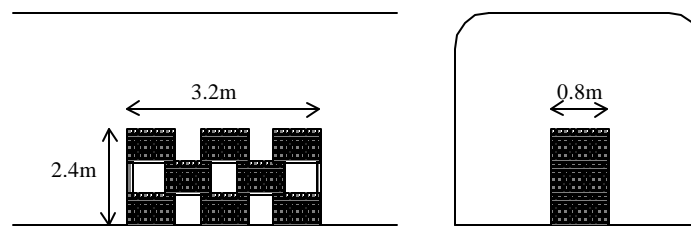


Figure A.06 – The layout of the fire load for both tests

One test (W31) was carried out with natural ventilation, with the removable wall in place to minimise the airflow rate. A second test (W41) was carried out with forced ventilation, this was measured to be about 2.9ms^{-1} (averaged across the tunnel cross-section). Both tests were ignited by means of small pool fires under the load.

Natural ventilation test:

The heat release rate of the fire rose steadily from ignition to about 8.5MW in ten minutes. The fire then burned with a “steady” heat release rate of about $8\text{--}9\text{MW}$ for about 12 minutes. The fire had reduced to 1MW about 40 minutes after ignition.

Forced ventilation test:

The heat release rate of the fire increased to a maximum of 27MW at about 18 minutes after ignition. The stack of cribs was observed to collapse at about this time. There was

no period of “steady” burning; the heat release rate gradually decreased from 27MW to 5MW over a period of 20 minutes. The development of HRR with time for both wooden crib tests is shown in Figure A.07.

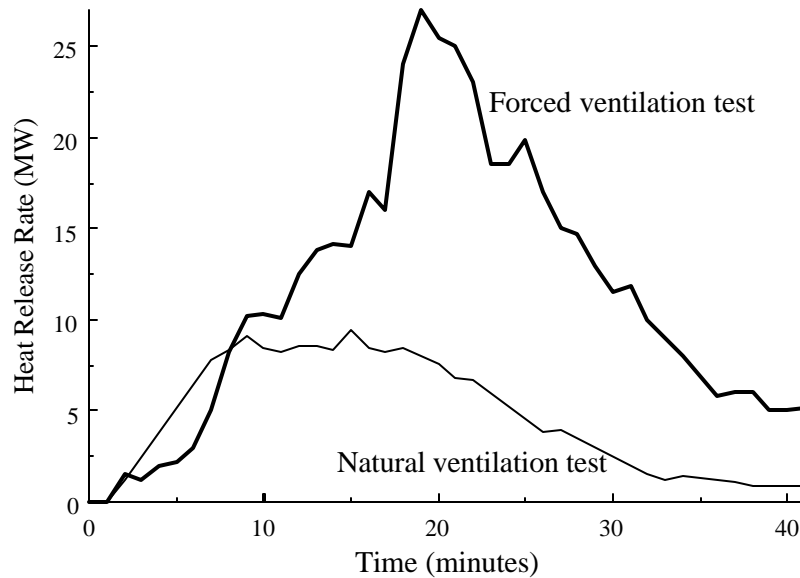


Figure A.07 – HRR development for the naturally ventilated and longitudinally ventilated wooden crib fire tests in the Repparfjord tunnel.

Fire tests carried out in the Health & Safety Laboratory fire gallery, Buxton, UK, 1993

A series of nine tests were carried out in the fire and explosion gallery at Buxton, Derbyshire, UK. Only two of these tests have been used as evidence in this thesis. The tunnel is constructed of reinforced concrete, is 366m long, has a slope of 1 in 1000, has a fan house at one end and the other end is open. The cross-sectional area of the tunnel is 5.6m², the height is 2.44m at the apex and the width is 2.75m at the widest point. The tunnel walls in the vicinity of the test fire were coated with fire protection, this reduced the cross-sectional area to 5.38m² [81,84].

“HGV simulation” fire test

One test (test 8) was carried out to reproduce many of the features of the EUREKA HGV test. The test was set up to model the situation of a HGV fire on a carrier wagon in the

Channel Tunnel more faithfully than the Repparfjord test. The “vehicles” used in the test were one third scale models based on the Channel Tunnel case - a pulling locomotive, an amenity coach, a HGV loader wagon and two HGV carrier vehicles: the first carrier held a 3 axle tractor unit and trailer, the second carrier held a tractor unit without a trailer. The 1st HGV trailer housed a fuel tray which was the main source of fuel in the test. A variety of measurements were made in the tunnel including heat flux measurements at the amenity coach and the 2nd HGV, and oxygen depletion measurements. The maximum blockage of the tunnel is 25% at the HGV - the blockage is less than 20% at the locomotive. See Figure A.08

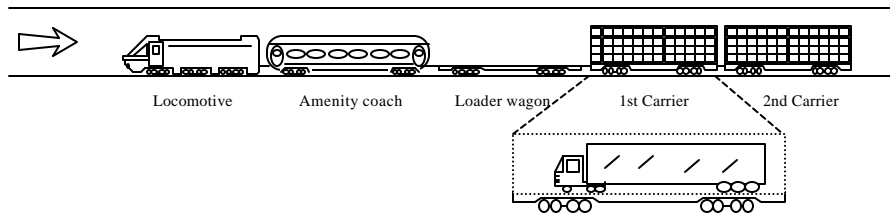


Figure A.08 – The arrangement of the models in this test series.

The fuel tray was ignited using a pilot flame. The initial airflow velocity used was 3.7ms^{-1} , at this airflow velocity the fire reached a maximum of 10MW. After 15 minutes the ventilation was reduced to 1.5ms^{-1} and the HRR decreased to 7.4MW. After a further 10 minutes the velocity was reduced again to $\sim 1.0\text{ms}^{-1}$ and the HRR decreased to 4.3MW. A graph of HRR (and ventilation velocity) with time is shown in Figure A.09.

Using Froude scaling techniques (see Chapter 2) these values can be scaled up to 156MW for 6.3ms^{-1} , 115MW for 2.5ms^{-1} and 67MW for 1.7ms^{-1} for “full size” vehicles in a tunnel of comparable size to the channel tunnel (7.6m diameter).

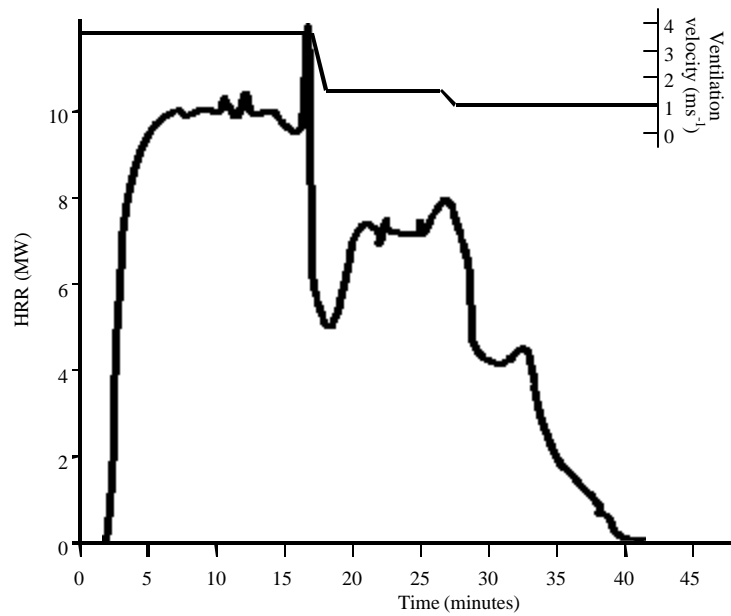


Figure A.09 – HRR development in the model simulation of the HGV fire test

Wooden crib fire test

Another test (test 5) carried out in the HSL fire gallery has been used as evidence in this thesis. In this instance the configuration of vehicle models was the same as described above, but two wooden cribs were used as the fire source, in place of the fuel pan. The two cribs were made up of 150mm × 25mm × 800mm sheets of red pine; each of the eleven “layers” of each crib were made up of three double sheets of wood, as shown in Figure A.10, below. The two crib piles were positioned in the centre of the HGV trailer model, spaced 0.2m apart.

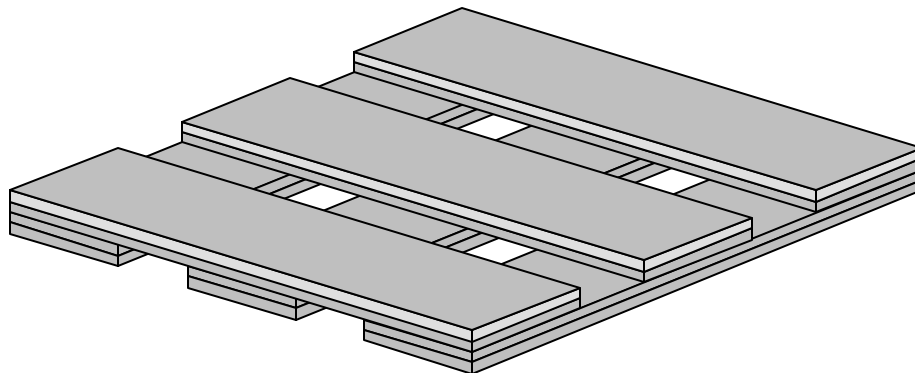


Figure A.10 – Two layers of the wooden crib used in test 5.

The ventilation rate in most of the test was about 1.1ms⁻¹ and the HRR of the fire grew quickly to about 1.6MW and then slowly fell to about 1.3MW. After about 25 minutes, the first (upstream) crib collapsed, the second crib collapsed just over 3 minutes later.

The HRR decreased to about 0.9MW after the collapse of the cribs. After 35 minutes, the ventilation velocity was increased to 1.8ms^{-1} and the HRR increased to 1.3MW as a result. The fire continued to burn for a considerable time after the data logger was stopped. The development of HRR with time is shown in Figure A.11, below.

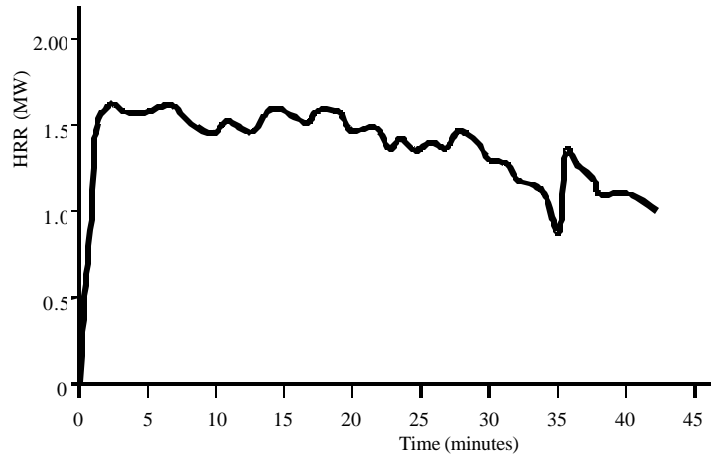


Figure A.11 – HRR of the wooden crib fire test in the HSE fire gallery.

Fire tests carried out in a “blasted rock tunnel”, Sweden, 1997

A series of 24 fire tests were carried out by FOA (the Swedish Defence Research agency) in a 100m long “blasted rock tunnel”, approximately 3m wide by 3m high [86]. The tunnel was open to the air at one end and had a large chimney (13.2m high) at the other. There was no mechanical ventilation system installed in the tunnel, but the natural ventilation was restricted in some of the tests to investigate under-ventilated burning conditions. In each test the fire load was placed on a $2\text{m} \times 2\text{m}$ weighing platform. The tunnel configuration is shown in Figure A.12, below.

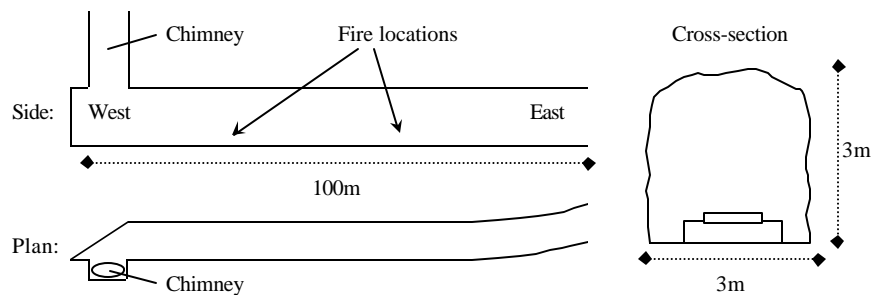


Figure A.12 – Configuration of the blasted rock tunnel.

Wooden crib fire tests

Three wooden crib tests were carried out in the blasted rock tunnel under natural ventilation conditions. Two tests were carried out at the location 22.5m away from the centre of the chimney, the third was carried out 65m away from the chimney. The cribs were $0.7 \times 0.7 \times 0.53\text{m}$ high and were constructed out of 20 layers of seven pine sticks, each $22 \times 50 \times 700\text{mm}$. The fires were ignited using an electrically heated wire wrapped round a small plastic bag filled with 0.6l of methanol, this was placed on the top of the load; when ignited, the burning methanol leaked down into the crib igniting the centre of all the layers. The fires achieved peak heat release rates of approximately 1.1MW, 0.6MW and 0.9MW. The ventilation flow during the second test was significantly restricted, so the data from that test has not been used in this study. The heat release rate data from these experiments are shown in Figure A.13, below.

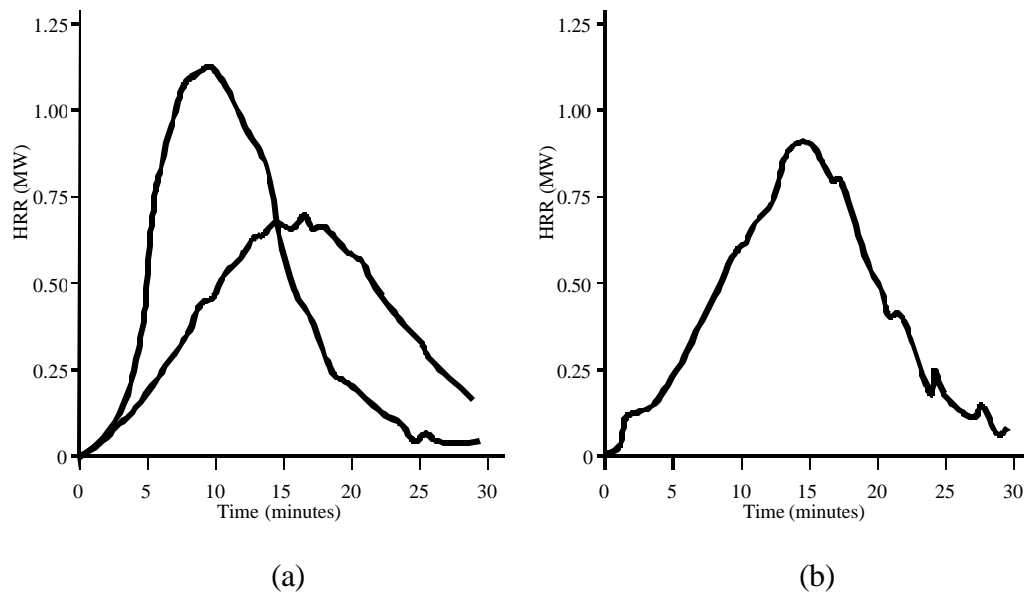


Figure A.13 – Heat release rate data for the wooden crib fire tests carried out in the blasted rock tunnel. Fire locations: (a) at 22.5m from the chimney and (b) at 65m from the chimney.

A.2 Experiments relevant to the small pool fire case (see Chapters 4 & 5)

Fire tests carried out in the Ofenegg Tunnel, Switzerland, 1965

A series of tests were carried out in a disused tunnel in Switzerland in 1965 [63]. The tests were carried out primarily to investigate the behaviour of a spill fire in the event of a tanker truck accident. The effects of longitudinal and semi-transverse ventilation were studied, as was the effect of a sprinkler system. As the tests were aimed at investigating the chances of survival and escape for people in the tunnel they were more concerned with smoke movement than with heat release rate data. However, approximate values of fuel consumption are available and so approximate HRR values can be calculated.

The tunnel was a disused single-track railway tunnel, it was blocked at one end and a partition was built along one side to form a ventilation duct. By blowing air through the duct an airflow velocity of 1.7ms^{-1} could be achieved in the main tunnel section. The tunnel had a cross-sectional area of 23m^2 in the vicinity of the fire pool. A number of different sizes of pool were used in these tests, of which two have been used as evidence in this thesis. The smaller fire pool was 1.75m long by 3.8m wide (the width of the tunnel) and 100l of “aircraft quality petrol”^d fuel was used in the pool as fuel.

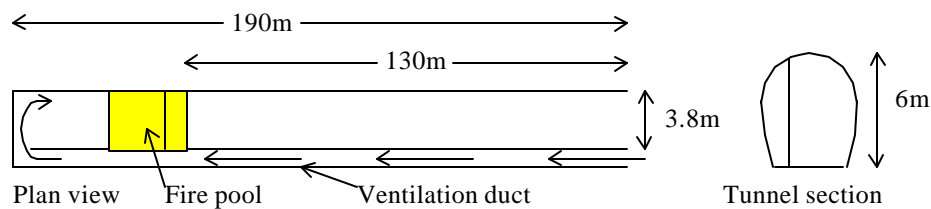


Figure A.14 – Layout of the Ofenegg tunnel

Two fire tests were carried out with the small pool which are relevant to this study. Exact data for the variation of HRR with time are not available, however approximate values for the average HRR values can be estimated from the duration of each fire:

^d Assumed to be petrol.

- All fuel (100l) in the small ($1.75 \times 3.8\text{m}$) naturally ventilated pool fire was consumed within three minutes. From this it can be estimated that the average HRR of the fire was about 12-14MW.
- All fuel (100l) in the small ($1.75 \times 3.8\text{m}$) pool fire with forced ventilation was consumed within four minutes. From this it can be estimated that the average HRR of the fire was about 9-11MW.

Thus, it is clear that for the small pool fire the ventilation tended to reduce the HRR of the fire.

Fire tests carried out in the Memorial Tunnel, USA, 1995

A series of tests was carried out in the Memorial Tunnel, near Interstate 77, Charleston, West Virginia, USA [13]. The tunnel is a disused two-lane road tunnel, 860m long with a 3.2% slope (south to north). The tunnel is 8.85m wide and 7.31m high with an arched roof, it has a cross-sectional area of about 56m^2 . Fire pools of various sizes were located 240m from the south portal. The ventilation system was modified to allow testing of various large-scale pool fires under a range of ventilation conditions. In this thesis, only the tests with natural ventilation and longitudinal ventilation have been considered, the tests involving (semi) transverse ventilation are not relevant. In the longitudinal ventilation tests the ventilation was produced by several banks of jet fans along the length of the tunnel; in general the fans blew towards the south portal. The configuration of active jet fans was changed several times during each test so periods of constant airflow velocity were rare. The tunnel layout is shown in Figure A.15.

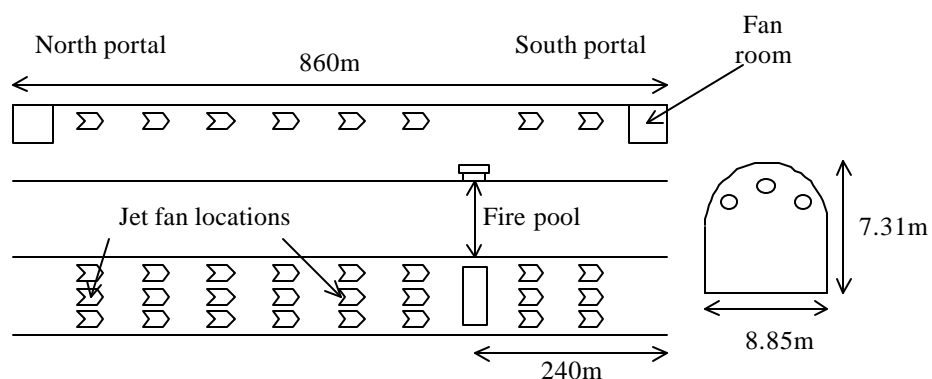


Figure A.15 – Layout of the Memorial Tunnel

“10MW” pool fire tests

Three diesel pool fire tests with forced ventilation were carried out using the smallest fuel pan (3.66m × 1.22m), nominally 10MW. No natural ventilation tests were carried out with this size of fuel pan. The fuel pan was maintained at a constant volume of fuel for the first 25 minutes of each test (22 for test 606a).

Heat release rates have been estimated from fuel consumption data. Graphs of HRR vs. time and airflow velocity for the three tests are shown in Figures A.16 – A.18. The airflow velocity presented is the bulk airflow velocity at the entrance to the tunnel (north portal).

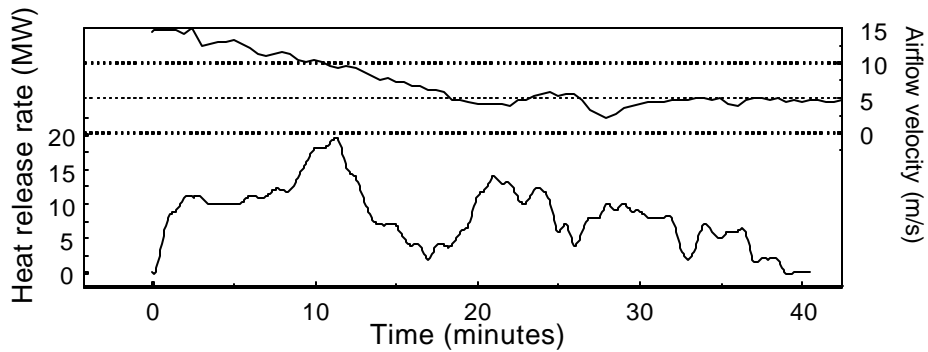


Figure A.16 – Memorial Test 605, HRR and forced airflow velocity with time

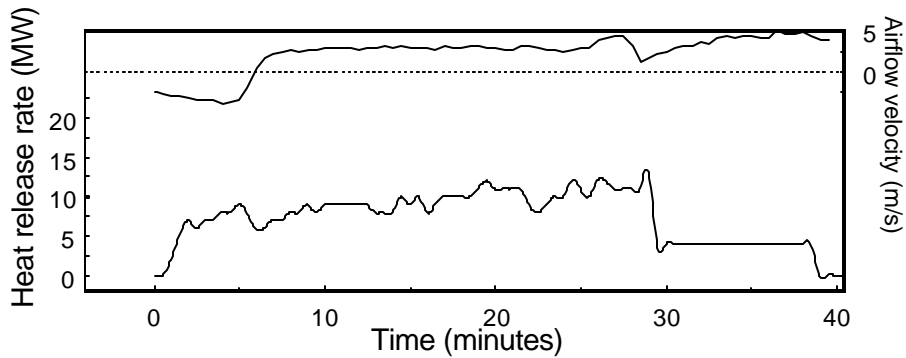


Figure A.17 – Memorial Test 606a, HRR and forced airflow velocity with time

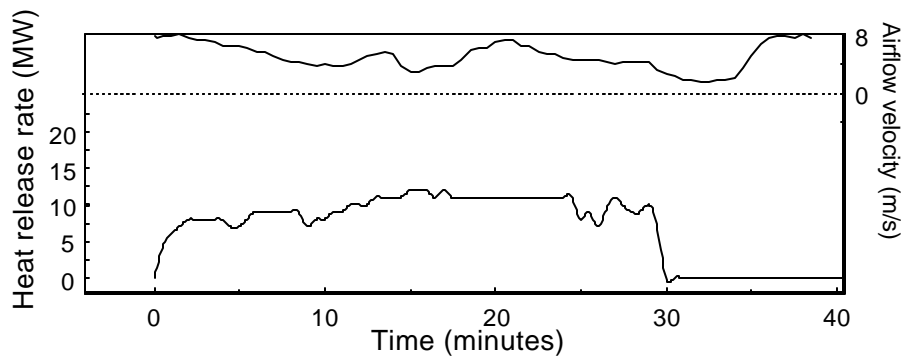


Figure A.18 – Memorial Test 617a, HRR and forced airflow velocity with time

Pool fire tests in the Repparfjord tunnel, Norway

EUREKA heptane pool fire tests

Three fire tests involving heptane pools were carried out in the Repparfjord tunnel^e[70,115], described above. Tests “H11” and “H21” were carried out using a circular pool, 1m² in area (0.56m diameter), test “H32” was carried out using a 3m² circular pool (0.98m diameter, see section below). The tests were carried out at the same location as the HGV and wooden crib fire tests. The ventilation conditions were changed midway through each test, so the influence of the changing velocity is easily observed. In each test the volume of fuel in the pool was maintained at a constant level by pumping fresh fuel in as the test progressed.

In test H11 the fire was started under natural ventilation conditions. After an hour of mostly steady burning at about 1-2MW (occasionally peaking to over 6MW), a forced ventilation of about 1ms⁻¹ was switched on. This resulted in a very slight increase in “steady” HRR with occasional peaks to about 4MW. The high HRR peaks were attributed to chunks of falling concrete splashing into the pool, causing the fuel to spill over the edges of the pool and temporarily creating a pool with a larger surface area.

Test H21 was started with a forced ventilation rate of about 1.5ms⁻¹. This was increased to 2.0ms⁻¹ after 45 minutes. The heat release rate increased slightly, from 3.5MW to 4.0MW when the ventilation was increased.

^e There were actually four heptane fire tests carried out, but one of them was not used as evidence in this study.

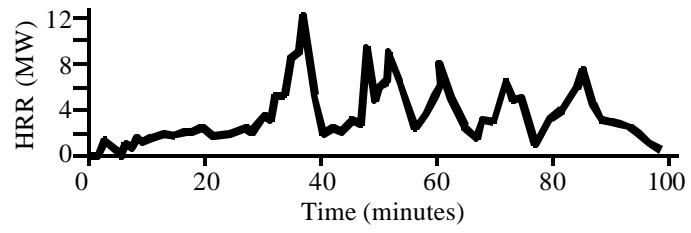
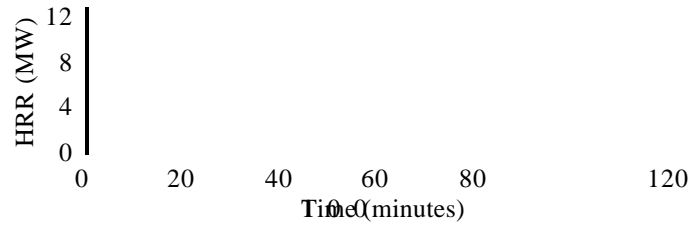


Figure A.19 – HRR development and ventilation velocity for test H11



studied with ventilation velocities of 0.5, 0.85 and 2.0ms⁻¹. No tests were carried out with natural ventilation. A graph of mass loss flux vs. time is shown in Figure A.22. As can be seen, a 25% reduction in mass loss flux (and also therefore in heat release rate) is observed by increasing the ventilation velocity four times (from 0.5ms⁻¹ to 2.0ms⁻¹).

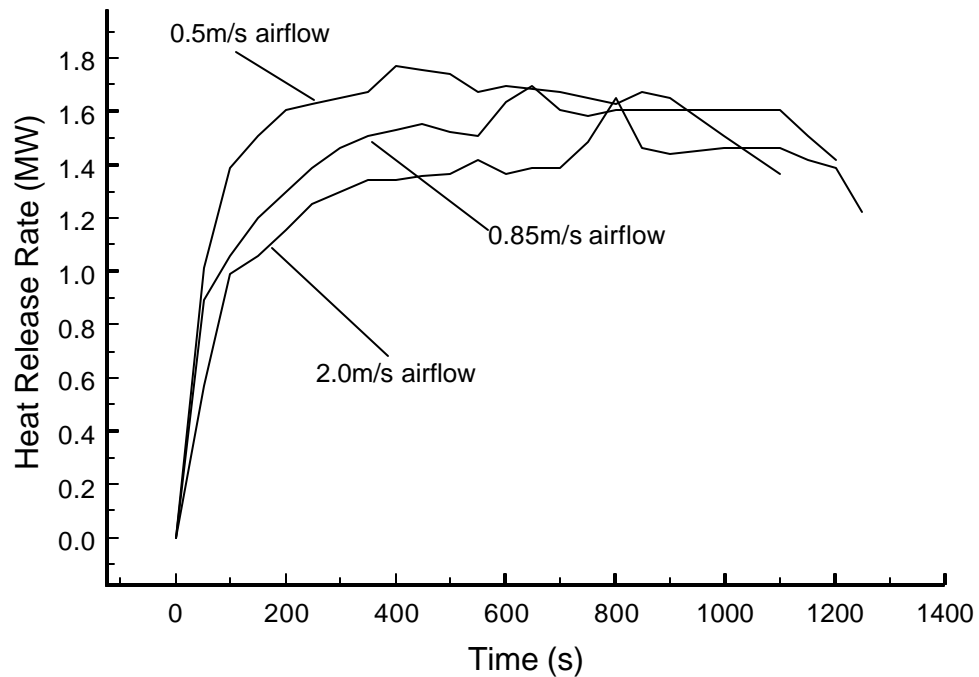


Figure A.22 – Heat release rate curves for the three 1m diameter pool fires

Fire test series carried out in a lab scale wind tunnel, Japan, 1995

A series of small scale fire tests were carried out in a laboratory at the Fire Research Institute, Ministry of Home Affairs, Japan [89]. The tests were carried out in a 0.3m × 0.3m × 21.6m wind tunnel with a fuel pool near the mid-point of the tunnel. The section of the tunnel between the ventilator and the pool fire was angled at 5 or 10° in some tests to investigate smoke behaviour, it is assumed that these small variations in tunnel angle have little effect on the heat release rate.

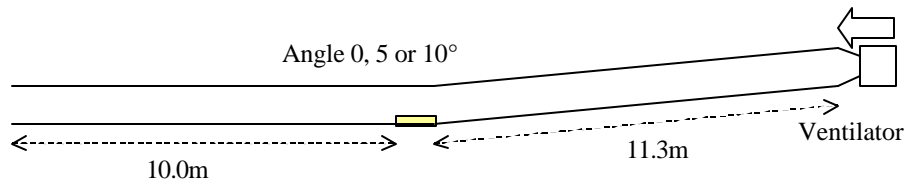


Figure A.23 – The layout of the model tunnel

Heptane pool fire tests

A series of tests were carried out using heptane fuel in a 0.15m diameter pool (0.0177m³). A fuel feed system kept the pool surface at a constant level and recorded the mass burning rate. From these data the heat release rates for tests with different ventilation airflow velocities have been calculated.

Carbon monoxide / dioxide levels were monitored in the tunnel, in all tests the level of carbon monoxide produced by the fire was negligible. Heat release rate values have been calculated from the mass burning rate data. From these tests it is evident that the HRR of a small pool fire in a tunnel decreases as the ventilation velocity is increased. The HRR appears to tend towards the HRR for a pool fire in the open air. Results are presented as graphs of HRR vs. time for airflow velocities of 0.43 – 1.30ms⁻¹.

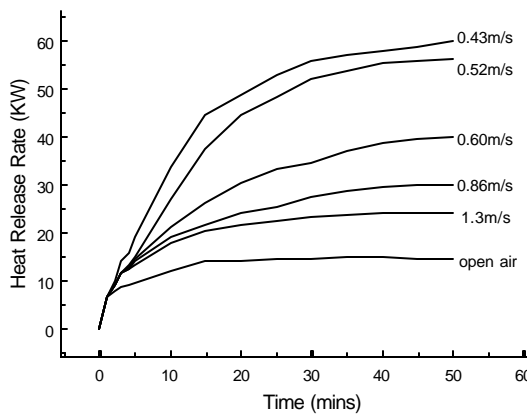


Figure A.24 – HRR curves for 30cm diameter heptane pool fires

Methanol pool fire tests

A series of methanol pool fire tests were carried out in the same lab-scale tunnel as the heptane tests (see above). The pools were 0.10, 0.15, 0.20 and 0.25m in diameter (0.008, 0.018, 0.031 & 0.049m³). The heat release rates for tests with different ventilation airflow velocities have been calculated from the mass loss data of the fuel.

From these tests it is evident that the HRR of a small/medium pool fire in a tunnel decreases as the ventilation velocity is increased. The HRR appears to tend towards the HRR for a pool fire in the open air. Results are presented as graphs of HRR vs. time for the 0.25m diameter pool, and as graphs of “steady state” HRR (taken to be the HRR after 40 minutes of burning) vs. velocity for all tests.

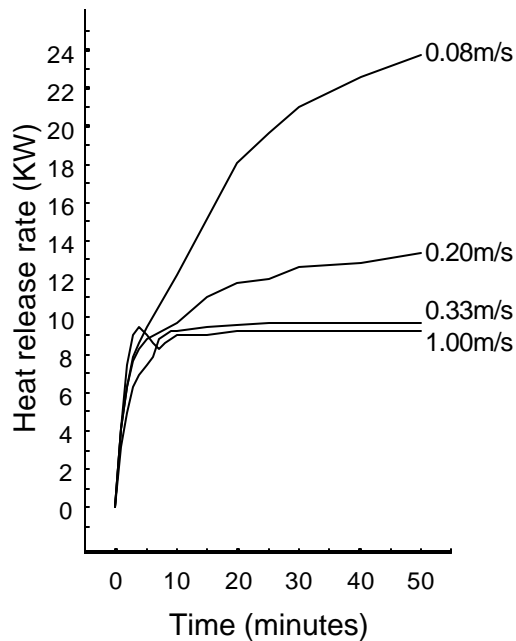


Figure A.25 – HRR data for a 0.25m diameter (area 0.049m²) methanol pool fire in the lab-scale tunnel

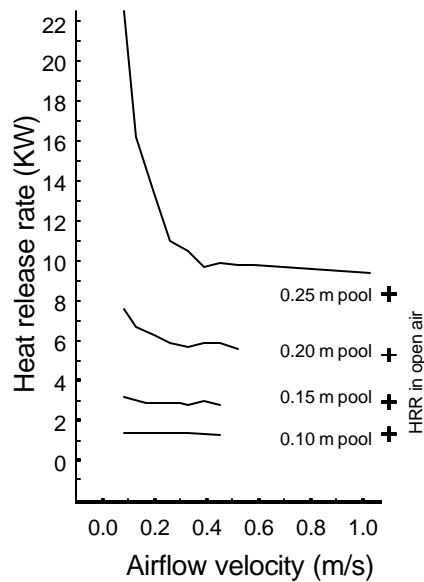


Figure A.26 – “Steady state” HRR data for methanol pool fires in the lab-scale tunnel

Pool fire tests in the Repparfjord tunnel, Norway

EUREKA heptane pool fire test H32

One fire test, denoted H32, was carried out in the EUREKA test series in the Repparfjord tunnel using a larger fire pool (3m²), otherwise the test conditions were as described above. The test was started with a longitudinal ventilation rate of 1.5ms⁻¹, this was increased to 3ms⁻¹ after 45 minutes. The heat release rate of the fire was observed to drop slightly (from 11MW to 10MW) when the ventilation rate was increased.

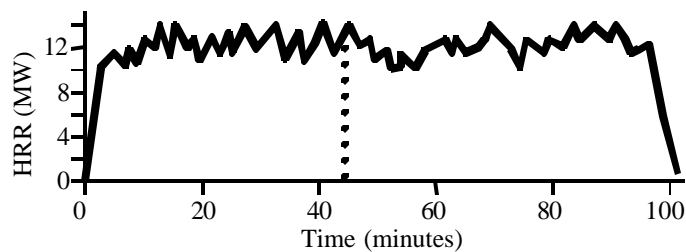


Figure A.27 – HRR development and ventilation velocity for test H32

A.4 Experiments relevant to the large pool fire case (see Chapters 4 & 5)

Fire tests carried out in the Ofenegg Tunnel, Switzerland, 1965

Of the fire tests involving larger pools that were carried out in the Ofenegg tunnel [63], two were used as evidence in this thesis. The experimental configuration was the same as that described above, except that the pool was 12.5m long by 3.8m wide (the width of the tunnel) and was filled with 500l of fuel. Once again the average HRR of each test has been estimated:

- All fuel (500l) in the large (12.5 × 3.8m) naturally ventilated pool fire was consumed within six minutes. From this it can be estimated that the average HRR of the fire was about 30-35MW.
- All fuel (500l) in the large (12.5 × 3.8m) pool fire with forced ventilation was consumed within four minutes. From this it can be estimated that the average HRR of the fire was about 45-55MW.

Fire tests carried out in the Memorial Tunnel, USA, 1995

“50MW” pool fire tests

Five tests with forced ventilation were carried out using the largest fuel pan (3.66m × 6.2m), nominally 50MW. One natural ventilation test was carried out with this fuel pan (Test 502). The fuel pan was maintained at a constant volume of fuel for the first 25 minutes of each test. Heat release rates were calculated from fuel consumption data. Graphs of HRR vs. time and airflow velocity for the tests with forced ventilation are shown in Figures A.28 – A.32. In each case the HRR history for the natural airflow test is overlaid. The airflow velocity presented is the bulk airflow velocity at the entrance to the tunnel (north portal).

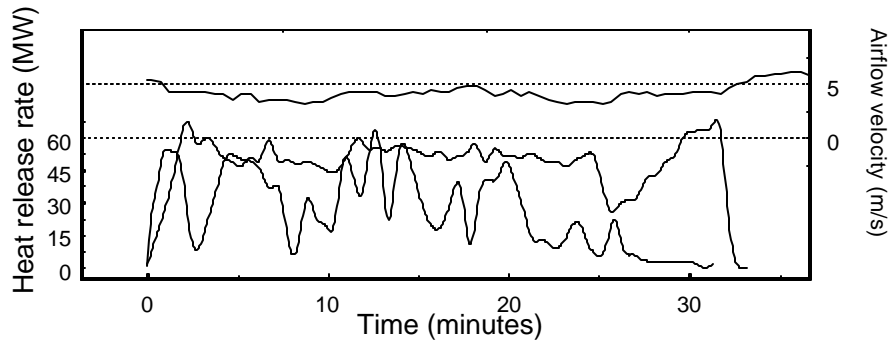


Figure A.28 – Memorial Tests 610 and 502, HRR and forced airflow velocity with time

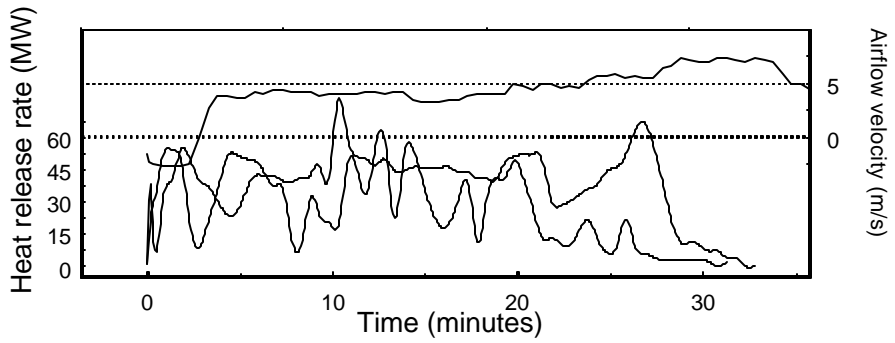


Figure A.29 – Memorial Tests 611 and 502, HRR and forced airflow velocity with time

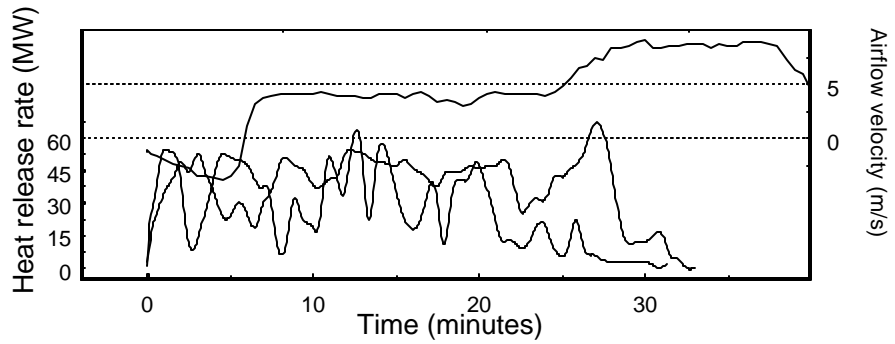


Figure A.30 – Memorial Tests 612b and 502, HRR and forced airflow velocity with time



Airt

RR and forced airflow velocity with time

Hea

Three tests

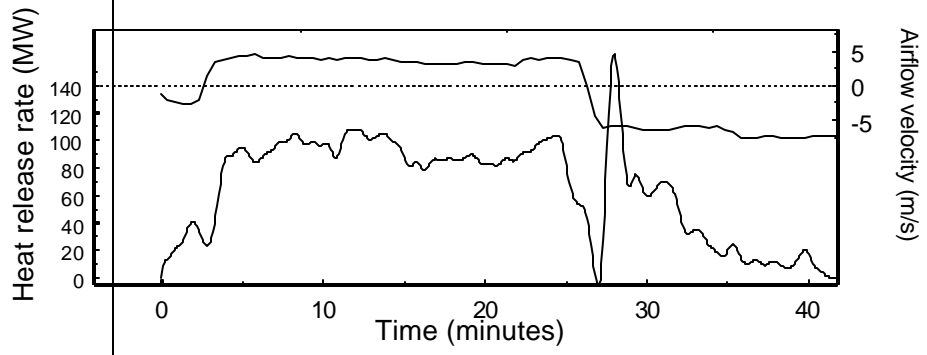
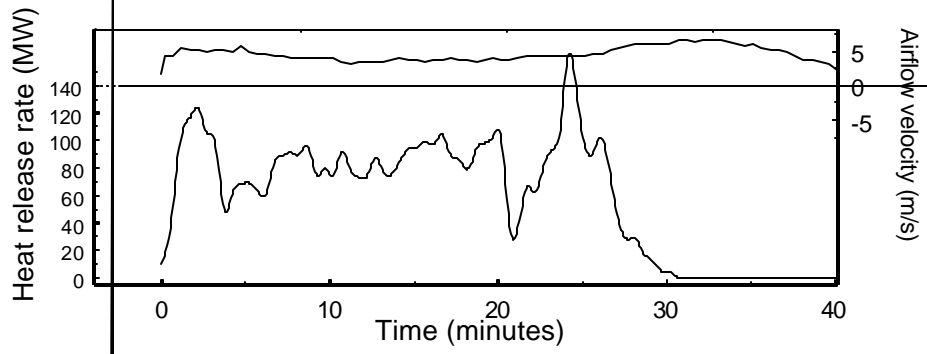


Figure A.33 – Memorial Test 615b, HRR and forced airflow velocity with time



A.5 Experiments relevant to the car fire case (see Chapters 4 & 5)

Fire test carried out in the Repparfjord tunnel

EUREKA “plastic” car fire test

This test was carried out as part of the EUREKA test series, in the Repparfjord tunnel described in section A.1. In this test a plastic bodied passenger car, a Renault Espace “people carrier”, was set on fire in the tunnel. It was located in the same part of the tunnel used for all the previous tests. The removable wall was placed across the tunnel portal to minimise the airflow velocity, before the test the natural airflow was about 0.4ms^{-1} .

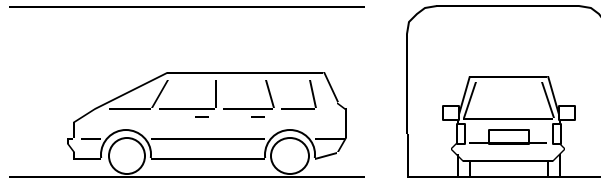


Figure A.36 – The layout of the fire load

The fire was started inside the car to simulate an electrical fire. For the first seven minutes the fire was contained inside the car compartment. After seven minutes the windscreen shattered, the fire spread to the car exterior and the heat release rate increased quickly to a maximum of about 6MW within three minutes. This intense burning was only sustained for a few minutes, then the HRR decreased, reaching a minimum of less than 2MW at about 18 minutes after ignition. Thirty minutes after ignition there was a sudden increase in HRR, reaching a peak of 5MW, but this was not sustained and the fire diminished quickly and burned out totally in about an hour. The second peak was possibly due to either the engine or the fuel tank becoming involved in the fire. The heat release rate graph for this test is shown in Figure A.37, below.

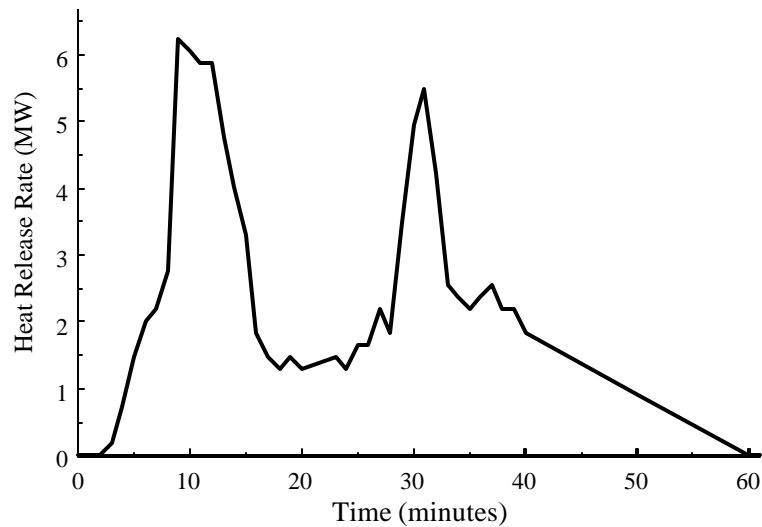


Figure A.37 – HRR development for the naturally ventilated “plastic” car fire test

Fire test carried out in the Des Monts tunnel

“Private van” fire test

The only recorded car fire test with significant longitudinal forced ventilation was carried out in the Des Monts Tunnel in France, with a longitudinal ventilation velocity of 1.3ms^{-1} . The tunnel is 850m long with a cross section of 80m^2 . The vehicle burned was a small van. The fire was started by igniting a load of tyres and hay, soaked in petrol, in the back of the van. The only details reported about that fire [79] were that the maximum HRR was recorded 4 minutes after ignition and was approximately 2MW.

Fire test carried out in the blasted rock tunnel

Car fire test

In addition to the wooden crib fire tests that were carried out in the blasted rock tunnel, as described in section A.1 above, a Fiat 127 car was also burned under natural ventilation conditions [86,87^f]. A graph of the HRR development is shown in Figure A.38, below.

^f The report cited makes reference to the car fire test but does not include the HRR data. The data presented in Figure A.38 were kindly provided by Dr. Ingason directly.

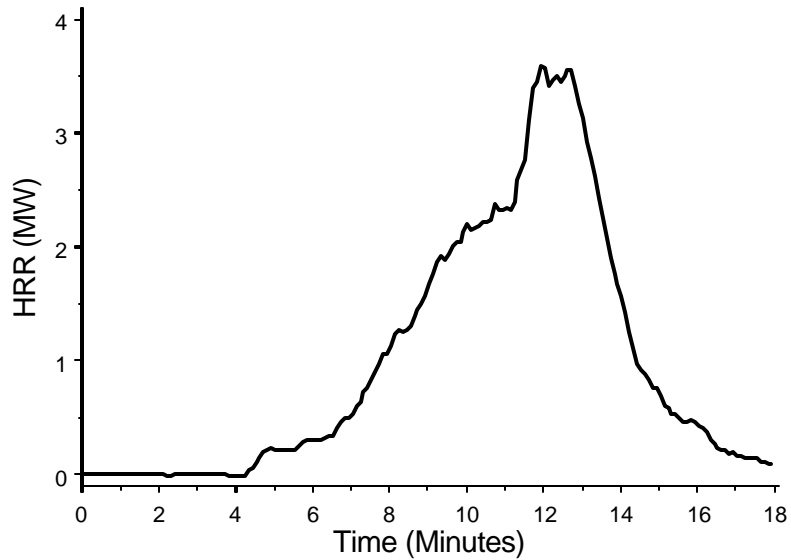


Figure A.38 – The HRR of a Fiat 127 fire in the blasted rock tunnel.

Fire tests carried out by VTT, Finland

Wooden crib fire tests

Two fire tests involving wooden cribs were carried out in a quarry tunnel at Lappeenranta in Finland in 1985 [68]. The tunnel is part of a cavern network, is approximately horizontal, 140m long and joins two large caverns. The cavern at the eastern end is connected to the quarry outside by means of a short horizontal tunnel, whereas the cavern at the western end is connected to the open air by a steep shaft. The tunnel varies from 5.5 to 6.1m wide and from 4.3 to 5.0m high, the cross-sectional shape is approximately rectangular with a slightly concave ceiling, as shown in Figure A.39, below.

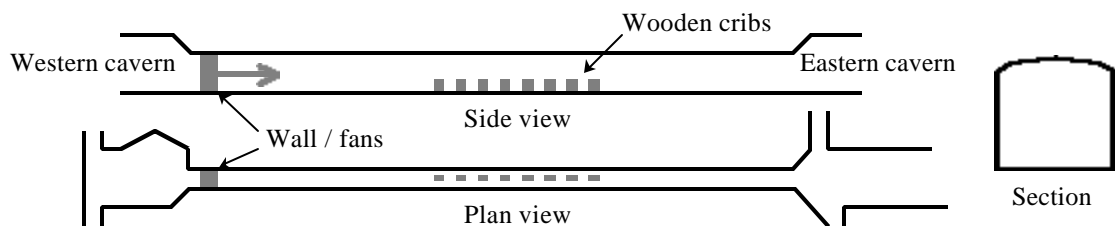


Figure A.39 – The quarry tunnel at Lappeenranta.

A longitudinal ventilation of about 1.3ms^{-1} was maintained in the tunnel by means of two fans installed in a wall at the western end of the tunnel, the wall also included a window for observation of the fire tests.

The first fire test (not used for evidence in this study) involved a 43m long wooden crib and was intended to model fire spread along a train carriage. The second test involved eight wooden cribs, arranged in such a way as to investigate the possibility of fire spread between cars in a longitudinally ventilated tunnel. Each crib was $1.6 \times 1.6 \times 0.8\text{m}$ high, weighed 500kg and the spacing between cribs was 1.6m. The queue was located in the middle of the tunnel.

The test was started by igniting the two westernmost (i.e. upstream) cribs. After about 15 minutes, a peak HRR of just over 8MW (i.e. just over 4MW per “car”) was achieved. The fire did not spread to the third crib and after the first two cribs had burned out, the two cribs at the eastern (downstream) end of the queue were ignited. The fire did not spread upstream to the sixth crib. A maximum HRR of almost 4MW (i.e. almost 2MW per “car”) was achieved after about 20 minutes. The HRR graph is shown in Figure A.40.

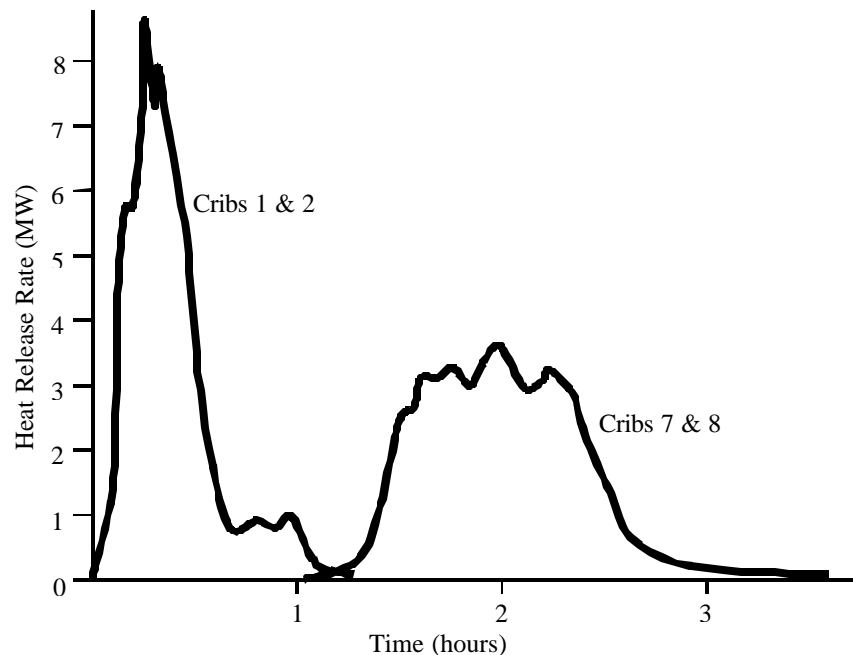


Figure A.40 – The HRR^g of the wooden crib fire tests in the quarry tunnel.

^g The HRR values have been estimated from mass loss rate data assuming complete combustion, therefore the actual HRR may have been slightly less than that presented.

A.6 Open air experiments relevant to the geometry study (see Chapters 7 & 8)

A number of fire experiments carried out in the open air were used as ‘evidence’ in the geometry study, these were:

Car fire tests carried out at VTT, Finland, 1993

Three passenger cars were burned in the open air (under a fume hood) at VTT to investigate burning behaviour [62]. The cars were all typical cars from the late 1970s and were equipped with fuel, oil and ordinary passenger car materials. The vehicles were: (i) a Ford Taunus 1.6 (990kg), (ii) a Datsun 160J Sedan (918kg) and (iii) a Datsun 180B Sedan (1102kg). The first car was ignited using a small pool fire under the driver’s seat, the other two were ignited using a small pool fire in the engine compartment. The windows of each of the cars were left several centimetres open to ensure that there was sufficient oxygen for the fire to establish itself and burn inside the passenger compartment. The HRR graphs for the three car experiments are shown in Figure A.41, below.

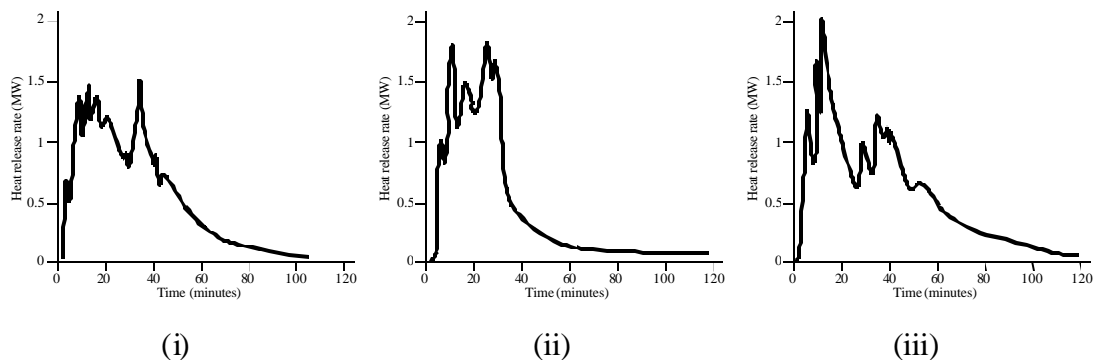


Figure A.41 – Open air HRR graphs for three passenger cars.

Pool fire and wooden crib fire tests carried out at SP, Sweden, 1995-97

A series of four pool fire experiments were carried out in the open air (under a calorimeter hood) using the same rectangular fuel pans that were used in a series of tunnel fire tests (see below) [124]. A 0.3×0.3 m pan was used with heptane and xylene fuels and a 0.4×0.4 m pan was used with heptane and methanol fuels. The heat release rate graphs from each of the four experiments are shown in Figure A.42, below.

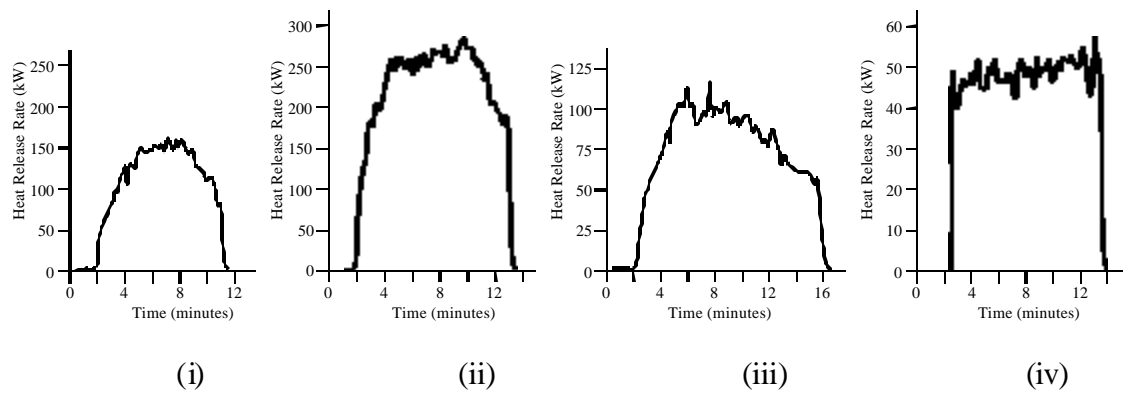


Figure A.42 – SP pool fire experiments in the open air. (i) $0.3 \times 0.3\text{m}$ heptane fire, (ii) $0.4 \times 0.4\text{m}$ heptane fire, (iii) $0.3 \times 0.3\text{m}$ xylene fire, (iv) $0.4 \times 0.4\text{m}$ methanol fire.

A wooden crib fire test was also carried out in the open air. This test used exactly the same design of wooden cribs as those used in the blasted rock tunnel test series, described above [87]. The heat release rate graph from this test is shown in Figure A.43, below.

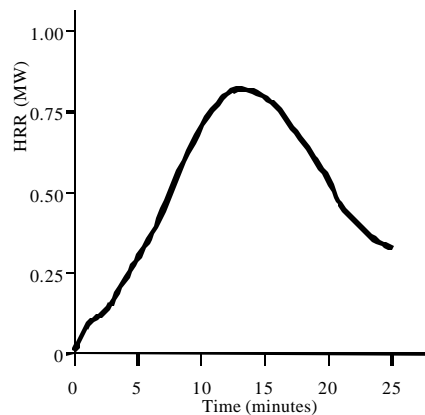


Figure A.43 – SP wooden crib fire experiment in the open air.

Wooden crib fires carried out by D. Gross, 1961

A series of 41 wooden crib fire tests was carried out in the open air^h in 1961 [55]. The cribs were mostly made of sticks of Douglas fir, each stick was square in cross section

^h The tests were actually carried out in a large, high ceilinged enclosure to minimise the effects of wind and drafts. However, the enclosure was sufficiently large to ensure no

and was ten times as long (L) as it was wide (b). The cribs were mostly made of ten (N) layers of sticks, with the sticks in each layer being perpendicular to those in the layer below, see Figure A.44.

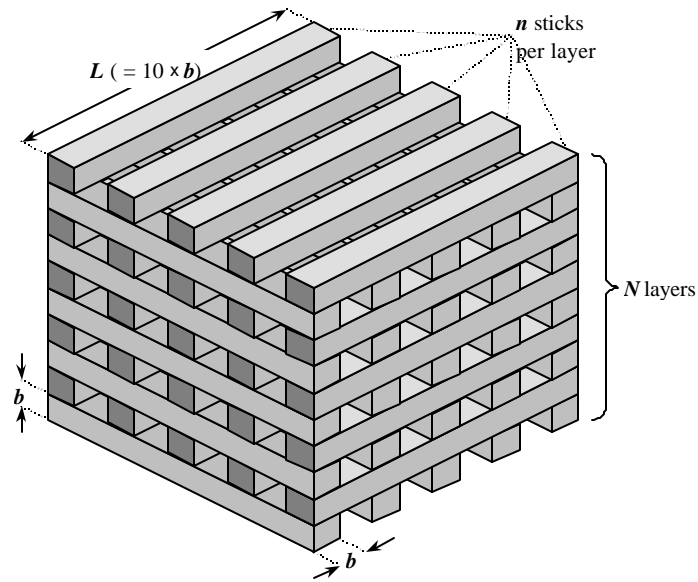


Figure A.44 – The arrangement of the wooden cribs used by Gross.

The burning behaviour of the cribs was investigated with respect to changes in the thickness and packing density (i.e. number of sticks per layer, n) of the sticks. The burning rate of the cribs was estimated by recording the change in weight of the crib with time. Full weight-time graphs are recorded for some of the cribs tested and the peak rate of mass loss (gs^{-1}) is recorded for all cribs. There are too many experimental data to reproduce here. A number of conclusions regarding the relationship between crib porosity (i.e. the size of the vents in the crib) and peak mass loss rate are reported.

In this study, these mass loss data have been compared to mass loss data from naturally ventilated crib fire tests in tunnels to estimate values of ϕ .

Open air pool fire tests, Japan, 1995

In addition to the pool fire experiments carried out in the lab scale apparatus, Saito *et al.* [89] also performed open air fire experiments, using methanol and heptane fuels, with each of the different pool fire pan sizes used in the tunnel tests. These data are significant re-radiation effects from the walls and no constriction of the airflow towards or away from the fires.

represented in Figures A.24 (heptane pool fire) and A.26 (methanol pool fires), above. It is interesting to note that as the ventilation velocity in the tunnel tests was increased, the HRR of the pool fire tended towards the HRR recorded in the open air.

Open air pool fire tests for the MTFVTP, 1995

The MTFVTP report [13] alludes to some open air diesel pool fire experiments, but does not actually give details of the tests. Private correspondence with Dr. Luchian (principal engineer on the MTFVTP project) has confirmed that a small number of fire tests were carried out with rectangular fuel pans, containing diesel oil, in the open air. From each of the fires tested, the peak HRR was approximately 10MW per 48 square feet (4.46m²) of pool surface area. This was used to design the size of the fuel pans used in the Memorial Tunnel experiments.

A.7 Other, naturally ventilated, tunnel fire experiments relevant to the geometry study (see Chapters 7 & 8)

In addition to the fire test data presented in sections A.1 – 1.5, the geometry study also considered the following naturally ventilated tunnel fire experiments:

Pool fire test in the INERIS fire gallery, 1994

In addition to the 1m² and 3m² heptane pool fire tests carried out in the Hammerfest tunnel (see above), Institut National de l'Environnement Industriel et des Risques (INERIS) carried out some pool fire tests in their own fire gallery [134] at Verneuil-en-Halatte, France and in the open air as part of the EUREKA 499 test series [115]. The tests were primarily for comparison with the Hammerfest tunnel tests and for calibration of the heat release rate measuring apparatus. The INERIS fire gallery is 50 m long and has an approximately square (10m²) cross-section with a concave ceiling. There is a chimney with gas analysing equipment at one end of the gallery. The gallery is naturally ventilated but was configured in such a way that all smoke and fire gases moved towards the chimney end of the gallery. The HRR of the test was estimated from the gas analysis

data and is shown in Figure A.45. The peak followed by a brief reduction in heat release rate midway through the test was due to the fuel supply tank running dry and being manually replaced by a full tank.

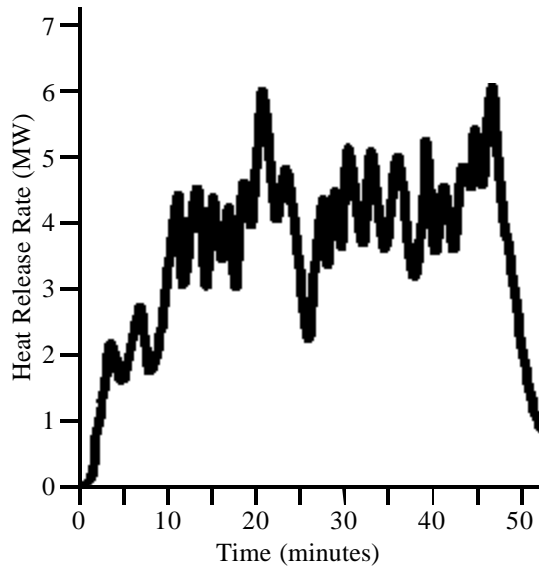
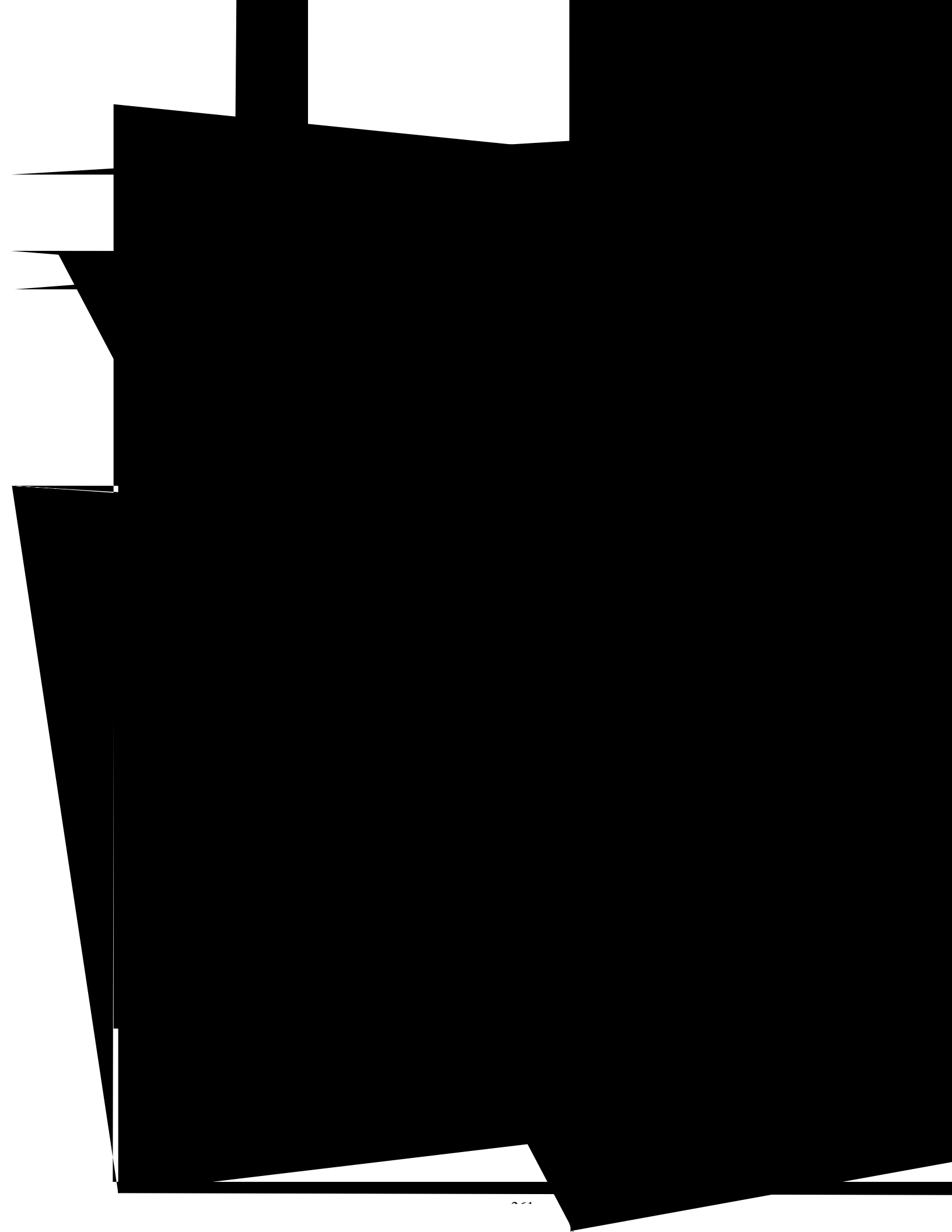


Figure A.45 – HRR of the heptane pool fire test in the INERIS fire gallery.

Pool fire tests carried out in a “blasted rock tunnel”, Sweden, 1997

A number of pool fire experiments were carried out in the “blasted rock tunnel” described in section A.1, above. These included twelve heptane pool fires (of which 10 used a $0.65 \times 0.65\text{m}$ fuel pan and the other two used $0.4 \times 0.4\text{m}$ and $0.8 \times 0.8\text{m}$ pans), two methanol pool fires ($2 \times 1\text{m}$) and two kerosene pool fires ($0.65 \times 0.65\text{m}$). In a number of the tests the airflow in the tunnel was considerably restricted to investigate fuel rich burning regimes. Some HRR graphs for the well ventilated pool fires are presented in Figure A.46.



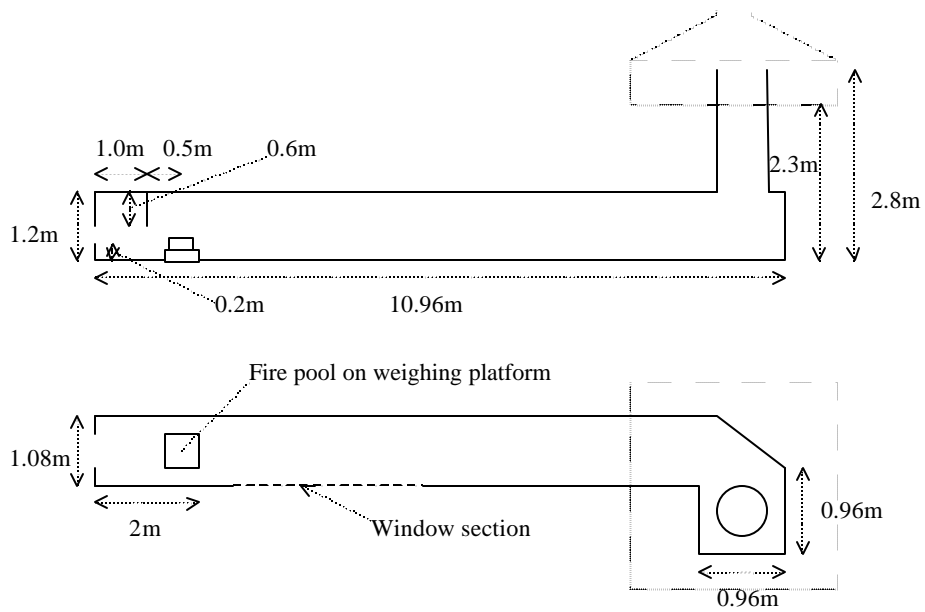


Figure A.47 – The model tunnel used at SP, Sweden.

The heat release rates were calculated from mass loss data and from gas analysis in the hood system. Pool fires tested under natural ventilation conditions were: heptane ($0.3 \times 0.3\text{m}$), methanol ($0.4 \times 0.4\text{m}$) and xylene ($0.3 \times 0.3\text{m}$). Approximations of the HRR graphs are shown in Figures A.48 – A.50.

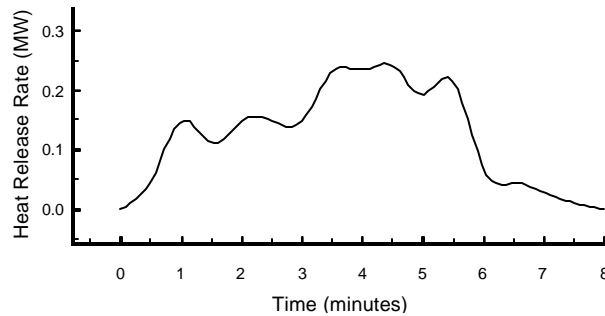


Figure A.48 – $0.3 \times 0.3\text{m}$ heptane pool fire in the SP model tunnel

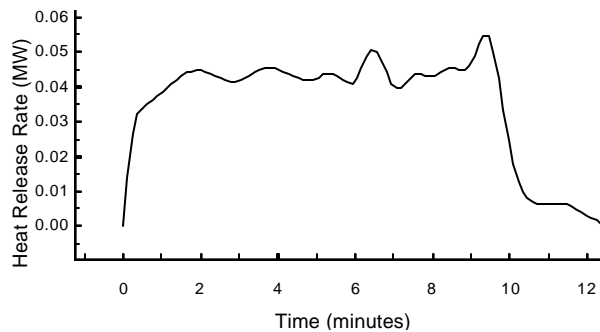


Figure A.49 – $0.4 \times 0.4\text{m}$ methanol pool fire in the SP model tunnel

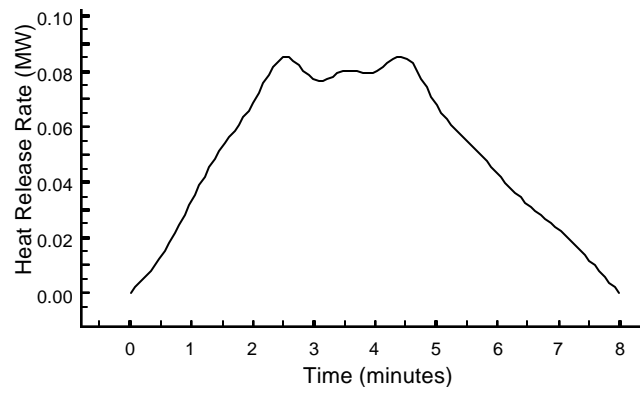


Figure A.50 – 0.3 × 0.3m xylene pool fire in the SP model tunnel

Appendix B. A History of Fire Incidents in Tunnels

This appendix contains a list of all known fatal, or otherwise significant, accidental tunnel fire incidents. Many other minor incidents are also included although the list cannot be fully comprehensive of such incidents. Fires are listed in reverse chronological order. Fatal tunnel fire incidents are named in **bold** type.

Fires since 2000

Frejus Tunnel, 12.9km long, France/Italy, 2004

On Saturday 21st February 2004 the braking system of a HGV caught fire. About 30 tunnel users evacuated their vehicles and took refuge in an emergency shelter, but the fire was extinguished easily. The tunnel was closed for about 2.5 hours, there were no recorded injuries. [135]

Trojane Tunnel, 2.9km long (under construction), Slovenia, 2004

On 10th February 2004 a fire broke out on a diesel powered air compressor about 1.6km into the tunnel. The fire brigade were unable to reach the fire location due to inadequate breathing apparatus. The fire was extinguished by a 'coal mine rescue group' with better breathing apparatus and experience of working underground.^j

Cointe Tunnel, 1.3km long, near Liège, Belgium, 2004

On 3rd February 2004 a HGV on fire stopped in the middle of the Cointe Tunnel (at the junction of the E40 & E25 motorways). The safety systems in the tunnel operated appropriately and no people were injured. The tunnel was closed for a few days for cleaning and repairs [136]. The Cointe Tunnel was ranked the best tunnel (with regard to safety installations) out of the thirty European tunnels surveyed by the German automobile association in its 'Eurotest 2002' [137].

^j Where no reference is given, incident details have been confirmed by direct contact with tunnel operators, fire brigades and other reliable sources.

Dullin Tunnel, 1.5km long, near Chambéry, France, 2004

On Sunday 18th January 2004 a fire started in the engine compartment at the rear of a coach carrying 37 tourists to the ski resort of Courchevel. Rather than stopping in the tunnel, the driver drove the bus for about 1km to the tunnel portal, despite flames in the passenger compartment forcing the passengers to the front of the coach. Once outside the tunnel the passengers were able to evacuate the bus safely, but the fire spread rapidly to consume the entire vehicle. The local fire brigade praised the bus driver for his actions. [138]

Golovec Tunnel, 0.7km long, Ljubljana, Slovenia, 2003

On 20th December 2003 a bus carrying 50 volunteer fire-fighters caught fire. They were able to extinguish the fire using the portable extinguishers on board.

Fløyfjell Tunnel, 3.1km long, Bergen, Norway, 2003

At about 4.20pm on Monday 10th November 2003 a car fire incident occurred about 1.9km into the southbound tube. The car initially crashed into the left hand wall before careering across the carriageway into an emergency telephone box on the right. The car immediately burst into flames and the fire soon spread to involve the tunnel lining materials. Unusually for a tunnel in Europe, the Fløyfjell Tunnel has a sprinkler system. Eleven sprinkler heads activated automatically (within one minute of the crash) and this quickly extinguished the fire involving the tunnel lining, but not the car fire. Some tunnel users attempted to fight the car fire with portable extinguishers but were unable to approach the car due to the severity of the fire. The fire brigade arrived after six minutes and quickly extinguished the car fire. The driver of the car was trapped in his vehicle because of the crash and died in the fire. [139]

Guadarrama rail tunnel, 30km long (under construction), Spain, 2003

An accident occurred on the 6th August 2003 on a train near the tunnel portal. The crew on the train escaped the tunnel before the smoke became too thick. 34 workers were trapped about 3km inside the tunnel by heavy smoke for five hours before they were rescued. They took refuge in an air pocket in the tunnel. Initial reports suggested, incorrectly, that the trapped workers had been on the train when it caught fire. [140]

Locica Tunnel, 0.8km long, Slovenia, 2003

On 25th July 2003 a HGV, carrying a cargo of aluminium beams, caught fire near the tunnel portal. The driver was unable to extinguish the fire using the two powder fire extinguishers carried in the cab. The natural ventilation in the tunnel moved the smoke in the direction of the nearest portal, only 30m away. The tunnel operators recorded 28 vehicles entering the tunnel after the red 'stop' signs had been illuminated. The fire brigade extinguished the fire on arrival. The cab and canvas cover of the trailer were destroyed in the fire, but there were no reported injuries.

Mornay Tunnel, 2.6km long, between Bourg-en-Bresse and La Cluse, France, 2003

On the 2nd of May 2003, a fire broke out in a passenger carriage on an 'autorail' train. Once the fire was detected the train stopped automatically, about 300m from the tunnel portal. The tunnel, constructed in 1877, is a single tube, single track tunnel with no lighting and no ventilation system. All of the 17 passengers on board were able to self-rescue before the arrival of the fire brigade. On arrival, however, the fire brigade had to overcome major problems to fight the fire; there was no local water supply and the railway company could not provide assistance immediately. The fire brigade blocked a nearby river (using parts of the railway fixtures) to obtain a water supply. The fire took 5 hours to control. [141]

Crêt d'eau Tunnel, 4km long, between Lyon and Geneva, France, 2003

On the 27th of April 2002 a fire broke out in a sleeper carriage of a train. Despite the lack of a planned emergency evacuation procedure, the train staff were able to evacuate quickly all 53 passengers to safety. The tunnel had previously been rated "hazardous" by a study of safety levels in existing French rail tunnels. [141]

Jungangno Underground railway/metro Station, Daegu, South Korea, 2003

On the morning of Tuesday 18th February 2003, an arson attack on an underground railway/metro train in Jungangno Station, near Daegu city centre, led to the deaths of at least 189 people. The arsonist used a small quantity of petrol and a cigarette lighter to start the fire on a stationary train in the station. The fire quickly spread to engulf the whole six-carriage train. After the underground railway/metro operators were aware of the fire, a second train entered the station and stopped near to the train on fire, the doors of this train did not open. The fire spread to the second train where most of the fatalities occurred. In addition to the fatalities, more than a

hundred people, including the arsonist, were treated for smoke inhalation. Following the incident, the head of the underground railway/metro corporation was fired and six members of the railway staff were arrested and charged with negligence. [142,143]

Homer Tunnel, near Milford Sound, New Zealand, 2002

On 3rd November 2002 the driver of a tourist coach noticed flames coming from the motor at the rear of the vehicle. He stopped the bus about 150m from the end of the tunnel and quickly evacuated all 32 passengers to safety before the brakes failed and the bus rolled backwards for 50m. Three of the passengers were flown to the nearest hospital and were treated for smoke inhalation. The bus wreckage blocked the tunnel, stranding 750 tourists in Milford Sound as the Homer Tunnel is the only land route between the town and the rest of South Island, New Zealand [144].

Ted Williams Tunnel, 2.6km long, Boston, USA, 2002

On Sunday 19th May 2002 a bus transporting most of the Seattle Mariners baseball team to the airport after a game caught fire in the Ted Williams Tunnel, part of the Boston Central Artery tunnel system. The fire is believed to have started in the electrical compartment at the rear of the bus. The fire produced a lot of smoke but did not damage the tunnel. The driver of the bus and several of the players were treated for smoke inhalation. [145]

Motorway tunnel on A86, near Versailles, France, 2002

Late in the evening on the 5th of March, 2002, the engine of a train, carrying construction materials into a partially built motorway tunnel, exploded and started a fire which burned for six hours. The 19 construction workers who were in the tunnel at the time took refuge in an air-tight compartment in the 200m long tunnelling machine. Approximately 150 fire-fighters attended the scene and two had to be treated for smoke inhalation. None of the construction workers were injured. [146]

Tauern tunnel, 6.4km long, south east of Salzburg, Austria, 2002

A lorry with a faulty engine caught fire on 18th January 2002, although a lot of smoke was produced the fire brigade were able to bring the fire under control very quickly. There were no reported injuries.

St. Gotthard tunnel, 16.9km long, near Airolo, Switzerland, 2001

A very large fire resulted from the head on collision between two HGVs, one carrying a load of rubber tyres, on Wednesday 24th October, 2001. The fire resulted in eleven fatalities, 23 vehicles destroyed and the collapse of over 250m of the tunnel lining. Had the tunnel not been equipped with a parallel service tunnel it is likely that the death toll would have been much higher. As the result of a review, following the Mont Blanc tunnel incident, the St. Gotthard tunnel had recently had its lighting improved and was scheduled to have its ventilation system upgraded in the summer of 2002. The fire burned for over two days. [147]

Gleinalm tunnel, 8km long, near Graz, Austria, 2001

On 3rd September a touring coach caught fire in the Gleinalm tunnel. There were no reported injuries but the tunnel was closed to traffic until the coach was removed.

Gleinalm tunnel, 8km long, near Graz, Austria, 2001

A fire resulted from the head on collision of two cars near the middle of the Gleinalm tunnel on Tuesday 7th August 2001. The fire was successfully extinguished by the fire brigade shortly after their arrival. Five people died and four were injured.[148]

Gleinalm tunnel, 8km long, near Graz, Austria, 2001

On 29th July the engine of a Swedish tourist coach caught fire in the Gleinalm tunnel. Rather than stopping in the tunnel, the driver was able to drive the coach out into the open air before stopping.

Howard Street Tunnel, Baltimore, USA, 2001

At 3:10pm on Wednesday 18th July 2001, a freight train passing through a tunnel in downtown Baltimore had an “emergency brake application”. Following standard procedure, the drivers detached the locomotives from the train and removed them from the tunnel. Of the 60 cars that made up the train, eight were carrying hazardous materials including hydrochloric acid, chemicals used to make adhesives and various solvents. By mid-morning the following day the fire was mostly extinguished except for a few hot spots. All the wreckage was removed within four days. The fire resulted in gridlock on the roads in Baltimore as all the major routes

were closed to traffic for about twelve hours. Two baseball games at the nearby Camden Yards had to be re-scheduled. [149]

Schipol Airort, The Netherlands, 2001

A small fire started in an electrical connection box in a rail tunnel at Schiphol Airport, near Amsterdam on the 11th of July 2001. The nearby railway station was closed for a short period, but no injuries were reported.

Tauern tunnel, 6.4km long, south east of Salzburg, Austria, 2001

On 10th July a head on collision involving two cars started a fire. The fire was extinguished quickly by the driver of one of the cars.

Underground metro tunnel, Kurt Schumacher Platz station, Berlin, Germany, 2001

On 7th July 2001 a fire was started by an arc lamp in the rear carriage of a 100m long train. Despite the small size of the fire, the amount of smoke inside the carriage and the tunnel area was considerable. No injuries were reported. [150]

Prapontin tunnel, near Susa, Italy, 2001

Monday 28th May 2001. HGV fire, cause unknown. 14 people treated for smoke inhalation. [151]

Dusseldorf Underground railway/metro Tunnel, 2001

The roof of a underground railway/metro train caught fire. There were two reported injuries. [152]

Toronto underground railway/metro, Canada, 2000

At 2am on the 8th of December 2000 a fire broke out on a underground railway/metro train being used to collect refuse from Old Mill station on the Bloor-Danforth line of the Toronto Underground railway/metro (TTC). Three people were treated for smoke inhalation. The line was closed for 24 hours. [153]

Laerdal Tunnel, 24.5km long, Norway, 2000

On the 27th of November 2000, a bus transporting about fifty attendees to the opening ceremony of the Laerdal Tunnel, at the time the longest road tunnel in the

world, caught fire whilst passing through the tunnel. The fire was small and was easily dealt with by the bus driver.

Kitzsteinhorn funicular tunnel, 3.3km long, near Kaprun, Austria, 2000

At about 9am on Saturday 11th November 2000, a fire broke out at the rear of the ascending train shortly after leaving the lower terminal. The train stopped automatically 600m inside the tunnel. The doors of the train failed to open. Twelve passengers escaped by smashing the windows and fleeing down the tunnel. The remaining 150 people on the train died on the train or attempting to flee up the smoke filled tunnel. The smoke also killed two people on the descending train, some 1.5km further up the tunnel and three people in the arrival hall of the upper terminal, 2.7km away. The fire on the supposedly fire proof train is thought to have started by hydraulic oil leaking into the heater in the rear driver's cab and spread via the clothes and baggage of the passengers on the train. The ventilation velocity in the tunnel at the time of the incident was approximately 10ms^{-1} . [2]

Oslofjord Tunnel, Norway, 2000

On the 28th of September a minor incident involving a truck fire occurred. [154]

Saukopftunnel, 2.7km long, Weinheim, Germany, 2000

At 5.45pm on the 24th of August 2000, a car caught fire and stopped in a lay-by near to the eastern end of the tunnel. The fire produced a lot of smoke, but did not trigger the fire alarms in the tunnel. The fire brigade extinguished the fire easily. There were no injuries. [155]

New York City underground railway/metro, USA, 2000

At 4.30pm on the 2nd of August 2000, two fires broke out in the electrical supply of the New York underground railway/metro system. All passengers were safely evacuated before the tunnels filled with smoke, but the fire-fighting operations took over two hours and 20 underground railway/metro stations were closed for over three hours. [156]

Rotsethorn Tunnel, 1.2km long, Norway, 2000

On the 29th of July 2000 a collision and subsequent fire lead to the deaths of two people. [157]

Seljestad Tunnel, 1.3km long, Norway, 2000

Just before 9pm on the 14th of July 2000 a truck collided with the rear of a line of stationary vehicles in the tunnel, causing an eight vehicle pile up. Immediately after the collision, one of the vehicles caught fire and the fire spread to involve all the vehicles within minutes. The fire quickly destroyed the communications cables in the tunnel. An ambulance arrived within 15 minutes and the fire brigade within half an hour. Twenty people were admitted to hospital but none had major injuries. Despite the fact that four people were trapped in the smoke for over an hour, there were no fatalities. Due to the prevailing wind there was breathable air in the tunnel and the fire brigade were able to approach the scene of the fire easily. It has been estimated that if the wind had not been as strong there would have been at least four fatalities due to smoke inhalation. [157,158]

Berlin Underground railway/metro Tunnel, Germany, 2000

A fire broke out on a underground railway/metro train at “Deutsche Oper” underground railway/metro station in July 2000. There were 350 people evacuated and 28 reported injuries, mostly smoke inhalation. [150]

Cross-harbour tunnel, Hong Kong, 2000

A car caught fire inside the Kowloon bound tube of the Hong Kong Cross Harbour Tunnel on 29th May 2000. The fire was detected at about 1.25pm and the first emergency response (tunnel personnel) arrived within three minutes, but they were unable to control the fire. The fire brigade arrived two minutes later. All people were evacuated and the fire was extinguished within half an hour. The tunnel was re-opened less than an hour after the incident began. There were no fatalities. [159]

Montreal underground railway/metro, Canada, 2000

At 7.45am on the 15th of April 2000, a cable fire lead to the complete closure of the Montreal underground railway/metro system for six hours. The fire filled several tunnels with smoke, triggered three explosions and brought about the failure of the electrical, communication and ventilation systems on the entire underground railway/metro network. There were no recorded injuries. [160]

Motorway tunnel, Toulon, France, 2000

On 1st February 2000 during construction works there was a fire involving two of the construction vehicles. The fire-fighting operations took four hours due to the lack of fire safety installations and emergency access in the unfinished tunnel. [151]

Tauern tunnel, 6.4km long, south east of Salzburg, Austria, 2000

On 10th January 2000, just over seven months after the fatal fire in this tunnel, another HGV fire occurred. This fire was dealt with rapidly and was extinguished within half an hour by fire-fighters on both sides of the vehicle. [151]

1990s

Candid Tunnel, 252m long, Munich, Germany, 1999

At 7.30am on 30th August 1999 a fire broke out due to problems with a car engine. The tunnel is part of Munich's busiest road and the fire occurred during the morning rush hour. Passing cars ignored the smoke and continued to enter the tunnel until the police blocked the tunnel entrance. Due to the volume of traffic, the fire brigade took a long time to reach the fire, but on arrival the fire was quickly extinguished. [161]

Amsterdam underground railway/metro, The Netherlands, 1999

On 12th July 1999 an express tram caught fire in the Weesperplein underground railway/metro station in Amsterdam. The tram driver and station staff were unable to extinguish the fire and smoke filled the station. The fire brigade arrived quickly at the scene but were unable to begin fire-fighting until the electric power had been switched off. Two people were treated for smoke inhalation. [162]

New York City underground railway/metro, USA, 1999

At 5pm on 1st July 1999, a rubbish fire broke out on the "A" line of the New York Underground railway/metro. The fire spread rapidly to the electrical cabling in the tunnel causing a power failure in parts of the system. Many passengers were trapped on trains in smoke filled tunnels for up to 45 minutes. 51 passengers and one fire-fighter suffered smoke inhalation and other injuries. [163]

Tauern tunnel, 6.4km long, south east of Salzburg, Austria, 1999

On Saturday 29th May 1999, a HGV collided with a queue of stationary traffic 800m from the northern portal of the tunnel. Eight people died as a direct result of the crash. A fire broke out and quickly engulfed the incident HGV, another HGV loaded with a cargo of spray cans including paints and the four car pile-up between them. There were four fire-related fatalities: one HGV driver who was overcome by fumes in the tunnel, two car passengers who did not leave their car and one HGV driver who had initially fled to safety, but returned to his vehicle to collect some documents. The fire destroyed 16 HGVs and 24 cars and took 15 hours to extinguish. The transverse ventilation system worked very well during the incident. [164,165]

Railway Tunnel, 9km long, near Salerno, Italy, 1999

On Sunday 23rd May 1999, a train carrying Italian football fans caught fire as a result of the so-called “rowdy” behaviour of the passengers. Four people died and at least nine were injured. It was alleged that the fire started as a result of one of the passengers lighting a smoke bomb. [166]

Mont Blanc tunnel, 11.6km long, France / Italy, 1999

On Wednesday 24th March 1999, a HGV carrying a refrigerated cargo of margarine and flour entered the Mont Blanc tunnel from the French side at 10:46am, no fire or smoke was observed. A few kilometres into the tunnel the HGV began emitting “white smoke”. The HGV stopped at 10:53 am, near lay-by 21, some 6.3km into the tunnel. Immediately the cab burst into flame, producing “black smoke” which propagated mostly in the direction of the French portal, the driver fled towards Italy. One motorcycle, nine cars, 18 HGVs and a van were in the tunnel behind the HGV which was on fire, eight HGVs and several cars also entered the tunnel from the Italian side before the tunnel was closed. Nobody who entered the tunnel from the Italian side was injured. The fire resulted in the death of 39 people (27 of them in their vehicles), the destruction of 34 vehicles (over 1.2km of tunnel), severe damage to the tunnel lining (over 900m) and a blaze which took 53 hours to extinguish. The fire is thought to have started because of diesel fuel leaking onto hot surfaces in the HGV engine compartment. The uncontrolled spread of the toxic smoke (responsible for the majority of the deaths) has been blamed on poor

operation of the ventilation system and lack of communication between the French and Italian operators. [6]

Leinebusch Tunnel, near Göttingen, Germany, 1999

On 2nd March a fire broke out on a high speed goods train after a ball bearing overheated and the train derailed. The cargo, mostly paper and pulp, caught fire and took twelve hours to extinguish, one fire-fighter was injured. [167]

Oslofjord Tunnel, Norway, 1999

An explosion during construction started a fire. Two fire-fighters were killed and several people were injured during the fire-fighting and rescue operations. [152]

Gueizhou tunnel, 800m long, between Guiyang and Changsha, China, 1998

On 10th July 1998, gas canisters exploded on a train in south west China killing more than 80 people. The tunnel collapsed and railway workers sent to repair the damage were also killed by a further explosion caused by a build up of gas. [168]

Gleinalm tunnel, 8km long, near Graz, Austria, 1998

A double deck coach caught fire as a result of a short circuit. Heavy smoke filled 3km of the tunnel for over an hour. The fire spread to one of the fire-fighting vehicles. No injuries were reported. [151]

St. Gotthard tunnel, 16.9km long, near Airolo, Switzerland, 1997

On 31st October 1997 a car transporter engine overheated and started a fire which ultimately involved the transporter and the eight cars it was carrying. The fire burned for three hours, causing only small damage to the tunnel and only one person was reported injured. [151,169]

On 17th September 1997 a bus engine overheating started a small fire. It was extinguished within 20 minutes and nobody was injured. [169]

Toronto underground railway/metro, Canada, 1997

On the 6th August 1997 a fire broke out on some rubber matting which was stored under the tracks in a shunting area on the Toronto underground railway/metro system. Large volumes of thick black smoke were produced but there were no injuries. A spokesperson for the TTC, which accepted complete responsibility for

the incident, said that the mats had been stored under the tracks because it was “just a convenient place to put them.” [170]

Exilles rail tunnel, 2.1km long, near Susa, Italy, 1997

On the 1st July 1997 a train transporting 216 cars on 18 wagons caught fire. The fire began because one of the car doors swung open and was dragged along the electrical wiring on the tunnel wall. The fire alarm was raised at 1.30pm. Fire-fighters from Susa arrived 20 minutes later and were joined by fire-fighters from Turin after a further 25 minutes. Due to the gradient, the downhill side of the tunnel was smoke free and allowed the fire-fighters to approach the blaze. Fire-fighting was hazardous due to the high temperatures and explosive spalling of the concrete lining. The fire took five hours to control and was eventually extinguished by 8pm. One locomotive, thirteen freight wagons and 156 cars were destroyed. The two train crew members self-rescued by running uphill out of the tunnel, they were both treated for smoke inhalation. [171]

Prapontin tunnel, 4.9km long, near Susa, Italy, 1997

On the 13th January 1997 the brakes of a HGV transporting textiles overheated, causing a fire. The alarm was raised just after 3pm and the fire brigade were on the scene within five minutes. Fire-fighting was hindered by thick smoke, high temperatures, explosive spalling of the concrete lining, inappropriate use of the ventilation system and a lack of water in the hydrants. The fire was extinguished at 7pm. Five people were treated for smoke inhalation. [172]

Channel Tunnel, 51km long, France / UK, 1996

On 18th November 1996 one of the HGVs onboard a HGV carrier shuttle in the Channel Tunnel caught fire. Upon entering the tunnel the fire size has been estimated to have been about 1.5MW, when the fire reached its maximum extent the size was as much as 350MW and involved ten HGVs and their carrier wagons. The train was stopped in the tunnel and it took about half an hour to get the emergency ventilation system working properly. All the HGV drivers and the crew were evacuated safely into the service tunnel with no fatalities and only two escapees requiring significant hospital attention. Following the evacuation of all the people, the ventilation system maintained an airflow of 2.5ms^{-1} in the tunnel which may have helped fan the fire to grow to such a size. The main fire was extinguished by

fire-fighters working in relays some seven hours after the fire was first detected. Minor smouldering fires were still in evidence 24 hours later. [4]

Ekeberg tunnel, 1.5km long, Norway, 1996

On the 21st August 1996 the engine of an articulated bus caught fire. The fire lasted two hours and destroyed the bus. There were no fatalities. [169]

Washington DC underground railway/metro, USA, 1996

On Saturday 11th May 1996 a short circuit on a underground railway/metro train lead to an explosion and a fire. Fire-fighting efforts were hampered by the failure of the underground railway/metro operators to switch off the electrical power, stop other trains and also by the incompatibility of the fire-fighters' radio system with the underground railway/metro radio system. [173]

Isola delle Femmine, 148m long, near Palermo, Italy, 1996

On the 18th of March 1996 a sixteen vehicle pile-up occurred in the two lane eastbound tube of the Isola delle Femmine motorway tunnel. A tanker carrying liquid petroleum gas (LPG) safely performed an emergency stop in the tunnel without joining the pile-up. However, the tourist coach following the tanker and four other vehicles crashed into the back of the tanker. The upper part of the tank ruptured and a small explosion followed within seconds. This lead to only minor injuries and started a fire at the front of the tourist coach. All but five passengers evacuated the bus through a smashed window at the rear. Four of the five remaining passengers were later found dead on the bus and another found dead on the roadway. After about six or seven minutes, by which time all surviving people had evacuated the tunnel, there was a massive explosion; thick smoke and violent flames were observed at both ends of the tunnel and at cross-passages into the other tunnel tube. Eye witnesses report experiencing a "shock wave" from the blast outside of the tunnel. The second explosion is believed to have been a boiling liquid expanding vapour explosion (BLEVE) which occurred inside the body of the tanker; of which only four large pieces remained after the incident. 34 people were treated for burns, of them 16 were admitted to hospital. All of those hospitalised were kept in for over ten days, five of them for over a month. [169,174,175]

Baku underground railway/metro, Azerbaijan, 1995

An electrical fault led to a fire breaking out at the rear of the fourth car of a packed five car underground railway/metro train during rush hour on the 28th of October 1995. The train stopped 200m after departing Uldus station. Initially the ventilation conditions in the tunnel tended to move the smoke gently towards the rear of the train. There were problems getting the doors open for the passengers to escape. Windows were smashed and some passengers began to evacuate the train in both directions. Soon the fire grew such that it was impossible to pass – passengers in the front three cars would have to evacuate towards Narimanov station, 2km away. 15 minutes after the train stopped the ventilation conditions in the tunnel were changed, drawing all the smoke towards Narimanov and the front three cars. The entire tunnel was filled with smoke in this direction. 220 passengers were killed in the front three cars, forty were killed by the fumes in the tunnel in the direction of Narimanov station. Also 256 people were admitted to hospital following the incident, 100 of whom were still in hospital five days later. The tunnel re-opened within 24 hours. [3,176]

Pfänder tunnel, 6.7km long, Austria, 1995

On 10th April 1995 a car driver fell asleep in the Pfänder tunnel and his car strayed into the path of an oncoming truck. After colliding with the car, the truck skidded along the wall on the wrong side of the road ultimately colliding with a minibus. Three people on the minibus died as a result of the crash. Although emergency ventilation was activated almost immediately, it was not sufficient to control the smoke, which filled the tunnel and hindered the fire brigade. However, no one died as a result of the fire. The fire was extinguished after an hour, by which time it had caused serious damage to the tunnel lining. [177]

Hitra tunnel, 5.6km long, Norway, 1995

On 24th January 1995 the motor of a mobile crane caught fire. Although the fire was small and nobody was injured, the fire took over two hours to extinguish. [169]

Kingsway tunnel, 2km long, Liverpool, UK, 1994

On 15th October 1994 a bus fire lasted over an hour, disrupting traffic but causing only minor damage to the tunnel. [169]

Great Belt tunnel, near Korsør, Denmark, 1994

On the 11th June, during construction of the tunnel, there was an explosion on one of the tunnel boring machines. This led to a gigantic fire which filled the entire tunnel with dense smoke. All the crew were evacuated and by the time the fire brigade arrived the fire was too intense to get near. Investigation was not possible for several days due to fears of the tunnel collapsing. Eventually it was discovered that the explosion was probably due to oil leaking from the hydraulics. [178]

St. Gotthard tunnel, 16.9km long, near Airolo, Switzerland, 1994

On 5th July 1994 a tyre caught fire on a HGV carrying 750 bicycles in cardboard boxes. As a result of the two hour fire, the lorry was destroyed, there was significant damage to 50m of the tunnel lining but nobody was injured. [151,169]

Castellar tunnel, 570m long, France, 1994

On 14th April 1994 an exploding tyre led to a fire involving a truck carrying waste paper. There were no injuries. [169]

Huguenot tunnel, 4km long, near Paarl, South Africa, 1994

On Sunday 27th February 1994 a fire broke out in the gearbox of a bus carrying 45 passengers. After a failed attempt to smother the fire by the co-driver, several passengers jumped from the moving vehicle. The driver then lost control of the vehicle and veered across the oncoming traffic hitting the tunnel wall. An approaching articulated truck jack-knifed, blocking the tunnel, in an attempt to make an emergency stop. At this stage the fire was relatively small and could have been extinguished by using any of the nearby fire extinguishers, however this was not done and the fire grew, filling the tunnel with smoke and killing the bus driver. The fire destroyed the bus and many of the tunnel installations nearby, but it did not spread to any other vehicles. The fire brigade arrived at the scene within twelve minutes of the first alarm, made by one of the bus passengers. The fire took slightly over an hour to extinguish. The tunnel reopened, following temporary repairs, four days later. [179]

Hovden tunnel, 1.3km long, Norway, 1993

On 13th June 1993 a collision involving two cars and a motorcycle started a large fire which burned for 1.5 hours. The damage to the tunnel was significant and there were five injuries as a result of the crash. [169]

Vardo Tunnel, Norway, 1993

A minor car fire incident occurred. [154]

Serra a Ripoli tunnel, 442m long, Italy, 1993

An out of control vehicle crashed, starting a fire that ultimately involved five HGVs, one loaded with rolls of paper, and eleven cars. There were four fatalities and four reported injuries. The fire lasted 2.5 hours. [169]

New York Underground railway/metro, USA, 1992

On 11th October 1992 an electrical fire on the track produced dense smoke leading to 51 reported injuries. [180]

On 16th March 1992 an undercar fire in a tunnel resulted in 86 injuries, four hundred people being evacuated and the destruction of the underground railway/metro car. [180]

Bonn Underground railway/metro, Germany, 1991

11th September 1991, an electrical fire on a train in a station. No reported injuries.

Unnamed tunnel, South China, 1991

August 1991, a fire broke out aboard a train passing through a tunnel engulfing one of the cars. 15 passengers died when they jumped from the train into the path of an oncoming locomotive. [181]

Moscow Underground railway/metro, Russia, 1991

On 1st June 1991 an electrical fire under a train in a station resulted in seven fatalities and at least ten injuries. [180]

Hirschengraben Tunnel, 1.3km long, near Zurich, Switzerland, 1991

On 16th April 1991 a train was observed to be on fire as it left the main Zurich railway station. The driver was unaware of the fire. The train stopped almost

halfway through the tunnel when an emergency brake was pulled. The passengers were initially advised to remain on the train but after two to three minutes were instructed to evacuate. The tunnel quickly filled with smoke. Another train entered the tunnel to assist evacuation and several escaping passengers boarded the second train, only to have to evacuate this train after the electrical supply to the tunnel was switched off and the train was rendered powerless. All passengers were safely out of the tunnel within 20 minutes, there were no recorded injuries or fatalities. [182]

New York Underground railway/metro, USA, 1990

On 28th December 1990 a cable fire in a tunnel near a station produced dense smoke. A passenger pulled the emergency cord halting a train near the fire. The fire brigade arrived quickly but evacuated the wrong train first. Two people died, two hundred were injured. [180]

Røldal tunnel, 4.7km long, Norway, 1990

On 19th August 1990 an engine overheating lead to a fire involving a vehicle transporter. There was one injury. [169]

Los Angeles underground railway/metro (red line), USA, 1990

On 13th July 1990, during construction of the red line, a fire broke out on the timber supports of the partially built tunnel. This lead to the collapse of about 45m of the tunnel. There were no recorded injuries. [183]

Mont Blanc Tunnel, 11.6km long, France / Italy, 1990

On 11th January 1990 a HGV on fire stopped nearly 6km into the tunnel. The driver had first noticed the smoke about 1.5km into the tunnel but did not stop until flames entered his cab! He alerted the tunnel operators by telephone and the French fire-fighters arrived within ten minutes. Despite the fact that the fire had spread to involve the entire vehicle by this point, the fire-fighters are able to control the blaze and extinguish it. Two people were treated for smoke inhalation. [169,184]

Brenner tunnel, Austria, 1989

On 18th May 1989 dangerous goods used during construction works exploded resulting in a fire that lasted seven hours. 155 fire-fighters with 21 fire-fighting vehicles attended the scene. Two people were killed and another five were injured. [151,185]

Mont Blanc Tunnel, 11.6km long, France / Italy, 1988

On 2nd September 1988 a HGV on fire stopped just over 5km into the tunnel. The driver alerted the control centre and returned to fight the fire. He was able to control the fire using a portable extinguisher until the motorcycle patrol arrived. Despite the efforts of the driver and the patrolman, the fire spread to the trailer. The French fire-fighters were hindered in their approach by 500m of thick smoke but were able to extinguish the fire on arrival. There were no recorded injuries. [184]

Kings Cross Station, London, UK, 1987

On 18th November 1987 a fire involving the steps and sides of a wooden escalator, and which spread into the ticket hall, was responsible for the deaths of 31 people and many other injuries. The fire grew and spread very rapidly, probably due to pre-heating of the escalator floor by a fire which is thought to have started in the grease and fluff under the escalator track. It behaved in an unexpected manner: the flames and plume from the fire did not rise from the fire location toward the ceiling of the escalator tube, but rather they tended to hug the steps and sides of the escalator all the way up and into the ticket hall at the top of the escalator. This phenomenon has become known as the “trench effect”. The fire reached flashover in a matter of minutes and burned for six hours. [37]

Tanzenberg tunnel, 2.4km long, Austria, 1987

On the 2nd July 1987 a suicidal car driver deliberately crashed his vehicle into the tunnel wall. Dense smoke prevented fire fighting procedures and there was significant damage to the tunnel structure as a result. The suicide attempt was unsuccessful. [151]

Moscow Underground railway/metro, USSR, 1987

1st July 1987, a fire on a train stopped between stations. No reported injuries.

Brussels Underground railway/metro, Belgium, 1987

1st June 1987, a fire broke out in the station. Over 1000 people were evacuated but there were no reported injuries.

Gumefens tunnel, 343m long, Switzerland, 1987

On 18th February 1987 a collision resulted in a fire which ultimately involved two HGVs, one van and five cars. There were two fatalities and three reported injuries (possibly all as the result of the crash). The fire burned for two hours. [151,185,186]

Herzogberg tunnel, 2km long, Austria, 1986

On 30th December 1986 a HGV caught fire due to its brakes overheating. Although the fire brigade took over 20 minutes to arrive, the fire was extinguished quickly, apparently due to the 'oversized' capacity of the extraction ventilation which meant that the smoke and temperature conditions in the tunnel did not hinder the fire brigade's approach to the fire. [151]

L'arme tunnel, 1.1km long, France, 1986

On 9th September 1986 a collision involving a car started a comparatively small fire, involving the car and a trailer. The incident resulted in three fatalities and five other injured people. The duration of the fire and the damage to the tunnel are not recorded. [169,186]

Mexico City underground railway/metro, Mexico, 1985

On 28th October 1985 a fire on a underground railway/metro train resulted in 1700 injured people but no fatalities were reported. [185]

Grand Central station, New York, 1985

On 28th August 1985 an arson attack resulted in 15 injured people and almost \$3 million damages. [185]

Paris underground railway/metro, France, 1985

12th April 1985, a rubbish fire in a station. Many people evacuated, six reported injuries.

San Benedetto Tunnel, 18.5km long, Italy, 1984

On 23rd December 1984 a bomb attack was responsible for the deaths of 17 people and 120 injured. The resulting fire was surprisingly small. Fire-fighters and rescue personnel were unable to reach the scene of the incident for over two hours due to the destruction. [182]

Summit tunnel, 2.6km long, UK, 1984

On 20th December 1984 a train consisting of a diesel locomotive and 13 tankers carrying petroleum spirit derailed approximately a third of the way through the summit tunnel. After witnessing flames, the driver and the guard evacuated and called the fire brigade. At 9.30am (3.5 hours after the train derailed) one of the tankers exploded producing flames 120m high which extended up several of the ventilation shafts, into the open air. The fire was contained by introducing high expansion foam into one nearby ventilation shaft and water into another. By 10.30am the following day, no fire was in evidence but intense heat prevented anyone from reaching the fire location. A cooling, ventilation and inspection strategy was maintained until 6.30pm on the 24th of December, by which time the conditions in the tunnel were back to ambient. All train debris had been removed from the tunnel by the 17th January 1985. The tunnel was shut for several months. [187]

Oxford Circus underground railway/metro, London, UK, 1984

On 23rd November 1984 a fire involving equipment in a maintenance tunnel resulted in 15 injured people. [185]

Landungsbrücken underground railway/metro, Hamburg, Germany, 1984

On 30th September 1984 an arson attack resulted in one injured person and almost \$3 million damages. [185]

New York Underground railway/metro, USA, 1984

On 13th December 1984 an undercar fire lead to the evacuation of a station. No reported injuries.

On 11th October 1984 another undercar fire lead to the evacuation of a station. No reported injuries.

On 4th October 1984 a fire involving rubbish in a tunnel near a station lead to 54 injuries. Uninformed control of underground railway/metro train movements and ventilation systems lead to a train being stopped in a smoke logged tunnel. [188]

On 3rd July 1984 a fire was observed underneath a train in a station. The fire was considered to be minor and not reported to the fire brigade. However, the fire grew and after 48 minutes the fire brigade were called. 24 injuries were reported, mostly fire brigade and underground railway/metro staff. [188]

On 10th June 1984 a train motor exploded causing a fire that produced thick smoke. The tunnel was completely filled with smoke so that the driver could not identify his position. As a result of this the fire brigade did not arrive at the scene for an hour. 23 people were injured, 200 were evacuated. [188]

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Pecorile tunnel, 662m long, Italy, 1983

A collision involving a fish lorry started a fire that claimed nine lives and injured a further twenty people. [169,186]

Hauptbahnhof underground railway/metro, Munich, Germany, 1983

On 5th September 1983 an electrical fire resulted in 7 injured people and over \$2 million damages.[185]

Frejus tunnel, 12.9km long, France, 1983

On 3rd February 1983, a gearbox fault on a HGV loaded with plastics lead to a fire. In spite of the very fast response of the fire brigade, the fire took almost two hours to control and damaged 200m of the tunnel lining. There were no reported injuries. [151]

Salang tunnel, Afghanistan, 1982

On 2nd or 3rd November 1982 a gas tanker, part of a military convoy, exploded in a road tunnel. This started a large scale fire. Reports on the number of fatalities vary from 176 to several thousand. [189,190,191]

Piccadilly line, London underground railway/metro, UK, 1982

On 11th August 1982 an electrical cable fire lead to 15 people being injured. [185]

Caldecott tunnel, 1km long, Oakland, USA, 1982

On 7th April 1982 a collision came about when a passenger car, driven by a drunk driver, collided with the roadside and came to an abrupt halt. The stationary car was struck by a petrol tanker and subsequently the tanker was struck by a bus, causing the tanker to turn over, partially rupture and spill some of its load. This soon ignited and the blaze grew to involve the tanker, the car and four other vehicles in the tunnel. Seven people were killed. Although some of the petrol spilled out of the tanker, it appears that a large quantity of the fuel remained in the tank. Once the fire had reached a sufficient temperature to melt the aluminium walls of the tanker, the “top” of the tanker (i.e. the side that was uppermost after the crash) collapsed creating a large, deep pool of petrol which ignited and burned fiercely for over two hours until fire-fighters were able to extinguish it. [192]

Washington DC underground railway/metro, USA, 1982

On 13th January 1982 a derailment started a fire that led to 1200 people being evacuated. No fatalities were reported. [185]

Mont Blanc Tunnel, 11.6km long, France / Italy, 1981

On 17th September 1981 a HGV stopped about 4.5km into the tunnel. Thick smoke was observed to issue from the engine but the vehicle did not catch fire. There were no recorded injuries. [184]

Ramersdorf underground railway/metro, Bonn, Germany, 1981

On 11th September 1981 a technical fault started a fire which caused \$0.5 million damage. [185]

London underground railway/metro, UK, 1981

On 21st June 1981 fire between two underground railway/metro stations resulted in one fatality and 15 injured people. [185]

Okyabrskaya underground railway/metro, Moscow, USSR, 1981

On 10th June 1981 a short circuit started a fire which caused \$250,000 damage. [185]

New York Underground railway/metro, USA, 1980-82

On 2nd June 1982 a fire on a train in a tunnel led to ten injuries, over a thousand people evacuated and a fire that burned for six hours destroying four carriages. [193]

On 16th March 1982 a fire involving a train motor at Christopher Street station resulted in 86 injured people. [185]

On 15th May 1981 an electrical fire resulted in 16 injured people. [185]

On 6th May 1981 an undercar fire in a station occurred. There were no reported injuries.

On 29th April 1981 an undercar fire in a station resulted in two injuries.

On 21st April 1981 a fault in the current collectors on a underground railway/metro train led to an explosion 600m from the nearest station. 24 passengers were injured as they evacuated by breaking the windows of the train and walking along the smoke filled tunnel. The electricity was switched off and the ventilation was

switched to exhaust after 7 minutes. The fire brigade arrived after 20 minutes and took only six minutes to extinguish the fire. [193]

On the 25th June and the 10th & 11th of December 1980 there were three minor fires resulting in eleven injuries between them. [185]

Sakai tunnel, 459m long, Japan, 1980

On 15th July 1980 a collision involving a truck resulted in a fire which burned for 3 hours, ultimately involved ten vehicles, killed five people and injured five others. [169]

Kajiwara tunnel, 740m long, Japan, 1980

On 17th April 1980 a gearbox fire lead to a fire which ultimately involved two trucks, one laden with 200 cans of paint, which burned for 1hour and 20 minutes and resulted in one fatality. [169]

Altona underground railway/metro, Hamburg, Germany, 1980

On 8th April 1980 an arson attack resulted in \$5 million in damages and four injured people. [185]

1970s

Nihonzaka tunnel, 2km long, Japan, 1979

On July 11th 1979 an accident involving four trucks and two passenger cars lead to a fire in the westbound tube of the tunnel. Ultimately the fire killed seven people and spread to involve 189 vehicles. Traffic congestion lead to a delay in the arrival of the fire brigade and their fire fighting activities were cut off after only half an hour as the water tanks ran dry. The fire was not extinguished for 160 hours. [194]

New York Underground railway/metro, 1979

On 8th September 1979 a discarded cigarette ignited an oil spillage on the track in a station. There were four reported injuries.

Eric Street underground railway/metro station, Philadelphia, USA, 1979

On 6th September 1979 a transformer fire on a underground railway/metro train lead to 148 injuries. Many of the injuries were as the result of the train doors failing to open. [180]

Paris underground railway/metro, France, 1979

On 25th March 1979 a short circuit on a underground railway/metro train lead to a fire that produced heavy smoke. There were no fatalities but 26 people were injured and over a thousand people had to be evacuated. [180]

San Francisco underground railway/metro (BART), USA, 1979

On 17th January 1979 a short circuit underneath a underground railway/metro car lead to a fire. One person died and 56 were injured. The movements of other underground railway/metro cars spread the smoke rapidly and over a thousand people needed to be evacuated from the underground railway/metro. [195]

Hansaring underground railway/metro station, Cologne, Germany, 1978

On 24th October 1978 a fire caused \$1.2 million damages. [185]

Velsen tunnel, 768m long, Haarlem, Netherlands, 1978

On 11th August 1978 a collision killed five people and started a fire which ultimately involved two HGVs and four cars. [169]

Mont Blanc Tunnel, 11.6km long, France / Italy, 1978

On 15th April 1978 a HGV stopped about 400m into the tunnel at the Italian end. Although thick smoke was produced the vehicle did not show flames. There were no recorded injuries. [184]

Baltimore Harbour Freeway, USA, 1978

On the 23rd March 1978 a truck collided with a fuel tanker just outside of the Baltimore harbour tunnel. The resulting fire involved the two collided vehicles and another HGV. The fire lead to traffic queues and evacuation procedures in the tunnel but the fire itself did not spread into the tunnel. [192]

Paris underground railway/metro, France, 1977

On 9th March 1977 there was a minor fire in a underground railway/metro station. There were no reported injuries.

Berlin underground railway/metro, Germany, 1976

On 13th December 1976 there was a fire during construction of a underground railway/metro station. [185]

Christie Street underground railway/metro station, Montreal, Canada, 1976

On 15th October 1976 an arson attack lead to a fire which resulted in over \$3 million damages. There were no fatalities. [185]

San Bernardino tunnel, 6.6km long, Switzerland, 1976

On 21st of September 1976 a bus carrying 33 passengers caught fire. The fire brigade response was very fast, nobody was injured and the fire did not spread. [151]

Porte d'Italie tunnel, on B6 Motorway, 430m long, Paris, France, 1976

On 11th of August 1976 an engine fire on a HGV carrying 16 tons of polyester plastic resulted in a one hour fire which destroyed 150m of the tunnel lining. There were 12 injuries. [151,169]

Lisbon underground railway/metro, Portugal, 1976

On 25th May 1976 there was an electrical fire on a train. Damages in excess of \$1.8 million. [185]

Finsbury Park underground railway/metro, London, UK, 1976

On 6th February 1976 25 people were injured as a result of a cable fire. [185]

Château de Vincennes underground railway/metro, Paris, 1975

On 16th November 1975 a short circuit lead to an undercar fire. There were no fatalities. [185]

Guadarrama tunnel, 3.3km long, Spain, 1975

On 14th August 1975 a tanker transporting pine resin caught fire. Although nobody was seriously injured during the 2hr 45min fire, the fire brigade were seriously hampered in their efforts by thick toxic smoke. The tunnel suffered severe damage. [151,169]

Goodge Street underground railway/metro, London, UK, 1975

On 12th August 1975 a fire broke out in a cross passage between two tunnels. There were no fatalities. [185]

Boston Underground railway/metro, USA, 1975

On 2nd August 1975 a broken catenary at the front of a underground railway/metro car lead to a fire. There were no fatalities but 34 people were injured and four hundred people had to be evacuated. [180]

Moorgate underground railway/metro station, London, UK, 1975

On 28th February 1975 an incident involving a train hitting a wall and the subsequent fire resulted in 44 fatalities and 73 injured people. [185]

Mexico City underground railway/metro, Mexico, 1975

Fifty people died and another thirty were injured due to a train collision and the resulting fire. [185]

New York underground railway/metro, USA, 1974

On 13th August 1974 a technical fault on the rails started a train fire which injured 78 people. [185]

Congress tunnel, New York, USA, 1974

On 6th June 1974 a derailed goods train caught fire, only one person was injured. [185]

Chesapeake Bay tunnel, USA, 1974

On 3rd April 1974 an exploding tyre on a HGV started a fire which involved the fuel tank of the vehicle. The fire burned for four hours injuring one person. [169,192]

Mont Blanc Tunnel, 11.6km long, France/Italy, 1974

On 28th January 1974 a HGV on fire stopped about 450m from the French portal. The French fire brigade was quick to arrive on the scene and, despite thick smoke, was able to extinguish the fire quickly. [184]

Rosemont underground railway/metro station, Montreal, Canada, 1974

On 23rd January 1974 a short circuit caused a fire on an underground railway/metro train. There were no fatalities. [185]

Moscow Underground railway/metro, 1974

On 1st January 1974 there was a minor fire in an underground railway/metro station. Although the passengers were prevented from leaving the station, there were no reported injuries.

Porte d'Italie underground railway/metro station, Paris, France, 1973

On 27th March 1973 an arson attack on a underground railway/metro carriage in a station lead to two fatalities and several injuries even though the fire brigade response was very fast. [180]

Lötschberg tunnel, Switzerland, 1972

Train tunnel, three people injured as a result of a fire during construction work. [185]

Hokoriku tunnel, near Fukui, Japan, 1972

On 6th November a fire in the restaurant car of a passenger train ultimately lead to 30 fatalities, 690 injured people and the destruction of two carriages. [185]

Alexanderplatz underground railway/metro, East Berlin, Germany, 1972

On 4th October 1972 a derailment lead to a fire, there were no fatalities. [185]

Vierzy tunnel, France, 1972

The Vierzy tunnel collapsed on a passenger train, starting a fire. There were 108 fatalities, mostly due to the tunnel collapse. [185]

Henri Bourassa underground railway/metro station, Montreal, Canada, 1971

On 12th December 1971, a underground railway/metro train collided with the end of a tunnel, igniting a fire. There was one fatality. [180,185]

Paris underground railway/metro, France, 1971

On 28th March 1971 an arson attack on a underground railway/metro car lead to three injuries. [185]

Crozet tunnel, France, 1971

On 20th March 1971 a collision between a goods train and a train carrying hydrocarbon fuels caused a derailment and a fire. There were two fatalities. [185]

Wranduk Tunnel, 1.5km long, near Zenica, Yugoslavia, 1971

At 5.48am on 14th February, a train carrying workers to an iron works in Zenica was passing through a 1500m tunnel. It had to stop 300m from the exit as a fire had started in the engine. The heat was such that no passengers could pass the engine and had to return the 1200m to the other end. 33 Died, 120 taken to hospital and 57 admitted. [181]

Sylmar tunnel, 8km long, USA, 1971

On 24th June 1971, during the tunnel construction, a gas explosion killed seventeen of the eighteen man team working in the tunnel at the time. The explosion occurred as a result of “a complete breakdown of corporate safety” and the tunnel project manager, Loren Savage was sentenced to twenty years and six months in prison, on sixteen counts of gross negligence and nine labour code violations. [196]

New York City underground railway/metro, USA, 1970

On 1st August 1970 a tunnel fire near Bowling Green station resulted in fifty injuries and one fatality. The woman who died did so because she returned to the train, after evacuation, in an attempt to recover her purse. [197]

Wallace tunnel, 1km long, USA, 1970

An engine fire became a large fire involving a camper truck. However, there were no injuries and little damage to the tunnel. [169]

Simplon Tunnel, 19.8km, Switzerland / Italy, 1969

On the 8th of November a fire started on the rear carriage of a passenger train shortly after entering the tunnel. The passengers were moved to the front carriages of the train and the train was driven to an emergency station in the tunnel. The railway operators were alerted by phone from the emergency station. The carriage on fire was de-coupled from the train and the rest of the train was driven safely from the tunnel. A small number of passengers who disregarded the instructions and evacuated the train were picked up by another train some time later. There were no recorded injuries. [182]

Moorfleet tunnel, 243m long, Hamburg, Germany, 1968

On the 31st of August 1968 a HGV carrying a load of 14 tons of polyethylene bags caught fire as the result of its brakes overheating. There were no casualties as a result of the one hour fire, but 34m of the tunnel lining were totally destroyed. [151]

Suzuka Tunnel, 244m long, Japan, 1967

On the 6th of March 1967, a 7 ton truck loaded with about 600 polystyrene boxes and other combustible goods caught fire at 5:00am. The fire originated in the engine compartment when the truck was about 30m from the entrance of the Suzuka tunnel. The driver attempted to fight the fire without success using a portable fire extinguisher taken from another truck. Due to inadequate operational procedures the fire spread to 12 other trucks in the tunnel; two people were injured. Fire fighting operations ended over eleven hours later. [198,199]

Blue Mountain tunnel, 1.3km long, USA, 1965

The motor of a truck carrying fish oil caught fire. The truck was destroyed in the fire but nobody was injured. [169]

Stockholm underground railway/metro, Sweden, 1960

On 23rd November 1960 a fire started as the result of a short circuit. An underground railway/metro train carriage was destroyed. [185]

London underground railway/metro, Redbridge, Essex, UK, 1960

38 passengers taken to hospital and admitted with smoke inhalation on 11th August 1960. The fire was caused by arcing in the receptacle box at the front end of the leading car. The circumstances were similar to the accident at Holland Park.

London underground railway/metro, Holland Park, UK, 1958

On 28th July 1958, a fire occurred in an underground railway/metro train. 48 passengers and 3 staff were taken to hospital with smoke inhalation. 10 passengers were admitted and one subsequently died. [200]

Stockholm underground railway/metro, Sweden, 1955

On 11th March 1955 a fire started as the result of overheating. An underground railway/metro train carriage was destroyed. [185]

Penmanshiel Tunnel, UK, 1949

23rd June 1949. Fire on a train. No fatalities.

Holland Tunnel, New York, USA, 1949

On 13th May 1949 a fire started as the result of a HGV shedding its load. The fire burned for four hours, destroying 10 HGVs and 13 cars. 66 people were injured. [185]

London underground railway/metro, UK, 1945

On 31st December 1945, three people died as the result of a collision and fire. [185]

Torre Tunnel, Spain, 1944

On 3rd January 1944 a multi-train collision in a tunnel lead to a fire which lasted for at least a day. There were 91 fatalities as a result of the collision and fire. [182]

St. Gothard, Giorinco, Switzerland, 1941

A train derailment and the resulting fire lead to seven fatalities. [185]

Fires before 1940

Gütschtunnel, Lucerne, Switzerland, 1932

Six people died due to a train collision and the fire that started as a result. [185]

Riekentunnel, Switzerland, 1926

Nine people died from smoke inhalation when a goods train caught fire and stopped in a tunnel. [185]

Batignolles tunnel, 1km long, Paris, France, 1921

On the 21st October 1921 a passenger train was allowed into the Batignolles tunnel while another train was stationary inside. The trains collided, resulting in a very large fire. At least 28 people died, mostly as a result of the fire rather than the crash. The severity of the fire is thought to have been due to the gas light system installed in the carriages. These gas light systems were removed from all passenger trains in France following this incident. [182]

London underground railway/metro, UK, 1905-1909

]

Appendix C. Expert estimates

The ‘prior’ probability distributions described in chapter 5 were based on the estimates of a panel of experts, as explained in Scheme 5á. The actual estimates of each of the experts are presented here.

The estimates were collected in different ways for each of the cases. The estimates presented here have been converted into ‘ k ’ values (see chapter 4) for ease of comparison between cases. In each instance, the experts were asked to estimate maximum, mean and minimum values; these are shown on the graphs below. It was stated that the minimum and maximum values would be taken to correspond to the 5th and 95th percentiles of the probability distribution in each case.

As in the main body of the thesis, the estimates presented will not be attributed to named experts. However, the expert denoted ‘Expert 1’ in each case is the same person, and so on.

C.1 Estimates of k for the HGV case.

For the HGV case, 5 out of the 8 experts returned estimates. These are shown graphically in the figures below.

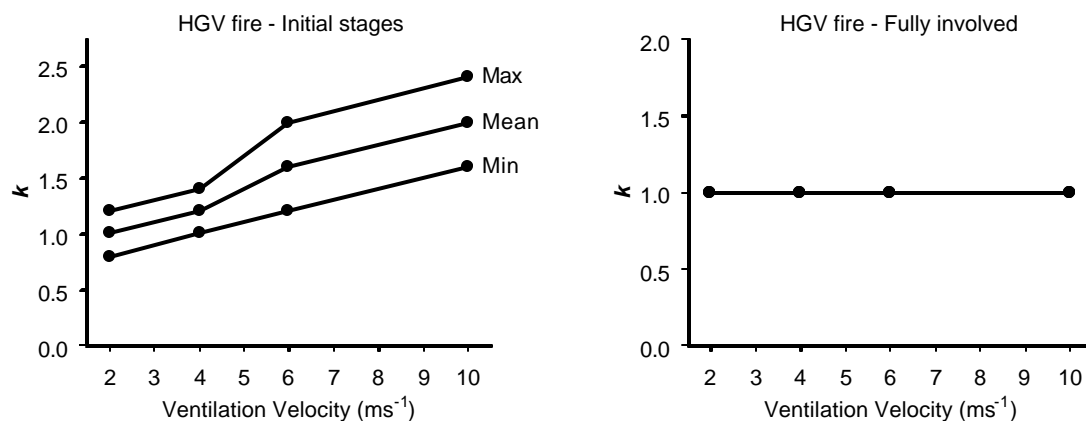
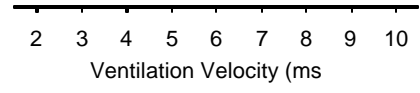
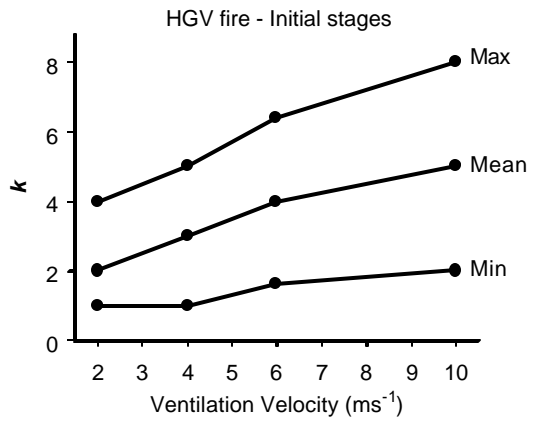


Figure C.01 – The estimates of Expert 1 for HGV fires

Note: in the case of a fully involved fire, this expert did not estimate a range of k values, he expected that k would have a value of 1 under all circumstances.



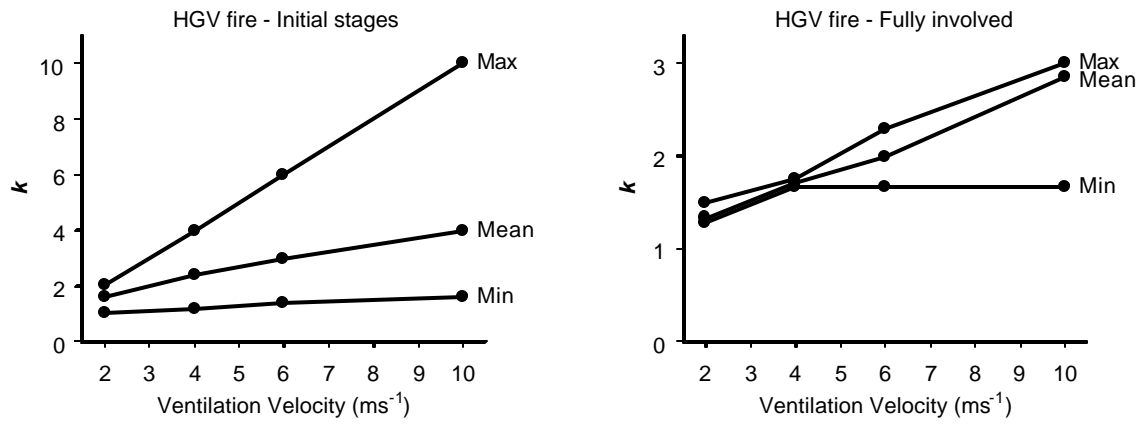


Figure C.05 – The estimates of Expert 5 for HGV fires

C.2 Estimates of k for the pool fire cases.

For the pool fire cases, 6 out of the 8 experts returned estimates. These are shown graphically in the figures below. ‘Expert x ’ below is the same person as ‘Expert x ’ in the HGV case, above.

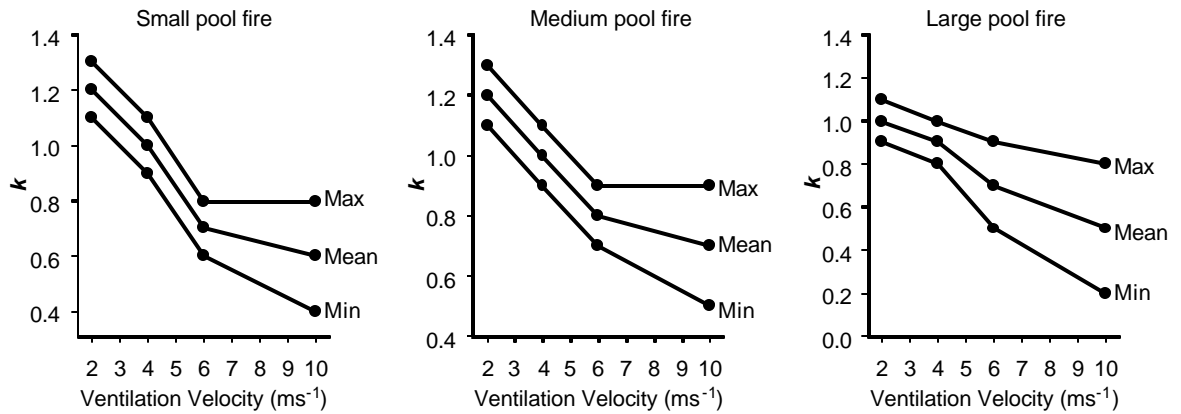


Figure C.06 – The estimates of Expert 1 for pool fires

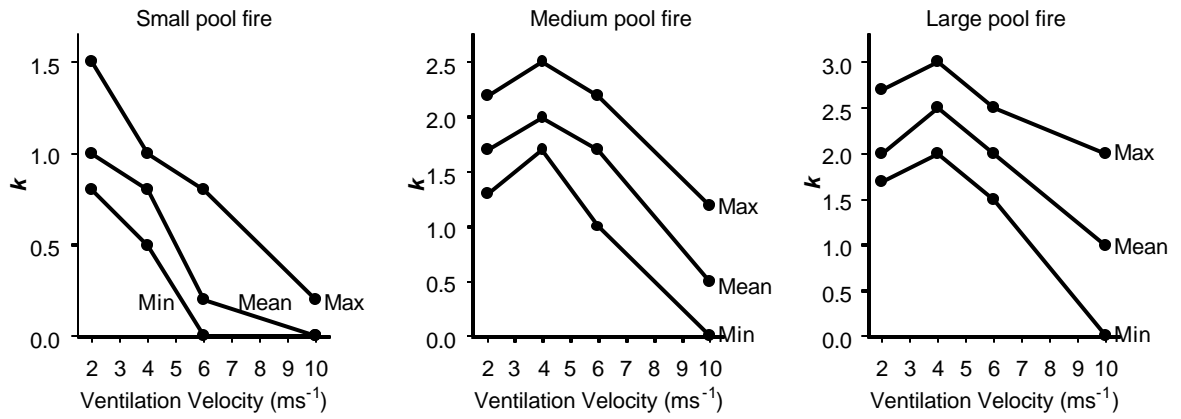


Figure C.07 – The estimates of Expert 2 for pool fires

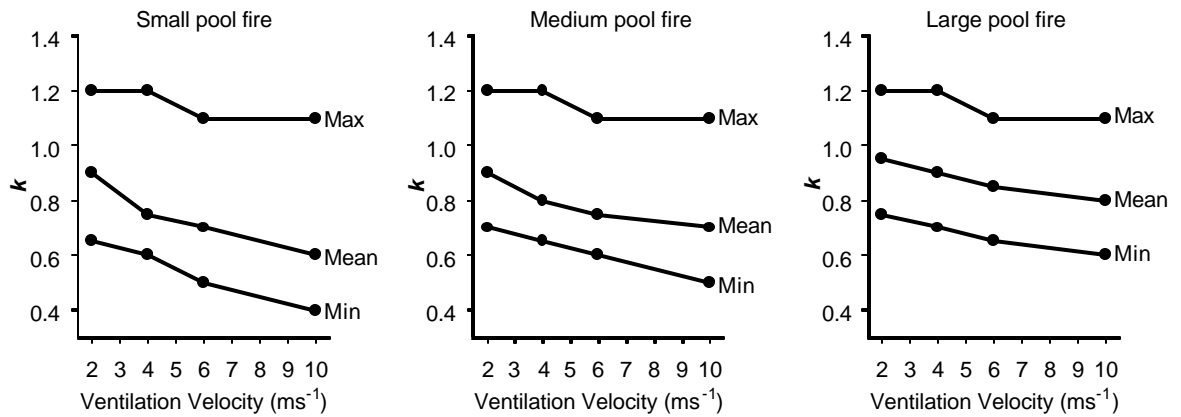


Figure C.08 – The estimates of Expert 3 for pool fires

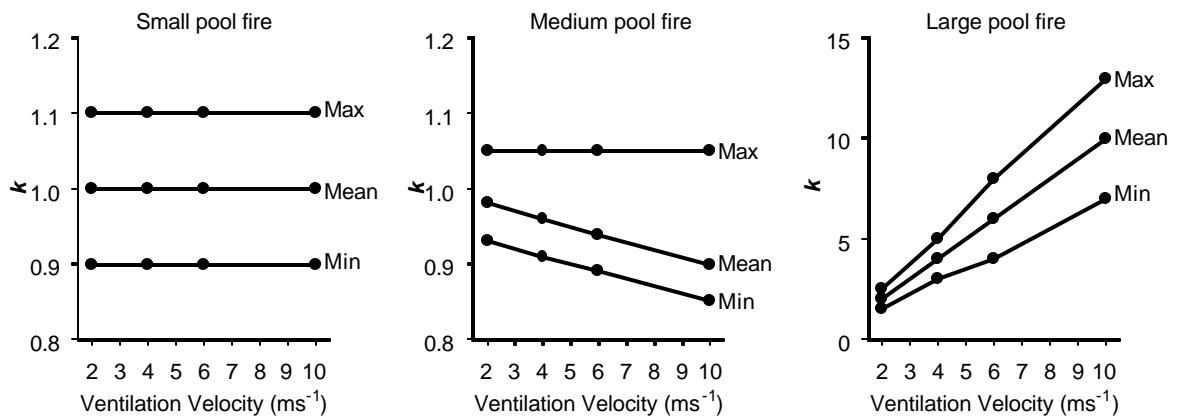


Figure C.09 – The estimates of Expert 4 for pool fires

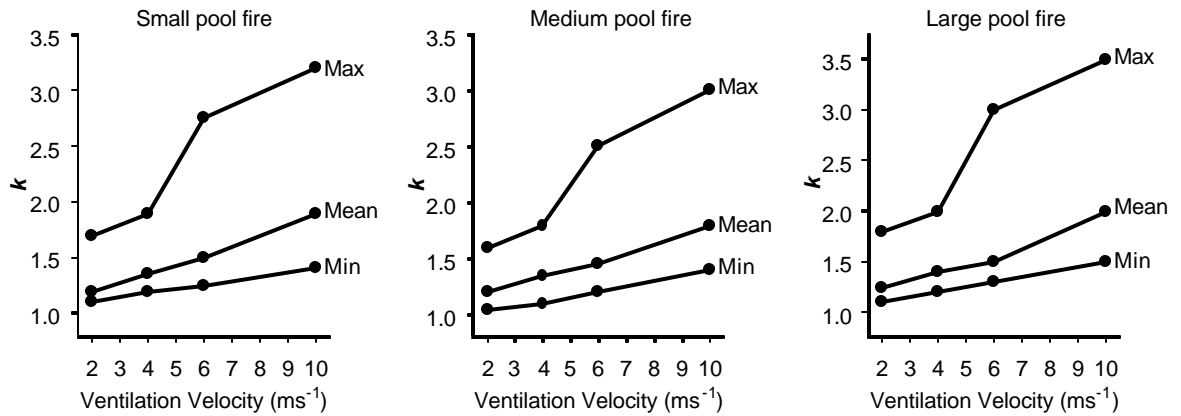


Figure C.10 – The estimates of Expert 5 for pool fires

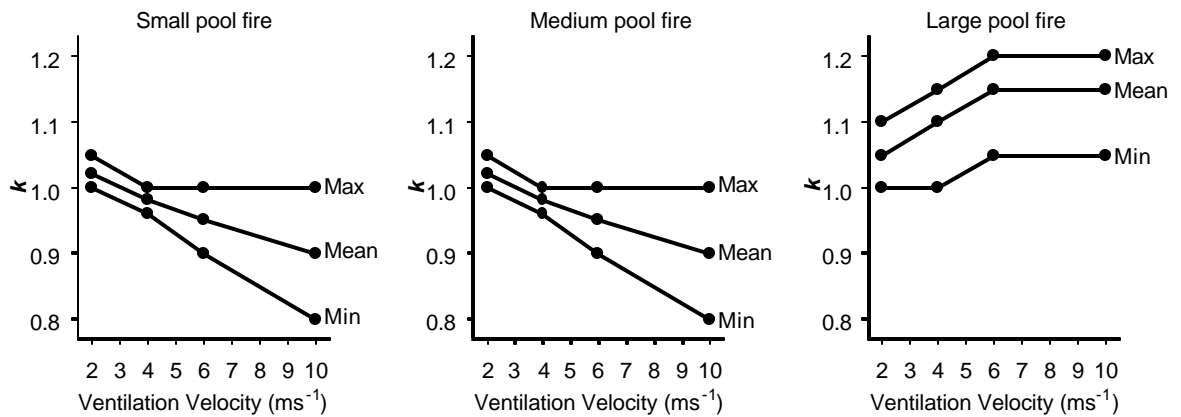


Figure C.11 – The estimates of Expert 6 for pool fires

C.3 Estimates of k for the car fire case.

For the car fire cases, 6 out of the 8 experts returned estimates. These are shown graphically in the figures below. In this case the experts made estimates of k and k_{time} for five different shapes and sizes of tunnels as discussed in section 5.9; the tunnel shapes are shown in Figure 5.02. Once again, ‘Expert x ’ below is the same person as ‘Expert x ’ in both the HGV and pool fire cases, above.

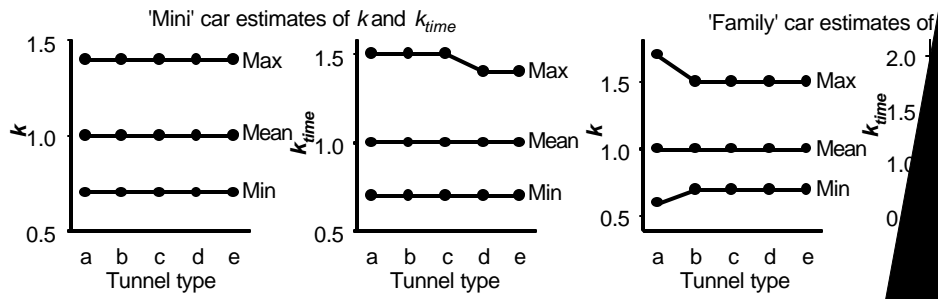


Figure C.12 – The estimates of Expert 1 for car f

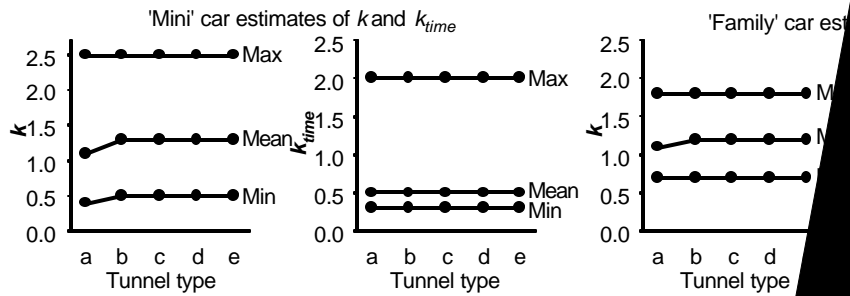
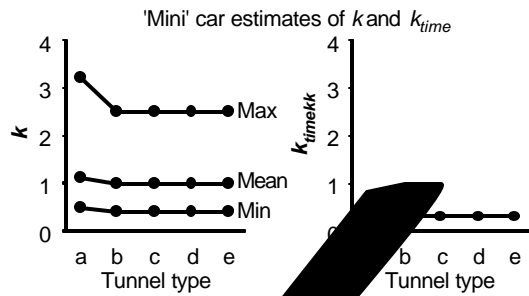


Figure C.13 – The estimates of Expert 2 fo



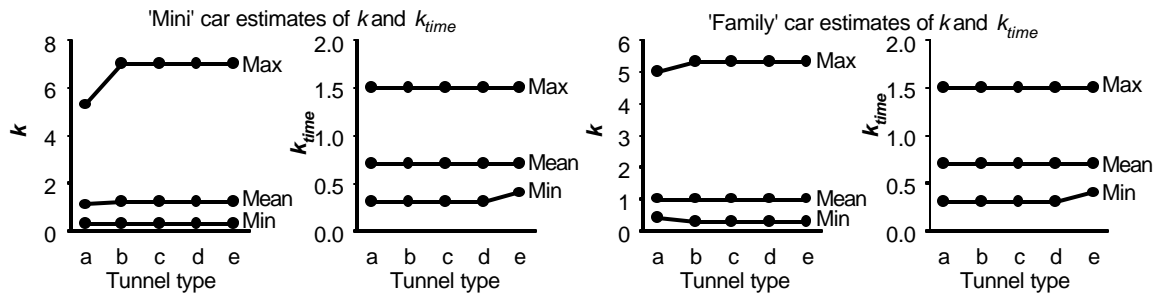


Figure C.16 – The estimates of Expert 5 for car fires

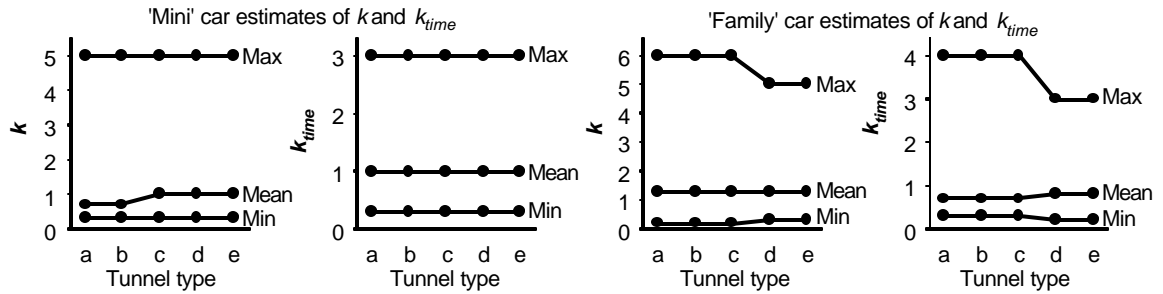


Figure C.17 – The estimates of Expert 6 for car fires

Copies of the actual estimate sheets which the experts used to make their estimates are presented on the following pages.

Consider a HGV in a tunnel with *no* forced airflow. The trailer contains a load of furniture. A fire is ignited at the front of the trailer. After time t_1 the fire has a HRR of 5MW.

Suppose a fire is ignited on a similar HGV in a tunnel *with* a forced airflow, please estimate the range¹ and most likely value of the HRR (in MW) for that fire at time t_1 in the following tunnels:

	Case 1a			Case 1b			Case 1c			Case 1d			Case 1e		
Forced airflow velocity															
	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR
2ms ⁻¹	5	10	7.5												
4ms ⁻¹	5	15	10												
6ms ⁻¹	5	10	7.5												
10ms ⁻¹	3	10	6												

After a further period of time the fire becomes fully involved, please estimate the range and most likely value of the HRR for fully involved HGV fires in these tunnels:

	Case 1a			Case 1b			Case 1c			Case 1d			Case 1e		
Forced airflow velocity	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR
	None														
2ms ⁻¹	0.75	3	1.9												
4ms ⁻¹	2	6	4												
6ms ⁻¹	2	8	6												
10ms ⁻¹	6	14	10												

Figure C.20 – Copy of the original HGV estimate sheet from ‘Expert 3’
 Note, this expert made his estimates for the fully involved fire in terms of k rather than HRR.

Consider a HGV in a tunnel with *no* forced airflow. The trailer contains a load of furniture. A fire is ignited at the front of the trailer. After time t_1 the fire has a HRR of 5MW.

Suppose a fire is ignited on a similar HGV in a tunnel *with* a forced airflow, please estimate the range¹ and most likely value of the HRR (in MW) for that fire at time t_1 in the following tunnels:

	Case 1a			Case 1b			Case 1c			Case 1d			Case 1e		
Forced airflow velocity															
	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR
2ms ⁻¹	20	50	35	25	55	40	20	55	35	30	60	40	30	60	45
4ms ⁻¹	35	65	50	40	70	55	35	65	55	45	75	55	45	75	60
6ms ⁻¹	50	80	65	55	85	70	45	85	65	60	90	70	60	90	75
10ms ⁻¹	65	100	75	70	105	80	65	100	80	75	110	80	75	110	85
				+ 5mw			+ not much			+10 +10 +5			+10 +10 +10		

After a further period of time the fire becomes fully involved, please estimate the range and most likely value of the HRR for fully involved HGV fires in these tunnels:

	Case 1a			Case 1b			Case 1c			Case 1d			Case 1e		
Forced airflow velocity	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR	Range min	Range max	Mean HRR
	None	15	25	20	18	28	23			20	19	30	23	19	30
2ms ⁻¹	60	250	140	90	308	184				114	360	184	114	350	234
4ms ⁻¹	105	325	200	144	392	253				171	450	253	171	450	312
6ms ⁻¹	150	400	260	198	476	322				228	540	322	228	540	390
10ms ⁻¹	195	500	300	252	588	368				285	660	368	285	660	442
	↙						↘ as here,								

Figure C.21 – Copy of the original HGV estimate sheet from ‘Expert 4’

Velocity	(i) Square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>10</u> % increase / decrease *	<u>20</u> % increase / decrease	<u>30</u> % increase / decrease
4ms ⁻¹	<u>10</u> % increase / decrease	<u>0</u> % increase / decrease	<u>10</u> % increase / decrease
6ms ⁻¹	<u>10</u> % increase / decrease	<u>20</u> % increase / decrease	<u>30</u> % increase / decrease
10ms ⁻¹	<u>10</u> % increase / decrease	<u>30</u> % increase / decrease	<u>50</u> % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>10</u> % increase / decrease	<u>20</u> % increase / decrease	<u>30</u> % increase / decrease
4ms ⁻¹	<u>10</u> % increase / decrease	<u>0</u> % increase / decrease	<u>10</u> % increase / decrease
6ms ⁻¹	<u>20</u> % increase / decrease	<u>30</u> % increase / decrease	<u>40</u> % increase / decrease
10ms ⁻¹	<u>20</u> % increase / decrease	<u>40</u> % increase / decrease	<u>60</u> % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>10</u> % increase / decrease	<u>0</u> % increase / decrease	<u>10</u> % increase / decrease
4ms ⁻¹	<u>0</u> % increase / decrease	<u>10</u> % increase / decrease	<u>20</u> % increase / decrease

Figure C.23 – Copy of the original pool fire estimate sheet from 'Expert 1'

Velocity	(i) Square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>30</u> % increase / decrease	<u>70</u> % increase / decrease	<u>120</u> % increase / decrease
4ms ⁻¹	<u>70</u> % increase / decrease	<u>100</u> % increase / decrease	<u>150</u> % increase / decrease
6ms ⁻¹	<u>0</u> % increase / decrease	<u>70</u> % increase / decrease	<u>120</u> % increase / decrease
10ms ⁻¹	<u>100</u> % increase / decrease	<u>50</u> % increase / decrease	<u>20</u> % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>20</u> % increase / decrease	<u>0</u> % increase / decrease	<u>50</u> % increase / decrease
4ms ⁻¹	<u>0</u> % increase / decrease	<u>20</u> % increase / decrease	<u>50</u> % increase / decrease
6ms ⁻¹	<u>20</u> % increase / decrease	<u>80</u> % increase / decrease	<u>100</u> % increase / decrease
10ms ⁻¹	<u>80</u> % increase / decrease	<u>100</u> % increase / decrease	<u>100</u> % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	<u>70</u> % increase / decrease	<u>100</u> % increase / decrease	<u>170</u> % increase / decrease
4ms ⁻¹	<u>100</u> % increase / decrease	<u>150</u> % increase / decrease	<u>200</u> % increase / decrease
6ms ⁻¹	<u>50</u> % increase / decrease	<u>100</u> % increase / decrease	<u>150</u> % increase / decrease
10ms ⁻¹	<u>0</u> % increase / decrease	<u>100</u> % increase / decrease	<u>100</u> % increase / decrease

Figure C.24 – Copy of the original pool fire estimate sheet from ‘Expert 2’

Velocity	(i) Square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	30 % increase / decrease	10 % increase / decrease	20 % increase / decrease
4ms ⁻¹	35 % increase / decrease	20 % increase / decrease	10 % increase / decrease
6ms ⁻¹	40 % increase / decrease	25 % increase / decrease	10 % increase / decrease
10ms ⁻¹	50 % increase / decrease	30 % increase / decrease	10 % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	35 % increase / decrease	10 % increase / decrease	20 % increase / decrease
4ms ⁻¹	40 % increase / decrease	25 % increase / decrease	20 % increase / decrease
6ms ⁻¹	50 % increase / decrease	30 % increase / decrease	10 % increase / decrease
10ms ⁻¹	60 % increase / decrease	40 % increase / decrease	10 % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	25 % increase / decrease	5 % increase / decrease	20 % increase / decrease
4ms ⁻¹	30 % increase / decrease	10 % increase / decrease	20 % increase / decrease
6ms ⁻¹	35 % increase / decrease	15 % increase / decrease	10 % increase / decrease
10ms ⁻¹	40 % increase / decrease	20 % increase / decrease	10 % increase / decrease

Figure C.25 – Copy of the original pool fire estimate sheet from 'Expert 3'

Velocity	(i) Square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	7 % increase / decrease #	2 % increase / decrease	5 % increase / decrease
4ms ⁻¹	9 % increase / decrease	4 % increase / decrease	5 % increase / decrease
6ms ⁻¹	11 % increase / decrease	6 % increase / decrease	5 % increase / decrease
10ms ⁻¹	15 % increase / decrease	10 % increase / decrease	5 % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	10 % increase / decrease	0 % increase / decrease	10 % increase / decrease
4ms ⁻¹	10 % increase / decrease	0 % increase / decrease	10 % increase / decrease
6ms ⁻¹	10 % increase / decrease	0 % increase / decrease	10 % increase / decrease
10ms ⁻¹	10 % increase / decrease	0 % increase / decrease	10 % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	50 % increase / decrease	100 % increase / decrease	150 % increase / decrease
4ms ⁻¹	200 % increase / decrease	300 % increase / decrease	400 % increase / decrease
6ms ⁻¹	300 % increase / decrease	500 % increase / decrease	700 % increase / decrease
10ms ⁻¹	600 % increase / decrease	900 % increase / decrease	1200 % increase / decrease

Figure C.26 – Copy of the original pool fire estimate sheet from ‘Expert 4’

Velocity	(i) Square pool (~25m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	5 % increase / decrease	20 % increase / decrease	60 % increase / decrease
4ms ⁻¹	10 % increase / decrease	33 % increase / decrease	60 % increase / decrease
6ms ⁻¹	20 % increase / decrease	45 % increase / decrease	150 % increase / decrease
10ms ⁻¹	40 % increase / decrease	60 % increase / decrease	200 % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	10 % increase / decrease	20 % increase / decrease	30 % increase / decrease
4ms ⁻¹	20 % increase / decrease	35 % increase / decrease	90 % increase / decrease
6ms ⁻¹	25 % increase / decrease	50 % increase / decrease	175 % increase / decrease
10ms ⁻¹	40 % increase / decrease	40 % increase / decrease	220 % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in HRR	Mean change in HRR	Maximum change in HRR
2ms ⁻¹	10 % increase / decrease	25 % increase / decrease	20 % increase / decrease
4ms ⁻¹	20 % increase / decrease	40 % increase / decrease	100 % increase / decrease
6ms ⁻¹	30 % increase / decrease	50 % increase / decrease	200 % increase / decrease
10ms ⁻¹	50 % increase / decrease	100 % increase / decrease	250 % increase / decrease

Figure C.27 – Copy of the original pool fire estimate sheet from 'Expert 5'

Velocity	(i) Square pool (~25m ²)		
	Minimum change in IRR	Mean change in IRR	Maximum change in IRR
2ms ⁻¹	0 % increase / decrease	2 % increase / decrease	5 % increase / decrease
4ms ⁻¹	0 % increase / decrease	2 % increase / decrease	4 % increase / decrease
6ms ⁻¹	0 % increase / decrease	5 % increase / decrease	10 % increase / decrease
10ms ⁻¹	0 % increase / decrease	10 % increase / decrease	20 % increase / decrease

Velocity	(ii) Small rectangular pool (~10m ²)		
	Minimum change in IRR	Mean change in IRR	Maximum change in IRR
2ms ⁻¹	0 % increase / decrease	2 % increase / decrease	5 % increase / decrease
4ms ⁻¹	0 % increase / decrease	2 % increase / decrease	4 % increase / decrease
6ms ⁻¹	0 % increase / decrease	5 % increase / decrease	10 % increase / decrease
10ms ⁻¹	0 % increase / decrease	10 % increase / decrease	20 % increase / decrease

Velocity	(iii) Large rectangular pool (~100m ²)		
	Minimum change in IRR	Mean change in IRR	Maximum change in IRR
2ms ⁻¹	0 % increase / decrease	5 % increase / decrease	10 % increase / decrease
4ms ⁻¹	0 % increase / decrease	10 % increase / decrease	15 % increase / decrease
6ms ⁻¹	5 % increase / decrease	15 % increase / decrease	20 % increase / decrease
10ms ⁻¹	5 % increase / decrease	15 % increase / decrease	20 % increase / decrease

Figure C.28 – Copy of the original pool fire estimate sheet from 'Expert 6'






Case:		3a	3b	3c	3d	3e											
Area:		10m ²	25m ²	40m ²	50m ²	80m ²											
Lanes:		One	One	One	Two	Three											
Tunnel:																	
Please enter HRR values (in MW) and time (in minutes) for:		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
"Mini" car	HRR	Natural vent.	5	6	7	4	5	6	4	5	6	4	5	6	4	5	6
		Forced at 1.5ms ⁻¹	5	6	7	4	5	6	4	5	6	4	5	6	4	5	6
	Time	Natural vent.	8	10	12	8	10	12	8	10	12	10	12	14	10	12	14
		Forced at 1.5ms ⁻¹	8	10	12	8	10	12	8	10	12	10	12	14	10	12	14
"Family" car	HRR	Natural vent.	6	8	10	6	7.5	9	6	7.5	9	6	7.5	9	6	7.5	9
		Forced at 1.5ms ⁻¹	6	8	10	6	7.5	9	6	7.5	9	6	7.5	9	6	7.5	9
	Time	Natural vent.	10	15	20	10	15	20	10	15	20	12	18	24	12	18	24
		Forced at 1.5ms ⁻¹	10	15	20	10	15	20	10	15	20	12	18	24	12	18	24

Figure C.29 – Copy of the original car fire estimate sheet from 'Expert 1'





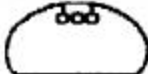
Case:		3a			3b			3c			3d			3e			
Area:		10m ²			25m ²			40m ²			50m ²			80m ²			
Lanes:		One			One			One			Two			Three			
Tunnel:																	
Please enter HRR values (in MW) and time (in minutes) for:		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
"Mini" car	HRR	Natural vent.	10	18	25	10	15	20	10	15	20	10	15	20	10	15	20
		Forced at 1.5ms ⁻¹	10	20	25	10	20	25	10	20	25	10	20	25	10	20	25
	Time	Natural vent.	5	10	12	5	10	12	5	10	12	5	10	12	5	10	12
		Forced at 1.5ms ⁻¹	3	5	10	3	5	10	3	5	10	3	5	10	3	5	10
"Family" car	HRR	Natural vent.	20	28	30	20	25	30	20	25	30	20	25	30	20	25	30
		Forced at 1.5ms ⁻¹	20	30	35	20	30	35	20	30	35	20	30	35	20	30	35
	Time	Natural vent.	4	10	12	4	10	12	4	10	12	4	10	12	4	10	12
		Forced at 1.5ms ⁻¹	3	6	10	3	6	10	3	6	10	3	6	10	3	6	10

Figure C.30 – Copy of the original car fire estimate sheet from 'Expert 2'






Case:		3a	3b	3c	3d	3e								
Area:		10m ²	25m ²	40m ²	50m ²	80m ²								
Lanes:		One	One	One	Two	Three								
Tunnel:														
Please enter HRR values (in MW) and time (in minutes) for:		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
"Mini" car	HRR	Natural vent.	2 ⁵	4 ⁵	6	2	4	5	2	4	5	2	4	5
		Forced at 1.5ms ⁻¹	3 _{Min}	5 _{Mean}	8 _{Max}	2	4	5	2	4	5	2	4	5
	Time	Natural vent.	3 _{min}	5 _{min}	10 _{min}	4	6	12	→					
		Forced at 1.5ms ⁻¹	2 _{min}	4 _{min}	6 _{min}	4	6	12	as for 3b.					
"family" car	HRR	Natural vent.	3 _{Min}	5 _{Mean}	8 _{Max}	2.5	4.5	7	→					
		Forced at 1.5ms ⁻¹	4 _{Min}	6 _{Mean}	10 _{Max}	2.5	4.5	7	as for 3b.					
	Time	Natural vent.	3 _{min}	5 _{min}	10 _{min}	4	6	12	→					
		Forced at 1.5ms ⁻¹	2 _{min}	4 _{min}	6 _{min}	4	6	12	→					

Figure C.31 – Copy of the original car fire estimate sheet from 'Expert 3'






Case:		3a			3b			3c			3d			3e			
Area:		10m ²			25m ²			40m ²			50m ²			80m ²			
Lanes:		One			One			One			Two			Three			
Tunnel:																	
Please enter HRR values (in MW) and time (in minutes) for:		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
"Mini" car	HRR	Natural vent.	6	8	11	5	7	10	5	6.5	10	4	6	10	4	5.7	9
		Forced 1.5ms ⁻¹ at	10	32	65	9	27	60	8	25	55	7	23	50	6	20	45
	Time	Natural vent.	4	10	20	4	13	20	5	15	20	5	15	20	5	15	20
		Forced 1.5ms ⁻¹ at	4	7	15	5	9	15	5	10	15	5	10	15	5	10	15
"Family" car	HRR	Natural vent.	7	9	12	6	8	11	6	7.5	11	5	7	11	5	6.7	10
		Forced 1.5ms ⁻¹ at	20	45	96	18	40	86	16	36	76	14	32	67	12	28	58
	Time	Natural vent.	3	11	20	4	14	22	6	16	24	6	16	24	6	16	24
		Forced 1.5ms ⁻¹ at	2	8	15	2	10	16	3	11	16	3	11	16	3	11	16

Figure C.32 – Copy of the original car fire estimate sheet from 'Expert 4'

Case:		3a	3b	3c	3d	3e								
Area:		10m ²	25m ²	40m ²	50m ²	80m ²								
Lanes:		One	One	One	Two	Three								
Tunnel:														
Please enter HRR values (in MW) and time (in minutes) for		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
"normal" car	HRR	Natural vent.	1/2	3 1/2	7	1	3	6	1	3	6	1	3	6
		Forced at 1.5ms ⁻¹	2	4	8	1 1/2	3 1/2	7	1 1/2	3 1/2	7	1 1/2	3 1/2	7
	Time	Natural vent.	8	12	15	8	12	15	8	12	15	8	12	15
		Forced at 1.5ms ⁻¹	4	7	12	4	8	12	4	8	12	7	8	12
"family" car	HRR	Natural vent.	2	5	8	1 1/2	4	8	1 1/2	4	8	1 1/2	4	8
		Forced at 1.5ms ⁻¹	3	5	10	2 1/2	4	8	2 1/2	4	8	2 1/2	4	8
	Time	Natural vent.	8	12	15	8	12	15	8	12	15	8	12	15
		Forced at 1.5ms ⁻¹	4	7	12	4	8	12	4	8	12	4	8	12

Figure C.33 – Copy of the original car fire estimate sheet from 'Expert 5'






Case:		3a	3b	3c	3d	3e											
Area:		10m ²	25m ²	40m ²	50m ²	80m ²											
Lanes:		One	One	One	Two	Three											
Tunnel:																	
Please enter HRR values (in MW) and time (in minutes) for:		Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
Mini car	HRR	Natural vent.	7	3	4	1	3	4	1	2	4	1	2	4	1	2	4
		Forced at 1.5ms ⁻¹	1	2	5	1	2	5	1	2	5	1	2	5	1	2	5
	Time	Natural vent.	5	10	15	5	10	15	5	10	15	5	10	15	5	10	20
		Forced at 1.5ms ⁻¹	5	10	15	5	10	15	5	10	15	5	10	15	5	10	15
Family car	HRR	Natural vent.	7	4	5	1	4	5	1	4	5	1	3	4	1	3	4
		Forced at 1.5ms ⁻¹	1	5	6	1	5	6	1	5	6	1	4	5	1	4	5
	Time	Natural vent.	5	15	20	5	15	20	5	15	20	10	20	30	10	20	30
		Forced at 1.5ms ⁻¹	5	10	20	5	10	20	5	10	20	5	15	30	5	15	30

Figure C.34 – Copy of the original car fire estimate sheet from ‘Expert 6’

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