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CABIN WATER SPRAYS FOR FIRE SUPPRESSION: AN EXPERIMENTAL EVALUATION

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EXECUTIVE SUMMARY

This report describes the results of a series of experiments to investigate the effectiveness of on-board low volume water sprays in reducing the risk to passengers in an aircraft cabin exposed to a severe external fire.

The risk to passengers arises from exposure to the effects of fire, including radiated and convected heat, toxic and irritant gases and particulates and reduced visibility due to smoke. These may cause harm directly or, indirectly, by impeding escape and increasing the probability of exposure to other effects. The nature of these effects and the manner in which they may combine to cause varying degrees of incapacitation have been examined and criteria set for the tenability of the cabin atmosphere.

A number of preliminary experiments were undertaken to isolate and examine some of these mechanisms under laboratory conditions. The results of these indicated that fine water sprays could substantially reduce thermal radiation and that, as expected from theoretical considerations, performance increased with smaller diameter droplets and increased flow rate.

The principal experimental programme consisted of a series of full-scale tests undertaken using a Boeing 707 fuselage. A severe fire scenario was chosen, representing an external 12 MW fuel fire adjacent to an opening in a fuselage resting directly on the ground. Without water spray, survival time was less than 2.5 minutes. Based upon observation of the fire development in the cabin, the measured levels of fire products and the degree of damage to furnishings and fittings, the primary effect of water sprays was found to be to reduce fire penetration into the cabin and to inhibit fire spread in the cabin contents.

Life threat analysis, based solely on the measured levels of toxic components showed, in all cases, the use of water sprays increased the time for incapacitation of standing passengers, some 8 metres from the fire, by about 4 minutes. However, when the effect of air temperature, including the maximum potential latent heat content of fully saturated air, was included, this improvement was reduced to 1.7 minutes for the fully sprayed cabin and to 0.7 minutes for reduced flow rate, zoned spray. These levels were improved to 3 and 1.5 minutes respectively at crouching height. When a full flow rate zoned spray was used no degradation in the extension of survival time occurred when air temperature was considered.

The use of water sprays considerably reduced the amount of solid particles and liquid droplets capable of penetrating the lungs, and also the irritants attached to them, thereby reducing the risk of lung damage. However, there was little effect on visibility by smoke removal, when the full cabin was sprayed the water spray tended to pull down the developing hot smoke layer in the cabin reducing visibility at lower levels earlier than in the unsprayed case. When the spray was restricted to the zone near the fire the smoke quickly re-established a buoyant layer, the effect of this combined with the reduced burning rate was for visibility to be improved in the full flow rate zoned test.

Overall, the most effective spray arrangements of those tested was found to be the zoned spray, with nozzles delivering water at a rate of 1 litre per minute per square metre of floor area and with mean droplet diameter (measured as Sauter mean diameter) of about 250 μm.

TABLE OF CONTENTS

1. INTRODUCTION

Passenger survival following post-crash aircraft fires depends to a large extent upon the time available for escape before the conditions in the passenger cabin become untenable. The work described in this report was designed to investigate the effect of fine water spray on the development of fire atmospheres in an aircraft cabin and the implications for increasing survivability.

Studies carried out on a VC10 fuselage and later on a Trident II gave preliminary evidence that a spray system, developed by Safety (Aircraft & Vehicles) Equipment Ltd (SAVE) could maintain viable conditions within the passenger cabin to allow passengers to evacuate the aircraft using openings away from the fire. The work described in this report was commissioned by the Civil Aviation Authority (CAA) to investigate the possibility of optimising the spray system and to carry out full-scale tests on selected systems, under controlled conditions, using a narrow body aircraft fuselage. Concurrently the Federal Aviation Administration has carried out similar full-scale trials of systems using narrow and wide body aircraft fuselages.

2. BACKGROUND

An analysis of survivable passenger aircraft accidents (Reference 1) indicates that the proportion of passengers killed by post-crash fire is broadly similar to those killed as a result of impact. Appropriate means of reducing the incidence of post-crash fires or limiting their effects to enable escape or rescue to take place are, therefore, to be welcomed.

Following the fire involving a Boeing 737 at Manchester Airport in 1985 (Reference 2), which involved multiple deaths and injuries to passengers, the CAA supported the development of onboard water spray systems, initially by trials using a VC10 fuselage (Reference 3) and subsequently with more detailed tests involving a Trident II fuselage (Reference 4). While the latter tests were not conclusive, they indicated that a spray system, developed by SAVE, could maintain survivable conditions within the passenger cabin, in the presence of a substantial external fuel fire, for a sufficiently long period to allow passengers to escape from the aircraft.

There are a number of possible ways in which onboard water sprays can reduce the impact of a fire, the principal of which are:

(a) Restriction or prevention of the development of fire within the cabin either by suppression or by prewetting of cabin contents.

(b) Reduction in temperature of the fire gases and attenuation of thermal radiation.

(c) Removal of toxic components from fire gases entering or generated within the cabin.

(d) Removal of smoke and particulates from the fire gases, improving visibility and reducing the inhalation of toxic components adsorbed to particulates.

While there were indications from the Trident II studies that many of these factors were in operation, it was not possible to demonstrate this conclusively because the experiments were not undertaken under controlled conditions and the effects of sprays could not readily by isolated from other effects, such as burn-through of the cabin roof and, since the tests took place in the outside air, the effects of wind.

The aims of the present investigation were, therefore, to obtain information on the following points:

(a) The extent to which the application of water spray to the fire reduces the overall concentration of the toxic gases carbon monoxide (CO), and carbon dioxide (CO_2) and maintains oxygen oxygen (O_2) level by impeding the rate of fire development.

(b) The extent to which the application of water spray to the fire reduces the overall concentration of smoke particulate in the cabin atmosphere;

  (i) by impeding the rate of fire development, particularly by inhibiting combustion of cabin furnishings, or

  (ii) by washing smoke particulate out of the fire atmosphere in the cabin.

(c) The extent to which the application of spray reduces the concentration of water soluble acid gases (particularly hydrogen chloride (HCl) and hydrogen cyanide (HCN)) in the smoke by either impeding the fire or washing the smoke.

(d) The extent to which the use of a fine spray creates water droplets of a size range capable of being inhaled by persons in the aircraft cabin. Also, if such a droplet spray is created, whether it includes droplets of a size likely to be deposited in the upper respiratory tract (mouth, nose and large airways) or lower respiratory tract (small airways and alveoli).

(e) The extent to which water droplets, if created, pick up significant concentrations of acid gases from the smoke, and whether they are therefore likely to present a greater inhalation hazard than the original smoke atmosphere created when no spray is used.

(f) The radiant heat flux, air temperature and humidity conditions in the cabin beneath the smoke layer during water spray application, and the effect that water spray application may have on heat stress hazard for persons in the cabin.

(g) The effect that the use of the spray has on the optical density of the atmosphere in the cabin.

This information provides the basis for making a formal assessment of the effect of water spray on the survivability of aircraft cabin fires and for comparing the performance of different systems. However, the evaluation of the fire atmosphere in terms of the above parameters presents a considerable technical challenge. The flows generated within an aircraft cabin in the presence of fire products and water sprays are necessarily transient and multiphase involving complex, simultaneous heat transfer, mass transfer and chemical processes and as such are not open to any but the most simplistic theoretical treatment. For this reason the present study has concentrated on a controlled experimental approach.

3. PHYSIOLOGICAL EFFECTS OF EXPOSURE TO FIRE ATMOSPHERES

3.1 Introduction

Exposure to heat and toxic smoke in fires results in a number of physiological effects causing varying degrees of incapacitation and ultimately leading to death (Reference 5). Incapacitating effects include:

(a) Impaired vision resulting from the optical opacity of smoke and from the painful effects of irritant smoke products and heat on the eyes.

(b) Respiratory tract pain and breathing difficulties or even respiratory tract burns resulting from the inhalation of irritant smoke which may be very hot. (This may lead to lung inflammation, usually after some hours).

(c) Narcosis from the inhalation of toxic gases resulting in confusion and loss of consciousness.

(d) Pain to exposed skin and the upper respiratory tract followed by burns, or hyperthermia due to the effects of heat.

All of these effects except the first can be fatal if the degree of exposure is sufficient. Although it is important to determine the time in a fire when a victim will have received a lethal exposure, it is more important to determine incapacitating effects which might inhibit or prevent escape, since survival depends upon the ability to escape.

Up to a certain level of severity, the hazards listed above cause partial incapacitation, by reducing the efficiency and speed of escape. These effects lie on a continuum from little or no effect at low levels to relatively severe incapacitation at high levels, with a variable response from different individuals. In evaluating the situation of a rapidly growing cabin fire, with the need to evacuate a planeload of passengers within a few minutes, it is important to make some estimate of effects which are likely to delay escape, which may result in fewer passengers being able to escape during the short time before conditions become untenable. Most important in this context is exposure to optically dense and irritant smoke, which tends to be the first hazard confronting fire victims. Although it is currently not possible to quantify how exposure to irritant smoke affects escape behaviour as smoke density increases, attempts have been made in this report to identify when it is considered that conditions may be bad enough to have some effect on escape speed or efficiency.

At the upper end of the intensity scale a point may be reached where incapacitation is predicted to be sufficiently severe to prevent escape. For some forms of incapacitation, such as narcosis which leads to a rapid change from near normality to loss of consciousness, this point is relatively easy to define. For other effects an endpoint is less easily defined; for example the point at which smoke becomes so irritant that pain and breathing difficulties lead to the cessation of effective escape attempts, or the point where pain and burns prevent movement. Nevertheless it is considered important to attempt some estimate of the point where conditions become so severe in terms of these hazards that effective escape attempts are likely to cease and where occupants are likely to suffer severe incapacitation or injuries.

For the assessments of the survivability of aircraft cabin fires presented in this report the main criterion has been the time to a point when incapacitation is predicted to be sufficient to cause serious impairment of escape capability or when injuries are likely to have been sustained capable of threatening survival following escape or rescue. In addition, comments have been made on points in time during the fires when it is considered that conditions may be such as to delay escape attempts.

3.2 Evaluation of the Effects of Visual Obscuration

It is common to assess the level of visual obscuration due to smoke by measuring the attenuation of a light beam, traversing the area of interest, measured by a suitable detector. Based upon assumptions that the Beer-Lambert Law applies, opacity can be expressed in terms of Optical Density/metre, defined as follows:

$$OD/m = \mathrm{Log}_{10}\,(I_o/I)/L \qquad (1)$$

where, I_o and I are, respectively, the detector output in the absence of smoke and with smoke present. L is the path length between source and detector.

A tenability limit for simple visual obscuration by smoke has been set at an OD/m of 0.5, on the basis that obscuration at this level is likely to slow or impede escape attempts.

In relation to evacuation of an aircraft cabin the important parameter is visibility. While this will depend upon factors other than opacity it is common to take visibility (in metres) as the reciprocal of the magnitude of the optical density/metre where light is reflected from the object viewed. However, where illuminated signs are present visibility can be substantially extended. Mulholland (Reference 6), writing in the SFPE Handbook, suggests a factor of 2.7, based upon the work of Jin (Reference 7). While some aspects of Jin's work are open to debate (Reference 8), the general principle of improved visibility of an illuminated sign as opposed to a sign lit by reflected light is agreed and for present purposes the ratio quoted by Mulholland will be used.

3.3 Evaluation of the Effects of Irritants

Smoke irritants consist of inorganic gases (such as hydrogen chloride) and a variety of organic compounds, particularly low molecular weight aldehydes (such as formaldehyde and acrolein). More than twenty irritant substances have been detected in smoke and it is considered that others remain to be identified (Reference 9). As opposed to narcotic gases, which have little effect until a well-defined endpoint (loss of consciousness) occurs, the incapacitating effects of irritants are more varied and difficult to quantify.

The first effect of exposure to smoke irritants is sensory irritation. This consists of painful stimulation of the eyes, nose, throat and lungs. Sensory irritation causes a degree of incapacitation as it is likely to impede escape attempts due to effects on vision and breathing and also contributes to narcosis by causing static hypoxia.

Sensory irritation depends upon the immediate concentration of irritants to which the subject is exposed rather than a dose acquired over a period of time, the effects lying on a continuum from mild eye irritation to severe eye and respiratory tract pain. In evaluating this aspect of irritancy, the aim is to predict what concentration of mixed irritant products is likely to cause such pain and difficulty in breathing that escape attempts would be seriously disrupted or escape might be prevented, a degree of incapacitation approximately equivalent to that at the point of collapse resulting from exposure to narcotic gases. In addition it is likely that somewhat lower exposure concentrations of sensory irritants, in conjunction with visual obscuration by smoke, would produce a degree of incapacitation by slowing or partially impeding escape attempts.

The other important effect of irritants is that a proportion of those inhaled penetrate into the deep lung. If a sufficient dose is inhaled for long enough this may cause respiratory failure and death, usually some hours after exposure, or permanent lung damage in survivors.

Smoke irritants may be present partly as vapour and partly adsorbed on solid or liquid particles in the smoke. The form in which they occur may affect the toxicity. A highly water-soluble gas such as hydrogen chloride tends to dissolve in the aqueous fluids lining the upper respiratory tract, so that the degree of penetration into the lung may be small and upper respiratory tract (sensory) irritation is a major effect. A less soluble gas such as nitrogen dioxide is better able to penetrate the lung, so that lung inflammation is the major effect.

If hydrogen chloride, instead of being present in the vapour phase, is attached to smoke particles small enough to penetrate into the deep lung, or becomes dissolved in small water droplets condensing in the smoke (or small water droplets from the extinguishing spray) then it is more easily able to penetrate into the lung and cause lung inflammation. Alternatively, if the acid gases and/or smoke particles become adsorbed by larger (greater than 5 µm diameter) water droplets from the spray, then they will impact in the upper respiratory tract or, if large enough, will not be inhaled at all, thereby protecting the lung from damage that would have otherwise occurred.

In general, particles of a diameter less than approximately 5 µm will penetrate into the lung, while particles between 5 µm and approximately 15 µm diameter will deposit in the upper respiratory tract (nose, mouth and throat). However, patterns of deposition in the human respiratory tract are complex and it is considered that people breathing fairly deeply by mouth, as is likely in an emergency situation, may suffer penetration of somewhat larger particles. As Figure 1 shows it is possible that some large particles may deposit in the mouth, although it is unlikely that particles greater than 10 µm diameter will penetrate significantly into the smaller airways or deep lung.

For these reasons, it is important to measure concentrations of irritants and the extent to which they are attached to particles and water droplets of various sizes in the smoke and spray.

3.4 Time to Incapacitation Due to the Effects of Narcotic Gases

Narcotic gases (carbon monoxide, hydrogen cyanide, carbon dioxide and reduced oxygen) affect the nervous and cardiovascular systems, causing confusion followed by loss of consciousness and ultimately death from asphyxiation.

As narcotic gases are inhaled during a fire, an increasing dose builds up in the body. There is little effect initially, but when a critical threshold dose level is reached severe effects occur suddenly. These consist of a brief period of intoxication (similar to severe alcohol intoxication), followed by a collapse into unconsciousness. Time to incapacitation from the effects of narcotic gases is regarded as the time to the point where loss of consciousness is predicted. An unconscious victim continues to inhale narcotic gases until death occurs at a dose level approximately twice that causing incapacitation.

Time to incapacitation (loss of consciousness) in a fire occurs when a critical dose of narcotic gases has been inhaled. This is a function of the concentrations of narcotic gases and the time for which they have been inhaled.

If the concentration/time profiles in the fire of the major narcotic gases are measured, then it is possible to calculate the dose presented to an occupant of the cabin during the fire. In practice, the dose inhaled each minute during the fire is expressed as a fraction of the dose required to cause incapacitation. These Fractional Effective Doses (FEDs) are summed throughout the duration of the fire until the total FED reaches unity when incapacitation is predicted to occur.

An algorithm has been developed by Purser (Reference 6) for calculating the FEDs for each narcotic gas and the interactions between them, according to the formula:

$$FED_{IN} = [(FED_{ICO} + FED_{ICN}) \times VCO_2 + FED_{IO}] \qquad (2)$$

or $FED_{IN} = FED_{ICO2}$, whichever is the greater.

Where:

FED_{IN} = fraction of an incapacitating dose of all narcotic gases

FED_{ICO} = fraction of an incapacitating dose of carbon monoxide

FED_{ICN} = fraction of an incapacitating dose of hydrogen cyanide

VCO_2 = multiplication factor for carbon dioxide induced hyperventilation

FED_{ICO2} = fraction of incapacitating dose of carbon dioxide.

Expressions for various fractions are presented in Reference (9).

3.5 Evaluation of the Effects of Exposure to Heat

The main sources of heat exposure in fires are radiant heat from the fire and hot objects and convected heat from contact with hot smoke. In the case of a sprayed fire there may also be a significant source of heat exposure by conduction from the contact of exposed skin with heated spray droplets. Exposures to high radiant heat fluxes, high air temperatures or hot water cause skin pain and burns. The point of incapacitation is taken as that when a subject would be expected to experience severe pain to unprotected areas of skin (such as the face and hands), since this is closely followed by burns and it is considered that such conditions would inhibit escape. The effects of heat exposure have been reviewed by Purser (Reference 9), where tenability limits and methods for calculating time to incapacitation are presented.

As shown in Figure 2(a), which is derived from several literature sources, there is a fairly obvious intensity limit for tolerance to radiant heat at 2.5 kW/m^2. Below this intensity radiant heat can be tolerated for at least several minutes, but above this intensity for a few seconds only. The point of incapacitation is therefore taken as the time when 2.5 kW/m^2 is exceeded.

Figure 2(b) also shows the tolerance time for convected heat, also derived from a number of literature sources. At air temperatures above approximately 120°C tolerance is limited by skin pain and burns, while at lower temperatures tolerance time is limited by hyperthermia. Hyperthermia results in confusion followed by loss of consciousness and death when the body core temperature reaches 42.5°C. Since the tolerance time takes the form of an exponential curve, it is feasible to consider a victim as taking up a 'dose' of convected heat, much as the dose of a toxic product would be taken up. It is, therefore, possible to use the FED concept of a fractional incapacitating dose of heat acquired each minute and, from these data, an expression has been developed for time to incapacitation which is presented in reference (6). However, while it is considered that the curve shown in Figure 2 provides a reasonable basis for calculating tolerance times for dry air, problems arise for high temperature air with a high water vapour content. There are two considerations with regard to water vapour content. One, of relatively minor concern in the context of short duration aircraft cabin fires, is the effect of high humidity on evaporative cooling. The more major concern is that air, even at the relatively low temperature of 60°C, has a high capacity for water vapour (saturated vapour pressure 199 mbar) and, when this air is inhaled and cooled to body temperature, 37°C (saturated vapour pressure 62.8 mbar), the condensation of this water will release considerable amounts of latent heat which may cause burns to the respiratory tract or the skin.

At moderately elevated temperatures, a high humidity will decrease time to hyperthermia. The curves in Figure 2 make some allowance for this in that, for temperatures below 100°C, tolerance curves for dry and 'humid' air are presented. A difficulty is that the relative humidity under which this tolerance curve was derived is unknown. The effects of hot, fully-saturated, air have been tested on human subjects in experiments related to the use of certain types of closed-circuit breathing apparatus. In these experiments, subjects at room temperature were able to tolerate breathing saturated air at up to 50°C for up to one hour at moderate work loads (Reference 10). In earlier work Killick (Reference 11) found that saturated air, up to 53°C, would be tolerated at work and up to 59°C at rest in cool environments.

On this basis it is considered that fully saturated air at temperatures up to 60°C could be tolerated during aircraft cabin fires. The effects of breathing saturated air at higher temperatures are unknown but it is likely that skin and respiratory tract burns would occur. Table 1 shows the approximate heat delivery to the lung from breathing dry air at 200°C (which can be tolerated for from one to a few minutes), with the heat delivery of saturated air at various temperatures. Since inhaled air equilibrates rapidly in terms of temperature and water content within the lung, it should be reasonable to assume that all available heat is deposited in the lung. On this basis it is possible to compare the potential heat deliveries of saturated air at different temperatures to the lung. This consists of two components - sensible heat, resulting from the cooling of the air alone and latent heat resulting from the condensation of water vapour. For the purposes of calculation a moderate resting ventilation rate (Respiratory Minute Volume - RMV) of 10 l/minute was assumed and, further, that the exhaled air was at 37°C and saturated. On this basis the heat delivery (22 W) of saturated air at as low a temperature as 50°C would be greater than that (13 W) of dry air at 200°C. As shown in Table 1, the heat delivery more than doubles for each 10°C rise in the temperature of saturated air. It is likely that both skin and respiratory burns could occur at high temperatures if there is a high degree of saturation. There might also be the possibility of skin pain and burns from contact with hot water spray droplets if the water temperature and rate of delivery to the skin were high enough. It is thus important to control not only the sensible heat content of the cabin atmosphere but the latent heat content also.

4. PRELIMINARY STUDIES

4.1 Introduction

As discussed in Section 2, prima facie evidence from earlier trials (References 3 and 4) indicated that the possible actions of water sprays, to extend the period of time for which the conditions within an aircraft cabin may be kept survivable, included the following:

(a) Attenuation of thermal radiation.

(b) Removal of toxic and irritant components of the fire gases.

(c) Removal of particulates and smoke.

(d) Reduction in temperature of the fire gases.

The interaction of a spray with the flow of combustion products is complex and not well understood. The problem is not yet susceptible to detailed theoretical analysis except for relatively simple cases.

However, in an attempt to examine these mechanisms and, if possible, to provide a basis for optimising spray characteristics to give the most favourable results a number of preliminary, empirical studies were undertaken. Since the physical processes involved to not allow scaling these were undertaken at full-scale but were designed to isolate possible actions of water sprays on fire gases and to examine each in more detail.

Appendix A outlines some of the characteristics of water sprays. These are principally,

(a) droplet size distribution, and

(b) volume flow rate.

In view of the previous development work, the SAVE nozzle was taken as the starting point and three other nozzle types were also considered. These included two disc and core type sprays, giving a medium and coarse droplet size distribution and a 'fogjet' spray giving a fine distribution. Characterising the spray produced by a nozzle in detail is a time-consuming process since, even at a given point in the flow field, droplet size is not constant but has to be described in terms of a statistical distribution. Further this distribution varies from one point in the flow field to another as droplets break up or coalesce. To describe the spray completely the spray field from a nozzle would involve measurement at a large number of points in the spray field. Further, as noted in Appendix A, although a number of techniques are available for measuring size distribution these do not give consistent results. For present purposes, four types of spray nozzle, designated as Types A, B, C and D in Table 2, have been characterised by the Sauter Mean Diameter, measured at a point 0.15 m below the nozzle, using a method based upon a helium/neon laser system, described briefly in Appendix A. Nozzle flow rates were measured separately and are also included in Table 2.

Three separate studies were carried out:

(a) An investigation of the effect of nozzle type and operating pressure on the ability of the resulting spray to attenuate thermal radiation from high temperature source.

(b) An investigation under static conditions, using a closed chamber, of the ability of a Type A (SAVE) water spray to improve visibility by removing smoke particles and to confirm the expected effects on the concentration of two key fire gases hydrogen chloride and, with use of additives, carbon monoxide.

(c) An investigation, under repeatable conditions, of the interaction of a spray field arising from different arrangements of spray heads and different nozzle types, with a moving layer of fire gases.

The results of these studies are summarised in the following sections. A fuller account of the work is given in Reference 12.

4.2 Water Spray Performance - Radiation Attenuation

4.2.1 Introduction

Water sprays are commonly used as a method of protection against thermal radiation by fire-fighters. However, for this purpose very large volume flow rates of water are generally required. Evidence from previous aircraft cabin water spray trials (Reference 4) indicated that the spray provided protection from radiation. It was not, however, clear whether this was due to attenuation of the radiation by the airborne spray or cooling of the exposed test surfaces by incident droplets. In order to investigate the ability of the four types of nozzle listed in Table 2 to attenuate radiation, a series of measurements was undertaken using a gas-fired radiant panel as a source and the results of these experiments are described here.

4.2.2 Experimental arrangement

4.2.2.1 Test apparatus

A 1 m x 1 m gas-fired radiant panel was mounted vertically, with its centre at a height of 1.35 m. A radiometer was mounted facing the panel at a distance of 3 m and on a line perpendicular to the centre of the panel. The output from the radiometer was recorded on a potentiometric chart recorder.

A 15 mm diameter spray boom was mounted at a height of 2.25 m, perpendicular to the line joining the panel and the radiometer at a distance of 2 m from the panel. The general layout is shown in Figure 3. The spray boom was equipped with three nozzle mounting points, separated by 0.5 m. The radiometer and the nozzles were located so as not to allow interaction of the spray with either the radiometer surface or the panel surface. Water was supplied to the nozzles from a 200 litre tank with the flow rate regulated by an electric pump and measured using an in-line flowmeter. Pressure was measured with an in-line gauge.

4.2.2.2 Test procedure

The panel was ignited and allowed to reach a steady output of 3.6 kW/m^2 (as recorded by the radiometer). The spray was then turned on and allowed to reach a steady flow rate at a pressure of 2 bar for 2 minutes during which time the output of the radiometer was recorded. The spray was switched off and the output of the panel checked. The process was repeated up to a pressure of 9 bar at 1 bar intervals. Following this a repeat reading was made at the 3 bar condition. Measurements were made on each of the four nozzle types, A, B, C and D.

4.2.3 Results

The reduction in radiation measured by the gauge, as a percentage of the incident radiation in the absence of the spray, was calculated and the results are plotted in Figure 4 for the four nozzle types operating at pressures between 2 and 9 bar.

The maximum radiation attenuation was achieved by the Type C (fogjet) nozzle, followed in descending order by Type A (SAVE) nozzle, Type B and Type D. Approximately 40%; reduction (1.4 kW/m^2) could be obtained by operating the fogjet nozzles at 9 bar pressure, at a flow rate of 1.6 l/min per nozzle. At 3 bar the percentage attenuation achieved by the Type A nozzle was 16%.

4.2.4 Discussion

Thomas (Reference 13) showed theoretically that, for droplets with diameters above 50 µm, radiation attenuation should be proportional to flow rate and inversely proportional to droplet size. The results accord well with this prediction. For all nozzles attenuation increased with applied pressure which is linked as noted in Appendix A, to increased flow and reduced droplet size. For the same flow rate the Type C nozzle yields smaller diameter droplets than nozzles Type A and B. Similarly the increased flow rate of the Type D nozzle is offset in comparison with the other nozzles by the larger diameter of its droplets.

Thomas proposed the following simple extinction equation for droplets above 50 µm:

$$D = e^{-aq\,L/D} \qquad (3)$$

where D = fraction of total heat that passes through the spray
L = length of spray zone (m)
d = droplet diameter (m)
q = volume of water per unit volume of spray jet
a = a constant

This allows the results for a single spray to be extrapolated to arrangements of several sprays.

4.2.5 Conclusions

The results, while principally aimed at providing a basis for comparison between the nozzle types, indicate that the Type A nozzle, while not as effective as the more bulky and complex Type C nozzle is likely to provide a significant degree of protection against thermal radiation. For instance, a row of three Type A nozzles situated at intervals of 1 metre (equivalent to the width of a narrow body aircraft fuselage) would, operating at 3 bar, yield a reduction in incident radiation of 40%.

4.3 Water Spray Performance - Chamber Experiments

4.3.1 Introduction

Carbon monoxide (CO) is recognised as the most important toxic species in fire products. As it is virtually insoluble in water, its removal from a fire atmosphere by means of a spray system would require the use of a solvent of high efficiency. The use of additives to improve its take up by water sprays has been suggested (Reference 3) and a literature review yielded ammoniacal cuprous chloride (ACC) solution as the most likely contender. ACC solution could never be used in an aircraft spray system, but it was decided to investigate its effectiveness on the basis that if it could be shown to provide a significant reduction in CO, it would indicate that there would be value in searching for a more benign alternative. Experiments were therefore carried out, using gas mixtures in an enclosed chamber. The opportunity was also taken to investigate the ability of water spray to reduce the 'wash-out' smoke particles and to confirm the expectation that soluble gaseous fire products, such as hydrogen chloride would be readily absorbed. Full details of the series of experiments are given in Reference 12 and only a limited description of the experimental arrangement and principle results will be given here.

4.3.2 Experimental arrangement

Figure 5 shows the test chamber which had the following dimensions - 1.25 m x 1.25 m x 2.0 m high, and was constructed using galvanised sheeting on an angle iron frame with a transparent Perspex door (0.56 m x 1.05 m). Ports were provided for the introduction of test gases and for the removal of samples. An extract duct was fitted near the top rear corner, away from the door, and a low level vent for make-up air was also provided. Both were closed by sliding shutters. Otherwise, the box could be made almost air-tight for the tests involving atmospheres containing CO and HCl. A small fan, directed downwards, was fitted to the 'ceiling' to assist mixing the contents of the box. In later experiments involving HCl, a small fan with an externally mounted motor was used near floor level.

The spray nozzle under test was located centrally in the ceiling and supplied from a reservoir which could be pressurised to a maximum of 100 psi using an air cylinder.

4.3.3 Investigation into the possible removal of carbon monoxide

Initial tests using water without any additives failed to produce any reduction of carbon monoxide concentration, in 1% and 4% CO in air mixtures, after an exposure to a 10 minute discharge of the spray. A similar result was obtained when a 4% CO in air mixture was exposed to a spray consisting of a solution of ACC in water.

It was concluded that, even with the addition of ammoniacal cuprous chloride, the water spray would not reduce the concentration of carbon monoxide in an aircraft cabin fire scenario.

4.3.4 Investigation into the removal of hydrogen chloride gas

As expected, hydrogen chloride was found to be highly soluble in the water spray. Although problem sampling occurred in developing a suitable production and sampling due to the high reactivity of hydrogen chloride, it was found that the discharge of spray at a pressure of 3 bar using a Type A (SAVE) nozzle reduced hydrogen chloride concentration by two orders of magnitude.

4.3.5 Investigation into the possible removal of smoke particles

4.3.5.1 Smoke generation

In the experiments designed to test the effectiveness of sprays in removing smoke particles from the atmosphere, smoke was generated by burning small quantities of fuel inside the chamber. Three fuels were originally selected: (a) 50 ml n-hexane; (b) 5 ml benzene; and (c) a 100 g wood crib. The liquids were burned in a Petri dish which rested on a 25 mm thick piece of Kaoboard located on the floor in the centre of the chamber. The cribs were burned on a metal tray which also rested on Kaoboard. Some additional experiments were carried out with 20 ml benzene and also with 30 g of polystyrene.

The optical density of the smoke, calculated from the reduction in the intensity of a beam of light passing through the smoke and falling on a photocell, according to Equation 1.

4.3.5.2 Results

When the water spray was activated, the apparent obscuration increased, due to the presence of the water droplets. When it was turned off, there was a net reduction in the obscuration, to a value less than that observed before the discharge. The principle results are summarised in Table 3, which gives the average percentage falls in optical density for water, two AFFF (aqueous fire-fighting foam) solutions and two 'soap' solutions, at three discharge pressures. It is assumed that this gives an adequate representation of the amount of smoke washed out for comparative purposes.

Within the level of confidence applicable to the derived results, there appeared to be little difference between the various liquids used, although the AFFF and detergent solutions appeared to be marginally more effective than water at removing the smoke produced by benzene. Moreover, it must be noted that while the water spray is operating, there is a net increase in obscuration due to the presence of the water droplets. In most experiments, this was sufficient to negate the apparent reduction in the concentration of smoke particles which could be deduced from the optical density as measured after the water spray had been turned off.

Test runs performed at sprinkler operating pressures of 1.5, 3 and 4.5 bar, indicated that the spray was most effective at reducing the particulate smoke concentration at 4.5 bar and least effective at 1.5 bar. The effect was most pronounced for benzene smoke, while the results for hexane were less consistent.

4.3.6 Discussion

It appears that, even with the use of additives it is not possible to reduce the concentration of the most common toxic species present, carbon monoxide. However, it has been clearly demonstrated that a highly soluble gas such as hydrogen chloride, if present in the vapour phase, (a product of the combustion of PVC) can be rapidly washed out of an HCl/air mixture. It seems reasonable to assume that it would also be washed out of a fire atmosphere. As hydrogen cyanide is also highly soluble in water, it is likely that it would also be removed but the efficiency would depend on the speed of dissolution and would need to be tested.

The effect on the concentration of smoke particles can be measured, but the effect is not considered to be significant enough to make much difference to the ability of people to move towards an escape exit, particularly as when the water spray is turned 'on', the obscuration actually increases. Indeed, in many of the tests, the 'gain in visibility' apparently due to the loss of smoke particles over a discharge time of several minutes was more than offset by the presence of the water droplets while the spray was still active.

4.4 Water Spray Performance - Moving Gas Layer Experiments

4.4.1 Introduction

In operation in an aircraft, water sprays will generally interact with a developing fire and moving layers of combustion products, rather than the static scenario considered in the chamber experiments described above. In order to provide a more realistic situation, a test rig was constructed to give an approximate simulation of conditions in a length of aircraft cabin. A hot, reproducible moving gas layer was produced by setting a fire at the closed end of the rig. Experiments were carried out to compare the performance of different nozzle types and spray arrangements in reducing the smoke, toxic gas content and temperature of the layer. It is emphasised that the purpose of these experiments was to compare the relative performance of different methods of deploying water sprays under repeatable conditions, not to simulate exactly the way that any one arrangement would perform when installed in an aircraft cabin.

4.4.2 Experimental arrangement

The general layout of the test rig is shown in Figure 6. It consists of an enclosure 8 m long, 3.5 m wide and 2.3 m high open at one end. In addition to the open end, another opening, 1 m wide by 1 m high, was located along one of the side walls 1 m from the closed end of the rig. The test fire was situated on the centreline of the chamber, approximately 0.9 m from the closed end. For all of the tests described in this section, the fuel for the test fire consisted of 2 lites of Avtur (aviation turbine fuel). This was placed in an 0.45 m diameter metal tray 0.15 m deep, part filled with water. The rate of heat release was approximately 180 kW.

The water spray system was constructed from copper tubing and consisted of three parallel branches, one metre apart, mounted on the ceiling of the test rig. Tee-pieces were fitted at 0.5 m intervals in each of the branches, allowing a maximum of 32 nozzles to be fitted, if required. The branches were connected via a supply pump and a pump to a tank of capacity 270 litres, external to the rig.

The open end of the test rig was positioned just below one edge of a large calorimeter collection canopy of standard design. The canopy, which was open on its other three sides, was designed to collect fire effluent which, under the action of an extract fan, was drawn through a small plenum chamber to an 0.4 m diameter horizontal duct. At a measuring station at a distance of 4 m along the duct, provision was made for measuring the temperature, opacity and velocity of the fire effluent and also for gas sampling. The gases sampled were carbon monoxide, carbon dioxide and oxygen. The rate of heat release from the fire was determined from the measured mass flow rate and the depletion of oxygen concentration below atmospheric level.

Temperatures within the rig were measured by two thermocouple trees, each consisting of eighteen chromel/alumel thermocouples positioned so as to give readings of temperature for the full height of the rig. Measurements of optical density were made using light sources mounted externally on the side walls of the rig with detectors mounted at the corresponding position on the external face of the opposite wall. The positions of the thermocouples and optical density meters are shown in Figure 6.

4.4.3 Test procedure

A period, usually 3 minutes, was allowed for the fire to become fully established and for steady conditions to apply. The spray system was then switched on an allowed to operate for a period of time, usually 3 minutes. The spray was then switched off. The fire began to die down after between 7 and 8 minutes following ignition.

All tests with sprays operating were associated with an unsprayed test undertaken close in time, usually on the same day. This allowed a direct comparison to be made between measurements with and without the spray in operation. Because they are unaltered by the presence of the spray, the rate of heat release profiles enabled a check to be made that fires were repeatable.

4.4.4 Results

4.4.4.1 Test series

The principal series of tests, Table 4a, was designed to compare the four different types of spray, using an identical arrangement of the spray heads, with five rows of three heads at 1.0 m apart. The sprays were operated at pressures of 3, 6 and 9 bar.

In addition a subsidiary series of tests is also reported here, Table 4b. These tests were undertaken using the Type A (SAVE) nozzle only. They include the effect of changing the number of operating spray heads. The series was partly undertaken with the small 0.5 m downstand at the open end of the test rig absent. In two tests, B10 and B11, the spray heads were arranged with unequal spacing between rows.

The results obtained in each series of tests are summarised in Tables 5 and 6.

4.4.4.2 Effect on smoke

(a) *Within the Test Enclosure*

In the absence of the spray, the plume of hot gas from the fire formed a stable layer flowing towards the open end of the enclosure and thence into the calorimeter hood. The depth of this layer was typically about 0.75 m. The smoke was retained within this layer. However, on operation of the sprays the hot layer was cooled and, losing buoyancy, the base of the smoke layer descended to a depth much closer to the floor by the time that it had passed through the spray. This phenomenon of 'downdrag' has been observed in relation to the operation of conventional sprinklers, although these operate at substantially higher flow rates and droplet sizes.

(b) *Smoke Removal*

Because of the effect of the spray on the distribution of smoke in the enclosure, it is not possible to determine whether the spray is removing smoke and particulate material to any extent. However, smoke density measured in the calorimeter duct does, when normalised by the volume flow rate of gases in the duct, provide an indication of the magnitude of any smoke removal. Figure 7 shows in histogram form the normalised optical densities measured in the principal test series for the four nozzle types. Also included are the results for a number of the comparison unsprayed tests. These are, as expected, very similar, within the expected experimental errors. The results with sprays in operation show that, while there is a trend for optical density to reduce with increasing applied pressure and increased flow rate, only the results for the Type C nozzle at 9 bar and the Type D nozzle at 6 and 9 bar show significant reductions in smoke density and, by inference, washout of smoke particles by the spray. However, even in case of the Type D nozzle at 9 bar the reduction is only approximately 30%. As with the results from the chamber experiments, described in 4.2, these results provide no evidence that fine water sprays will remove particulates.

4.4.4.3 Heat content

It is difficult to measure the heat removed from the hot, moving layer of fire gases by the spray. One simple approach, which requires a number of assumptions, uses the temperature and mass flow rate of gases measured in the duct. The difference between the convected heat in the duct for otherwise identical test conditions with the spray on and off gives a measure of the heat removed. This assumes that other heat losses, (by radiation, by convection to the surfaces of the enclosure and the calorimeter) are the same in both cases and that, at the temperature of the gas layer, relatively little water is evaporated (ie the latent heat content of the gas flows in the duct are similar). The calculated rates of heat removal for the each of the tests are included in Tables 5 and 6 and are shown, plotted against total water flow rate in Figures 8 to 10. It is interesting to note that, taking into account the uncertainties involved in this approach, the rate of heat removal by the Type A spray (Figure 8), depends principally on the total delivery rate and is relatively independent of the arrangement of the spray heads. Similarly when the results of the comparison of the different types of nozzle, but the same arrangement of spray heads, are considered (Figures 9 and 10) only the Type D nozzle departs from the approximately linear variation with flow rate. The average rate of heat removal for all of the results except for those for the Type D nozzle is approximately 2.7 kW per l/minute. This implies an average rise in temperature of the water droplets of approximately 40°C as they pass through the hot gas layer. The average rate of heat removal for the Type D nozzle is lower and this may be due to two factors. Firstly the droplet sizes are significantly larger and will fall through the hot layer more quickly and, in consequence, not approach as closely to the equilibrium temperature as the sprays with smaller droplets. Secondly the substantially larger total mass flow rate of water may mean that the heat removal capacity of the Type D nozzles may be saturated (ie the addition of more nozzles would have little effect as the gas stream would have been cooled to a temperature close to the delivery temperature of the water).

4.4.4.4 Carbon monoxide

Carbon monoxide concentrations were measured in the calorimeter duct. These were low and there was no significant difference in concentration between those tests with and without the spray operating.

4.4.5 Conclusions

Except for the Type C and Type D sprays operating at high driving pressures, the water sprays had no significant effect on the smoke content, measured in terms of the effect of the total aggregate of smoke on visibility. However, the cooling effect of the spray did tend to lower the base of the smoky layer, hence producing poorer visibility at lower levels than occurred without the spray.

Estimates of heat removed by the spray, principally by convection, indicated that this depended principally on the total flow rate and that there was little to choose between the nozzle types A, B and C.

As expected there was no measurable effect of water spray from any of the nozzles on carbon monoxide content of the hot gas layer.

5. FULL-SCALE STUDIES

5.1 Design of the full-scale trials

The preliminary studies, described in Section 4, indicated that although water sprays were capable of reducing incident thermal radiation and absorbed acid gases such as hydrogen chloride, their capability for removing heat, particulate matter and carbon monoxide is limited. The absorption of radiation was improved by using finer sprays but convective removal, provided that drop size was below a maximum, was primarily determined by overall flow rate per unit area, rather than by the spray characteristics.

For these reasons the full-scale tests were designed, principally, to investigate, under controlled and repeatable conditions, the effectiveness of sprays similar to those proposed by SAVE. A severe fire scenario was chosen, representing an external fuel fire adjacent to an opening in a fuselage resting directly on the ground. The chosen fire, using aviation fuel in a tray, was designed to have a total output of approximately 12 MW. Since it was considered likely, in real situations, that wind could influence the penetration of the fire into the cabin, the tests were carried out with a flow of air induced through the fire opening, by a fan situated in an opening at the opposite end of the fuselage. Both this and the fire arrangement were chosen to replicate conditions used by the FAA (Reference 14) in a parallel study. The intention was to allow a common basis to link the two sets of results.

Seven tests were undertaken, identified as CFT1 to CFT7. These are listed in Table 7. CFT1 and CFT3 were base-line tests with no spray operating. In CFT1 the cabin was completely unfurnished but the spray system was operated over the full fuselage, using standard SAVE (Type A) sprays. The intention in CFT4 was to repeat CFT2, but with a furnished cabin. In practice, one of the spray lines ruptured and this test was repeated as CFT7. In CFT5 and CFT6 the cabin was furnished but the sprayed zone was restricted to the region nearest the door. A full description of the tests and the analysis of the results is given in References 15 and 16.

5.2 Experimental Arrangement

5.2.1 The fuselage

The work was undertaken using a Boeing 707 fuselage situated at the FRS Cardington Laboratory. This building was originally designed as a hangar for airship construction and has dimensions - 250 m long, 80 m wide and 50 m high. Its size allows full-scale fire experiments to be carried out independently of prevailing weather conditions. The fuselage was delivered with the wings and tail section, beyond the pressure dome, removed. Metal box-section support frames were constructed to allow the fuselage to be supported at normal height with undercarriage extended as shown in Figure 11.

The original fuselage was stripped of all interior fittings (seating, decorative panels, wiring etc). A rectangular opening, 1.7 m high and 0.9 m wide, was cut into the port side, approximately 11 m forward from the rear pressure dome. The base of the opening was level with the floor of the fuselage. Bulkheads, made of non-combustible boarding, were fitted to the front and rear of the interior of the fuselage, leaving an unobstructed cabin space, approximately 28 m long. The rear bulkhead was positioned just forward of the rear galley and contained a door to allow access to the main cabin space. The front bulkhead was constructed to protect the flight crew cabin at the front of the fuselage, while allowing access to the cabin space via the forward port doorway.

In order to protect the structural components of the fuselage from exposure to hot fire gases the cabin was lined with a mineral fibre blanket, held in place by wire mesh and covered with a protective layer of aluminium foil as shown in Figure 12(a). In the region 3.5 m either side of the opening cut in the fuselage wall, additional protection was provided as shown in Figure 12(b). This consisted of an inner layer, adjacent to the fuselage skin, of 75 mm of ceramic fibre, held in place by an outer layer of 2 mm steel sheet attached to Z-section steel supports. The exterior fuselage, in the region of the opening, was provided with a similar form of protection, extending to ground level beneath the opening and terminating at the top centre of the fuselage where a vertical steel deflector plate, 1 m high, was fitted.

Figures 13(a) and 13(b) show this protection. The cabin floor to 2 m either side of the opening was protected by 6 mm thick steel sheet.

Three other fitments were associated with the experimental arrangement of the fuselage. A steel tray, 2.4 m by 3.0 m, to contain the fuel for the fire, was fitted to a steel supporting structure so that it abutted the fuselage at the base of the opening, as shown in Figure 13(a). The tray was centrally placed with respect to the opening, with its long axis parallel to the fuselage. An emergency extinguishing system, consisting of four standard sprinklers fitted to a 50 mm pipe, terminating outside the fuselage at ground level at a point where it could be attached to a fire appliance. A platform was erected close to the forward on the port side of the fuselage on which was placed an Angus Turbed MkII water turbine-driven fan. The function of this during the tests is described later.

5.2.2 Instrumentation

5.2.2.1 Temperature measurement

The interior of the cabin was fitted with 138 thermocouples in order to measure air temperature. The thermocouples were positioned in the form of 22 vertical ‘trees’. The location of these is shown, schematically in Figure 14, labelled from A to V. Each tree consisted of thermocouples set at intervals of 0.305 m (1 foot) with the lowest at 0.305 m from the floor. The centrally-placed trees consisted of 7 thermocouples whilst those nearest the side-walls of the cabin (G, J, K, N, O, R, S and V) consisted of only 5 because of the restricted headroom. For convenience of reference within this report, each thermocouple will be identified by the letter of its tree and its height in feet (ie B5 is located at a height of 5 feet (1.53 m) on tree B). The 42 thermocouples along the centre-line of the cabin (trees A to F) were of principal interest. The second group (trees G to V) was fitted to give information on lateral distribution of temperature in the context of another related study.

The thermocouples were made from chromel/alumel, with the hot junctions formed from welded 0.2 mm wire. The leads were sheathed in fibreglass sleeving, designed to be resistant to high temperatures. Additional protection, against the possible effects of flame impingement, was provided by running the leads inside 25 mm diameter steel tubing. At each position the thermocouple wire was fed through a 2 mm hole in the tubing with the hot junction located at 10 mm from the tubing. Each thermocouple was connected to the data-logging system described in section 5.2.2.6.

5.2.2.2 Smoke opacity

The reduction in visibility due to the presence of smoke (or water droplets) was characterised by optical density measurements made at two locations in the cabin close to thermocouple trees A and C, as indicated in Figure 14. At each of these locations three smoke meters were installed at heights of 0.3 m, 1.1 m and 1.7 m (approximating to eye-level in crawling, sitting and standing positions, respectively). Each meter consisted of a source illuminating a detector set at a distance of 0.66 m across the expected path of the smoke flow. Opacity expressed in terms of Optical Density/metre was determined from the intensity measured at the detector, using Equation 1.

5.2.2.3 Thermal radiation

Four radiometers were installed, at positions along the centre-line of the fuselage as indicated on Figure 14, and identified as RD1 to RD4. The radiometers were set at a height of 1.2 m and orientated in the direction from which the highest intensity radiation was expected. Thus, RD1 and RD2 in the forward part of the cabin were orientated to the rear; RD3 was orientated directly towards the door and RD4 towards the front.

5.2.2.4 Concentration of toxic fire products

Measurements were made at selected locations of the concentrations of toxic gases, smoke particulates and the extent of partitioning of toxic chemical species in the fire atmosphere between the gas phase, water droplets and solid particulates within different size ranges. Full details of the methods and procedures for sampling gases and particulates are set out in Appendix B.

Four heated and epoxy-lined gas sampling lines were used, complete with particulate filters and vapour traps, carbon monoxide, carbon dioxide and oxygen analyzers. The sampling points are shown in Figure 15, and all were along the centre-line (in plan) of the fuselage. Point G1 was at standing height (1.7 m), adjacent to the fuselage opening used for the fire entry. Points G2 and G3 were half way along the fuselage, G2 at standing height (1.7 m) and G3 at crouching height (1.1 m). Point G4 was furthest from the fire entry door adjacent to the front crew cabin bulkhead and at crouching height (1.1 m). The transit time of all gas samples from the measuring point, to the analysis point was 15 seconds.

At point G2, 'grab' samples were taken at fixed points during the fire for analysis of hydrogen cyanide, hydrogen chloride and organic species as shown schematically in Figure 16. Particulate was collected on open face surface filters using 37 mm glass fibre filters in aluminium holders. Three of these filter units were positioned at point G2 (designated units 1, 3 and 5) and three at point G3 (designated units 2, 4 and 6). The flow rate through the filters was 1.0 l/min and each was connected to a twin bubbler collection system. The filter pads were positioned horizontally, facing the floor.

Particle sizing samplers (the Andersen and Casella cascade impactors and the May liquid impinger), together with a horizontally sampling open face filter were also mounted at point G2. Twin bubblers were placed behind the Andersen impactor and the open face filter. During selected sprayed tests, water was collected in 'floor pots' inside the fuselage for subsequent analysis of hydrogen cyanide, hydrogen chloride and pH. A similar analysis of the water source for the spray was also carried out. The spray water was also 'spiked' with sodium or potassium bromide as a tracer for water droplets deposited in the particulate trapping devices.

In addition to the main sets of thermocouples, described in the previous section, a further thermocouple was placed at gas sampling point G2 (at 1.7 m in the mid-cabin position) and a further two thermocouples were placed at gas sampling point G3 (at 0.8 m in the mid-cabin position). In order to make estimates of humidity, cotton tape soaked with water, with one end in a small vial of water, was wrapped around one end of one of the lower thermocouples. The temperature difference between the wet and dry thermocouples was then used as an approximate indication of relative humidity at G3 during the tests.

5.2.2.5 Photographic and video records

Two remotely-operated video cameras were installed in the fuselage as shown in Figure 17. One was mounted in the vestibule at the tail end of the fuselage, viewing the region close to the fire opening through an oven glass window. The other was mounted in a protective box and placed close to the open door, containing the fan unit, at the front end of the fuselage. A third portable video camera was used to record external events. The interior of the fuselage was illuminated by 800 W halogen lamps, situated at floor level.

Still photography was used to record the fire development and to provide a permanent record of the fire damage within the fuselage.

5.2.2.6 Data recording

The output from the instruments measuring smoke density, radiation and from the centre-line thermocouples was recorded and preliminary data manipulation carried out using a Schlumberger Orion datalogger. A similar datalogger was used to record the temperature from the laterally-placed thermocouple trees with the output also being transferred to an IBM PC equivalent desktop computer for ease of analysis.

5.2.3 Cabin furnishings

In order to provide a realistic fire load in the vicinity of the opening a standard arrangement of cabin furnishings was devised. This consisted of three rows of seats, arranged as shown in Figure 17, with the central row in line with the opening and one to either side. The central row consisted of a triple seat unit immediately adjacent to the opening and a double seat unit against the opposite wall. The other two rows consisted only of triple seat units. The floor in the vicinity of the opening was carpeted. The seats and carpeting material were stored in a conditioning room at 50% RH and 20°C and f in the cabin one hour prior to testing. Cabin fittings and luggage racks were simulated by the use of typical cabin lining materials attached to a permanent steel framework situated in the zone near to the opening. This extended 2 m forward of the opening and 2 m to the rear.

The materials used were chosen to represent those typically in current use. The seating units consisted of standard aircraft seats, with metal frames supporting polyurethane seat and back squabs, covered by a layer of protective material and a wool mixture covering, fire-blocked in accordance with CAA requirements (Reference 17). The seat frames also contained arm units and folding tray supports.

The floor in the vicinity of the fire opening was carpeted with wool carpeting on a hessian backing. The vertical surfaces of simulated overhead bins and the ceiling were constructed using 'Flitelam' composite board. The lower surfaces of the simulated bins were constructed from 'Aerolam' board covered with 'Schneller' material. The cabin sidewalls were covered with sheets of 'Ultem', held in position by metal strips at the vertical edges. The 'Schneller' material was glued to the composite board using Tretobond non-flam prior to fitting. These materials complied with CAA flammability requirements for cabin interior materials (Reference 18). Figure 18 illustrates a typical furnishing arrangement just prior to a test.

5.2.4 The spray system

The arrangement of the water spray system is shown schematically in Figure 19. The system consists of three parallel lines, one along the centre-line of the fuselage, and one on each side of the fuselage at the approximate position of junction of the overhead bins with the fuselage wall. An electrically operated solenoid valve controlled the water supply to the whole system, manually operated valves fitted to each branch to allow the system to be zone if required. An in-line flow meter was installed upstream of the solenoid valve in order to monitor overall water supply rate. Two pressure gauges were fitted as shown in Figure 19 in order to monitor the pressure of the supplied water.

The nozzles were installed at a spacing of 1 m in each branch. Additional nozzles were installed in the furnished zone to provide direct protection to the overhead bin surfaces. The arrangement was derived following preliminary tests which showed that the standard nozzle positions and angles were not giving sufficient wetting of the vertical surfaces of the bins. Figure 20 shows the arrangement of the water supply system used for the zone spray tests. The total number of nozzles operated during the full and zoned tests were, respectively, 76 and 30. The water supply pressure was 3 bar in all tests.

Two types of spray nozzle were used in these tests. Type A (SAVE) nozzles were used for tests CFT2, CFT4, CFT5 and CFT7. The nozzle used for test CFT6, supplied by the CAA, was stated to have a flow rate equal to 0.7 times that of the Type A nozzle but with a similar droplet size distribution.

5.2.5 Safety systems

5.2.5.1 Fuselage skin temperature monitoring

Additional chromel-alumel thermocouples were installed between the insulation and the aluminium skin of the fuselage at a number of points close to the fire opening. These were separately monitored using a screen display so that the test could be terminated if at any stage the temperature at any of these points were to approach a predetermined safe level.

5.2.5.2 Fire crew

The principal safety protection was supplied by a fire crew and tender provided by the Bedfordshire Fire and Rescue Service. The crew were responsible for extinguishing the fire both in the fire tray and in the cabin after each test. During each test, members of the crew were stationed to hose the external surface of the fuselage should this prove necessary.

5.2.5.3 Emergency extinguishing system

The region within the fuselage in the region of the fire opening was protected with an emergency extinguishing system, consisting of a 50 mm water main, fitted with open sprinkler heads. The main was connected by hose to the fire tender and could be operated should the fire threaten to damage the structure of the aircraft.

5.2.5.4 Fuselage fuel tanks

The fuselage contained several inboard fuel tanks. In order to ensure that there was no risk from an explosion due to the vaporisation, during the tests, of any small quantity of residual fuel, these tanks were thoroughly cleaned and large ventilation openings provided. In addition, the level of hydrocarbons present was monitored during each test.

5.3 Test Arrangements

5.3.1 The external fire

The fuel for the external fire consisted of 200 litres of Avtur (Jet A1). In order to provide a level base for the fuel and to protect the fire tray, water was introduced to a depth of 75 mm, prior to charging it with the fuel. The following data, supplied by the CAA, apply to the fuel:

Flash point:	38°C
Auto-ignition:	245°C
Rate of surface spread:	0.5 m/s

The approximate burn time for this volume of fuel in a 2.3 m by 3.0 m tray was calculated to be 10 minutes, using published data for density (800 kg/m^3) and burn rate (36/m^2/s).

5.3.2 Test procedure

Prior to each test the instrumentation was calibrated and checked. In those tests where a furnished cabin was required, the seating items and carpet were removed from the conditioning room and installed in the hour immediately before the test. The fire tray was loaded with fuel. The speed of the extractor fan in the forward doorway was adjusted to give a mean airflow rate of 0.5 m/s at the fire opening and maintained at this speed throughout the test. One minute prior to ignition, the dataloggers and video cameras were started.

Ignition was achieved by adding 10 litres of heptane to the fuel in the fire tray and igniting this using a gas torch. The solenoid valve controlling the water supply to the spray system was actuated to ensure that the spray came into operation shortly after the fire was fully ignited. The spray operated continually throughout the test. during the test the thermocouples inserted in the skin of the fuselage were continuously monitored. The test was terminated either if the temperature at any of the monitored points on the fuselage skin rose above 200°C or when sufficient data had been gathered at which point the spray was also turned off. The external fire and any internal fire was extinguished by the fire crew.

Once safe conditions were established the interior of the fuselage was inspected and the condition of the remaining furnishings recorded.

5.4 Results

5.4.1 Temperatures

The temperatures recorded by the centre-line thermocouple trees (A to F) are set out graphically in Appendix C. Each graph shows the variation of the measured temperature at each thermocouple with time over the full period of the test, except for CFT4, where the datalogger failed for the first three minutes of the test.

The data from the dry thermocouples placed at the midcabin gas sampling points G2 and G3, and from the wet thermocouple placed at point G3 were used in the life threat analyses. These data are presented in Reference 16.

5.4.2 Smoke opacity

The variation of smoke opacity with time for each of the measuring stations is shown graphically in Appendix D. Due to instrument failure it was only possible to obtain records for tests CFT1, CFT2, CFT3, CFT5, CFT6 and CFT7.

5.4.3 Thermal radiation

Appendix E contains the results of the measurements made using the three radiometers RD1, RD2 and RD3 for tests CFT1 to CFT7.

5.4.4 Carbon monoxide, carbon dioxide, oxygen

Figures 21 to 27 are plots of these data for tests CFT1 to CFT7 respectively. Each plot shows the concentrations of these gases for each of four sampling points.

5.4.5 Hydrogen cyanide, hydrogen chloride and hydrogen bromide

Since the acid gases hydrogen cyanide and hydrogen chloride were expected to partition between the vapour phase and the particulate phase (solid and liquid) of the smoke, it was necessary to analyse both the soot deposits on the horizontal and vertical sampling open face filters and the various stages of the cascade impactors, and also the gas traps placed in the lines behind them. These give integrated samples of the total acid gas content of the smoke over the period 1-4 minutes.

The timed grab samples of total smoke (vapour and particulate) give an indication of the changing concentration of HCl and HCN at one minute intervals. Figure 28 gives plots of hydrogen cyanide and hydrogen chloride analysis from the timed 'grab' samples during tests CFT3 to CFT7 from sampling point G2. Also, floor pots were placed for collection and analysis of spray water for HCl and HCN. These results are shown in Table 8.

Tables 9 and 10 present the HCl and HCN data in a slightly reduced form while the salient features are summarized in Table 11. In each case the gas data are presented in terms of ppm vapour for vapour phase gases and ppm vapour equivalent for gases recovered from particles and water droplets and in nearly all cases HCl was recovered almost entirely from particulate traps (open face filters and impactor stages). The highest recoveries were obtained from the May impinger, particularly the middle stage (associated with particles 0.5-1.5 µm in size), and the horizontally sampling open face filter. The open face filters sampling vertically upward generally gave lower recoveries (except for CFT6 where a very low recovery was obtained from the horizontal filter). Recoveries were also low from the Andersen and Casella cascade impactors, which may be due partly to difficulties in extracting the soot from the plates. The lowest recoveries were obtained from the grab samples, and these data are considered to be unreliable.

The highest concentration of HCl was obtained from the unsprayed, furnished fire (CFT3) at 1027 ppm from the May impinger and 591 ppm from the horizontal open face filter. The vertical open face filters recovered 287 and 171 ppm respectively. Pooling the data from the two devices with the best recoveries (May impinger and horizontal open face filter), the fully sprayed tests (CFT4 and CFT7) showed an average 70-82% reduction in HCl concentration at G2 (mid cabin 1.7 metres height) compared to the unsprayed test, while the zone sprayed tests showed an even larger reduction of 91-97% in HCl concentration. The zoned spray reduction effect was particularly marked in CFT5, where the general fire development was greatly reduced compared to the other tests, the HCl concentration being reduced by approximately 97% compared to the unsprayed test (CFT3).

High bromide ion concentrations were recovered from the unsprayed test (1228 ppm HBr equivalent from the May impinger) and some from the zone sprayed test CFT6 (160 ppm HBr equivalent), while traces were recovered from other tests. These results are significant in that while the spray water was spiked with bromide for all the sprayed tests, no added bromide was present in the unsprayed test CFT3.

The recovery of HCN seemed to be the reverse of that for HCl, in that most was recovered from the vapour phase traps, and virtually none from particulate filters, impactor stages or from the May impinger (Tables 9 and 10). The highest recoveries were obtained from the grab samples and the bubblers in line behind the horizontally sampling open face filter. Similar, but generally slightly lower recoveries were obtained from the bubblers behind the open face filter sampling vertically upwards and the bubblers behind the Andersen impactor. Bubblers were not used behind the May and Casella samplers because of the high sampling rate.

Very high HCN concentrations were obtained in the unsprayed fire (CFT3), with a peak grab sample concentration of 1937 ppm, and an average concentration over for the grab samples taken over the period of 1-4 minutes of 836 ppm. This was greatly reduced in the sprayed tests, and taking all the devices into account the reduction was approximately 95% for fully sprayed tests and 98% for zone sprayed tests.

5.4.6 Smoke particulate and water droplets

Table 12 gives data for particulate recoveries from the various devices for tests CFT1 and CFT3-CFT7. All these devices functioned well except the Casella impactor.

The Casella is a very high volume sampler (sample flow rate 17.5 l/min) and was included because it should trap some of the larger particles or water droplets (up to the 200 μm diameter limit for the device) which would not be trapped by the other devices. Unfortunately, because of this high sampling rate, the device became rapidly clogged when the smoke was thick. For test CFT3 the device was run throughout the 3 minutes sampling period, the sampling rate gradually slowing throughout the run, but for subsequent tests it was run through the fourth minute only, in an attempt to avoid the problem. However, the device still became rapidly clogged, perhaps because the smoke was thickest at the end of the three minute sampling period. Some usable data were obtained, but these can be regarded as approximate only.

The highest particulate recoveries were obtained from the horizontally sampling open face filter and the Andersen sampler. The recoveries from the open face filters sampling vertically upwards and the Casella sampler were somewhat lower, particularly for the fully sprayed tests.

The particulate recoveries on the horizontal open face filter and the Anderson and Casella impactors are illustrated in Figure 29, and the particle size distribution data from the Andersen sampler are illustrated in Figure 30.

The fuel only fire (CFT1) produced a light sooty particulate, 76% of which was respirable. The furnished, unsprayed fire (CFT3), produced approximately four times as much particulate, which left an oil deposit on the collection plates and contained some larger particles, 64% being respirable according to the Andersen sampler and 61% according to the Casella sampler. The total deposit on the Andersen sampler was similar to that on the horizontal open face filter (Figure 29). As stated above, the particulate contained high levels of hydrogen chloride and bromide equivalent to approximately 2000 ppm hydrogen halide, as well as organic components.

The fully sprayed tests produced considerably less particulate in the respirable fraction (Figure 30, in which the results for the two tests are averaged), but the total particulate deposited on the horizontal open face filters was greater than that in the unsprayed test. In fact, the deposits on the horizontal open face filters were much greater than the total deposits in the Andersen sampler and those on the vertically sampling open face filters.

For Test CFT4 some water was found on the first stage of the Casella, while for CFT7, the horizontal open face filters was very heavy and wet, while water was found on the top plate of the Andersen sampler and the upper two plates of the Casella sampler.

In Figure 30 the data for the two fully sprayed fires are averaged. The fully sprayed tests produced considerably less particulate in the respirable fraction, but the total particulate deposited on the horizontal open face filters was greater than that in the unsprayed test (Figure 29). In fact, the deposits on the horizontally open face filters were much greater than the total deposits in the Andersen sampler and those on the vertically sampling open face filters.

For the zone sprayed tests there was a difference between CFT6 and CFT5. CFT6 produced an internal cabin fire of similar, or perhaps slightly greater size than that in the fully sprayed tests, and the total particulate trapped by the Andersen sampler, and the lower stages of the Casella sampler was somewhat similar to that collected in the fully sprayed tests. The deposit on the upper two stages of the Casella sampler were sticky, as with CFT3, but not wet, as in the fully sprayed tests. The deposit on the horizontal filter was not wet, and was approximately half that in the unsprayed test, as was that on the vertically sampling filters. For CFT5 the recovery of particulate from all devices was considerably lower than that from the other tests, and as with CFT6, there were no signs of trapped water. In Figure 30 the particle size distributions for both tests are shown, since they were so different. The histograms for CFT5 barely extend above the base line.

5.4.7 Gas chromatography/mass spectrometry

Many samples were obtained during this study but only whose which satisfied the criterion 'greater than 200 ppm carbon monoxide' were subjected to a detailed analysis by gas chromatography and (sometimes) mass spectroscopy. The examples shown here have been chosen to illustrate the essential conclusion that the effect of spray is to reduce the concentration of organic species, some of which may be toxicologically significant.

Figure 31 shows chromatograph traces of 'total organics' from tests CFT3, CFT5 and CFT7 taken at 3.5 minutes into the tests. These diagrams show the dramatic reduction in yield of these species with sprayed conditions.

Figure 32 shows a plot summarising the results from gas chromatography for tests CFT3 to CFT7 for each sampling time. The results show a marked increase in organics during CFT6, and the high concentrations in CFT3.

5.4.8 Visual observations

The conditions inside the cabin were recorded by the fixed video and still cameras at each end of the fuselage. General observations of the fire development within the fuselage during each test are set out in Appendix F. It should be noted that visibility, as portrayed in the video screen, does not necessarily give a guide to reaction of the human eye under the conditions measured.

5.4.9 Residual fire damage

The residual damage to the seating after each test is shown diagrammatically in Appendix G.

6. THE EFFECTS OF WATER SPRAY ON FIRE DEVELOPMENT WITHIN THE CABIN

6.1 Effect of water spray in the unfurnished cabin

6.1.1 Radiation

As might be expected, the highest readings were obtained for radiometer RD3, situated opposite and facing the fire opening. The peak reading, in the absence of water spray was 31 kW/m^2 (after approx. 4 minutes 30 seconds) in comparison with a level of 23 kW/m^2 (after 3 minutes 50 seconds) with the water spray present. A more interesting comparison is, perhaps, made by comparing the average irradiance over the period between 1 and 3 minutes after ignition, ie after the external fire has become well established, but before substantial heating of internal surfaces (and consequent re-radiation). The approximate average for the unsprayed case is 17 kW/m^2, while that for the sprayed case is 12 kW/m^2. This represents an attenuation of approximately 30%, according well with the results of the preliminary tests described in Section 4.2.

The levels of radiation measured elsewhere in the cabin for the unsprayed test also show peaks, but at a much later time (approximately 6 minutes 30 seconds) after ignition than close to the door. This is probably due to the steady rise in temperature of both the internal surfaces of the cabin and the smoke and gases to which the radiometers are exposed. The magnitudes of these peaks range from 7 kW/m^2 for the forward and rearmost positions and 14 kW/m^2 at the mid-cabin position. All are substantially higher than the level of 2.5 kW/m^2 considered to be the tolerable limit (see section 3.5) as shown in Table 13. This level is reached within approximately 1 min at the rear position, within 4 min at the mid-cabin position and within 5 min 30s at the forward position. In the sprayed case, the tolerance level is never exceeded within the period of the test (approximately 7 min 20s). This can be attributed to attenuation of the radiation by the spray as well as generally lower temperatures of the cabin environment.

6.1.2 Temperatures

Figures 33 to 37 enable a comparison to be made between the temperatures measured along the centre-line of the fuselage for the sprayed and unsprayed conditions. Each figure shows, for a given thermocouple tree location, the variation with time of the temperature measured at the 0.3 m and 2.1 m height, effectively giving an envelope of temperatures measured in each test.

The temperatures for the sprayed case are lower than for the unsprayed case and, the peak temperatures, reached on termination of the test, are lower. The general trend is for the rise in temperature to be at a lower rate for the sprayed case. Inspection of the detailed results given in Appendix C indicates that the temperatures of the lower thermocouples tend to be very close to each other and well below 100°C.

6.1.3 Smoke

From the detailed results for optical density given in Appendix D, it is possible to determine the time taken for certain levels of Optical Density per metre, and hence visibility, to be reached for each of the six measuring positions. These are set out in Table 18 which gives results for each location for 3 values of Optical Density - 0.5, 1.0 and 2.0. Since the path length for each meter is 0.66 m, the respective values in OD/m are 0.75, 1.5 and 3.0.

From Table 14 it is apparent that in the unsprayed test, CFT1, the visibility is reduced at the forward end of the cabin substantially in advance of the time that this occurs at the mid-cabin position. Smoke density builds up rapidly at 1.7 m followed by a rapid build up at the 1.1 m position and then the 0.3 m position. Not until after this has occurred does any build-up occur at the mid-cabin position. These results are consistent with a layer of hot smoke moving forward from the fire opening, close to the cabin roof, passing above the highest smoke meter at the mid-cabin location. At the forward end of the cabin the combined effect of the bulkhead and restricted path to the door cause part of the smoke layer to be deflected downwards past the forward smoke meters. Subsequently due to a combination of return flow and deepening of the flowing layer the mid-cabin meters become enveloped.

The behaviour in the sprayed case, test CFT2, is different. Here the upper two levels at the mid-cabin location are the first to be affected, virtually simultaneously, followed some 20 seconds later by the upper two levels of the forward location. This is consistent with the smoke layer being drawn down to, at least 1.1 m by the spray and moving as a 'plug' towards the forward end of the cabin. In practice, this means that whereas in both cases the visibility of illuminated signs at the forward end of the cabin, at 1.1 m (crouching or sitting height), is reduced to 1.8 m after approximately 3 minutes 30 seconds in both the sprayed and unsprayed cases, this level of visibility at the same height at the mid-cabin position is available for substantially less time in the sprayed case, 3 minutes as opposed to 5 minutes. This interpretation is consistent with the video records.

6.2 Effect of water spray in the furnished cabin

6.2.1 Radiation

For the unsprayed case the intensity of radiation measured at RD3, opposite the fire opening, follows a broadly similar pattern to the unfurnished, unsprayed test for approximately the first two minutes after ignition. After this, however, its magnitude increases rapidly as the furnishings become increasingly involved in the fire with levels rising to above 100 kW/m^2. The levels in the mid-cabin and forward positions rise steadily to reach peaks of 45 and 9 kW/m^2 respectively, just before the time (4 minutes 20 seconds) at which the test was terminated. The level at the rear position peaks earlier (at 3 minutes) and maintains this level of approximately 7 kW/m^2 until termination. The tolerable level of 2.5 kW/m^2 is exceeded within 20 seconds opposite the opening and within 2 minutes 30 seconds to 3 minutes at the other locations.

In those tests, CFT4 to CFT7, with either a full or zoned spray the radiation at the locations other than that opposite the fire opening remains below the tolerable level in all cases. For tests CFT5 and CFT7, at the position opposite the door the average level over the period from 1 m to 3 m after ignition is approximately 10 kW/m^2, similar to but slightly lower than the value measured in the absence of furniture but with a spray. In test CFT4, the water supply to the sprinkler line closest to the fire opening failed. In this case, the average level for the same period was close to the value of 17 kW/m^2 found in the unfurnished, unsprayed test, CFT1. For the zone sprayed test with the type 2 nozzles the radiation at RD3 is similar to that in the unsprayed test, exceeding 100 kW/m^2 by 4 minutes, although the readings elsewhere in the cabin remained at low levels.

6.2.2 Temperatures

Figures 34 to 37 enable a direct comparison of temperatures at the measuring stations along the cabin centre-line to be made between the four sprayed tests and the unsprayed test, CFT3. Each figure shows the variation with time of the temperatures measured at 0.3 m and 2.1 m height, giving an envelope of temperatures measured in each test.

In all cases and for all locations the sprayed tests show lower temperatures than the unsprayed test. The temperatures remain lowest in test CFT5, the zoned test with the Type A spray nozzles, followed by test CFT7, also with the Type A nozzles but with the full cabin sprayed. Although the temperature profiles for test CFT4 are incomplete, due to a datalogger failure for the first 3 minutes, the profiles are quite similar to those for test CFT6, the zoned test with the type 2 nozzles. It is, perhaps, worth noting that, due to the water pipe failure in CFT4, the water delivery rate in the zone near to the fire opening would have been similar to that provided by the reduced flow nozzles used in test CFT6.

As an indication of the ability of the spray systems to control temperature, Table 15 lists the time taken from the start of the test for the temperatures to reach 60°C at 1.2 m (crouching or sitting height) for the positions A, B, C and D. For tests CFT5 this temperature is never reached. For test CFT3, the unsprayed test 60°C is reached within the time range of 2 minutes 10 seconds to 2 minutes 20 seconds at the four positions. For tests CFT4, CFT6 and CFT7 this time is approximately doubled.

6.2.3 Smoke

Referring to Table 14, although the level of smoke is registered first at the forward location this is only marginally (approximately 10 s) in advance of the mid-cabin position. Thereafter the depth of the layer increases rapidly with the 0.3 m level indicating a visibility to an illuminated source of 0.9 m after less than 3 minutes. The increased density of smoke is attributable to combustion of the cabin furnishings.

With the full cabin sprayed, test CFT7, the mid-cabin position is first to be affected, some 30 to 40 seconds ahead of the forward position. As with the unfurnished, sprayed test, CFT2, the smoke appears to advance as a 'plug', in this case with meters at all three heights affected simultaneously, rather than only the top two meters in the unfurnished case. Smoke development is also much more rapid, with all meters registering a visibility for an illuminated source of less than 0.9 m after 2 min 40s. At 1.1 m a visibility of 1.8 m for an illuminated source was only maintained for just over 1 min 30s at the mid-cabin position and for only just over 2 minutes.

In contrast, in the two partially sprayed cases, CFT5 and CFT6, the measurements indicate that the smoke layer steadily deepens broadly simultaneously at both the mid-cabin and forward positions. Visibility for an illuminated source at 1.1 m (crouching or sitting height) remained above 1.8 m for nearly 5 minutes in test CFT5 and 3 minutes in test CFT6. The better performance in test CFT5 may be attributed to the fact that less furnishing material was consumed. It appears that, when the sprayed zone is restricted to the region of the cabin containing the fire opening, the smoke layer retains sufficient buoyancy to remain stratified as it passes through the remaining part of the cabin.

6.2.4 Damage to furnishings

As indicated in the diagrams shown in Appendix G, the damage to the interior furnishings for the unsprayed test, CFT3, provides a baseline for comparison with the sprayed tests. In this case the central triple seat opposite the opening and the forward triple seat were severely damaged with the seat assembly nearest the door completely burnt away. The foam in rear triple seat was largely melted and the cover of the central double seat was charred. The roof and simulated fittings were either completely burnt or severely damaged.

In test CFT4 the seat nearest the fire of the central triple unit was completely burnt away as was the equivalent seat in the forward triple unit but damage to the remainder of these units were much less damaged than in test CFT3. The central double unit was completely undamaged and the rear triple unit was subject to some charring of the cover and a small amount of melting of the foam. The damage in CFT6 was similar.

In test CFT5 damage was almost entirely limited to the seat nearest the fire of the central triple unit. The equivalent seat in the forward triple unit sustained some charring and burning away of foam. In CFT7 the main damage was slightly more extensive with the major part of the seat nearest the fire opening burnt away and severe damage to the adjacent seat and to the outer seat of the forward unit.

In general the damage to the cabin furnishings and the material consumed in the fire correlated with the temperature levels measured in the cabin.

7. LIFE THREAT ANALYSIS

7.1 Introduction

This life threat modelling technique uses the cumulative doses of the various hazards of the fire atmosphere. At each small time interval into the fire (30 seconds has been used in this treatment) a comparison is made between the doses received, expressed as the numerator of a fraction, and the dose known to cause incapacitation or death, expressed as the denominator of the fraction. These Fractional Effective Doses (FEDs) are summed throughout the fire until the fraction equals unity, when incapacitation or death is predicted.

For the results presented here estimates have been made of the likely tenability time for passengers, in terms of incapacitation. A detailed examination has been made of four situations to give a basic comparison between conditions in an unsprayed fire (CFT3), a fully sprayed fire (CFT7) and two zone sprayed fires, one (CFT5) with standard Type A nozzles and one (CFT6) with nozzles giving a similar size distribution, but lower flow rate. The analysis is made for conditions in the mid passenger cabin at head height (1.7 metres) at sampling point G2, 13 metres from the front of the fuselage and about 8 metres from the fire opening.

7.2 Detailed Examination of Life Threat Hazard for Furnished Unsprayed Fire Test (CFT3)

The first part of the analysis is to calculate the cumulative FED for incapacitation (loss of consciousness) due to the effects of narcotic gases (carbon monoxide, hydrogen cyanide, carbon dioxide and low oxygen hypoxia). The analysis for the furnished, unsprayed test is shown in Table 16. The table shows the average concentrations of narcotic gases during each 30 second period for the first 3.5 minutes of the fire. The concentrations of carbon monoxide and hydrogen cyanide become toxicologically significant during the second minute, and incapacitation (loss of consciousness) is predicted at 2 minutes 15 seconds, due almost entirely to the effects of hydrogen cyanide. Approximately 30 seconds later incapacitation due to convected heat from pain and burns is predicted, with the level of radiant heat becoming unbearably painful, exceeding the tenability limit of 2.5 kW/m^2 at the same time.

Earlier in the fire some degree of incapacitation is predicted from the effects of smoke particulate containing irritant organic products, and acid gases, including HCl and HBr. Unfortunately, HCl data from the grab samples taken at one minute intervals are unreliably low, so that although it is known from the integrated samples that the average concentrations of irritant organic particulate and acid gases were high during the period from 1-4 minutes, the time concentration profile is unknown. However, based on the existing HCl grab sample data, data from a previous aircraft fire test (Reference 19), and the fact that PVC is known to release HCl at alow temperatures, and therefore early in fires, it is considered likely that the combined concentrations of HCl and HBr alone may have reached 1000 ppm early in the fire, between approximately 1 minute and 1 minute 30 seconds. Similarly, the concentration of particulate matter in the smoke was high, at approximately 12 mg/l (respirable fraction 6.6 mg/l). It is therefore considered that at this time the atmosphere would have been highly irritant causing extremely painful eye irritation and breathing difficulties that would be incapacitating and impair, or even prevent, escape attempts.

At 1 minute 40 seconds the tenability limit for smoke obscuration (2 metres visibility) is exceeded at 1.7 metres height, so that, combined with the painful eye irritation and respiratory tract pain, it would be very difficult to move through the aircraft cabin. Because the smoke was thick and irritant it is considered that occupants breathing it for more than approximately 2 minutes and surviving the immediate fire exposure are likely to suffer some degree of lung damage a few hours later, which could be fatal.

In summary, passengers standing upright in the mid cabin region would become exposed to an optically dense, choking, irritant smoke during the second minute which would severely impair escape attempts. Passengers still in the cabin at 2 minutes 15 seconds would collapse unconscious, and probably be dead approximately a minute later due primarily to cyanide poisoning. At 2 minutes 45 seconds any survivors would be severely burned, and this would be rapidly fatal if they were not already dead from the effects of toxic gases.

7.3 Detailed Examination of Life Threat Hazard for a Furnished, Fully Sprayed Fire Test (CFT7)

7.3.1 General analysis

Details of the life threat hazard analysis for a furnished, fully sprayed cabin fire test (CFT7) are shown in Table 17. As in the previous section, the analysis is for the mid cabin position at 1.7 metres height. Here, however, the analysis has been performed from 2.5 minutes onwards, since toxic gas levels were insignificant before this time.

Table 17 shows the average toxic gas concentrations during 30 second periods starting with the period 2.5-3.0 minutes up to the period 5.5-6.0 minutes. Toxic gases reach toxicologically threatening concentrations at approximately 4.5 minutes, and incapacitation (loss of consciousness)due to the effects of narcotic gases is predicted at 5 minutes 30 seconds.

The level of radiant heat does not reach the tenability limit of 2.5 W/m^2 at any time. The maximum level 1.2 W/m^2 was reached during the sixth minute of the fire.

Based upon the algorithm for dry or slightly humid air, convected heat did not reach threatening levels at any point during the first 6 minutes of the test. After 6 minutes the accumulated heat dose was only about a tenth of that required to cause incapacitation. However, it is possible that there may have been some added heat burden from the condensation of water vapour and the impact of heated spray droplets on the skin.

7.3.2 Problems with breathing hot, humid air

Since it is known that human subjects can tolerate breathing fully saturated air up to 60°C (References 10 and 11), there should be no problem up to 4 minutes into the test when the mean temperature at 1.7 m was 56°C. The approximate humidity measurements made at 0.8 m in the cabin at this point suggest that the cabin air was highly saturated with water vapour from approximately 4 minutes 30 seconds. It is therefore likely that the cabin air at 1.7 metres height would be very difficult to breathe after 4 minutes and might well cause serious skin and respiratory tract burns, although the air at 0.8 m, which did not exceed 60°C, would have remained breathable in terms of heat content throughout test.

7.3.3 Possible problems from skin contact with hot spray droplets

For the sprayed tests, water was sprayed at a rate of approximately 1 $l/min/m^2$ floor area, and the cabin temperature from 4 minutes 30 seconds to 5 minutes during this test was 87°C. Assuming that this water landed normal to the skin and was immediately cooled to 37°C, then the heat delivered would be 3.5 kW/m^2 or, if cooled to 45°C (skin pain threshold) then the heat delivered would be 2.9 kW/m^2. At the cabin temperature of 70°C, which occurred between 4 minutes to 4 minutes 30 seconds, the heat delivered would be 2.5 kW/m^2, if cooled to 37°C. It is known that radiant heat at 2.5 kW/m^2 causes severe pain after 20 seconds exposure. Therefore, assuming a similar heat transfer, there might be a problem from hot droplets after about 4 minutes 30 seconds. However, there are a number of mitigating factors which would reduce the actual heat flux to the skin:

(i) These temperatures were measured at 1.7 metres height, while the temperature at 0.8 metres was approximately 40°C cooler. The only part of the body likely to be at risk would be the skin of the face and the ears. Since it is likely that at this stage an occupant would be crouching to reduce their exposure to heat and smoke, it is likely that serious problems could be avoided.

(ii) During the early stages of the fire, a buffer layer of cold water would build up on the skin. This would reduce the skin temperature by diluting the impinging hot water.

(iii) Even a small amount of evaporation would reduce the droplet temperature. For instance a 5% reduction in mass by evaporation would cool a droplet from 87° to 60°C. Cooling further to 45°C at the skin would release only about 1.0 W/m^2, which would not be dangerous.

Therefore, from Table 17, there should not be a problem from contact with hot droplets during the first 4 minutes 30 seconds after operation of the spray, even if no droplet cooling occurred. If only minimal evaporative cooling occurred then there should not be a problem from this source up to the point when incapacitation is predicted from the effects of narcotic gases (5 minutes 40 seconds).

7.3.4 Particulates

Although the concentration of total particulate matter trapped by the horizontally sampling open face filter in this fire was very high, at 105.5 mg/l, the concentration of respirable particulate was relatively low, at 2.2 mg/l, compared to 6.6 mg/l in the unsprayed fire. Also, since the filter was wet, it is considered that the excess mass deposited represents water droplets of large particle size that might be trapped in the mouth and throat, but would not penetrate into the lung.

Since the concentration of acid gas (HCl) associated with the particulate was low (99 ppm equivalent) up to 4 minutes, it is considered that although the atmosphere would have been irritating, it would not be sufficiently irritant to seriously impair escape.

One problem is that the tenability for visual obscuration was exceeded early in the fire at 1 minute 30 seconds, slightly earlier than for the unsprayed fire (see sections 6.1.3 and 6.2.3). This may have some effect on escape capability possibly by reducing the efficiency and speed of escape movements. However, since the degree of visual obscuration in the forward cabin was less at this stage, and since the temperature and irritancy of the smoke were not extreme, it is considered that escape would not be prevented under these conditions.

7.3.5 Summary of effects

In summary it is predicted that although there would be some problems from visual obscuration and eye irritation during the early stages of the fire (at approximately 1 minute 30 seconds) no serious hazard develops for a person standing upright in the mid cabin until 4 minutes, after which the hot, humid, air at head height might cause pain and burns to the skin and respiratory tract. Following this, loss of consciousness is predicted at 5 minutes 30 seconds, mainly due to the combined effects of carbon monoxide and hydrogen cyanide. If these hazards were avoided (by keeping the head down at a lower, cooler level), then conditions could be tolerated up to at least 5 minutes 30 seconds, and possibly for longer. It is considered that skin contact with hot spray droplets is unlikely to be a problem up to this point. It is also considered that the presence of fine water spray droplets and smoke containing low concentrations of acid gases would not cause serious lung damage after exposure, in subjects remaining in the cabin up to 6 minutes.

The overall effect of the spray is to increase the time available for escape (time to incapacitation) based upon the measured hazards, by approximately 1 minute 45 seconds, from 2 minutes 15 seconds to 4 minutes, for a person standing upright in the mid cabin, and by at least 3 minutes 45 seconds, to 5 minutes 30 seconds, for a person keeping their head down at a lower level.

7.3.6 Comparison with replicate fully sprayed test (CFT4)

The results of the other fully sprayed test (CFT4) were substantially similar to those of CFT7, despite the failure of one of the spray nozzles. The concentration/time profiles for the toxic gases were similar, with incapacitation from narcosis being predicted approximately one minute earlier at approximately

4 minutes 30 seconds. The temperatures and radiant heat fluxes were also similar, so that incapacitation is not predicted during the test based upon the algorithm for dry or slightly humid air. However, the same problem with hot, humid air and hot spray droplets would apply from approximately 4 minutes as with CFT7. With regard to particulates, the respirable fraction was similar to that in CFT7, but the total particulate, although much higher than in any other tests at 24 mg/l, was considerably less than that of CFT7, and the filter was not damp. It is therefore considered that somewhat fewer water droplets were trapped. The concentration of acid gases (HCl) was similar to that of CFT7. It is therefore considered that the overall life threat of CFT4 would be similar to that of CFT7.

7.4. Detailed Examination of Life Threat Hazard for a Furnished, Zone Sprayed Test (CFT5)

7.4.1 General analysis

Details of the life threat analysis for a furnished, zone sprayed cabin fire test (CFT5) are shown in Table 18. As in the previous sections, the analysis is for the mid-cabin position at 1.7 metres height. As with the fully sprayed test described in the previous section, the analysis for the zone sprayed test has been performed from 2 minutes 30 seconds onward, since toxic gas concentrations were insignificant before this time.

Table 18 shows the average concentrations of toxic gases during 30 second periods starting with the period 2 minutes 30 seconds to 3 minutes up to the period 5 minutes 30 seconds to 6 minutes. Toxic gas concentrations were very low throughout the test and did not reach toxicologically threatening concentrations at any time, so that incapacitation is not predicted. By 6 minutes the accumulated dose of narcotic gases was less than a tenth of that required to cause incapacitation.

The level of radiant heat did not reach the tenability limit of 2.5 kW/m^2 at any time. The maximum level of 1.2 kW/m^2 was reached at 7 minutes.

Based upon the algorithm for dry or slightly humid air, convected heat did jot reach threatening levels at any point during the test, the temperature being only slightly above ambient during most of the test. After 6 minutes the accumulated heat does was only about one fiftieth of that required to cause incapacitation. However, as with the fully sprayed test, it is necessary to consider the effects of the possible added heat burden from the condensation of water vapour.

7.4.2 Possible effects of humid air in zone sprayed test

As Table 18 shows, up to the sixth minute the temperature was well below the upper experimental tolerance level of 60°C for breathing saturated air. For the thermocouple set at 1.7 metres height near the gas sampling point, the peak temperature was 46°C at 7 minutes, at which time the temperature at 0.8 metres was 23°C and the approximate relative humidity was 55%. For the cabin thermocouple (C5) nearest to sampling point G2, the temperature recorded at 7 minutes was somewhat higher, at 73°C. It is therefore considered that the heat at this point would be tolerable up to 6 minutes 30 seconds and, probably, up to 7 minutes (the end of the test), since the cabin air is unlikely to have been fully saturated.

7.4.3 Possibility of problems from skin contact with hot spray droplets in zone sprayed test

Since the fire zone was the only area sprayed, passengers in the mid-cabin position should not be significantly affected by spray drops. There was no evidence from the sampling devices indicating the presence of water spray droplets.

7.4.4 Particulates

The concentrations of both the total particulates and the respirable fraction in this zone sprayed test were by far the lowest of any test, being more than an order of magnitude lower than in the other tests with a furnished fuselage. There was no evidence for the deposition of water droplets carried from the sprayed zone. The small amount of particulates present may have been slightly irritant, but not sufficiently so to cause lung damage or to seriously affect escape. Similarly, the concentration of acid gas (hydrogen chloride) was too low to cause more than slight irritation.

Despite these low particulate concentrations, there was a significant concentration of optically dense smoke at the mid-cabin region at a height of 1.7 metres. Although the smoke was much less dense than for all of the other tests, the optical density still exceeded the tenability limit of an OD/m of 0.5, after approximately 2 minutes. However, since the smoke remained stratified the visibility at crouching height was much improved. It is therefore considered not to present a serious obstacle to escape.

7.4.5 Summary of effects

In summary, for a person standing upright in the mid-cabin, it is predicted that there might be some problems from visual obscuration and mild eye irritation after approximately 2 minutes, but much less than in the non-sprayed and fully sprayed tests. There may also be some eye and respiratory tract irritation from smoke but not sufficient to cause serious incapacitation and much less than from the other tests. There may also be some discomfort from breathing humid air after 7 minutes.

7.5 Detailed Examination of Life Threat Hazard for a Furnished, Zone Sprayed Fire Test (CFT6) Using Lower Flow Rate Nozzles

7.5.1 General analysis

The second zone sprayed test (CFT6) was designed to investigate the effect of reducing the volume of water delivered while retaining the same droplet size distribution. For this a nozzle similar to the type A nozzle, but with a reduced flow rate (70%) was used, with application over the same restricted zone as in test CFT5. The results show that this arrangement was less effective than CFT5. Reasonable control was maintained for about 4 minutes, after which conditions worsened rapidly (as to some extent in tests CFT4 and CFT7). Details of the life threat hazard analysis for the mid-cabin position at a height of 1.7 metres are shown in Table 19 which covers 30 second periods, starting with the period 2 minutes 30 seconds to 3 minutes, up to the period 5 minutes 30 seconds to 6 minutes. The concentration/time profiles for carbon dioxide and oxygen were somewhat similar to those in the full sprayed test, CFT7, but carbon monoxide was present at a relatively low concentration. Thus for tests CFT3, CFT5 and CFT7, the CO/CO_2 ratios at a similar stage of the fire (4 minutes for CFT5 and CFT7 and 2.5 minutes for CFT3) were 1:8, for CFT6, at the same stage, the ratio was 1:47. This suggests a more efficient combustion than for the other fires, with heat more likely to be a problem at an early stage than narcotic gases. This is, indeed, the case so that narcotic gases provide a predicted time to incapacitation of 6 minutes (principally based upon the effects of CO_2, hydrogen cyanide and reduced O_2. However, the cabin temperature becomes high at an early stage, so that incapacitation from heat and burns, based upon the algorithm for dry or slightly humid air is predicted at 5 minutes. The radiation tenability limit was not exceeded until 6 minutes 30 seconds.

7.5.2 Problems from hot, humid air

Because the cabin temperature rose early in the test, hot, humid air may become a serious problem at an early stage. As Table 19 shows, the cabin temperature at head height was already at an average of 72°C over the period 2 minutes 30 seconds to 3 minutes and was 61°C during the previous half minute. It is likely that, if the air was fully saturated, it would be breathable up to 2 minutes 30 seconds but that problems would occur after 3 minutes. At the lower level of 1.1 metre, however, the temperature remained below 60°C until 5 minutes 30 seconds.

In considering the probability that the air at 1.7 m was fully saturated it is useful to make a comparison with the fully sprayed test, CFT7, at the 1.1 metre height. The, albeit, approximate humidity measurements indicated that the air was much closer to saturation in the CFT7 than in CFT6, where levels of approximately 50% were measured. If it is assumed, similarly, that the level of humidity at

1.7 m was substantially below full saturation, say at 50% relative humidity, then the air would remain breathable at this height beyond 3 minutes.

As with the other zone sprayed test, CFT5, there would be no problem at the mid-cabin position from the deposition of water droplets on the skin.

7.5.3 Smoke and particulates

The smoke tenability limit is exceeded at 1.7 m after 2.5 minutes after which the smoke becomes dense. The total particulate concentration was approximately half of that found in the unsprayed test and was found to consist principally of sticky, brown particles, as in the unsprayed test. The concentration of acid gases (HCl and HBr) associated with the particulate was found to be high, although only a tenth of that in the unsprayed fire, and it is considered that the smoke would be irritant to the eyes and respiratory tract.

7.5.4 Summary of effects

In summary it is predicted that serious incapacitation due to the effects of heat and dense irritant smoke would occur at approximately 3 minutes.

7.6 Examination of life threat hazard for unfurnished fire tests and general comparison of all tests at different positions within the cabin

7.6.1 General

In order to give an overall impression of the effects of the cabin sprays on survivability Table 20 summarises predicted time to incapacitation from toxic products and from convected heat for all tests (CFT1-CFT7) for 4 positions in the fuselage, G1 near the fire at 1.7 m height, G2 and G3 at mid cabin, 1.1 and 1.7 m height, and G4 near the front of the fuselage at 1.1 m height. Since HCN was measured only at sampling point G2 (mid cabin, 1.7 m height), a full FED analysis for all toxic gases can be performed at this point only. Since the source of HCN is the cabin contents, this affects only the furnished fires. The FED calculations for the other sampling points show the effects of the other gases, and the influence of HCN at point G2 is illustrated by the set of calculations for this point with and without HCN.

7.6.2 Unfurnished tests

As Figure 21 shows, there was a peak of carbon monoxide and carbon dioxide, and a trough in oxygen concentration in the cabin between approximately 6 and 7 minutes into the fuel only, unsprayed fire, a profile not dissimilar to that of CFT7, apart from the absence of HCN. These gases are predicted to cause incapacitation after 6 minutes 40 seconds for CFT1. In contrast, the sprayed, fuel only fire (CFT2) showed little penetration of fire gases until 8 minutes, so that incapacitation is not predicted.

An examination of the effects of heat at point G2 (mid cabin, 1.7 m height) for CFT1 gives an FED for convected heat which exceeds unity after 4 minutes 55 seconds, from which point conditions become severe as the temperature exceeds 300°C. So for this fire temperature was the limiting factor for tenability rather than toxic gases as in the furnished fire tests. The table also illustrates the increased tenability time (by approximately 1 minute) nearer the floor, and the decreased time (by just over 1 minute, nearer the doorway and the fire). For (CFT2), although the temperature profile near the door is similar to that in the unsprayed test, the temperatures further inside the cabin are lower, but it is likely that the humidity would be high, so that incapacitation is considered to occur when the temperature exceeds 60°C, at approximately 4 minutes 30 seconds. At the lower level of 1.1 m, survivability is increased to approximately 5 minutes 30 seconds for both CFT1 and CFT2.

7.6.3 Furnished tests

Table 20 also shows the FEDs for the narcotic gases for the various furnished cabin tests. The table clearly illustrates the dramatic difference between the unsprayed test (CFT3) and the sprayed tests, all of which improve tenability based upon toxic gas concentrations by several minutes. The short time of 2 minutes 20 seconds to reach an FED of 1 for CFT3 is almost entirely due to the high HCN concentration in the fire at that time while the longer tenabilities in the other tests reflects the more gradually increasing concentrations, particularly of CO and HCN. Without HCN the tenability time for toxic gases is increased by approximately one minute for CFT3 at point G2. Results for the two fully sprayed tests CFT4 and CFT7 are similar (despite a partial malfunction of the spray system during test CFT4), but the zone sprayed tests gave better protection from toxic gases. This was especially true of the zone sprayed test CFT5, for which the atmosphere was tenable throughout the test.

Since the permanent gases were sampled at all four points it is possible to do a partial analysis of all the fires for comparative purposes. For the unfurnished fire, the cabin filled with smoke so rapidly that there is little difference between the toxic gas FEDs at different locations within the cabin. For the fully sprayed tests, where the fire development was slower, there was a tendency for a shorter tenability nearer the fire, and an increased tenability nearer the cabin floor at the mid cabin point. Another point concerning these figures is that for point G2 they provide an illustration of the effects of HCN on the toxic gas tenability time. Thus for the unsprayed fire CFT3, the presence of HCN reduces the tenability for toxic gas exposure by approximately 1 minute, for the sprayed fire CFT7 by approximately 35 seconds, and for the sprayed fire CFT4 by approximately 1 minute.

With regard to convected heat, Table 20 shows the results for the unsprayed test (CFT3), the rapidly increasing FED at point G2 exceeding unity approximately half a minute after the rapidly increasing HCN FED. The table also shows a tenability of approximately 1 minute 30 seconds near the fire opening, and the slightly increased tenability in the middle and front of the cabin at the lower level above the floor. For CFT5 there is an exceptionally good result with the tenability limit exceeded only for heat near the fire opening after 5 minutes 30 seconds. The results for the second zone sprayed test (CFT6) are rather disappointing when compared to the first (CFT5). In CFT6, the temperature near the door increased rapidly from 1 minute 40 seconds, which is similar to the unsprayed, furnished fire (CFT3), but approximately 100 seconds earlier than the time of rapid temperature increase in the other tests. This is reflected in the temperature further down the cabin at point G2, where the 60°C tenability limit for saturated air is exceeded after approximately 3 minutes, although the FED for toxic gases is low at this time. This contrasts with the fully sprayed test CFT7, where a rapid temperature rise near the door did not occur until approximately 3 minutes 20 seconds, and the 60°C temperature limit is not exceeded until 4 minutes at point G2. However, despite these lower temperatures, the concentrations of toxic gases became significant at an earlier stage, so that the FED limit for toxic gases was exceeded after 5 minutes 40 seconds for CFT7, but not until 6 minutes for CFT6. The effect of radiant heat at the various sampling points is presented in Table 13, which shows the time taken for radiation levels to reach the tenability limit of 2.5 kW/m^2.

8. DISCUSSION

8.1 Introduction

The main aim of these experiments was to determine whether the use of a fine water spray improved the survivability of fires in aircraft cabins resulting from external fuel fires, by increasing the time taken from ignition of a large fuel fire to the development of conditions in the cabin capable of preventing escape and endangering life.

It was anticipated that possible factors contributing to this improvement would be the following:

(a) Inhibition of fire development within the cabin.

(b) Reduction in temperature of fire gases and the attenuation of thermal radiation.

(c) Removal of toxic components from fire gases.

(d) Removal of smoke and particulates, improving visibility and reducing inhalation of toxic components adsorbed to particulates.

The extent of the evidence from the full-scale tests in support of the contribution of these factors is discussed in this chapter, together with consideration of some possible disbenefits from the use of water sprays.

8.2 Effects on Fire Development

It is very clear from the visual evidence, recorded on videotape and summarised in Appendix F, that the rate of spread of fire in the cabin furnishings was considerably reduced by the operation of the water sprays. Further evidence is given by the degree of damage to the furnishings after the fire had been extinguished. In the absence of a water spray the seating materials and the roof and wall linings were either completely burnt away or severely damaged, whereas only limited damage, principally to the seat immediately adjacent to the fire opening, occurred with the full (CFT7) and zoned (CFT5) sprays operating at 1 l/min/m^2. The damage was slightly more extensive where the delivered flow rate, per nozzle, was lower either by design (CFT6) or due to malfunction (CFT4), but still showed a considerable improvement over the unsprayed case.

Possible mechanisms for the effect of water sprays include wetting of cabin materials, attenuation of thermal radiation from the fire by the spray and deposited water (for instance on the wall surfaces) and the effect of spray evaporation on the combustion reaction. Radiation attenuation is discussed further later, but these processes, particularly the last, are not well understood and await detailed, fundamental investigation. Full evaporation of the water from one nozzle at 1 l/min/m^2 would remove sensible heat at a rate of approximately 37 kW. If this evaporation occurred near to the flame front, the reduction in temperature could inhibit the combustion process, affecting penetration of the external fire into the cabin.

8.3 Temperature and Thermal Radiation

As the comparisons, in figures 33 to 37, between the unsprayed and sprayed tests for both the unfurnished (CFT1 and CFT2) and furnished (CFT3 and CFT4 to CFT7) cases illustrate, the measured temperatures at all locations within the cabin were much lower with the presence of water sprays at a flow rate of 1 l/min/m^2, but not for the reduced spray volume test (CFT6). This is reflected in the calculated times to incapacitation based on sensible heat content of cabin atmospheres. Incapacitation related to temperature elevation at the mid-cabin location at a height of 1.7 m is predicted after about 2 minutes 45 seconds with no spray, was delayed to approximately 5 minutes with the reduced flow rate, zoned spray (CFT6) and was predicted not to occur at all with either the zoned or full spray at a flow rate of 1 l/min/m^2.

However, if the major mechanism for cooling the fire gases in their transit through the cabin has been the evaporation of the spray droplets, rather than convective transfer to droplets which fall to the floor, then the heat is retained in latent form and can be released if the fire gases are cooled and condensation occurs. As discussed in Section 3.5, this may be taken into account by assuming a worst case situation - that the cabin atmosphere is fully-saturated. On this basis, a conservative, maximum measured temperature would be 60°C, in order to ensure that no irreversible effects occurred to the lungs or respiratory tract. Using this temperature incapacitation would still not occur at 1.7 m at the mid-cabin location for the zoned, full flow rate spray (CFT5) but would occur after 4 minutes for the unzoned, full flow rate spray (CFT7) and after only about 3 minutes for the zoned, reduced spray (CFT6). The latter showing little improvement over the unsprayed case (CFT3) in relation to heat effects. However, in both cases considerable improvement over the unsprayed case is achieved at crouching height, extending the time to incapacitation by 2 minutes 30 seconds for the zoned, reduced rate spray (CFT6).

The presence of a water spray has a substantial effect on the levels of thermal radiation within the cabin. In the absence of water spray the tolerable level for skin exposure of 2.5 kW/m^2 is exceeded almost immediately at a position opposite the fire opening and at a time between 2 minutes 30 seconds and 3 minutes at other locations. In all of the sprayed tests the tenability limit was not reached for the latter locations and the levels at the position opposite the fire opening were considerably reduced.

8.4 Toxic Components

In the furnished, unsprayed test (CFT3), the limiting factor with regard to escape was exposure to narcotic gases, and in particular hydrogen cyanide, which reached the exceptionally high concentration of 2000 ppm at mid-cabin after just over three minutes into the fire. This concentration would be instantly lethal (2) and incapacitation (loss of consciousness) is predicted at 2 minutes 15 seconds. By comparison the predicted times to incapacitation due to the effects of toxic gas exposure at the mid-cabin location in the sprayed tests were approximately 6 minutes or more (with the exception of CFT4). This is because the concentrations of narcotic gases, particularly HCN in the sprayed fires are very much lower, and also because significant concentrations occur later in the fire. The contribution of hydrogen cyanide to inducing incapacitation is somewhat less in the sprayed cases than in the unsprayed cases. This may be partly due to its great solubility in water compared with the other major contributory gas carbon monoxide. However, it is likely that the reduced involvement of the cabin furniture, and the lower fire temperatures are also partly responsible for the lower HCN concentrations and the lower CO/HCN ratios in the sprayed tests.

With regard to the irritant components of the fire gases, integrated samples taken between 1 and 4 minutes in the unsprayed, furnished test (CFT3) showed very high average, HCl and HBr concentrations, with a combined concentration of over 2000 ppm. Whereas HCN was found principally in the gas phase the hydrogen halides were principally adsorbed to particulates. From the thick, oily particulate collected it is likely that high concentrations of organic irritants were also present. It is considered that these concentrations of acid gases alone would have been sufficient to have prevented passengers from escaping, due to extreme eye and respiratory tract pain and breathing difficulties.

The difficulty is in deciding when, during the first minute or so of the fire, these irritants reached incapacitating concentrations. In an earlier series of similar tests on a furnished wide bodied jet fuselage (Reference 19), HCl and HF concentrations were high within half a minute of ignition, and became very high after 1 minute 30 seconds. Also, it is known that HCl is released from PVC at low temperatures (over approximately 200°C), so that when heat enters the cabin, it is to be expected that HCl will be one of the first products evolved from the cabin lining materials and other sources. Although the HCl recoveries from the grab samples were low, those obtained early in the fire were not much lower than those obtained after three minutes. For these reasons it is considered likely that the hydrogen halide concentrations in the fire would have increased rapidly as soon as significant heat entered the cabin. By 1 minute, therefore, it is likely that conditions in the cabin would have been painfully irritant, and soon after that they would have been bad enough to cause incapacitation.

By comparison the concentrations of HCl and HBr, measured at 1.7 m at the mid-cabin location averaged over the same three minute period, were considerably lower in the sprayed tests, particularly with the zoned sprays. For both the unsprayed and sprayed tests HCl and HBr were found to mainly associated with the particulate phase of the smoke. Since the sprays were found to be ineffective in washing out smoke particulates it is likely that the reductions in irritant acid gas concentrations are due mainly to the reduced fire in the cabin furnishings and cabin lining materials, and to increases in the depth of the smoke layer (and therefore smoke dilution). Thus the CO/HCl ratios were similar in the sprayed tests to those in the unsprayed test. However, since the water collected in the floor pots was acidic, and for the sprayed tests neither gas was found in measurable concentrations in the vapour phase, it is possible that some degree of acid gas washout occurred. Whatever the mechanism of irritant acid gas reduction, it is predicted that although some degree of irritant effects on the eyes and respiratory tract might occur, these effects would not be expected to cause serious incapacitation, impair escape or cause serious post-exposure lung damage.

8.5 Smoke and Particulates

The total mass of particulates measured, at the mid-cabin location over a period from 1 to 3 minutes after the start of the fire, were higher for the unsprayed furnished test (CFT3) than any of the sprayed tests. However, only for the zoned spray test (CFT5) were they substantially lower. In broad terms the mass of particulate was related to the degree of involvement of the cabin furnishings in the fire, indicating that the water spray had no major effect in removing particulate by 'washing out@, confirming the finding of the preliminary laboratory studies.

The measurements of smoke opacity confirmed that water sprays had little effect on improving visibility. On the basis of a limit of 2 m visibility (for light reflecting signs) the sprayed tests showed little improvement over the unsprayed test at head height in the mid-cabin position. The tenability limit was reached in all cases less than a minute after the unsprayed case (CFT3) at 1 minute 40 seconds and, in the case of the fully sprayed test (CFT7), earlier. However, further inspection of the results of measurements at different heights and at both the mid-cabin and forward positions indicated that in both the zoned spray tests (CFT5 and CFT6) the smoke layer remained stratified allowing substantially improved visibility at crouching height in comparison with the unsprayed test. However, in the fully-sprayed test (CFT7) the smoke appeared to move as a 'plug' through the cabin interfering with vision equally at levels as low as 0.3 m as at head height. This phenomenon of 'downdrag' of smoke layers has been observed in the action of fire sprinklers within buildings and results from the loss of buoyancy of the smoke layer as it is cooled. There is clearly a major advantage in the use of sprays applied only to a zone near the fire source.

8.6 Possible Hazards from Water Droplets

Irritant products in unsprayed smoke exist partly as gases and partly attached to small solid particles and liquid droplets. Depending upon the aqueous solubility of the gases, and the size of the particles these are capable of penetrating into and damaging the respiratory tract to a varying extent. The water spray droplets are too large at formation to be inhaled into the lungs and it is therefore possible that water spray could be beneficial in scrubbing water soluble acid gases from the vapour phase of the smoke, thereby preventing them from being inhaled. There was, however, a possibility that the contaminated water spray droplets may themselves become small enough by evaporation to penetrate into the lungs and even increase the quantity of irritant toxic products deposited in the delicate small airways and alveolar region (some of which would otherwise tend to be absorbed in the upper airways). It was for these reasons that the particulate size distribution of the smoke and water spray atmospheres, and the associated dissolved or adsorbed acid gases, were measured.

The unsprayed, fuel only fire (CFT1), produced a light sooty particulate in the cabin, whereas the unsprayed, furnished fire (CFT3) produced a high concentration of thick, oily particulate, to which was attached high concentrations of HCl and HBr. In fact all the HCl was found to be attached to particulate, with none present as vapour. Of this particulate, 64% was respirable, capable of penetrating deep into the lung, and most of the HCl was attached to the smaller respirable fraction. The remainder of the particulate was also relatively small in size (less than approximately 20 µm diameter) and capable of penetrating into the nose, mouth and airways. It is therefore considered that this particulate would have been highly irritant, and capable of doing considerable damage to the lungs if sufficient was inhaled. It is likely to be more dangerous than the equivalent concentration of HCl in vapour form. since this is less able to penetrate deep into the lung. Nevertheless the inhalation of this atmosphere for 4 minutes would only provide approximately a tenth of the lethal dose of hydrogen chloride and bromide, so it is considered that these components alone would not cause serious lung damage.

However, it is known that fire survivors who have been exposed to smoke do suffer lung damage even if they are not burned, and it is possible that these acid gases, together with organic irritants, such as isocyanates, attached to the smoke particles, might present a more serious threat to the lungs. If such effects did occur they would normally develop some hours after exposure in the fire.

When spray is applied to the fire the effect is clearly beneficial, because the concentrations of acid gases are considerably reduced, as well as the other toxic gases. The total concentration of respirable particles is also decreased, by approximately a factor of three in the fully sprayed tests. The total amount of particulate, including any respirable water droplets, capable of penetrating into the deep lungs (< 5 µm diameter) is therefore reduced.

However, there was some evidence for the presence of some relatively small water spray droplets in the fully sprayed tests. This evidence derives from a comparison of the deposits on the horizontally sampling open face filter, and those in the cascade impactors and the open face filters which sampled vertically upwards. In the fully sprayed tests the horizontal filter collected 10-30 times as much particulate as the other devices, and in one case it was wet. This filter also picked up more HCl in the fully sprayed test than in the zone sprayed tests, where the particulate collected, both total and respirable, was low. There is, therefore, some evidence that water droplets, small enough to be collected by this filter and to wet the top plates of the Casella (therefore of a size in the range 10-100 µm diameter), are present in the cabin during the fully sprayed tests.

It is considered that in these fully sprayed tests part of this water droplet aerosol would be inhalable; ie capable of penetrating into the mouth and possibly the throat of a subject breathing heavily, but would be unable to penetrate into the deep lung. It is likely that the total amount of particulate inhalable (water droplets plus smoke particles) would be greater in this situation than in the unsprayed test. However, it is considered that these droplets would be innocuous, despite the small amount of acid present in them, and possibly even beneficial, in that they reduce the amount of acid present in the smaller smoke particles which are capable of penetrating into the deep lung. With the zone sprayed tests there was considerably less particulate than in the unsprayed test, and there was no evidence for trapped water droplets.

9. CONCLUSIONS

(i) Comparison tests have been carried out under controlled conditions, to determine the effect of on-board water sprays on the atmosphere within an aircraft cabin exposed to a severe external fire at a breach in the cabin wall. Tests were carried out with water spray applied both to the full cabin and to a limited zone close to the fire opening. In the latter case, the effect of a reduced water delivery rate was also investigated. The results show that, based upon observation of the fire development, the degree of fire damage to the cabin fittings and furnishings and the measured levels of fire products, that the principal action of the water sprays is to reduce fire penetration into the cabin and to inhibit fire growth in the cabin contents.

(ii) Water sprays significantly reduce the temperature and levels of toxic and irritant fire products within the cabin. Using a Fractional Effective Dose approach, which allows the separate effects of the various harmful components of the fire products to be combined, a life threat analysis was carried out. This shows that, in all of the tests, the use of fine water sprays increased the time at which passengers, standing in the central aisle about 8 metres from the fire, would become incapacitated due to toxic gases by at least four minutes.

(iii) Temperatures and levels of thermal radiation were also substantially reduced by all of the spray arrangements. If the effects of latent heat due to the possible saturation of the cabin atmosphere with water vapour are taken into account, in the case of the zoned, standard flow rate spray, the improvement in the time to incapacitation, based on air temperature, remains the same as for the toxic gas assessment. The improvement is reduced in the case of the fully sprayed cabin to 1.7 minutes and in the reduced flow, zoned case to 0.7 minutes. However, in these cases the improvement is increased to 3.0 and 1.5 minutes respectively for exposure at crouching height.

(iv) The full cabin spray reduced the degree of stratification of the developing smoke layer within the cabin and led to a faster reduction in visibility in the region of the cabin away from the immediate fire zone than with no spray. This effect was much less marked with both of the zoned spray cases where the layer remained stratified.

(v) The use of the water spray was found to decrease greatly the amount of solid particles and liquid droplets capable of penetrating into the lungs, and also the irritants attached to them, thereby reducing the risk of lung damage. Although a small amount of larger, non-respirable droplets in the smoke may have been due to the water spray, these had a low dissolved acid gas content and are considered unlikely to present any additional hazard.

(vi) Overall, the most effective spray arrangement of those tested was found to be the zoned spray using standard SAVE nozzles, delivering 1 $l/min/m^2$.

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TABLE 1. CALCULATED HEAT DELIVERY TO LUNGS FROM BREATHING DRY OR SATURATED AIR AT DIFFERENT TEMPERATURES

Temperature and humidity	Heat flux (W)
200°C (dry)	13
90°C (saturated)	615
80°C (saturated)	232
70°C (saturated)	110
60°C (saturated)	53
50°C (saturated)	22
200°C dry air can be tolerated for from one to a few minutes	

TABLE 2. CHARACTERISTICS OF THE NOZZLES USED IN THE PRELIMINARY TESTS

Nozzle	Description	SMD* (at 6 bar)	Flow rate (at 6 bar)
A	SAVE spray (hollow cone)	230 µm	1.40 l/min
B	Disc and core (full cone)	240 µm	1.13 l/min
C	Multiple orifice ('fogjet')	152 µm	1.47 l/min
D	Disc and core (full cone)	294 µm	4.67 l/min

* SMD - Sauter Mean Diameter

TABLE 3. REDUCTION IN OBSCURATION* AFTER 360s SPRAY DISCHARGE

Fuel	Liquid	Reduction of smoke (%) at pressures:- 1.5 bar	3.0 bar	4.5 bar
Hexane	Water	15	14	18
	3% AFFF	15	14	17
	6% AFFF	10	14	20
	3% soap	13	14	19
	6% soap	13	21	19
Benzene	Water	14	23	29
	3% AFFF	11	26	33
	6% AFFF	10	27	33
	3% soap	15	29	41
	6% soap	15	31	34

* Average values of two or three experiments: all ± 3.

TABLE 4(a). DETAILS OF SERIES A TESTS USING A RANGE OF NOZZLE TYPES

No.	Test Ref	Nozzle Type	Number of heads	Orientation	Water pressure (bar)
A1	28	A	15	45°	3
A2	29	A	15	45°	3
A3	54	A	15	45°	6
A4	50	A	15	45°	9
A5	43	B	15	45°	3
A6	44	B	15	45°	6
A7	46	B	15	45°	9
A8	58	C	15	45°	6
A9	59	C	15	45°	9
A10	47	D	15	45°	3
A11	48	D	15	45°	6

TABLE 4(b). DETAILS OF SERIES B TESTS USING TYPE A NOZZLE ONLY

No.	Test Ref	Nozzle Type	Number of heads	Orien-tation	Water pressure (bar)	Comment
B1	7	A	18	V	3	No downstand
B2	9	A	18	V	3	No downstand
B3	11	A	15	V	3	No downstand
B4	13	A	32	V	3	No downstand
B5	24	A	9	V	3	
B6	26	A	15	V	3	
B7	27	A	15	V	2	
B8	30	A	15	45°	2	
B9	31	A	15	45°	4	
B10	34	A	12	45°	3	Zoned arrangement
B11	35	A	12	45°	3	Zoned arrangement

TABLE 5. SUMMARY OF RESULTS FROM SERIES A TESTS

No.	Nozzle Type	Total flow rate (l/min)	Smoke density (OD/m)	Rate of heat removal (kW)
A1	A	16.0	-	44
A2	A	16.0	-	42
A3	A	21.0	3.1	45
A4	A	24.0	2.4	63
A5	B	12.5	2.7	42
A6	B	17.0	2.8	57
A7	b	21.0	2.6	59
A8	C	22.1	2.9	51
A9	C	25.1	2.2	74
A10	D	50.0	2.3	61
A11	D	70.1	1.7	66

TABLE 6. SUMMARY OF RESULTS FROM SERIES B TESTS

No.	Nozzle Type	Total flow rate (l/min)	Rate of heat removal (kW)
B1	A	19.2	50
B2	A	19.2	55
B3	A	16.0	45
B4	A	34.1	85
B5	A	9.6	29
B6	A	16.0	47
B7	A	13.1	41
B8	A	13.1	32
B9	A	18.4	48
B10	A	12.8	40
B11	A	12.8	42

TABLE 7. BRIEF DESCRIPTION AND SCHEDULE OF TESTS

Test	Date	Description	Duration
CFT1	31/10/90	Unfurnished fuselage. No sprays.	6 min 40 s
CFT2	9/11/90	Unfurnished fuselage. Spray Type A operating over full length of fuselage	7 min 40 s
CFT3	18/11/90	Furnished fuselage. No sprays.	5 min 50 s
CFT4*	26/11/90	Furnished fuselage. Spray Type A operating over full length of fuselage.	6 min 0 s
CFT5	4/12/90	Furnished fuselage. Spray Type A operating over zone in region of the fire opening.	6 min 50 s
CFT6	18/12/90	Furnished fuselage. Reduced flow spray operating over zone in region of fire opening.	7 min 20 s
CFT7	22/01/91	Furnished fuselage. Spray Type A operating over full length of fuselage.	6 min 50 s

* This test was affected by a water supply pipe failure.

TABLE 8. TESTS CFT1 TO CFT7: ANALYSIS OF SPRAY WATER AND "FLOOR POTS"

Test	HCl in spray reservoir mg/l	HCl (pot) mg/l	HCN in spray reservoir ug/l	HCN (pot) ug/l
CFT5	64	115	0	5
CFT6		152		2274
CFT7		264		1537

TABLE 9. TESTS CFT 1 TO CFT 7: HYDROGEN CHLORIDE CONCENTRATIONS (PPM)

Test	CFT1 fuel only	CFT3 furn unspray	CFT4 full spray	CFT5 zone spray	CFT6 zone spray	CFT7 full spray
Grab sample		21	26	0	10	16
Open face filters (H=sampling horizontally - 1,3, sampling vertically)						
Filter H		568.7	338.2	31.1	17.6	198.0
gas phase		22.0	nd	-	nd	nd
Total		590.7	338.2	31.1	17.6	198.0
Filter 1		72.0	72.0		72.0	66.0
gas phase		215.0	16.0		16.0	tr
Total		287.0	88.0		88.0	66.0
Filter 3		59.0	66.0		86.0	66.0
gas phase		112.0	3.0		nd	tr
Total		171.0	69.0		86.0	66.0
May impinger						
Upper stage		331.8	29.0	1.1	32.3	19.8
Middle		459.4	97.7	9.0	84.3	70.0
Lower		224.6	24.4	12.5	14.5	8.8
Filter		11.0	1.5	0.4	-	0.7
Total		1026.8	152.6	23.0	131.1	99.3
Andersen sampler						
Stage 1		100.4	11.0	nd	9.4	7.8
Stage 2		51.8	-	nd	nd	3.1
Stage 3		14.1	20.4	1.5	11.0	20.4
Stage 4		9.4	17.3	11.8	31.4	29.8
Filter		37.6	3.1	5.9	4.7	1.6
Gas phase		4.7	nd	nd	nd	nd
Total		218.0	51.8	19.2	56.5	62.7
Casella						
Stage 1		17.0	2.3	nd	0.4	nd
Stage 2		17.0	1.1	nd	0.4	1.1
Stage 3		3.8	9.0	0.2	6.0	18.1
Stage 4		-	nd	nd	0.4	2.6
Filter		39.1	5.6	1.4	1.9	1.9
Total		76.9	18.0	1.6	9.1	23.7

TABLE 10. TESTS CFT 1 TO CFT 7: HYDROGEN CYANIDE CONCENTRATIONS (PPM)

Test	CFT1 fuel only	CFT3 furn unspray	CFT4 full spray	CFT5 zone spray	CFT6 zone spray	CFT7 full spray
Grab sample		836.3	30.3	4.2	0.0	22.0
Open face filters (H=sampling horizontally - 1,3 sampling vertically)						
Filter H		0.12	0.00		0.0	tr
gas phase		797.70	11.90		29.7	11.90
Total		797.82	11.90		29.7	11.90
Filter 1		tr	tr		4.1	tr
gas phase		544.00	15.00		24.00	11.00
Total		544.00	15.00		28.1	11.00
Filter 3		tr	tr		0.40	tr
gas phase		371.00	14.00		27.00	11.00
Total		371.00	14.00		27.40	11.00
May impinger						
Upper stage		0.36	0.00	0.24	nd	0.68
Middle		9.34	0.01	0.62	0.06	2.31
Lower		6.70	0.01	0.24	0.03	0.65
Filter		0.00	2.07	0.00	nd	tr
Total		16.40	2.09	1.10	0.09	3.60
Andersen sampler						
Stage 1		0.01	0.01	0.12	nd	nd
Stage 2		0.02	nd	0.02	nd	nd
Stage 3		nd	0.02	0.01	nd	nd
Stage 4		nd	0.01	0.03	nd	nd
Filter		0.02	0.01	nd	nd	nd
Gas phase		404.60	110.20	-	29.70	17.10
Total		404.70	110.25		29.70	17.10

TABLE 11. HYDROGEN CYANIDE - CONCENTRATIONS (PPM) AND PARTITION BETWEEN GAS PHASE AND PARTICULATE PHASE OF SMOKE

Test	CFT3 fuel only	CFT4 full spray	CFT7 full spray	CFT5 zone spray	CFT6 zone spray
Grab samples	836	30	22	4	0
Open face filter					
Filter	tr	tr	tr		0
Gas phase	798	12	12		29
Total	798	12	12		29
May liquid impinger					
Total	16	3	4	1	0
Andersen cascade impactor					
Plates	tr	tr	0		0
Gas phase	404	110	17		30

HYDROGEN CHLORIDE - CONCENTRATIONS (PPM) AND PARTITION BETWEEN GAS PHASE AND PARTICULATE PHASE OF SMOKE

Test	CFT3 fuel only	CFT4 full spray	CFT7 full spray	CFT5 zone spray	CFT6 zone spray
Grab samples	21	26	16	0	10
Open face filter					
Filter	569	338	198	31	18
Gas phase	22	0	0		0
Total	591	338	198	35	18
May liquid impinger					
Total HCl	1027	153	99	23	131
Total HBr	1228				160
Andersen cascade impactor					
Plates	213	52	63	19	57
Gas phase	5	0	0		0

TABLE 12. TESTS CFT 1 TO CFT 7: PARTICULATE CONCENTRATIONS 1-3 MINUTES (g/m^3)

Test	CFT1 fuel only	CFT3 furn unspray	CFT4 full spray	CFT5 zone spray	CFT6 zone spray	CFT7 full spray
Open Face H		11.60s	23.99	0.65	7.13	105.45w
Open Face 1	<0.1	6.70	1.20	-	2.20	0.67
Open Face 3	0.4	4.70	0.60	-	2.40	0.20
Andersen						
Stage 1	0.658	3.729	0.681	0.040	2.548	1.255w
2	0.581	2.379	0.429	0.027	0.069	0.260
3	0.512	2.331s	0.931	0.054	0.379	0.986d
4	0.315	1.364s	0.231	0.115	0.926	0.890d
Filter	0.620	0.562s	0.043	0.047	0.079	0.029
Total	2.686	10.365	2.315	0.283	4.001	3.423
Respir	2.028	6.636	1.634	0.243	1.453	2.168
% respir	76	64	71	86	36	63
Casella						
Stage 1		0.497	0.429w	0.017	0.354s	0.235w
2		0.923	0.019	0.010	0.943s	0.990w
3		0.349s	0.326	0.078	0.423	1.443d
4		0.512s	0.283	0.037	0.017	0.046
Filter		1.362s	0.000	0.124	0.013	0.124
Total		3.643	1.057	0.266	1.750	2.838
Respir		2.223	0.609	0.239	0.453	1.613
% respir		61	58	90	26	57

Key: s = sticky brown liquid, w = wet, layer of water visible on plate
d = damp appearance of soot
H = filter sampling horizontally
1,3 = filters sampling vertically

TABLE 13. TESTS CFT1 TO CFT7: TIME TAKEN (SECONDS) FOR RADIATION LEVELS TO REACH 2.5 kW/m^2

TEST	RADIOMETER POSITION			
	RD1	RD2	RD3	RD4
CFT1	312	297	24	152
CFT2	NR	NR	20	436
CFT3	198	176	16	153
CFT4	NR	NR	0	NR
CFT5	NR	NR	20	NR
CFT6	NR	NR	20	NR
CFT7	NR	NR	40	NR

NR - level not reached during test

TABLE 14. TIME FOR SMOKE VISIBILITY TO REACH GIVEN LEVELS

Test No	OD	OD/m	Visibility* (meters)		Time (seconds) to reach visibility level					
			I	II	Mid-cabin			Forward		
					1.7m	1.1m	0.3m	1.7m	1.1m	0.3m
CFT1	0.5	0.75	1.3	3.5	275	300	315	115	200	205
	1.0	1.51	0.66	1.8	290	310	355	150	200	215
	2.0	3.03	0.33	0.88	315	330	NR+	175	210	250
CFT2	0.5	0.75	1.3	3.5	170	170	290	190	190	230
	1.0	1.51	0.66	1.8	175	190	NR	200	210	250
	2.0	3.03	0.33	0.88	210	240	NR	210	240	290
CFT3	0.5	0.75	1.3	3.5	95	120	130	80	110	175
	1.0	1.51	0.66	1.8	95	125	140	85	120	180
	2.0	3.03	0.33	0.88	135	135	150	100	135	190
CFT5	0.5	0.75	1.3	3.5	125	245	390	125	300	335
	1.0	1.51	0.66	1.8	200	295	NR	190	NR	375
	2.0	3.03	0.33	0.88	NR	375	NR	310	NR	NR
CFT6	0.5	0.75	1.3	3.5	155	180	280	140	170	250
	1.0	1.51	0.66	1.8	165	190	310	155	180	265
	2.0	3.03	0.33	0.88	185	215	345	165	240	290
CFT7	0.5	0.75	1.3	3.5	85	85	80	120	120	120
	1.0	1.51	0.66	1.8	95	95	95	125	125	125
	2.0	3.03	0.33	0.88	120	110	125	130	130	160

* I - for light reflecting signs; II - for light-emitting signs

\+ NR - level not reached during test

TABLE 15. TIME TAKEN TO REACH 60°C AT A HEIGHT OF 1.2 M AT FOUR LOCATIONS IN THE MID TO FORWARD CABIN FOR TESTS WITH CABIN FURNISHED

Test No	Time (seconds) to reach a temperature of 60°C A	B	C	D
CFT3	130	140	140	130
CFT4	220	300	260	280
CFT5	NR	NR	NR	400
CFT6	270	260	260	260
CFT7	250	270	280	320

NR - Temperature of 60°C not reached at this location.

TABLE 16. AVERAGE CONCENTRATIONS OF TOXIC AND PHYSICAL HAZARDS AND FRACTIONAL INCAPACITATING DOSES OVER 30 SECOND PERIODS GAS SAMPLING LINE 2 - MID CABIN HEAD HEIGHT FURNISHED UNSPRAYED TEST - CFT3

Fractional effective doses of narcotic gases							
Time(min)	0.5	1.0	1.5	2.0	2.5	3.0	3.5
Gas concentrations							
CO ppm	8	34	282	1157	3326	8410	19490
HCN ppm	0	10	38	143	340	740	1380
CO_2 %	0.0	0.0	0.4	1.2	2.8	4.1	6.0
O_2 %	21	21	21	20	18	16	13
Fractional incapacitating doses							
FED_{CO}	0.00	0.00	0.00	0.02	0.06	0.16	0.38
FED_{HCN}	0.00	0.00	0.01	0.06	5.65	>10	>10
VCO_2	1.00	1.00	1.12	1.31	1.77	2.27	3.26
FED_O	0.00	0.00	0.00	0.00	0.00	0.00	0.01
FED/30s	0.00	0.00	0.00	0.10	10.10	>10	>10
Σ FED	0.00	0.00	0.00	0.11	11.10	>10	>10
Fractional effective doses of convected heat							
Temp °C	12	14	28	81	156	274	408
FED/30s	0.00	0.00	0.01	0.03	0.20	4.96	>10
Σ FED	0.00	0.00	0.01	0.04	0.24	5.20	>10
Radiant heat flux							
kW/m^2	1.0	1.2	1.4	1.8	2.3	2.8	5.7

Time to exceed smoke tenability limit: 1 minute 40 seconds
Time to incapacitation by narcotic gases: 2 minute 15 seconds
Time to incapacitation by convected heat: 2 minutes 45 seconds
Time to tenability limit for radiant heat: 2 minutes 45 seconds

Effects of irritants:

Over period between 1 and 4 minutes:	average respirable particulates	6.7 mg/l
	average total particulates	11.6 mg/l
	average HCl concentration	1027 ppm
	average HBr concentration	1228 ppm

It is considered that the oily, organic rich, particulate collected, with its very high acid gas content, would be highly irritant and extremely painful to eyes and breathing, causing incapacitation and impairing escape attempts. It is considered likely that these irritants reached high concentrations (approaching 1000 ppm total acid gases) early in the fire at approximately 1-1.5 minutes, from which time escape capability would be significantly impaired. It is likely that occupants breathing the smoke irritants for more than approximately 2 minutes and surviving the immediate fire exposure may suffer lung damage a few hours later, which could be fatal.

TABLE 17. AVERAGE CONCENTRATIONS OF TOXIC AND PHYSICAL HAZARDS AND FRACTIONAL INCAPACITATING DOSES OVER 30 SECOND PERIODS GAS SAMPLING LINE 2 - MID CABIN HEAD HEIGHT FURNISHED FULL SPRAYED TEST - CFT7

Fractional effective doses of narcotic gases							
Time (min)	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Gas concentrations							
CO ppm	782	1152	1648	2616	5027	7235	8314
HCN ppm	28	35	62	121	181	211	216
CO_2 %	0.6	0.9	1.4	2.1	3.1	4.0	4.5
O_2 %	20.3	19.9	19.1	18.0	16.5	15.1	14.3
Fractional incapacitating doses							
FED_{CO}	0.01	0.02	0.03	0.05	0.09	0.14	0.16
FED_{HCN}	0.00	0.01	0.01	0.04	0.15	0.29	0.33
VCO_2	1.17	1.24	1.36	1.55	1.88	2.23	2.45
FED_O	0.00	0.00	0.00	0.00	0.00	0.00	0.01
FED/30s	0.01	0.03	0.04	0.14	0.45	0.96	1.21
Σ FED	0.01	0.04	0.08	0.22	0.67	1.63	2.84
Fractional effective dose of convected heat							
Temp °C	37	47	56	70	87	98	96
FED/30s	0.00	0.01	0.01	0.02	0.02	0.03	0.04
Σ FED	0.00	0.01	0.02	0.04	0.06	0.09	0.13
Radiant heat flux							
kW/m^2	1.0	1.1	1.4	1.4	1.6	1.6	1.7

Time to smoke tenability limit: 1 minute 30 seconds
Time to incapacitation by narcotic gases: 5 minutes 40 seconds
Time to incapacitation by convected heat: Based on the algorithm for dry and slightly humid air incapacitation would not occur. However, based on work with saturated air, it is considered that conditions would be tenable for up to 4 minutes, but that after 4 minutes hot, humid, air at head height might cause pain and burns to facial skin and the respiratory tract, although air at 0.8 metres would remain tenable.
It is considered that spray droplets falling on the skin are unlikely to be supplied at a sufficient rate and a sufficiently high temperature to cause skin pain or burns.

Time to tenability limit for radiant heat: limit not exceeded, maximum 0.12 w/cm^2

Effects of irritants:

Over period between 1 and 4 minutes:	average respirable particulate	2.2 mg/l
	average total particulate	105.5 mg/l
	average HCl concentration	99 ppm
	average HBr concentration	0 ppm

It is considered that the combined concentration of these and other irritants would have some irritant effect on the eyes and respiratory tract, but probably not sufficiently to cause serious incapacitation or seriously impair escape attempts, or cause serious post-exposure lung damage. The high total particulate is thought to represent trapped water spray droplets, too large to penetrate into the lung.

TABLE 18. AVERAGE CONCENTRATIONS OF TOXIC AND PHYSICAL HAZARDS AND FRACTIONAL INCAPACITATING DOSES OVER 30 SECOND PERIODS GAS SAMPLING LINE 2 - MID CABIN HEAD HEIGHT FURNISHED ZONE SPRAYED TEST - CFT5

Fractional effective doses of narcotic gases							
Time (min)	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Gas concentrations							
CO ppm	213	239	248	260	316	383	535
HCN ppm	4	6	9	9	8	8	8
CO_2 %	0.1	0.2	0.2	0.2	0.3	0.3	0.4
O_2 %	20.7	20.7	20.7	20.7	20.6	20.6	20.3
Fractional incapacitating doses							
FED_{CO}	0.004	0.004	0.004	0.004	0.005	0.007	0.009
FED_{HCN}	0.003	0.003	0.003	0.003	0.003	0.003	0.003
VCO_2	1.02	1.04	1.04	1.04	1.07	1.07	1.1
FED_O	0.000	0.000	0.000	0.000	0.000	0.000	0.000
FED/30s	0.007	0.007	0.007	0.007	0.009	0.011	0.013
Σ FED	0.007	0.014	0.021	0.028	0.037	0.048	0.061
Fractional effective dose of convected heat							
Temp °C	20	20	20	23	26	31	39
FED/30s	0.000	0.000	0.000	0.005	0.006	0.007	0.008
Σ FED	0.000	0.000	0.000	0.005	0.011	0.018	0.026
Radiant heat flux							
kW/m^2	0.9	0.9	1.0	1.0	1.0	1.0	1.0

Time to smoke tenability limit: 2 minutes
Time to incapacitation by narcotic gases: No incapacitation
Time to incapacitation by convected heat: Based on the algorithm for dry and slightly humid air incapacitation would not occur. Based on work with saturated air, it is considered that conditions would be tenable for up to 7 minutes (end of test). Since this was a zone sprayed test, there would be no spray droplets falling on the skin.

Time to tenability limit for radiant heat: limit not exceeded, maximum 0.12 w/cm^2 (at 7 minutes)

Effects of irritants:

Over period between 1 and 4 minutes:	average respirable particulate	0.24 mg/l
	average total particulate	0.65 mg/l
	average HCl concentration	23 ppm
	average HBr concentration	0 ppm

It is considered that the combined concentration of these and other irritants would have some irritant effect on the eyes and respiratory tract, but probably not sufficiently to cause serious incapacitation or seriously impair escape attempts, or cause serious post-exposure lung damage. The total particulate concentration is much lower than in the non-sprayed and fully sprayed tests, reflecting the low concentrations of combustion products and the absence of water spray droplets.

TABLE 19. AVERAGE CONCENTRATIONS OF TOXIC AND PHYSICAL HAZARDS AND FRACTIONAL INCAPACITATING DOSES OVER 30 SECOND PERIODS GAS SAMPLING LINE 2 - MID CABIN HEAD HEIGHT FURNISHED ZONE SPRAYED TEST - CFT6

Fractional effective doses of narcotic gases							
Time (min)	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Gas concentrations							
CO ppm	121	216	318	373	383	444	498
HCN ppm	0	0	0	0	13	106	206
CO_2 %	0.7	1.1	1.5	2.0	3.9	6.1	6.7
O_2 %	20.2	19.6	18.9	17.8	14.6	11.1	8.7
Fractional incapacitating doses							
FED_{CO}	0.002	0.004	0.005	0.006	0.007	0.008	0.009
FED_{HCN}	0.000	0.000	0.000	0.000	0.003	0.026	0.259
VCO_2	1.18	1.31	1.44	1.63	2.63	4.55	5.28
FED_O	0.000	0.000	0.000	0.001	0.004	0.029	0.324
FED/30s	0.002	0.005	0.007	0.011	0.030	0.184	1.739
Σ FED	0.002	0.016	0.037	0.048	0.078	0.262	2.001
Fractional effective dose of convected heat							
Temp °C	72	84	124	177	204	220	223
FED/30s	0.020	0.028	0.083	0.351	0.734	1.136	1.233
Σ FED	0.020	0.048	0.131	0.482	1.216	2.352	3.585
Radiant heat flux							
kW/m^2	1.3	1.4	1.4	1.6	1.6	2.0	2.4

Time to smoke tenability limit: 2.5 minutes
Time to incapacitation by narcotic gases: 6 minutes
Time to incapacitation by convected heat: Based on the algorithm for dry and slightly humid air incapacitation would occur after 5 minuutes. However, based on work with saturated air, it is considered that conditions would be tenable for up to 3 minutes, but that after 3 minutes hot, humid, air at head height might cause pain and burns to facial skin and the respiratory tract, although air at 0.8 metres would remain tenable for up to at least 5.5 minutes. The severity of the problem with the air would depend upon the degree of saturation. The indications were that at 0.8 metres height the air was less than 50% saturated during the critical part of the test, and it is likely that the water content of the air would be correspondingly low at 1.7 metres height. It is therefore possible that the air at head height would remain tenable beyond 3 minutes. Since this was a zone sprayed test, there would be no spray droplets falling on the skin.

Time to tenability limit for radiant heat: limit exceeded at 6.5 minutes, maximum 0.28 w/cm^2 (at 6.5 minutes)

Effects of irritants:

Over period between 1 and 4 minutes:	average respirable particulate	1.45 mg/l
	average total particulate	7.13 mg/l
	average HCl concentration	131 ppm
	average HBr concentration	160 ppm

It is considered that the combined concentration of these and other irritants would have a severe irritant effect on the eyes and respiratory tract, possibly sufficient to cause some impairment of escape movements, but not sufficient to cause serious incapacitation, or cause serious post-exposure lung damage. The total particulate concentration was just over half that of the non-sprayed test, with a similar, sticky, consistency reflecting relatively high concentrations of combustion products but the absence of water spray droplets.

TABLE 20. TESTS CFT1 TO CFT7 : TIME TAKEN (MINUTES) FOR FED TO REACH UNITY FOR DIFFERENT HAZARDS

Test	Description	Duration	Sampling Position and Hazard								
			G1		G2			G3		G4	
			CO, CO_2, O_2	Temp	CO, CO_2, O_2	Temp	CO, CO_2, O_2, HCN	CO, CO_2, O_2	Temp	CO, CO_2, O_2	Temp
CFT1	Unfurnished fuselage. No sprays.	6 min 40 s	5.3	3.6	6.7	4.9	6.7	NR	5.6	5.8	5.6
CFT2	Unfurnished fuselage. Spray Type A operating over full length of fuselage.	7 min 40 s	NR	2.0	NR	4.5	NR	NR	5.5	NR	4.5
CFT3	Furnished fuselage. No sprays.	5 min 50 s	3.1	1.5	3.3	2.8	2.3	3.5	3.1	3.3	3.1
CFT4	Furnished fuselage. Spray Type A operating over full length of fuselage.	6 min 0 s	5.8	-	5.6	4.0	4.6	NR	-	5.8	-
CFT5	Furnished fuselage. Spray Type A operating over zone in region of the fire opening.	6 min 50 s	NR	5.5	NR	NR	NR	NR	NR	NR	NR
CFT6	Furnished fuselage. Reduced flow spray operating over zone in region of fire opening.	7 min 20 s	NR	1.5	NR	3.0	6.0	NR	4.0	NR	3.5
CFT7	Furnished fuselage. Spray Type A operating over full length of fuselage.	6 min 50 s	NR	2.3	6.3	4.0	5.7	7.4	5.5	NR	4.5

Notes:- NR FED did not reach unity during course of test
- No data available
G1 Rear cabin 1.7 m
G2 Mid cabin 1.7 m
G3 Mid cabin 1.1 m
G4 Front cabin 1.1 m

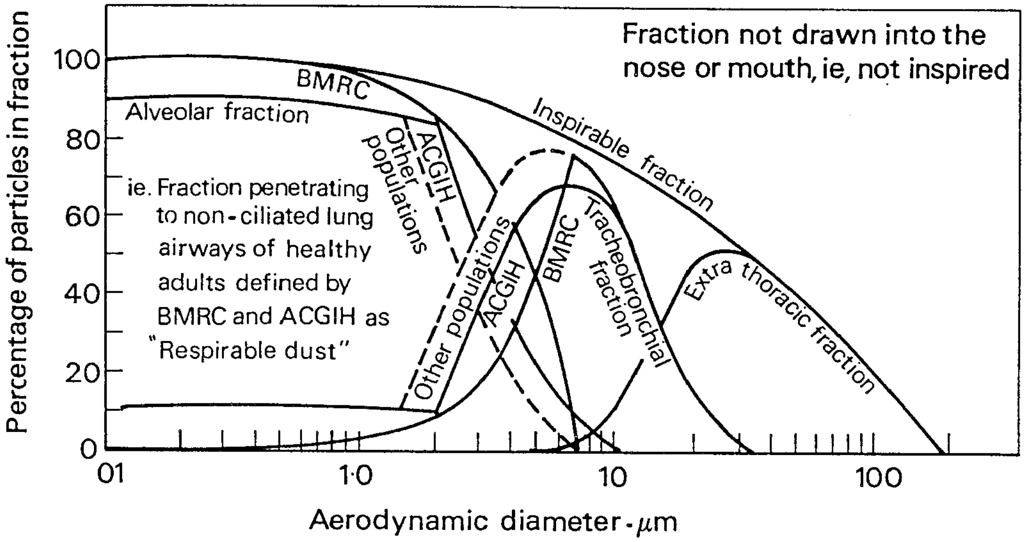
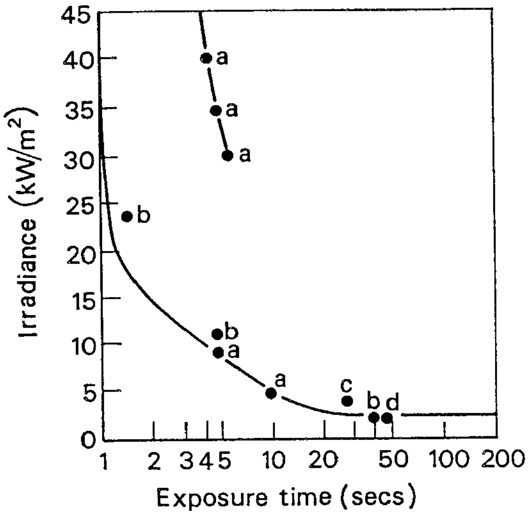
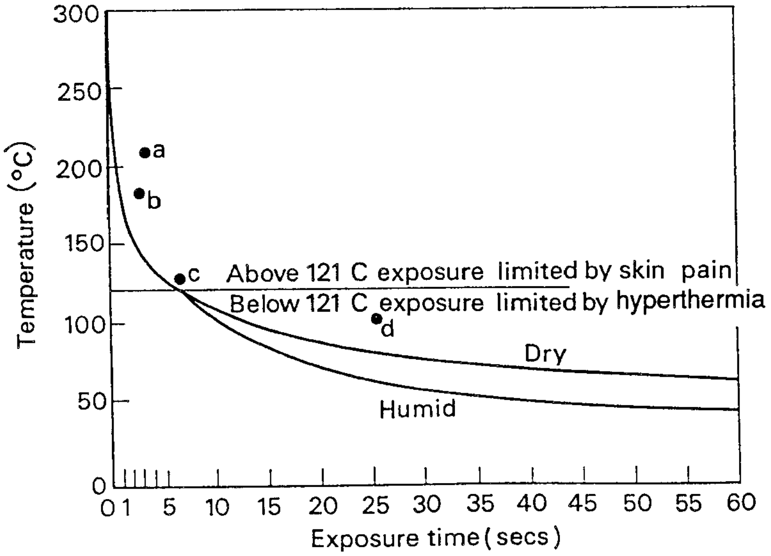


Figure 1 Depth of penetration of airborne particles of different sizes into the respiratory tract.



(a) Time to severe skin pain for exposure to radiant heat.



(b) Tolerance time for exposure to convected heat.

Figure 2 Tolerance times for exposure to radiant and convected heat.
(Note: the continuous curves are taken from one literature source, while the lettered points are from additional sources. Full details are given in Reference 9).

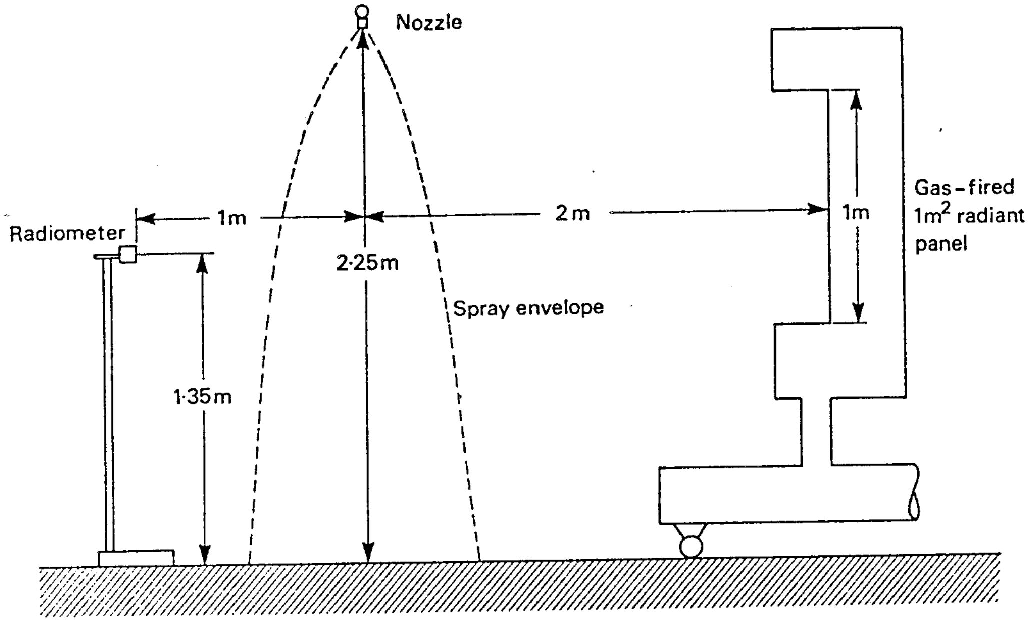


Figure 3 Schematic arrangement of apparatus for estimating the relative radiation attenuation by different types of water spray.

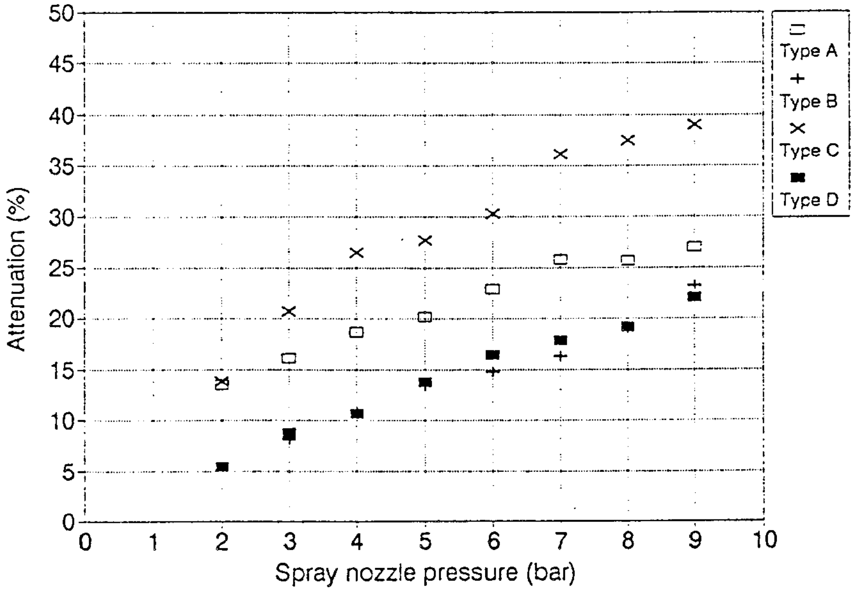
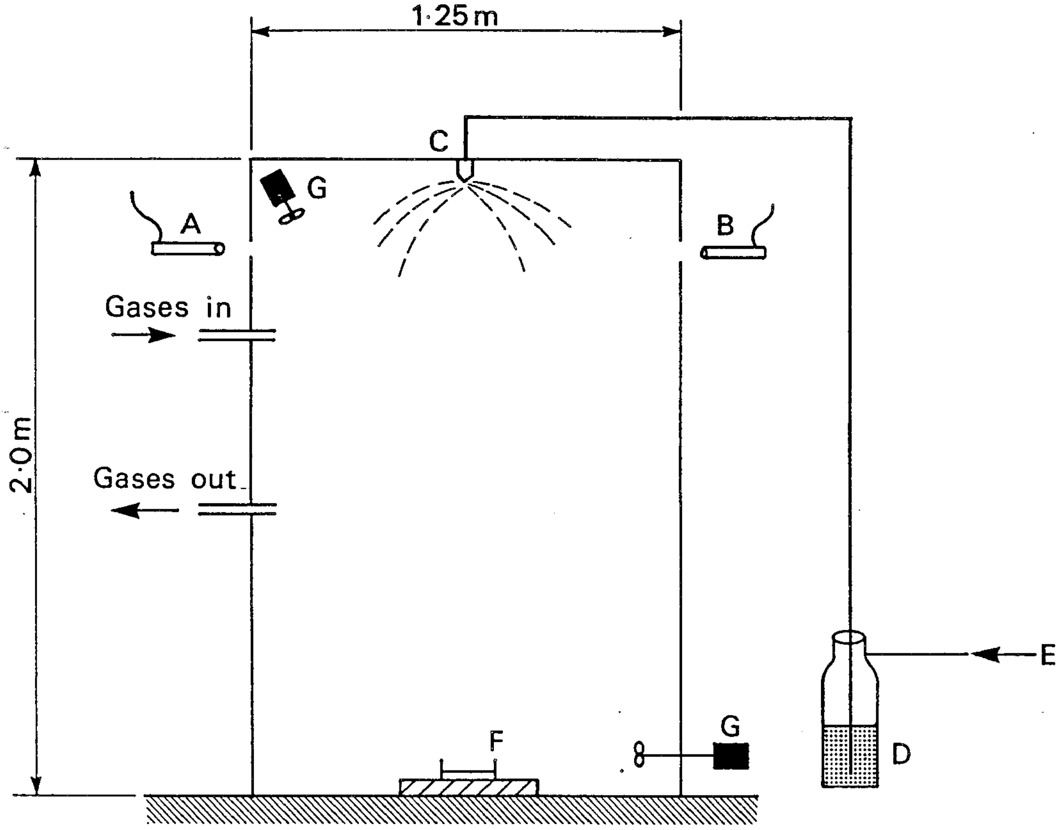


Figure 4 The effect of nozzle type and operating pressure on radiation attenuation by water sprays.



A – Light source; B – Photocell; C – Spray nozzle;
D – Pressure vessel (see Figure 2); E – From the compressed air cylinder; F – Fuel tray; G – Mixing fan

Figure 5 Schematic arrangement of test chamber to investigate the effect of water sprays on combustion products.

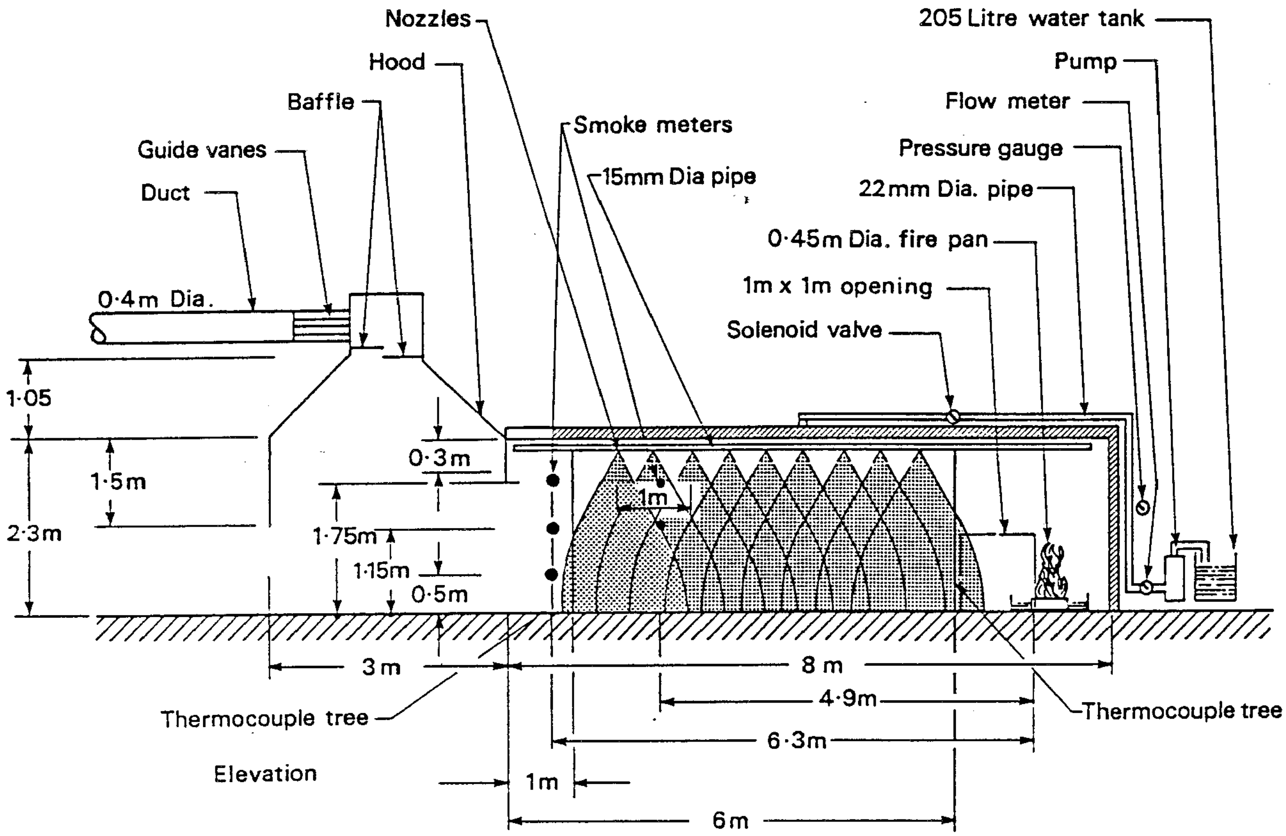


Figure 6 Schematic arrangement of test rig used for the moving gas layer experiments.

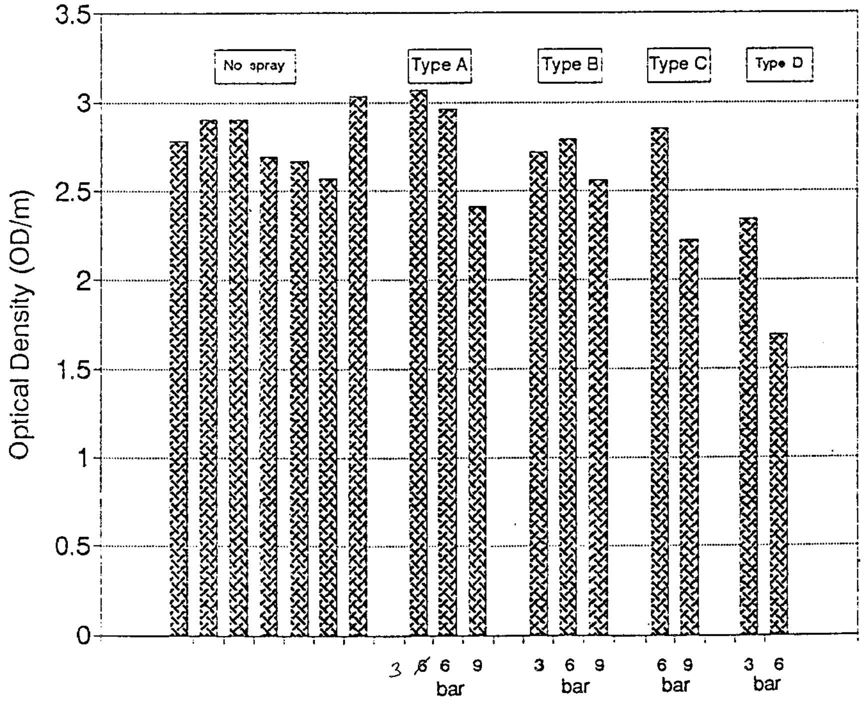


Figure 7 Histograms showing the effect of nozzle type and operating pressure on smoke density.

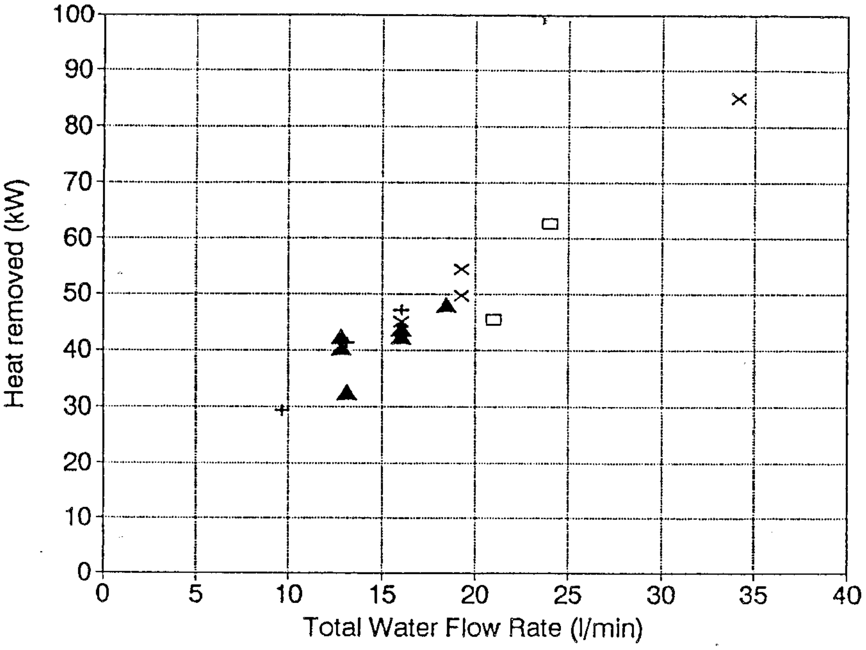


Figure 8 The effect of total water flow rate on the rate of heat removal by Type A spray nozzles in a range of test configurations.

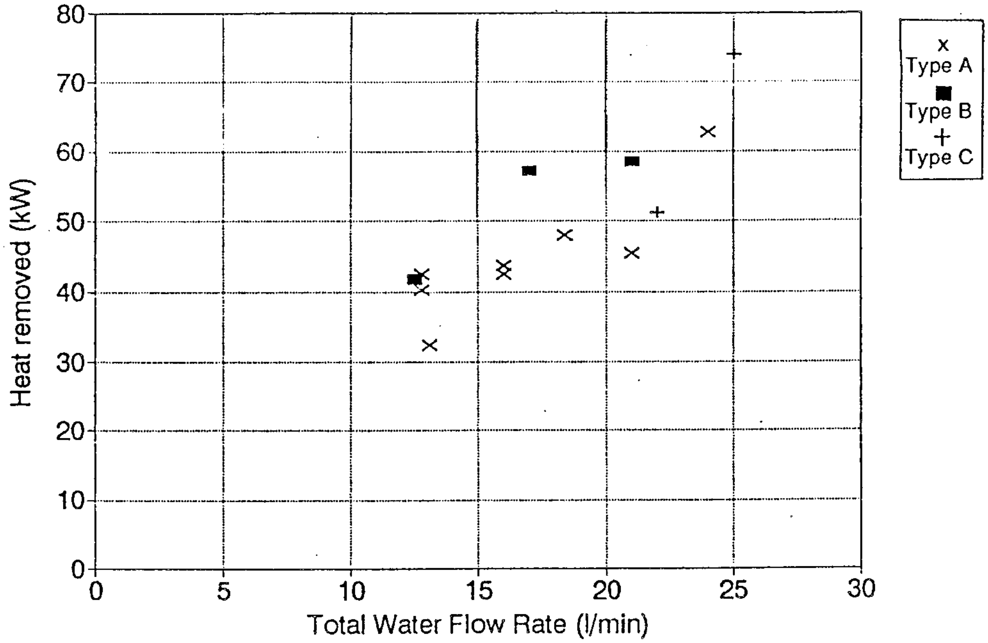


Figure 9 The effect of total water flow rate on the rate of heat removal by Type A, B and C spray nozzles in the same, standard configuration.

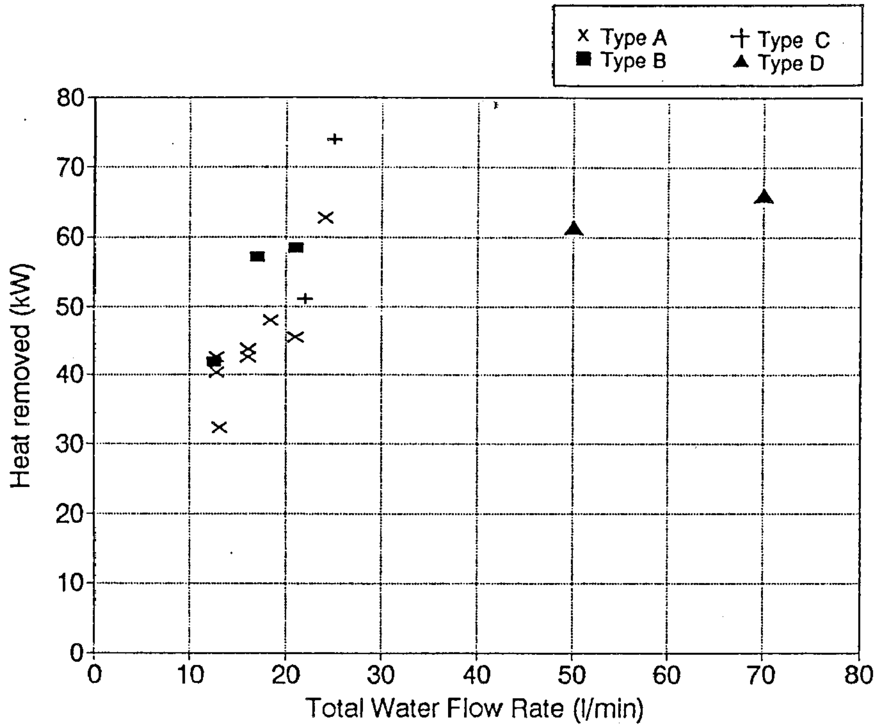


Figure 10 The effect of total water flow rate on the rate of heat removal by Type A, B, C and D spray nozzles in the same, standard configuration.

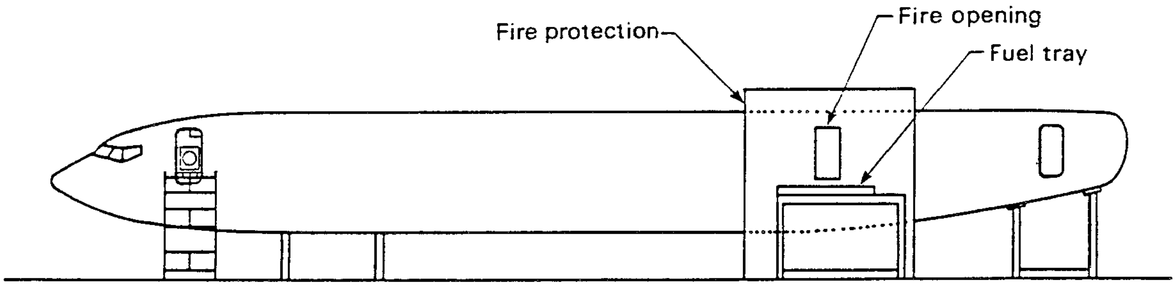
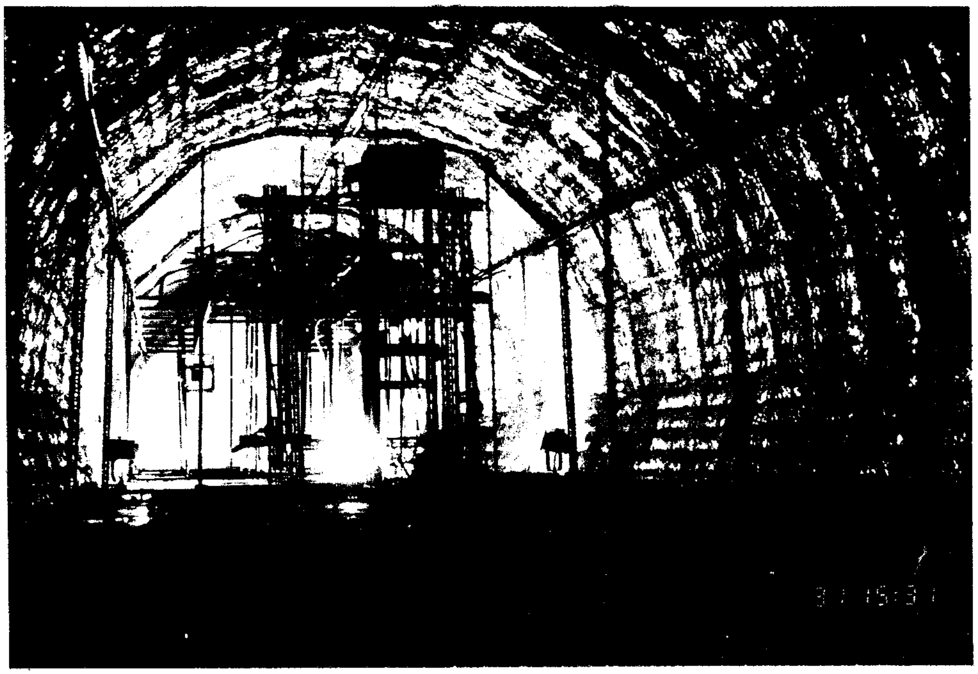
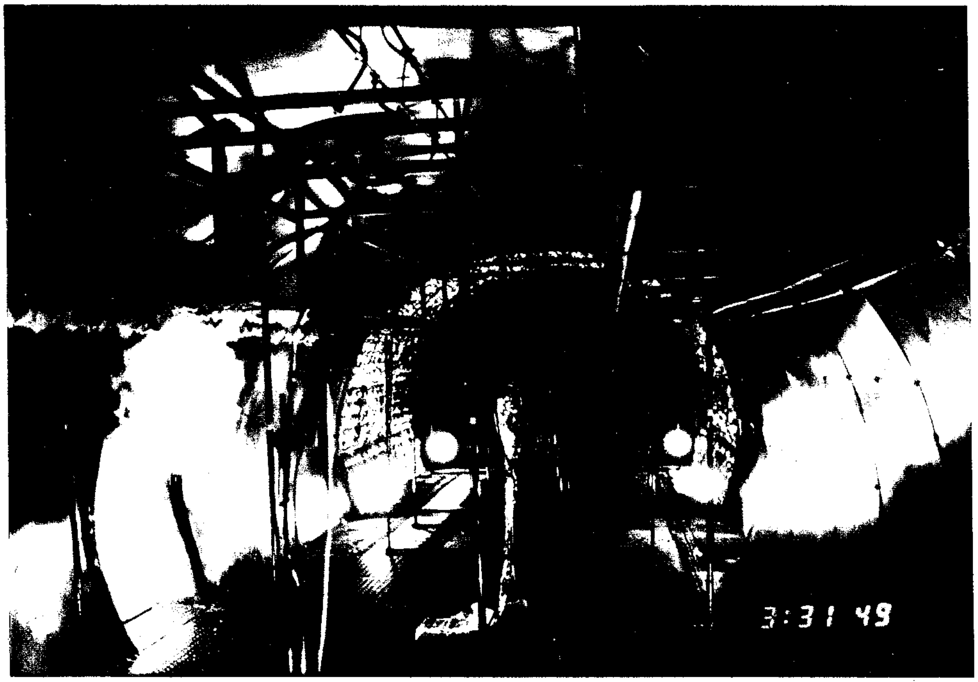


Figure 11 The Boeing 707 fuselage showing the location of the fire opening and external protection.

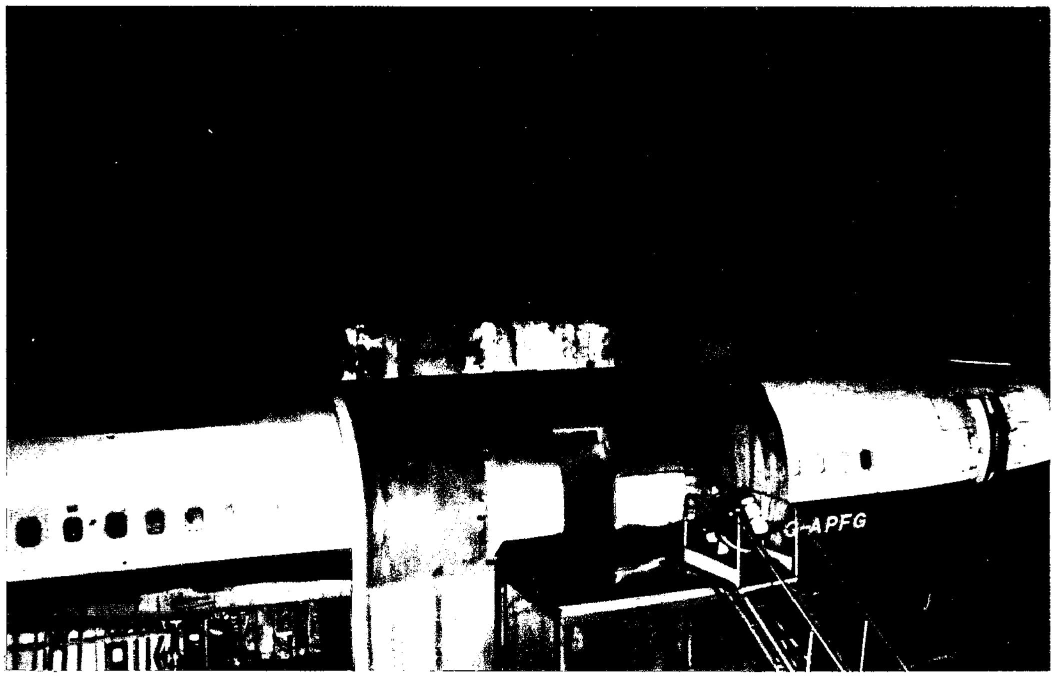


(a) The interior of the fuselage showing the protective lining and instrument supports

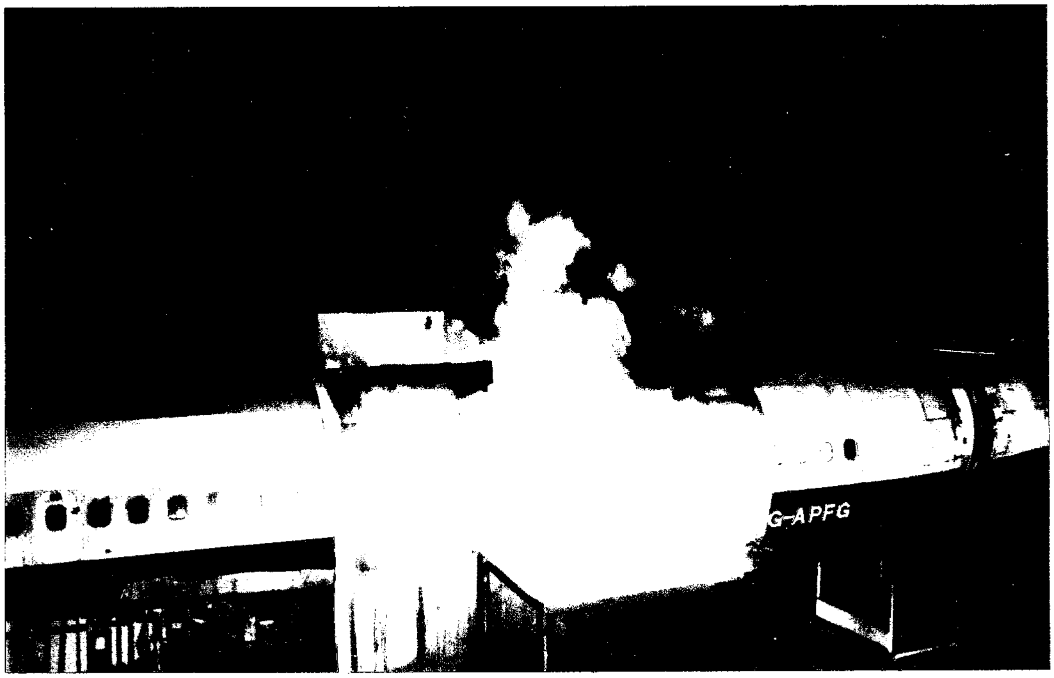


(b) The interior of the fuselage showing the additional fire protection in the vicinity of the fire opening

Figure 12 Interior views of the Boeing 707 fuselage after preparation for the fire tests



(a) The exterior of the fuselage showing the fire tray and the protected opening, prior to ignition



(b) The exterior of the fuselage showing the fuel tray and protected opening, after the fire has become established

Figure 13 Exterior views of the Boeing 707 fuselage after preparation for the fire tests

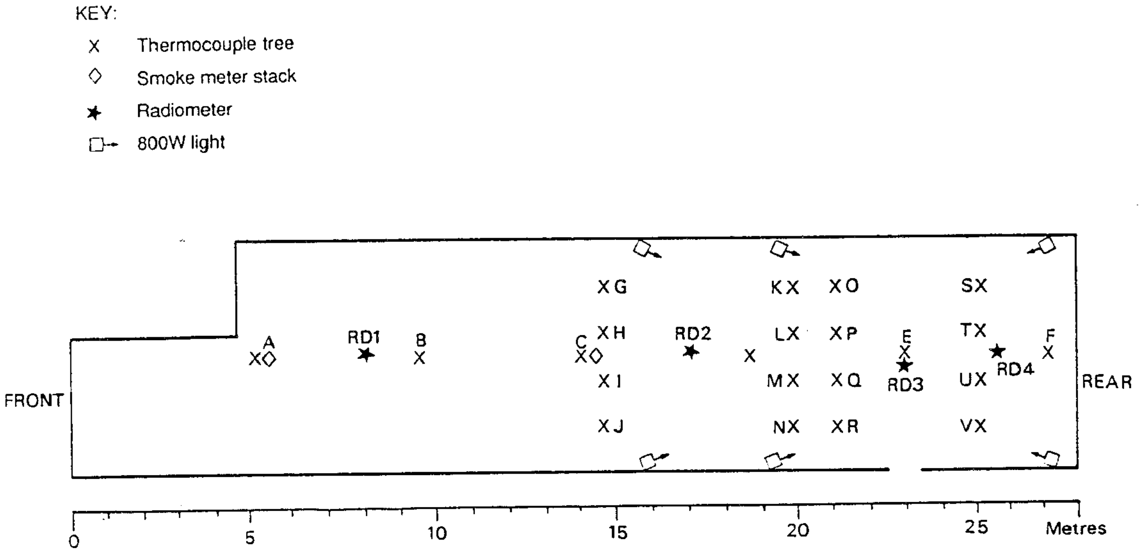


Figure 14 Schematic plan view of the cabin interior, showing the location of the principal measuring instruments.

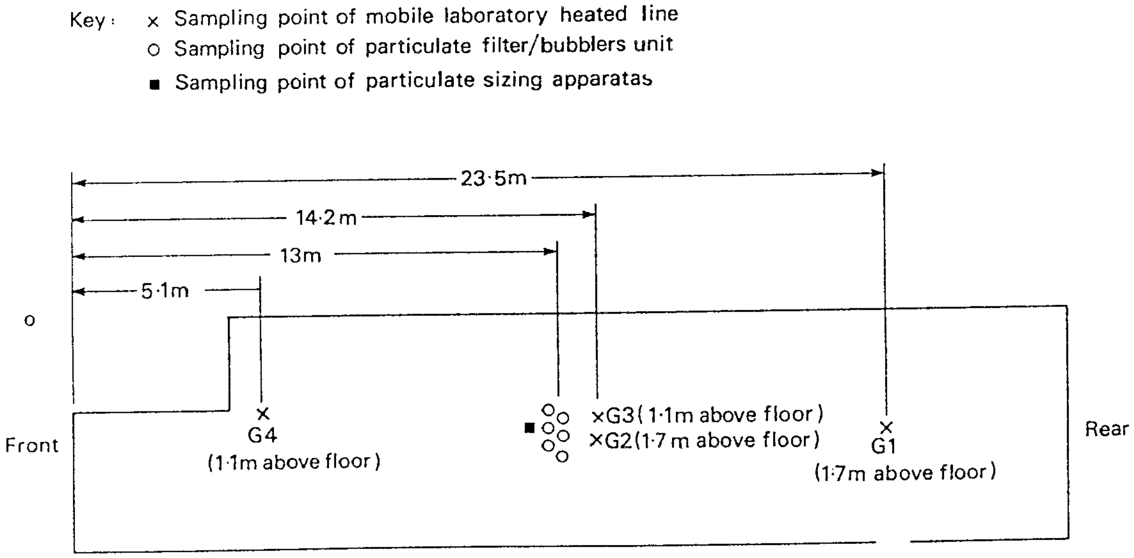


Figure 15 Schematic plan view of the cabin interior, showing the location of the gas and particulate sampling points.

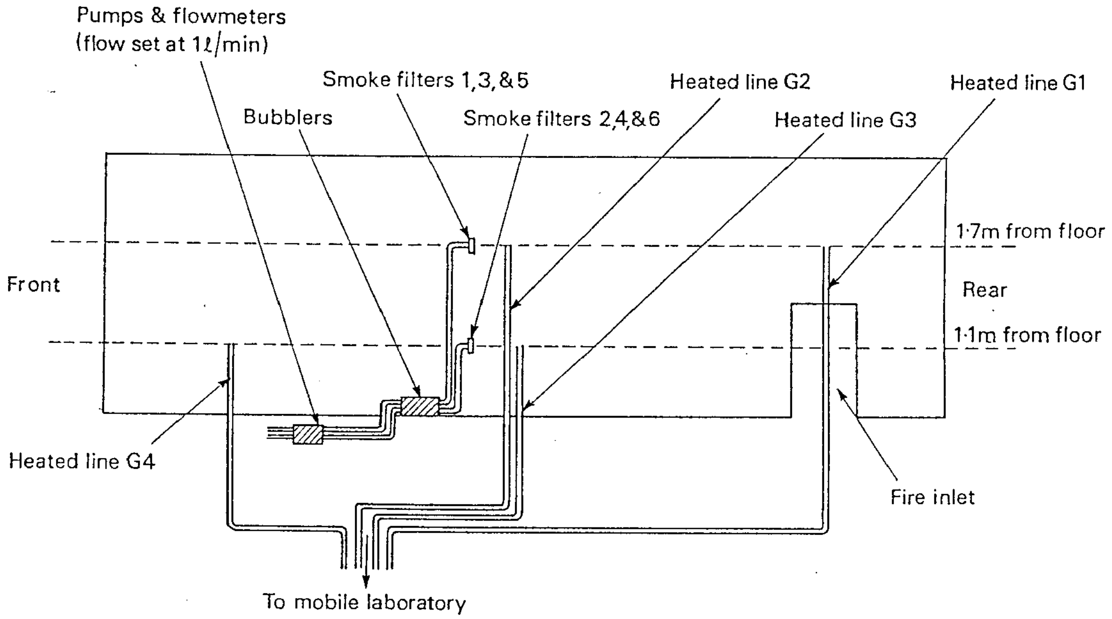


Figure 16 Schematic side view of the cabin interior, showing the vertical location of the gas and particulate sampling points.

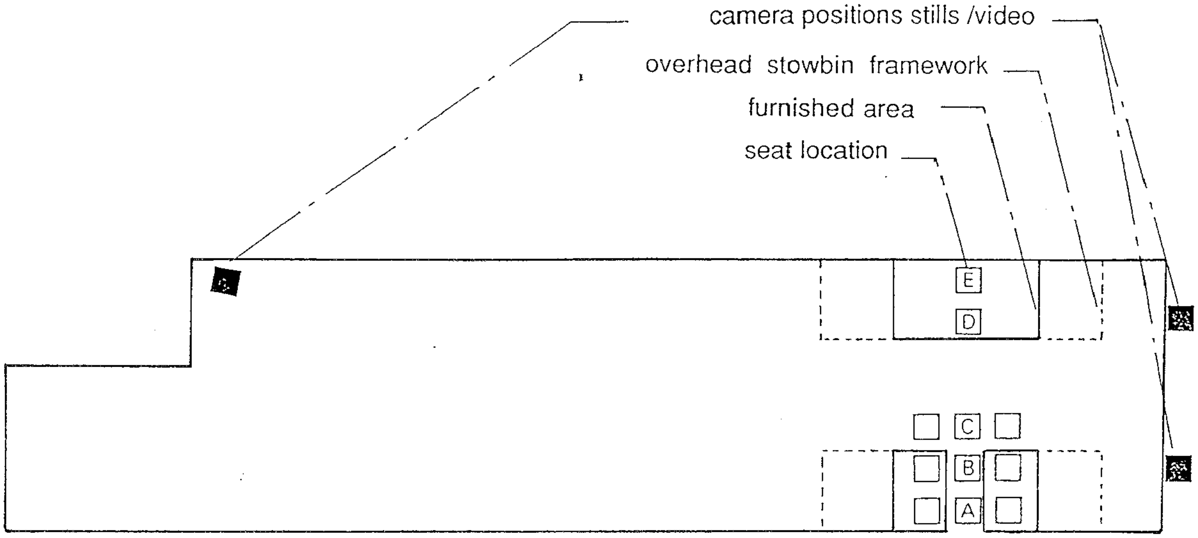


Figure 17 Schematic plan view of the cabin interior, showing the furnished zone and the camera locations.

Figure 18 Cabin furnishings prior to test

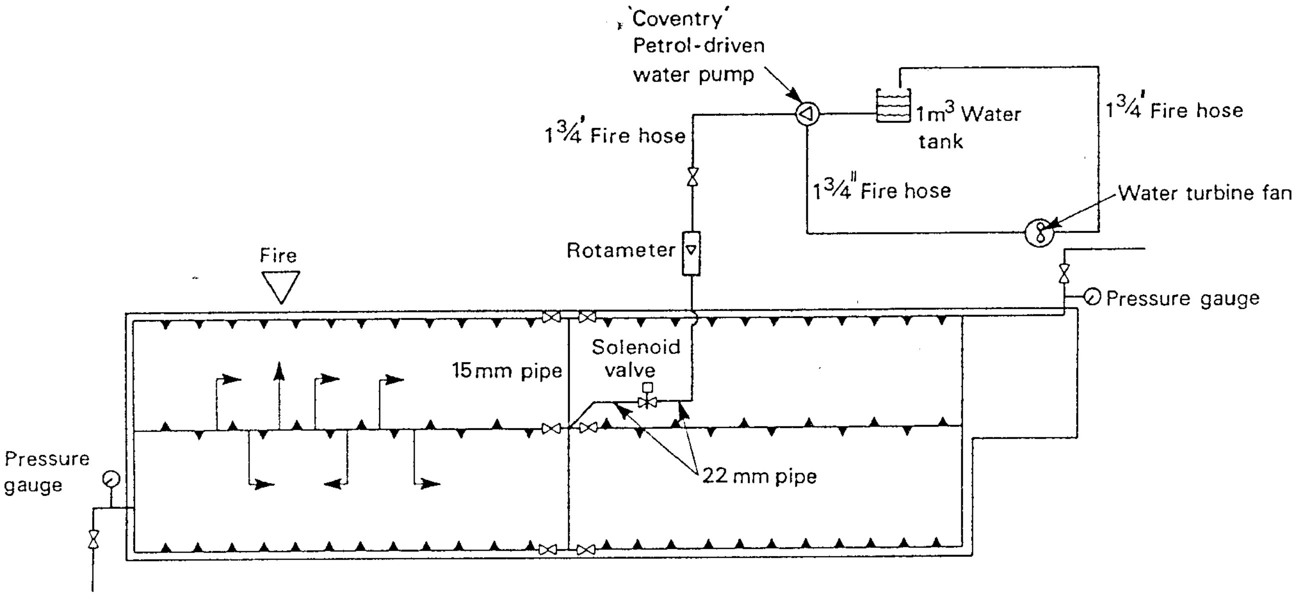


Figure 19 Schematic plan view showing the nozzle locations and water supply system for the full cabin spray tests (CFT4 and CFT7).

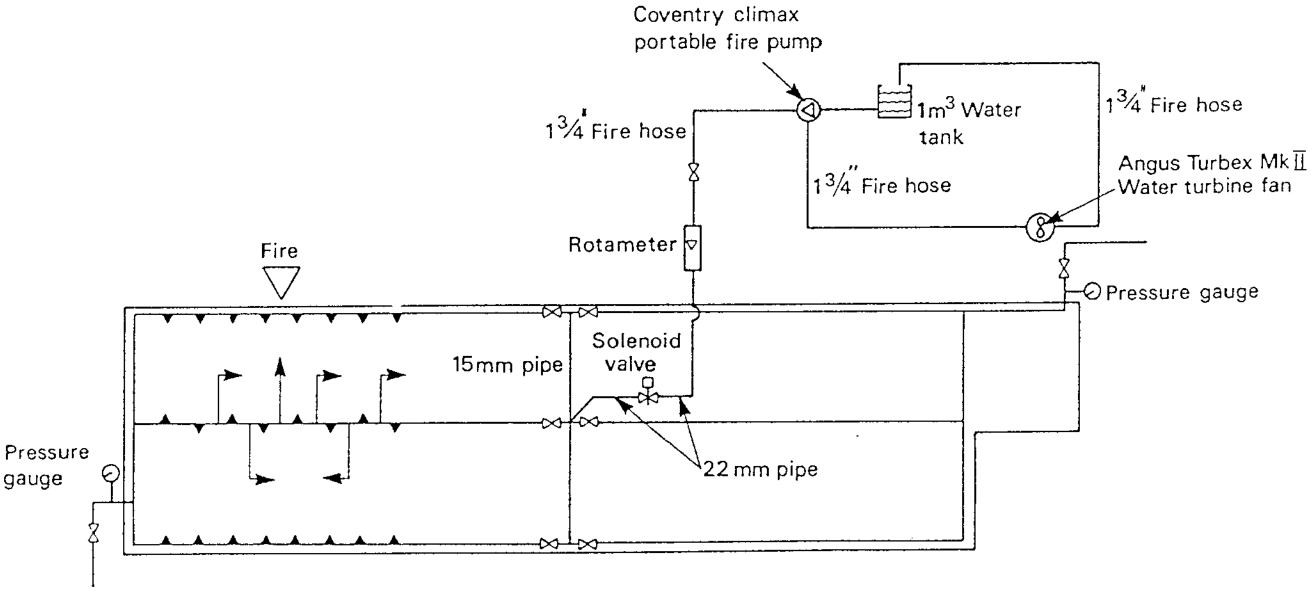


Figure 20 Schematic plan view showing the nozzle locations and water supply system for the zone spray tests (CFT5 and CFT6).

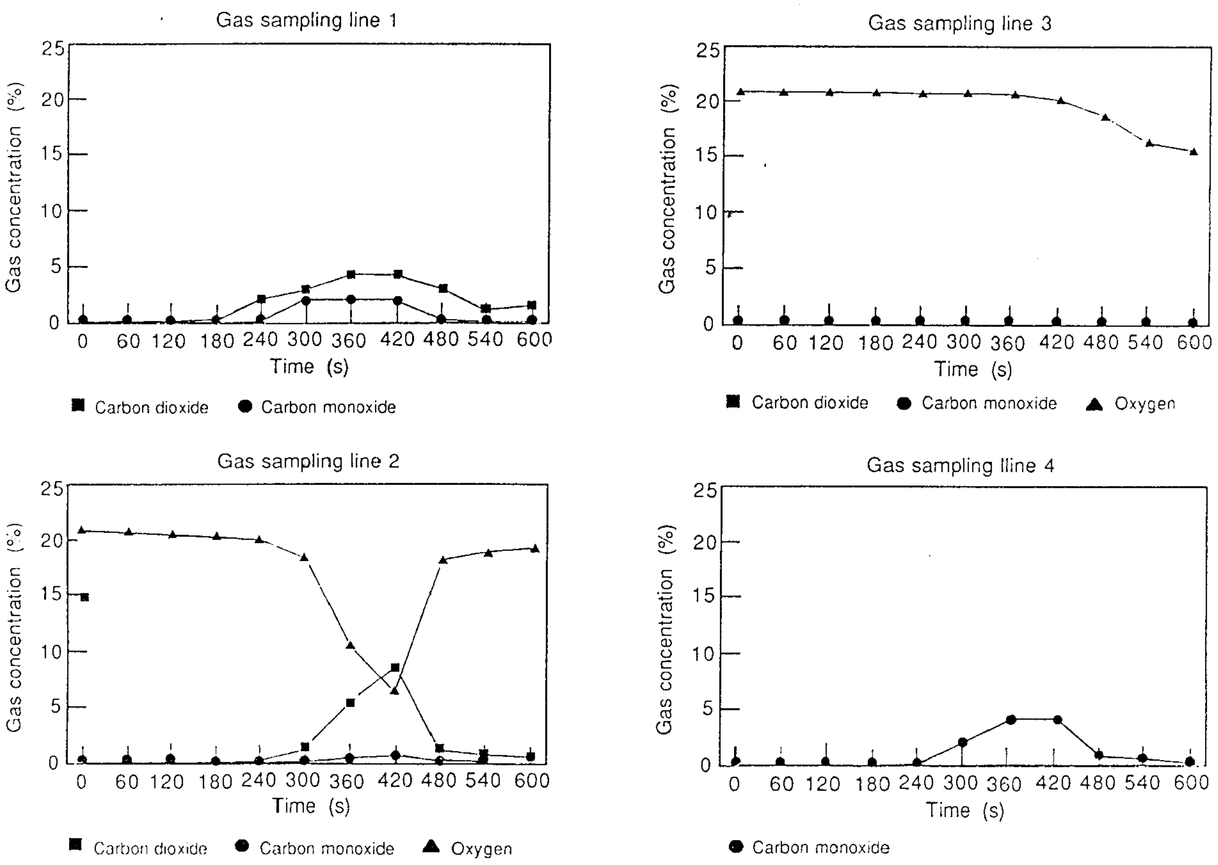


Figure 21 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT1.

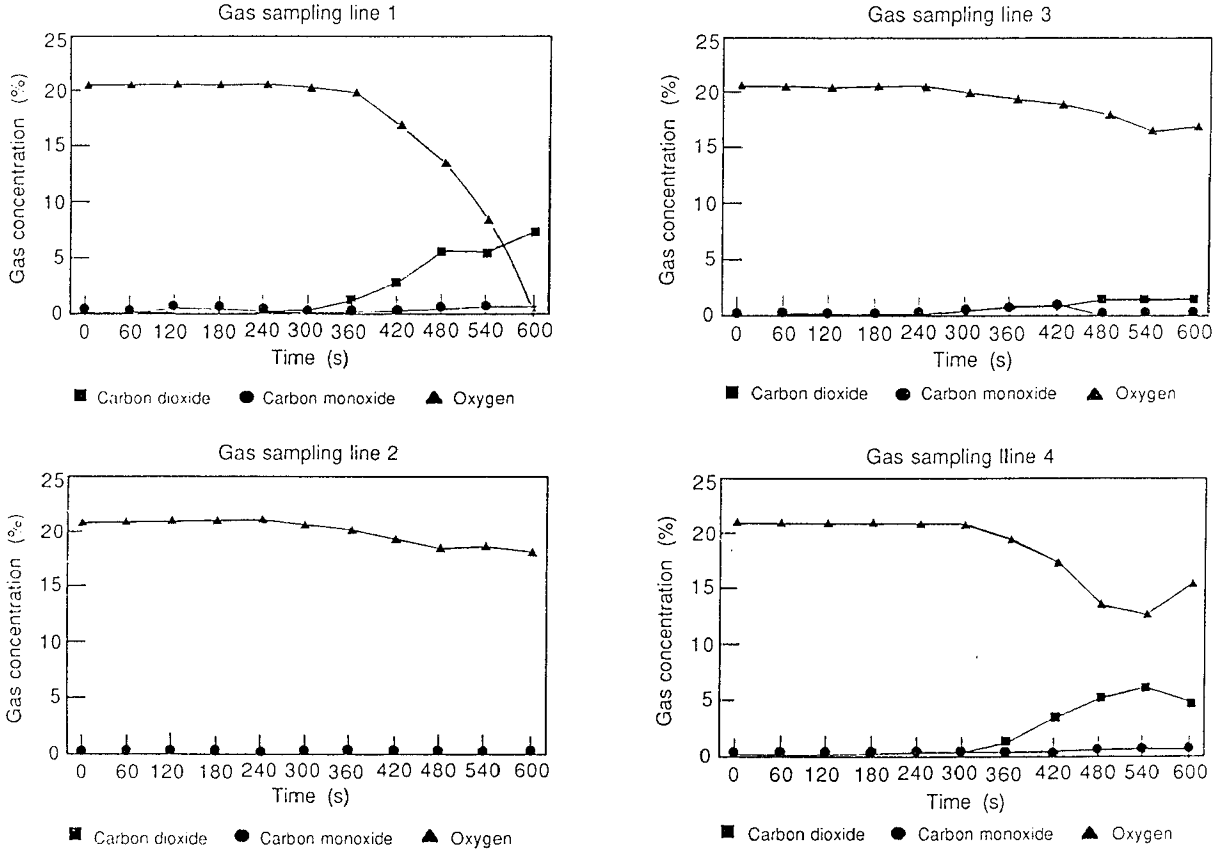


Figure 22 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT2.

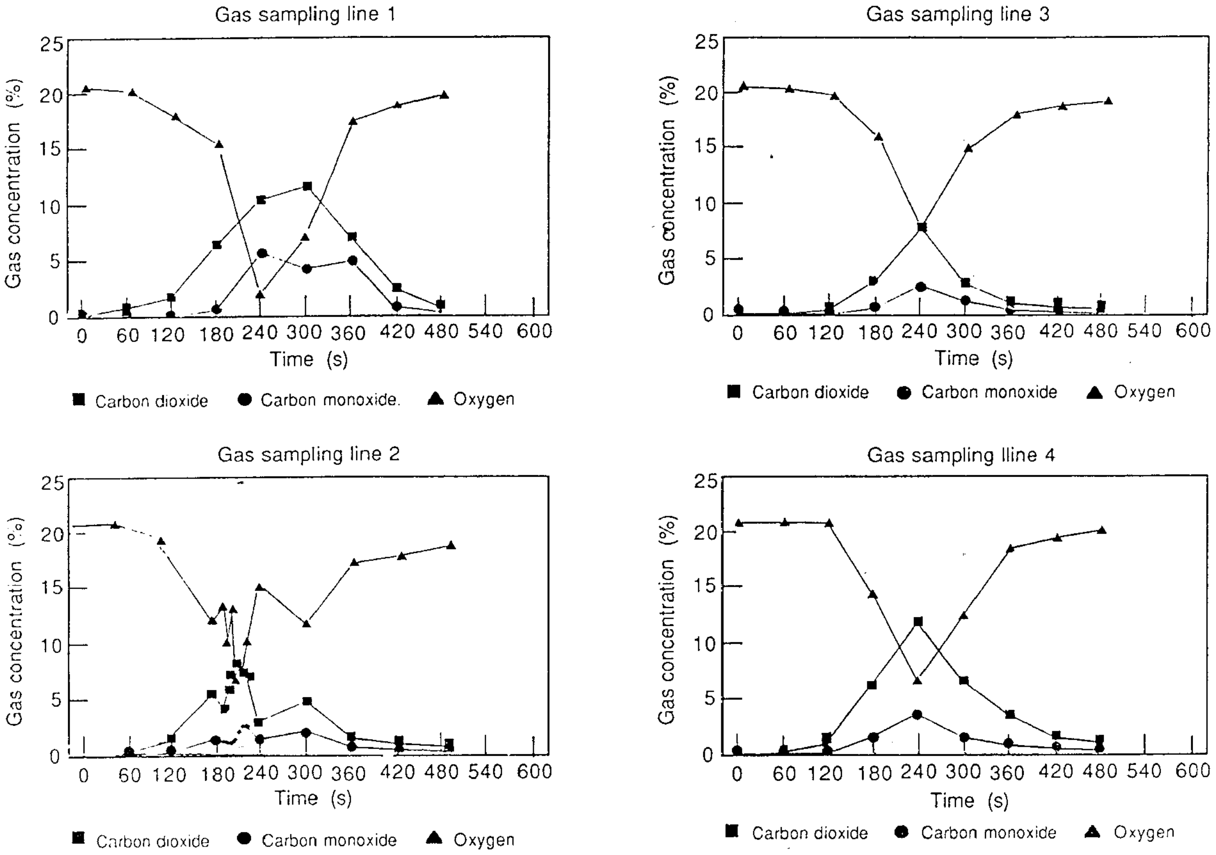


Figure 23 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT3.

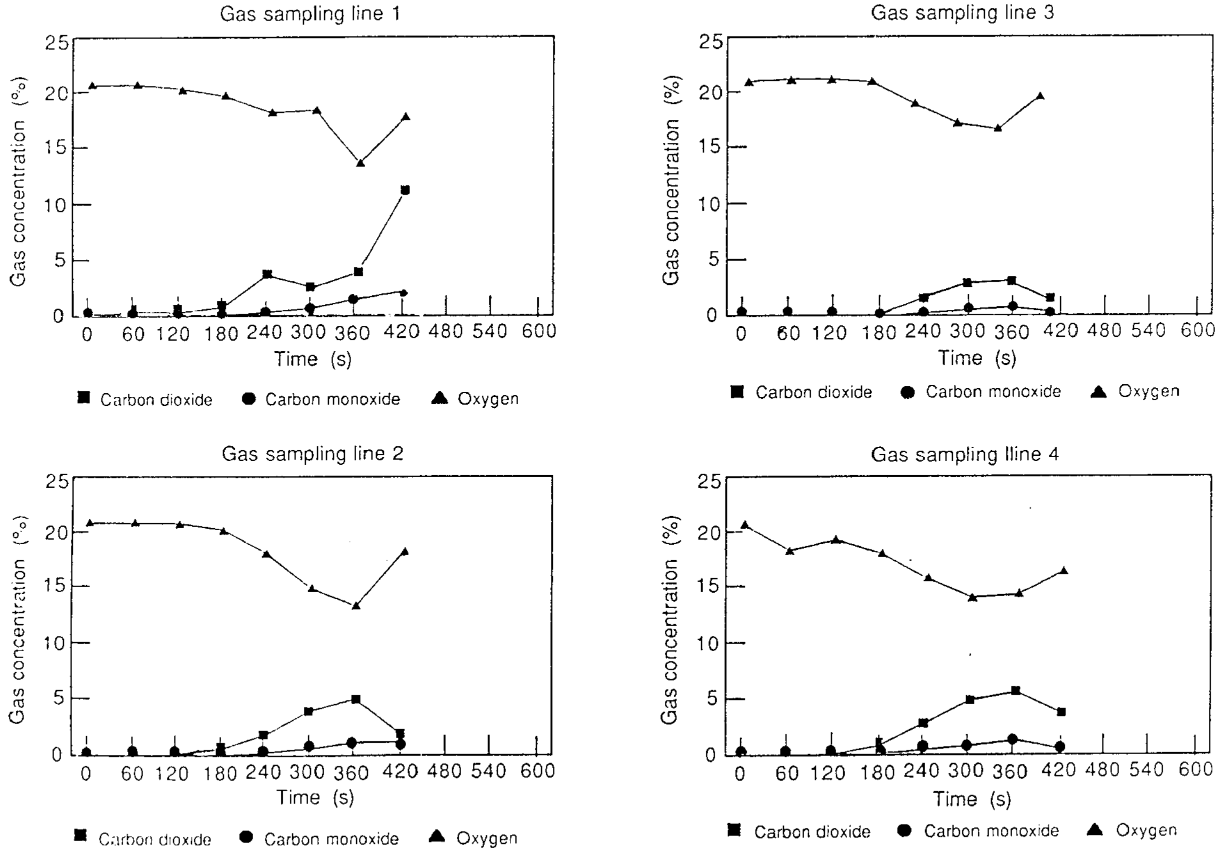


Figure 24 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT4.

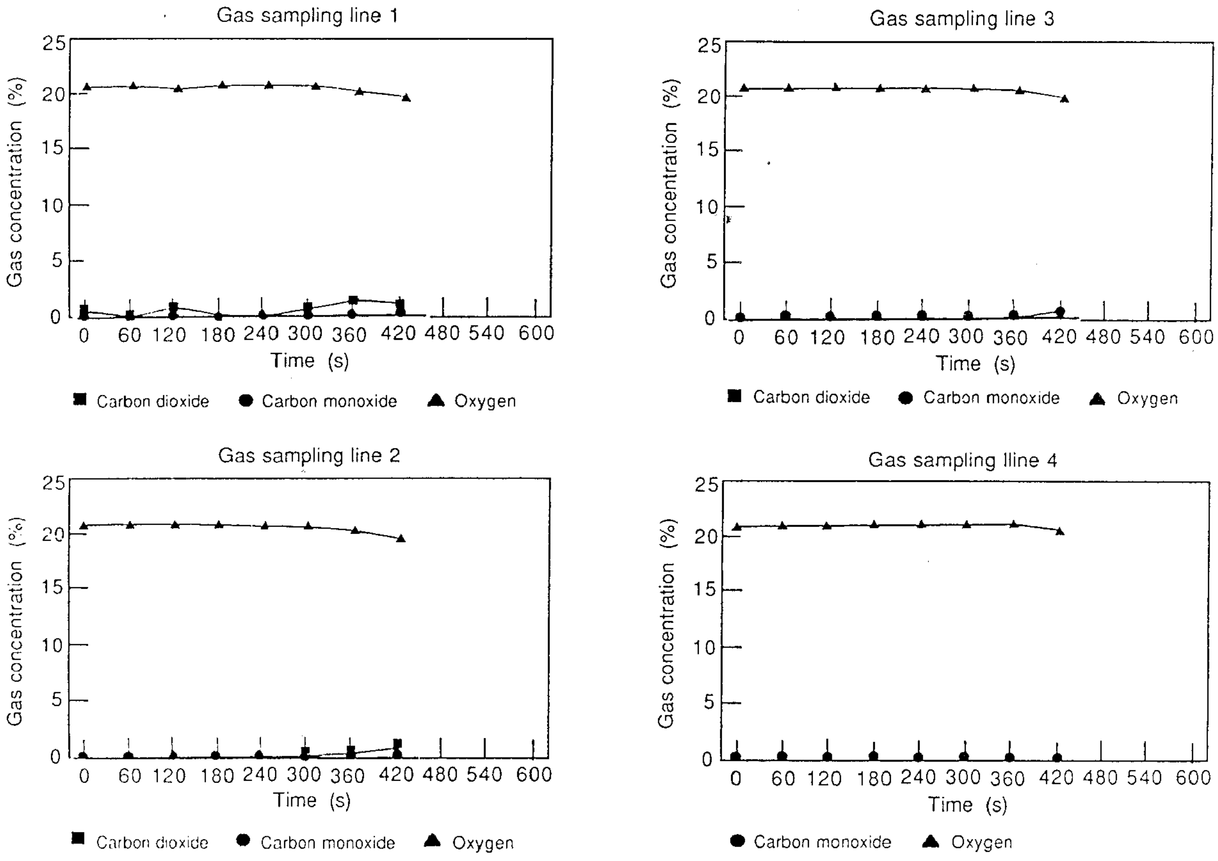


Figure 25 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT5.

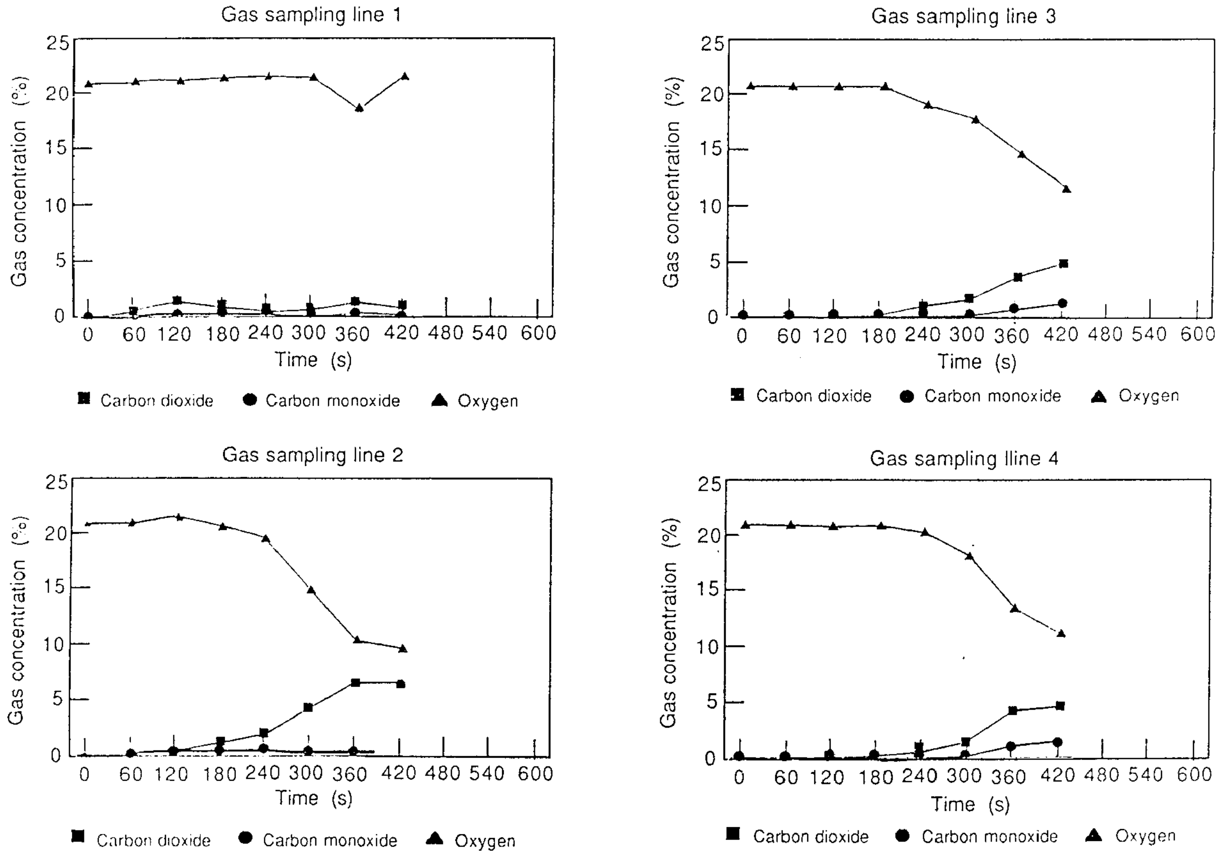


Figure 26 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT6

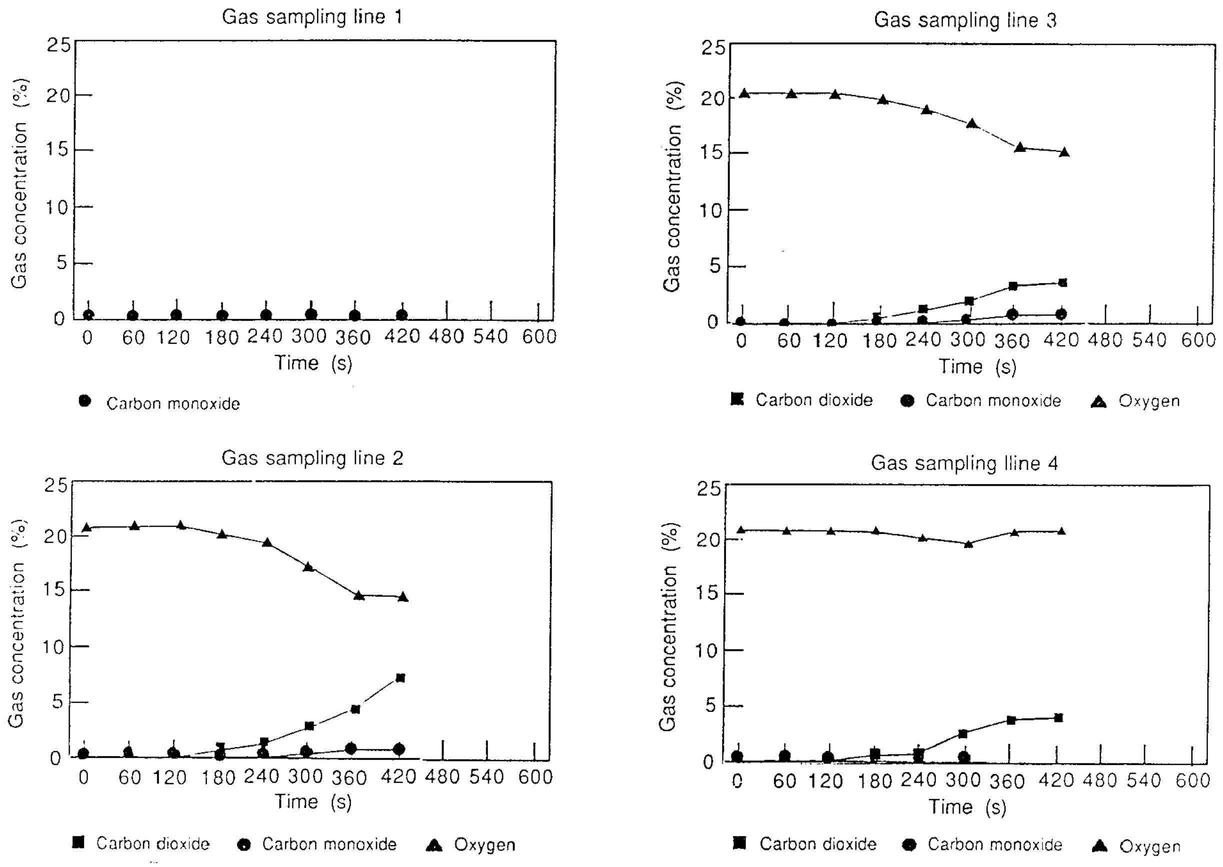


Figure 27 Concentrations of carbon dioxide, carbon monoxide and oxygen - CFT7

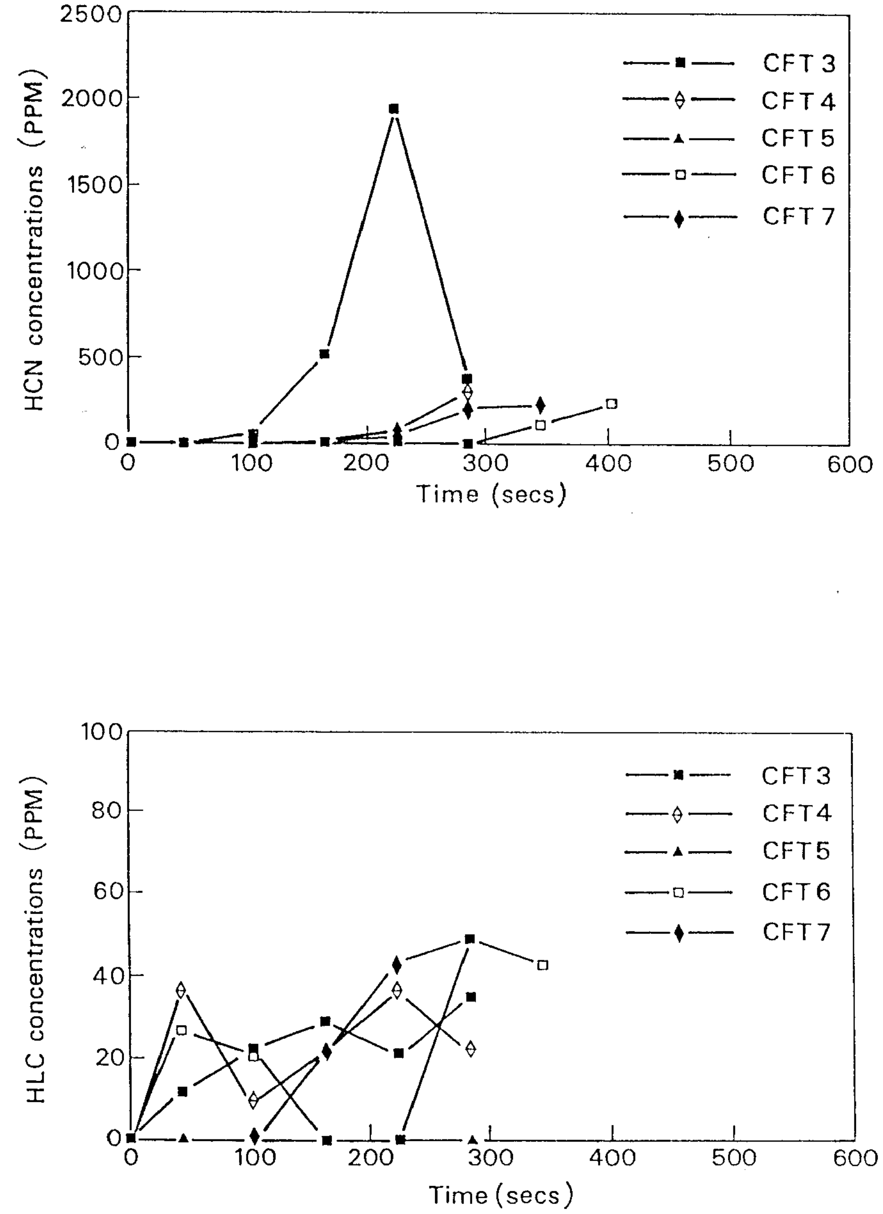
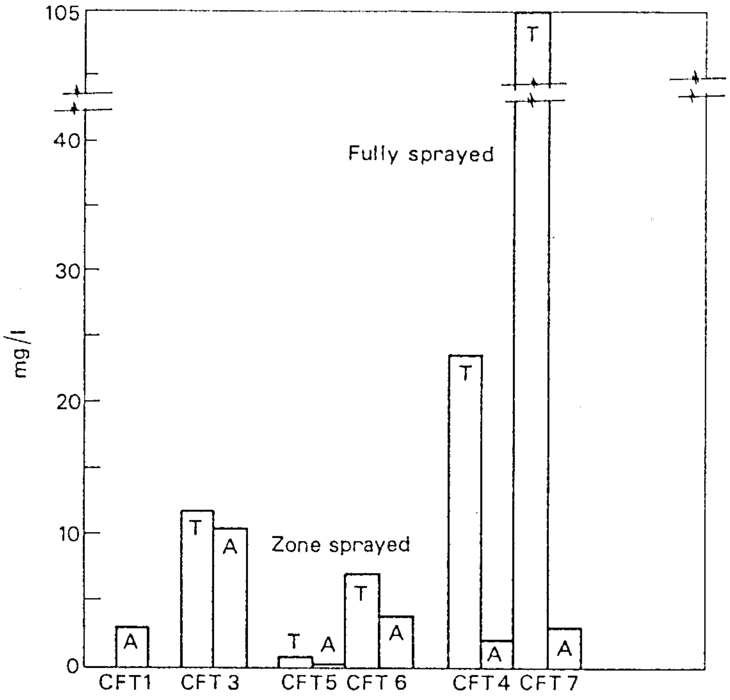
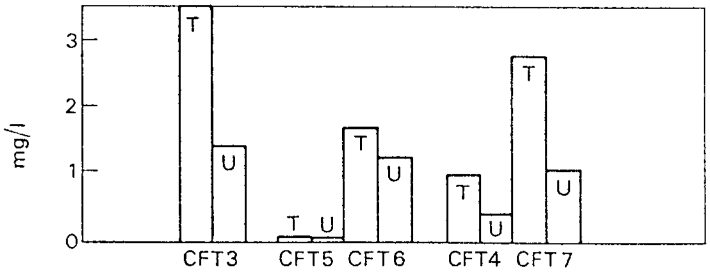


Figure 28 Concentrations of hydrogen cyanide and hydrogen chloride at gas sampling station G2, for tests CFT3 to CFT7.



(a) Total particulate concentrations (mg/l)



(b) Total particulates trapped by Casella sampler and on first two stages (4 - 200 μm)

T = Total particulate open face filter (upper) and Casella sampler (lower)
A = Total particulate Anderson sampler
U = Particulate on upper two stages of Casella sampler

Figure 29 Mass of particulate captured by the Anderson and Casella samplers.

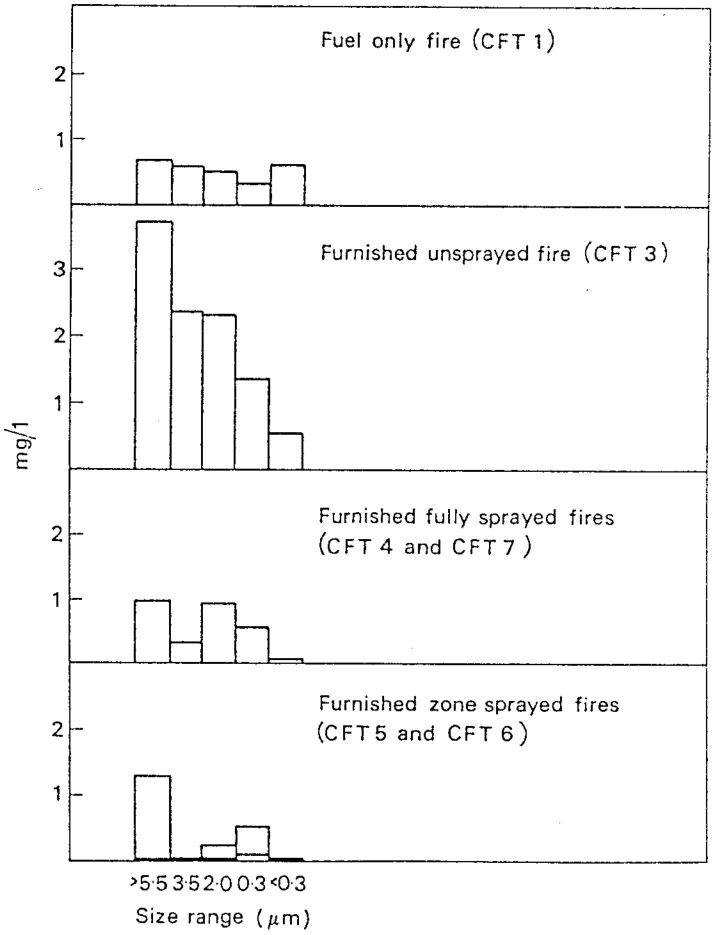


Figure 30 Particle size distribution derived from the Anderson sampler.

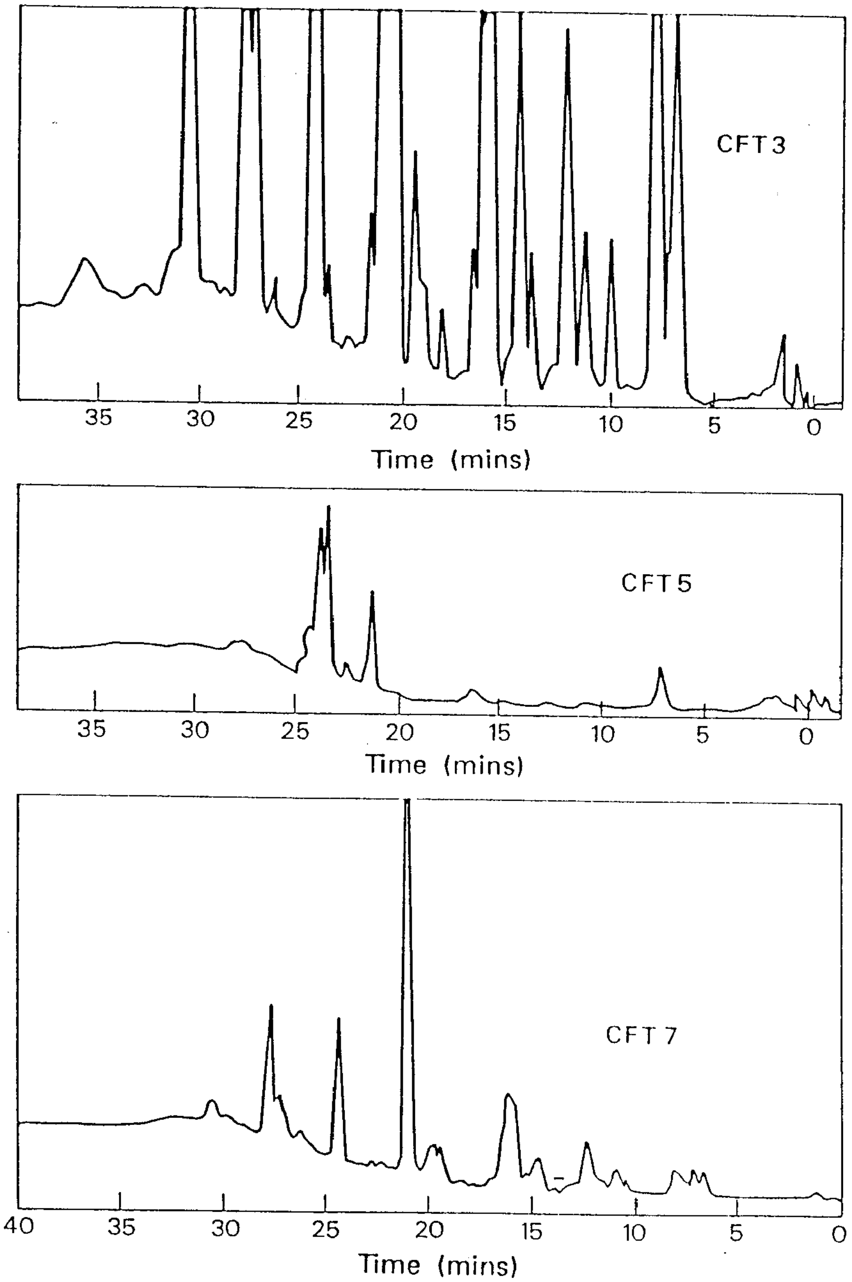


Figure 31. Typical gas chromatograms for 'total organics' from samples taken at 3.5 minutes after the start of tests CFT3, CFT5 and CFT7.

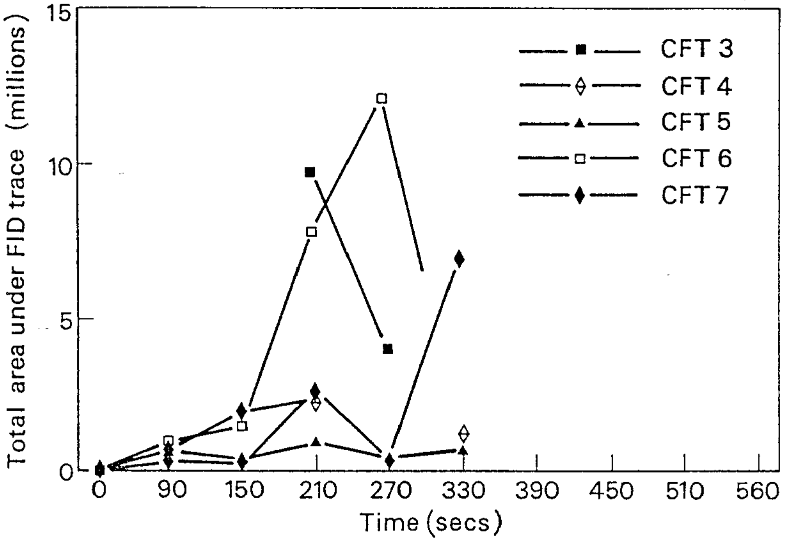


Figure 32 The variation of relative levels of 'total organics' with time from the start of tests CFT3 to CFT7.

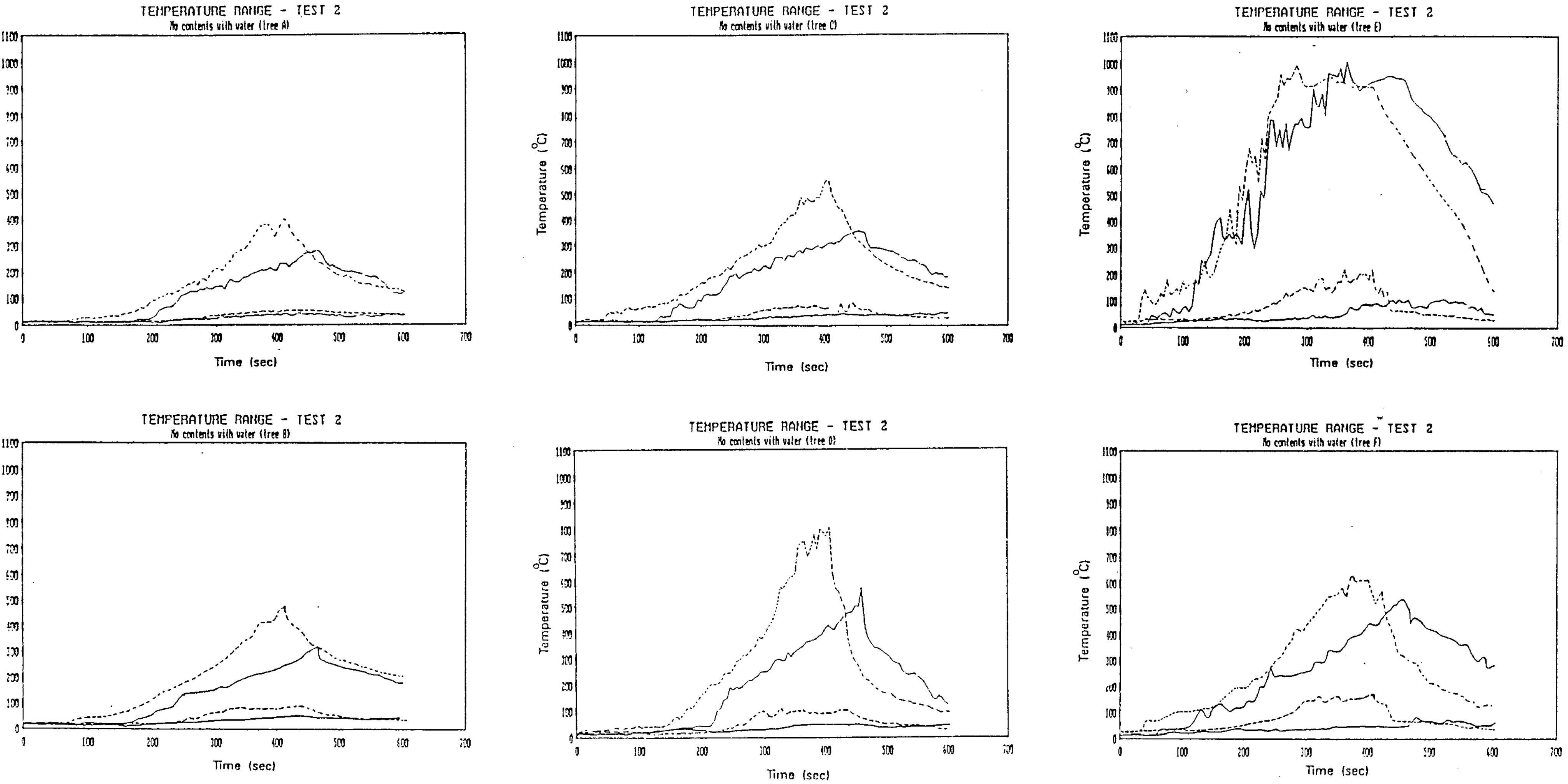


Figure 33 Comparison of centre-line temperatures for sprayed test CFT2 and unsprayed test CFT1 at heights 0.3 m and 1.7 m. (CFT1: .... , CFT2:____________)

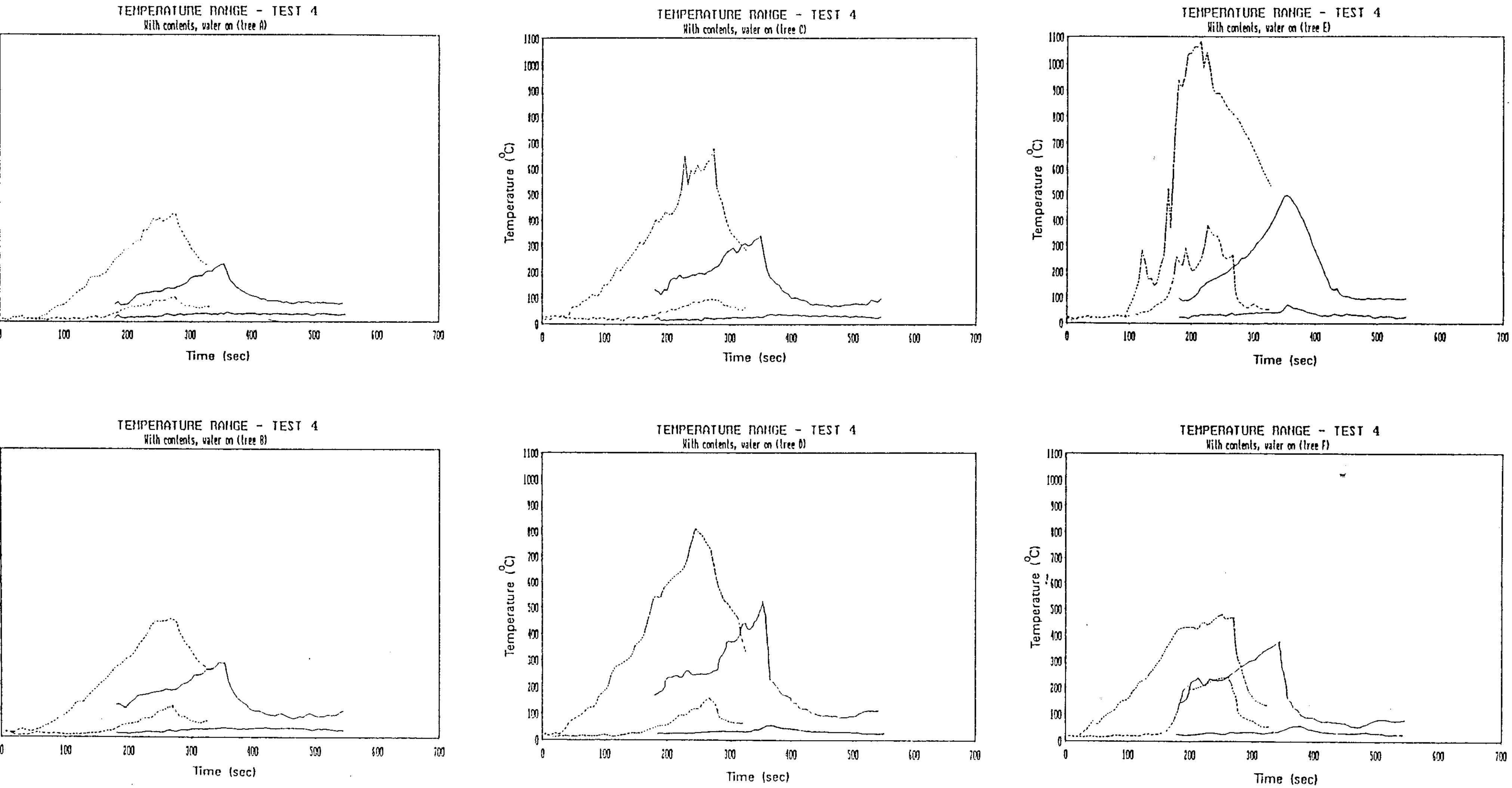


Figure 34 Comparison of centre-line temperatures for sprayed test CFT4 and unsprayed test CFT3 at heights 0.3 m and 1.7 m. (CFT3: .... , CFT4:____________)

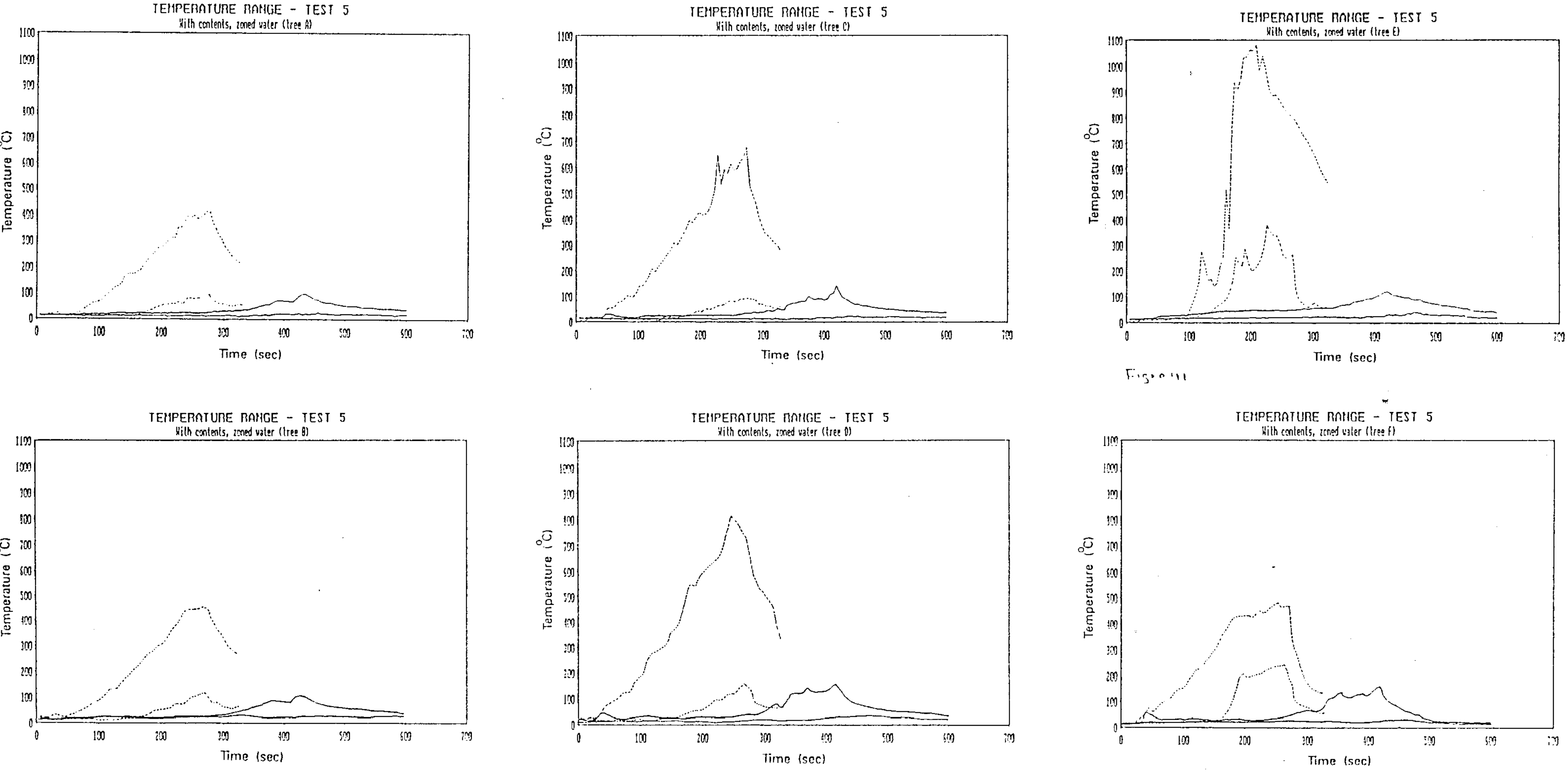


Figure 35 Comparison of centre-line temperatures for sprayed test CFT5 and unsprayed test CFT3 at heights 0.3 m and 1.7 m.
(CFT3: .... , CFT5:____________)

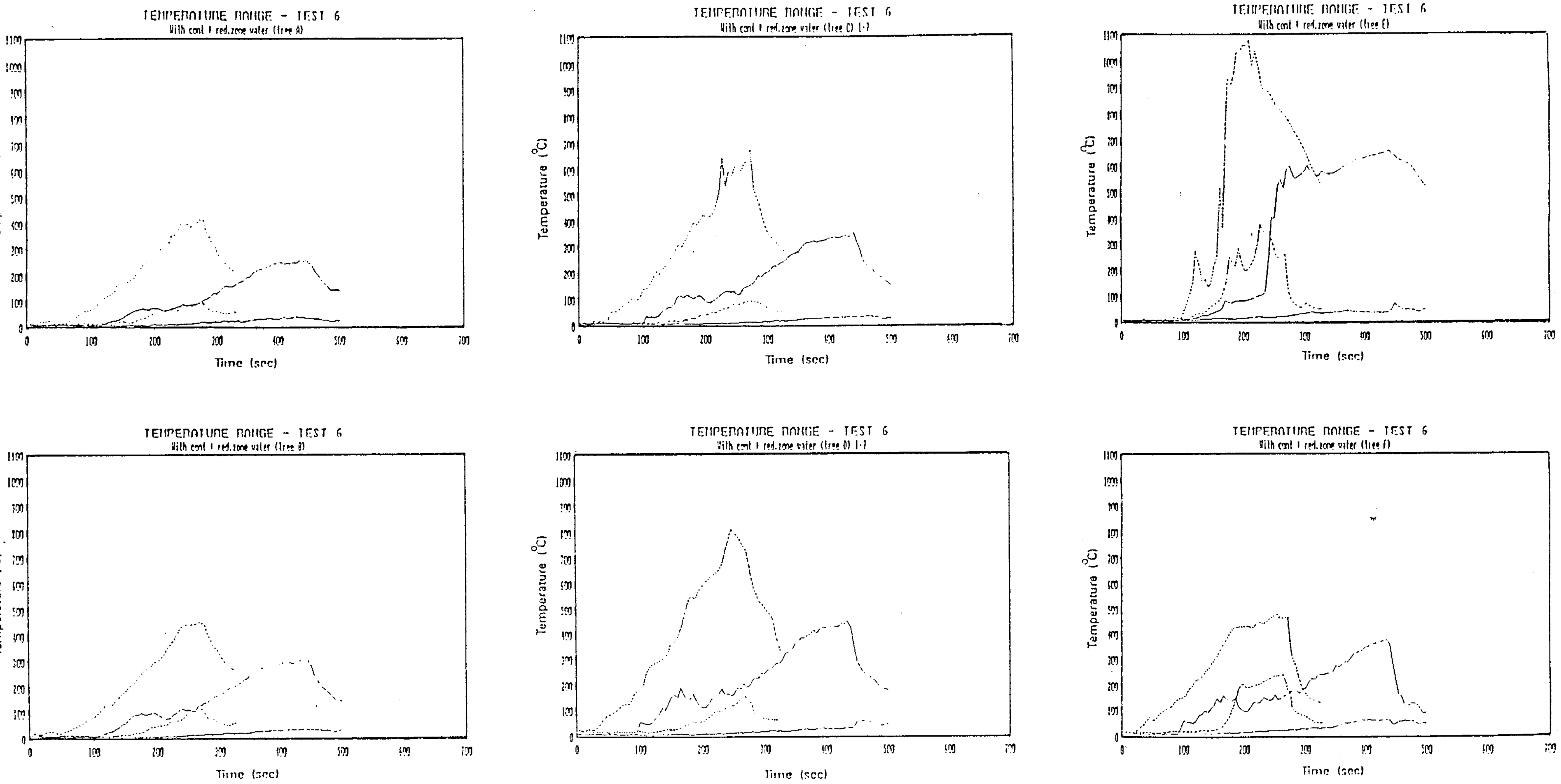


Figure 36 Comparison of centre-line temperatures for sprayed test CFT6 and unsprayed test CFT3 at heights 0.3 m and 1.7 m. (CFT3: .... , CFT6:____________)

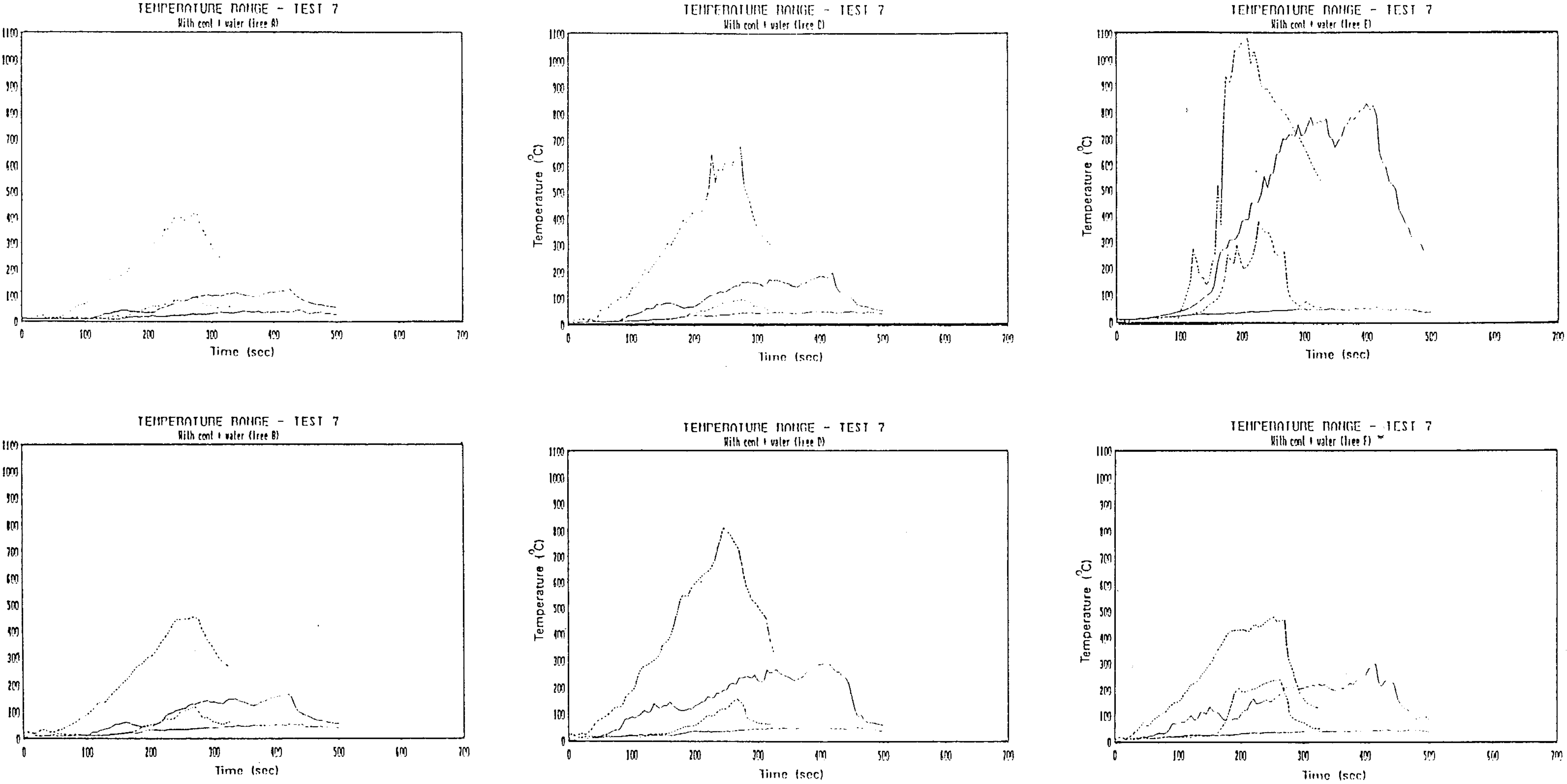


Figure 37 Comparison of centre-line temperatures for sprayed test CFT7 and unsprayed test CFT3 at heights 0.3 m and 1.7 m. (CFT3: .... , CFT7:___________)

APPENDIX A - CHARACTERISTICS OF WATER SPRAYS

1. Introduction

Four different types of spray were used in the tests described in Section 4 of the report. These are designated as follows:

Type A	Special head designed by SAVE Ltd.
Type B	Disc and core type nozzle (medium droplet size).
Type C	Multiple orifice 'fogjet' nozzle.
Type D	Disc and core type nozzle (coarse droplet size).

The Type B and D nozzles had the same body but different disc and core inserts. The body for the Type A nozzle was similar, but the insert was designed to give a hollow-cone distribution whereas Types B and D produced a full cone distribution. Figure A1 shows the four nozzles.

2. Theoretical considerations

2.1 Definition of spray characteristics

Most methods of spray production do not produce a uniform spray field nor a narrow band of droplet sizes. At any given point in the spray field a spectrum of droplet sizes will exist. A number of methods of expressing this distribution as a single number have been developed. The three most commonly used are as follows:

Sauter Mean Diameter (SMD):

This is defined as the droplet diameter which has the same volume to area ratio as the ratio of the total volume to total area for the whole spray.

Volume Median Diameter (VMD):

This is defined as the droplet diameter which divides the size distribution into two groups each with the same total volume.

Number Median Diameter (NMD):

This is defined as the droplet diameter which divides the sample into two groups of equal number.

The Sauter Mean Diameter is most commonly used in the context of fire suppression and will be the definition used in this Report unless otherwise stated.

2.2 Effect of operating pressures

For sprays produced by forcing water under pressure through an orifice the following general relationships apply:

$$d \propto D^{2/3}/\Delta p^{1/3}$$

$$d \propto D^2/Q^{2/3}$$

Thus for any given nozzle we would expect the volume flow rate to increase as $\Delta p^{1/2}$ and the size of the droplets to decrease as $\Delta p^{1/3}$,

3. Measurement techniques

3.1 Introduction

The characterisation of a water spray is a very difficult process. Few, if any, methods of producing a spray yield droplets of constant size. As noted above, droplet size at point in the spray must be described in statistical terms. Further, droplets may coagulate and the description will vary from point to point in the spray field. It follows that a full characterisation of a spray is a difficult and time-consuming process. A number of techniques are available, three of which were considered for use in this study and are described briefly below.

3.2 Measurement methods

3.2.1 Method A

This method has been developed by the South Bank Polytechnic, principally for use with standard automatic sprinkler systems for use in buildings. A small sample volume within the spray field is illuminated for brief periods by pulsing a high power copper vapour laser. During each period the droplets within the sample volume are illuminated and recorded photographically, together with a hypodermic needle point also within the sample volume. The resultant images can then be examined semi-automatically to determine the distribution of drop size, using the hypodermic needle as a reference.

The combination of pulsed illumination and high-speed photography also allows the speed and direction of droplets to be determined.

3.2.2 Method B

This method, produced by Particle Measuring Systems Inc, uses a helium/neon laser as an illumination source for an optical imaging unit, consisting of a linear array of photodiodes. The interruption of the laser beam by the passage of droplets casts a shadow on the photodiode array. The resulting output is processed to yield a droplet size distribution.

3.2.3 Method C

This method, produced by Malvern Instruments Ltd, also uses a helium/neon laser. The laser beam is directed onto a receiver, typically 500 mm from the beam source. Droplets passing through the beam scatter light which is focused via a Fourier optical lens. The resulting fringe pattern is recorded by a radially-arranged photodiode array. The resulting output from the photodiode array is processed to determine the distribution of droplet sizes.

3.3 Comparison of results

Because of the different techniques employed it is recognised that these methods tends to give different results for nominally identical sprays. To compare them measurements were made using the SAVE nozzle. Table A1 gives the results, expressed in terms of the three characteristic measures of droplet size set out in 2.1. Clearly the degree of agreement is poor. It is possible that this may, in part, be due to the use of different samples of the SAVE nozzle with the different test methods, although this would only be expected to be a minor contribution. In order to provide a basis for comparison it was decided to use Method B as a common basis for comparing the four nozzles used.

4. Spray nozzle characteristics

4.1 Droplet sizes

Using Method B, the droplet size characteristics of the four selected nozzles were determined and are set out in Table A2. The trends in sizes are as expected from the manufacturers' descriptions, with the Sauter Mean Diameter at 3 bar ranging from 150 μm for the finest nozzle, Type C, to 350 μm for the coarse nozzle, Type D, with the Type A and Type B nozzles lying approximately midway between these at 250 μm and 270 μm respectively.

4.2 Volume flow rates

The volume flow rates for each nozzle type were determined from in situ measurements made when they were installed in the test rig described in detail in Section 4.4. The total flow rate through fifteen nozzles was determined using a rotameter fitted to the supply pipe for applied pressures using an in-line gauge. The mean flow rate for each nozzle type at selected applied pressures are set out in Table A3.

TABLE A1. A COMPARISON OF DROPLET SIZE CHARACTERISTICS FOR THE TYPE A NOZZLE, USING THREE DIFFERENT MEASUREMENT METHODS

Method	Number Median Diameter (μm)	Volume Median Diameter (μm)	Sauter Mean Diameter (μm)
A	180	---	---
B	34	287	244
C	---	100	---

TABLE A2. DROPLET SIZE DATA FOR NOZZLES TYPE A TO D AT TWO APPLIED PRESSURES

Nozzle type	Number Median Diameter (μm)		Volume Median Diameter (μm)		Sauter Mean Diameter (μm)	
	4 bar	6 bar	4 bar	6 bar	4 bar	6 bar
Type A	34	25	307	286	253	230
Type B	42	36	321	289	269	240
Type C	23	23	199	184	170	152
Type D	36	31	454	365	350	294

TABLE A3. VOLUME FLOW RATES OF WATER FOR DIFFERENT APPLIED PRESSURES FOR SPRAY NOZZLES TYPE A TO D

Nozzle type	Applied pressure	Flow rate
Type A	3 6 9	1.07 1.40 1.60
Type B	3 6 9	0.83 1.13 1.40
Type C	3 6 9	1.13 1.47 1.67
Type D	3 6	3.33 4.67

APPENDIX B - GAS AND PARTICULATE SAMPLING METHODS

1. Introduction

This Appendix gives details of the methods and procedures used for sampling gases and particulates.

2. Choice of sampling methods

There are a number of particular problems in characterising a complex atmosphere such as that produced by a fire.

(i) Most particle trapping and sizing devices are designed to trap small numbers of particles from very dilute atmospheres over a long period of time. Fire and spray atmospheres are very dense and so likely to overwhelm and clog sampling devices.

(ii) Most particle trapping and sizing devices are designed to characterise solid particulate atmospheres containing particles of respirable size (capable of penetrating into the lower respiratory tract and defined as up to 5 µm MMAD, sometimes including particles classed as 'inhalable' defined as up to 10 µm MMAD). However, it is considered that in the context of this study larger water droplet particles may be important. This is because persons in an emergency situation, where they may be distressed, may breathe quite deeply through their mouths. In this situation it is considered that a proportion of larger particles, especially those between approximately 10-20 µm, and some of those up to approximately 100 µm, may deposit in the naso-pharyngeal region and upper airways. If these particles or droplets contain significant concentrations of acid gases, then they may present a hazard of laryngeal and bronchial inflammation and constriction. Smaller particles and droplets may penetrate into the deep lung and cause lung inflammation and oedema.

(iii) Although solid particles are relatively simple to trap and characterise, liquid droplets may coalesce and flood the collection plates of samplers or may evaporate before the collection plates can be weighed. Either way a false sample may be obtained. When the acid concentration of liquid droplets is under examination, there is the additional problem that once an acid droplet has been trapped, further vapour may dissolve in it from the atmosphere being drawn through the sampler, or both the liquid and its acid contents may be evaporated during or after sampling.

(iv) Continuous sampling and analysis of permanent gases (carbon monoxide, carbon dioxide and oxygen) is relatively straightforward, although care must be taken to ensure that gases are clean (free from particulate material) and dry before they enter the analyzers.

(v) Organic components and acid gases may be partitioned between the gas phase and particulate phase and may also condense out or react with surfaces. Thus consideration of these phenomena must be made when sampling. For these experiments atmosphere samples were taken as 'grab' samples into evacuated vessels at intervals during the tests. In order to minimise condensation or reaction with surfaces, the smoke atmosphere was continuously sampled through heated, epoxy resin lined stainless steel tubing. Grab samples were then taken from this atmosphere sample stream.

Due to these difficulties it is possible to obtain only a general impression of the composition of a fire atmosphere, but attempts were made to cover these problems as far as possible in the methods employed.

3. Sampling Methods

3.1 Permanent gases

Continuous concentration measurements of permanent gases (carbon monoxide, carbon dioxide and oxygen) were made using infra-red analyzers for the carbon oxides and a paramagnetic analyzer for oxygen. To achieve this, gases were continuously sampled from the aircraft cabin along four heated stainless steel tubes at a rate of approximately 3 l/minute. These sampling lines passed into a mobile laboratory which housed the gas analyzers.

3.2 Elutriators

During preliminary experiments using the test rig described in 4.3 some of the sampling devices were placed at the end of 1 metre lengths of copper tubing. These were designed to act as elutriators. The principle of these elutriators was that the larger water droplets from the spray would settle out of the atmosphere in the tubes, so that only the smaller, respirable, fraction would penetrate to the sampling devices. This was intended to prevent the sampling devices from being overwhelmed with water.

In practice it was found that in the large scale spray tests, water did not soak the sampling devices, even those not protected by elutriators. In these tests it therefore appeared that water droplets capable of being trapped on the samplers (less than approximately 20 µm MMAD) were not being formed in appreciable amounts, which was an encouraging sign for the spray system. Thus the decision was made not to use elutriators in the full scale aircraft tests, but to place the sampling devices directly in the cabin smoke.

3.3 Total smoke traps - open face filters and gas bubblers

These devices were used to trap the total contents of the smoke in terms of gas, liquid and solid particles. This was done by drawing samples of the fire atmosphere through open face filters (37 mm diameter, pre-weighed Whatman GF/A circular glass fibre filters) placed horizontally, facing downwards (ie sampling vertically upwards) or vertically (ie sampling horizontally), in the smoke, at a rate of 1 l/min. The filter holders were protected from vertically falling water droplets by small covers placed just above them.

These filters should trap all solid and liquid particles of 'inhalable' size, although it has not been possible to measure the upper size limit for collection. It is estimated that most particles up to 20 µm would be trapped, and possibly some larger particles.

Air passing through the filter was then passed through two gas bubblers containing
0.01 M sodium hydroxide (NaOH) solution, to trap any acid gases present in the vapour phase.

When sampling was complete the filter paper was re-weighed to determine the mass of deposited material and, then, place din 0.01 M NaOH solution for extraction and analysis of any acid gases adsorbed to the particulate.

3.4 Particle sizing of solids and adsorbed gas analysis

Since the toxic effects of inhaled particles depend partly upon the site within the respiratory tract where they are deposited, devices were used that are designed to trap particles within several different size ranges.

(a) Andersen Mini Sampler

One device used was the Andersen Mini Sampler. This device is a cascade impactor, which fractionates the sampled atmosphere onto 4 plates and an absolute filter. The device (Figure B1) samples at a rate of 1.4 litres/minute, and traps particles above 5.5 µm on the first stage, and respirable particles (>5.5 µm) on the subsequent stages. The full collection characteristics are as follows:

Stage 1 - Particles larger than 5.5 µm aerodynamic diameter (a.d).
Stage 2 - Particles with a cut-off point of 3.5 µm a.d.

Stage 3 - Particles with a cut-off point of 2.0 μm a.d.
Stage 4 - Particles with a cut-off point of 0.3 μm a.d.
Filter - Particles less than 0.3 μm a.d.

Two gas bubblers were placed in series after the sampler to trap acid gases.

The sampler was placed to point vertically into the smoke (sampling horizontally) so that, as with the open face filter, it should, in theory, trap all smoke constituents, up to a maximum particle size capable of entering the device. Unfortunately this size is not given in the literature, but is likely to be approximately 10-20 μm.

Liquid droplets are also fractionated by the sampler, and remain on the plates provided there is not a sufficient deposit to coalesce over the plate and interfere with the functioning of the device, or providing the liquid is not so volatile as to evaporate in the air stream once deposited.

In practice the total deposition in the Mini Sampler should be equivalent to that on the open face filter. The deposits on the plates and the filter were weighed to assess the deposited particulate. The plates were then washed into 0.01 M NaOH, and the filter was placed in 0.01 M NaOH solution for estimation of any acid gases adsorbed onto the particles or present as acid droplets.

(b) Casella Cascade Impactor

Another device used was the Casella Cascade Impactor. Like the Andersen Mini Sampler, this device is primarily designed to fractionate atmospheres containing solid particles, but it is also capable of trapping liquid droplets to some extent, subject to the same potential problems of flooding or evaporation.

The Casella Cascade Impactor (Figure B2) has four stages and a glass fibre filter, particles being deposited on glass plates and on the filter. The device is designed to sample atmospheres containing low concentrations of particles at a relatively high rate of 17.5 l/minute. The collection characteristics at this sampling flow rate are as follows:

Stage 1 - Particles larger than 12 μm aerodynamic diameter (a.d), up to approximately 200 μm a.d.
Stage 2 - Particles with a cut-off point of 4 μm a.d.
Stage 3 - Particles with a cut-off point of 1.5 μm a.d.
Stage 4 - Particles with a cut-off point of 0.5 μm a.d.
Filter - Particles less than 0.5 μm a.d.

The main reason for using this device in the study is that at this sampling rate the upper stage of the device is stated to trap larger particles than the Andersen Mini Sampler. With the Casella Cascade Impactor in the vertical position and the orifice sampling horizontally, it should trap 85% of particles smaller than 40 μm. Particles above 50 μm up to 100 μm should mostly be trapped, and a smaller percentage up to a maximum of 200 μm. It was therefore hoped that this device would trap the larger water droplets which could present a problem to a mouth-breathing person, and which might not be trapped by the other devices.

At the high sampling rate of 17.5 l/minute it was snot practicable to place a gas bubbler after the Cascade Impactor, but it should trap all of the solid and liquid particles trapped by the Andersen Mini Sampler and the open face filter. The Cascade Impactor plates and filter were extracted in 0.01 M NaOH solution for analysis of acid gases adsorbed on the particles.

3.5 Trapping and particle sizing of liquid droplets

Although the devices described above should trap liquid droplets, there was the possibility of flooding or evaporation that could affect the results. Also, the collection of very small deposits on the plates did not facilitate analysis of the adsorbed gases. For this reason a further particle sizing device, the May Multistage Impinger (Figures B3 and B4), was used.

The May Impinger is specifically designed for sampling liquid droplet atmospheres and traps particles (solid or liquid) in solution. The solution can then be removed for analysis. Particles are sampled at 10 l/minute vertically downwards through an orifice in the top of the device. The collection characteristics are as follows:

Stage 1	-	Particles larger than 5.5 µm aerodynamic diameter (a.d).
Stage 2	-	Particles with a cut-off point of 2.0 µm a.d.
Stage 3	-	Particles with a cut-off point of 0.5 µm a.d.
Filter	-	Particles less than 0.5 µm a.d.

Particles above approximately 5.5 µm are trapped in the upper stage, with a 100% trapping efficiency for particles above approximately 9 µm. The upper size limit is not defined.

Due to the high sampling rate, gas bubblers were not placed after the filter to trap vapours, so most vapour phase components will be lost, although some soluble vapours may be trapped in the impinger stages.

The advantage of the May Impinger is that any liquid acid droplets should be trapped up to the maximum trappable size. However, it cannot be said that any acid trapped is only from acid droplets, since some vapour may also be trapped. From the design of the device, it would seem likely that most vapour would be trapped in Stage 3, where the incoming air is blown against and across the large surface of liquid in the bottom stage in a swirl, whereas the opportunity for contact with the liquid interface is reduced in the upper stages.

3.6 Acid gases

Acid gases, both in the vapour phase and attached to particulates, were trapped in the various filters, impactors and gas traps described above. In addition, grab samples were taken into evacuated vessels from the continuous atmospheric sample passing through the heated lines. The acid gases were dissolved in 0.01 M NaOH solution inside the grab sample vessels. Halide and cyanide content was analyzed by High Performance Ion Chromatography (HPIC).

3.7 Organic atmosphere components

In addition to those used for the acid gases, grab samples were also taken from the heated lines for the collection or organic smoke constituents. These were analyzed by gas chromatography/mass spectrometry.

3.8 Bromide tracer for water droplets

In addition to the methods described a further attempt was made to discover whether any of the water spray had entered sampling devices by spiking the water in the spray tank with 100 g of either potassium or sodium bromide. Analysis of the various samples for bromide content might then reveal whether water droplets had penetrated the devices, since even if the water had evaporated, the bromide should remain on the plates and filters of the various sampling devices. For the tests CFT4 and CFT5, 100 g of potassium bromide was added to the spray and for tests CFT6 and CFT7,
100 g of sodium bromide was used.

4. Placement of particulate sizing devices

The sampling devices were placed near the centre of the passenger cabin at point G2. Because it was feared that high temperatures in the fires might damage the sampling equipment and destroy any samples, it was considered necessary to protect the samplers from excess heat exposure. The samplers were therefore placed in a box of approximately 2 litres volume. The box was constructed from wood and the exterior surfaces were lined with aluminium foil and 1 cm thick cement board. A thermocouple was placed inside the box during the hottest fire (Test No 3), and the maximum temperature recorded in the box was 35°C. The samplers were mounted so that their inlets were flush with the surface of the box. The Casella Cascade Impactor, Andersen Mini Sampler and an open face filter, were mounted in the front face of the box so that they sampled horizontally. The May Multistage Liquid Impinger was mounted in the top of the box so that its inlet faced upwards and it sampled vertically. A steel plate was suspended 15 cm above the box to prevent large water droplets from falling onto the samplers. In this way only airborne particles were taken into the samplers. The box was mounted on a steel frame so that the samplers were at a height of approximately 1.7 metres. After passing through the samplers the atmosphere was drawn through epoxy-lined stainless steel pipes to floor level, and then via plastic tubing to flowmeters and pumps placed under the passenger cabin in the cargo hold, from where they could be observed and controlled from outside the fuselage. A filter holder for the May Impinger was placed in the extract line at floor level, to trap any very small particles passing through the sampler.

5. Procedure

All devices except the Casella Cascade Impactor were run for three minutes from 1 to 4 minutes after ignition of the fire. The flow meters were observed and adjusted as necessary during the sampling period to maintain the correct sample extract rates. The Casella, which required a high sample flow rate, was found to clog quickly when first used during fire test No 3, the maximum obtainable extract rate dropping to low levels. For this reason the Casella sample was taken during the fourth minute only for tests CFT4-CFT7.

During the initial test (CFT1), only the open face filter and Andersen Mini Sampler were used. Sampling was not performed on test CFT2.

At the end of the sampling period (4 minutes after ignition) the sampling pumps were switched off and the samples left for approximately one hour after the fire was extinguished, when it was judged safe to enter the cabin and retrieve the samplers. The samplers were then dismantled and the collection plates weighed. The elapsed time between sample collection and weighing was approximately 2-4 hours. Where samples were observed to lose weight while being weighed, the first recorded (heaviest) weight was taken.

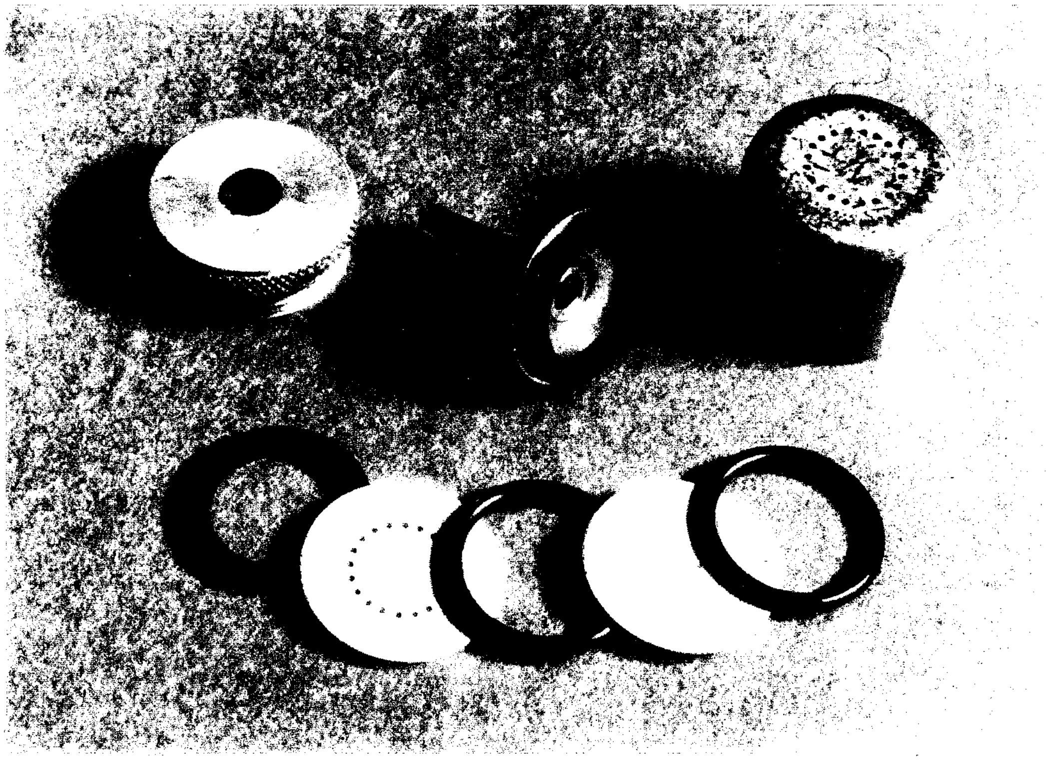


Figure B1 The Andersen mini-sampler - particle size analyser for solid aerosols

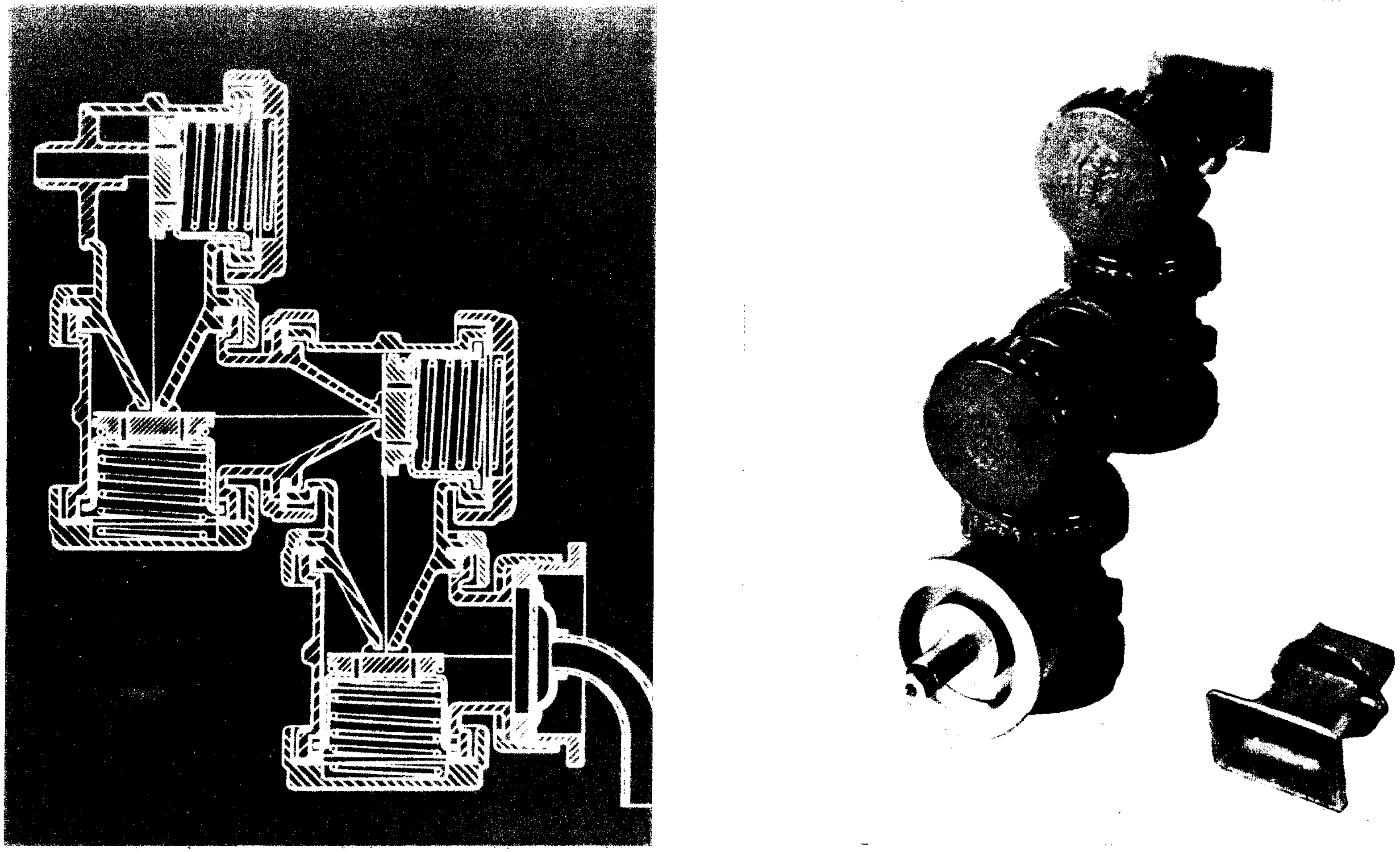
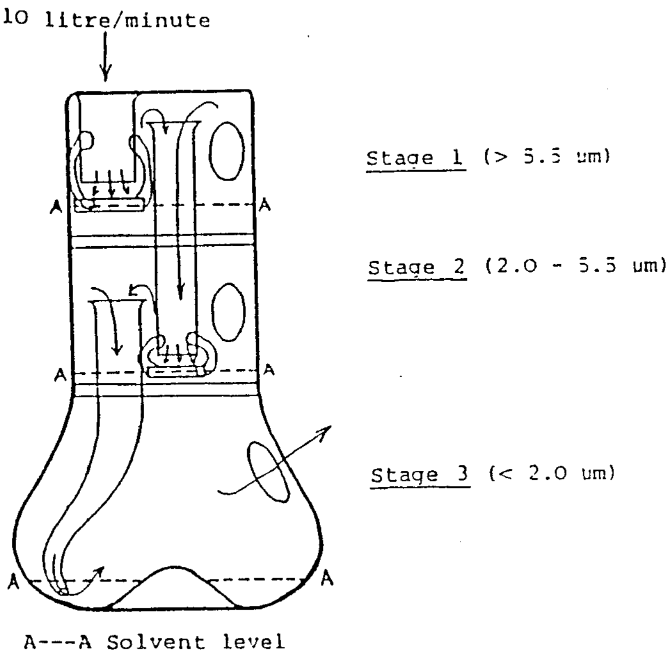


Figure B2 The Casella cascade impactor — particle size analyser for solid aerosols



Individual stage cut-off curves (after May K.R. 1966 Bacteriological Reviews Vol 30 No. 3)

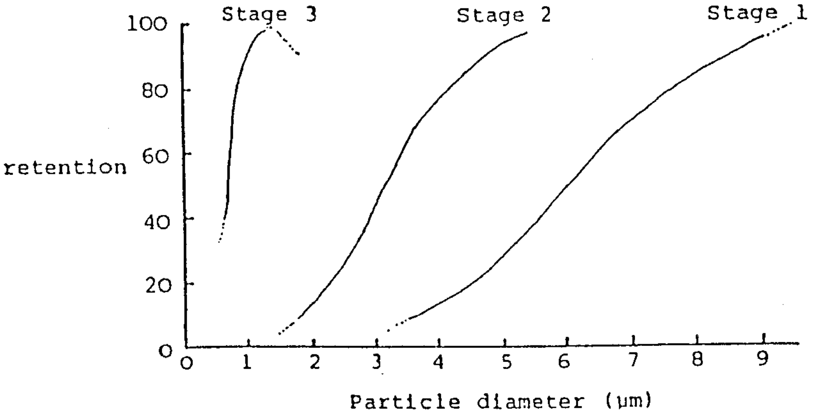


Figure B3 The May multi-stage impringer - particle size analyser Casella cascade impactor - particle size analyser for liquid aerosols

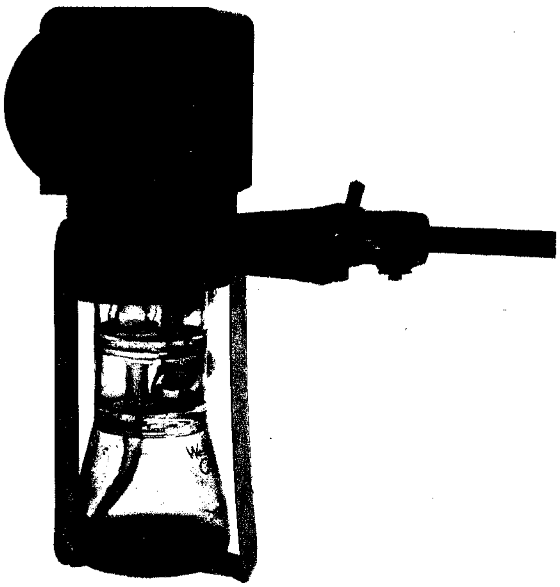


Figure B4 May multi-stage impringer containing trapped smoke particles of less than 2.0 μm diameter

APPENDIX C - TEMPERATURE MEASUREMENTS

This appendix shows for each of the tests CFT1 to CFT7 the variation of temperatures with time from the beginning of the test at measuring stations A, B, C, D, E and F along the centre line of the aircraft cabin. The locations of the measuring stations are shown schematically in Figure 14. At each measuring station, temperatures were measured at heights of 0.3, 0.6, 0.9, 1.2, 1.5, 1.8 and 2.1 metres.

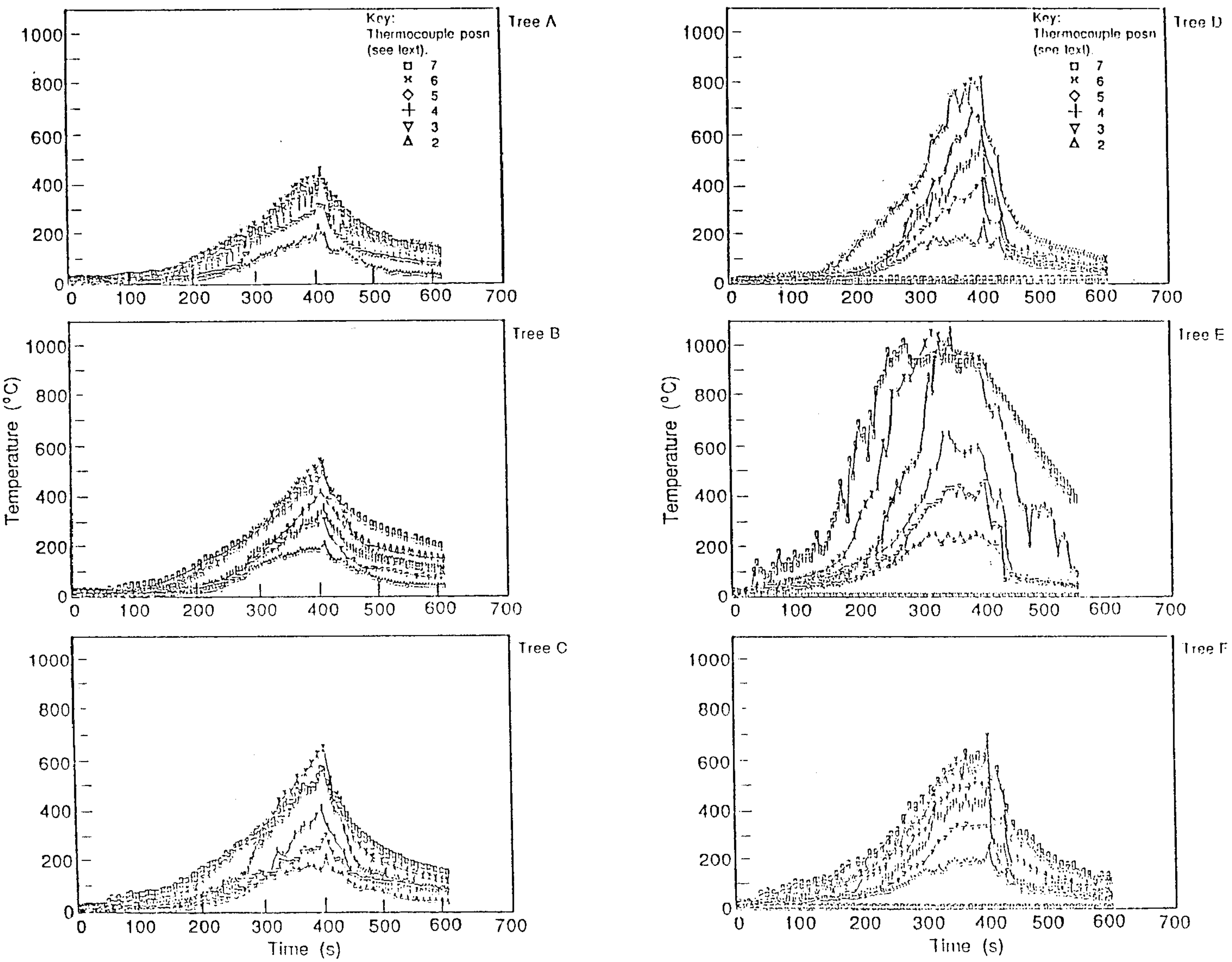


Figure C1 Fuselage centre-line temperatures - Test CFT1

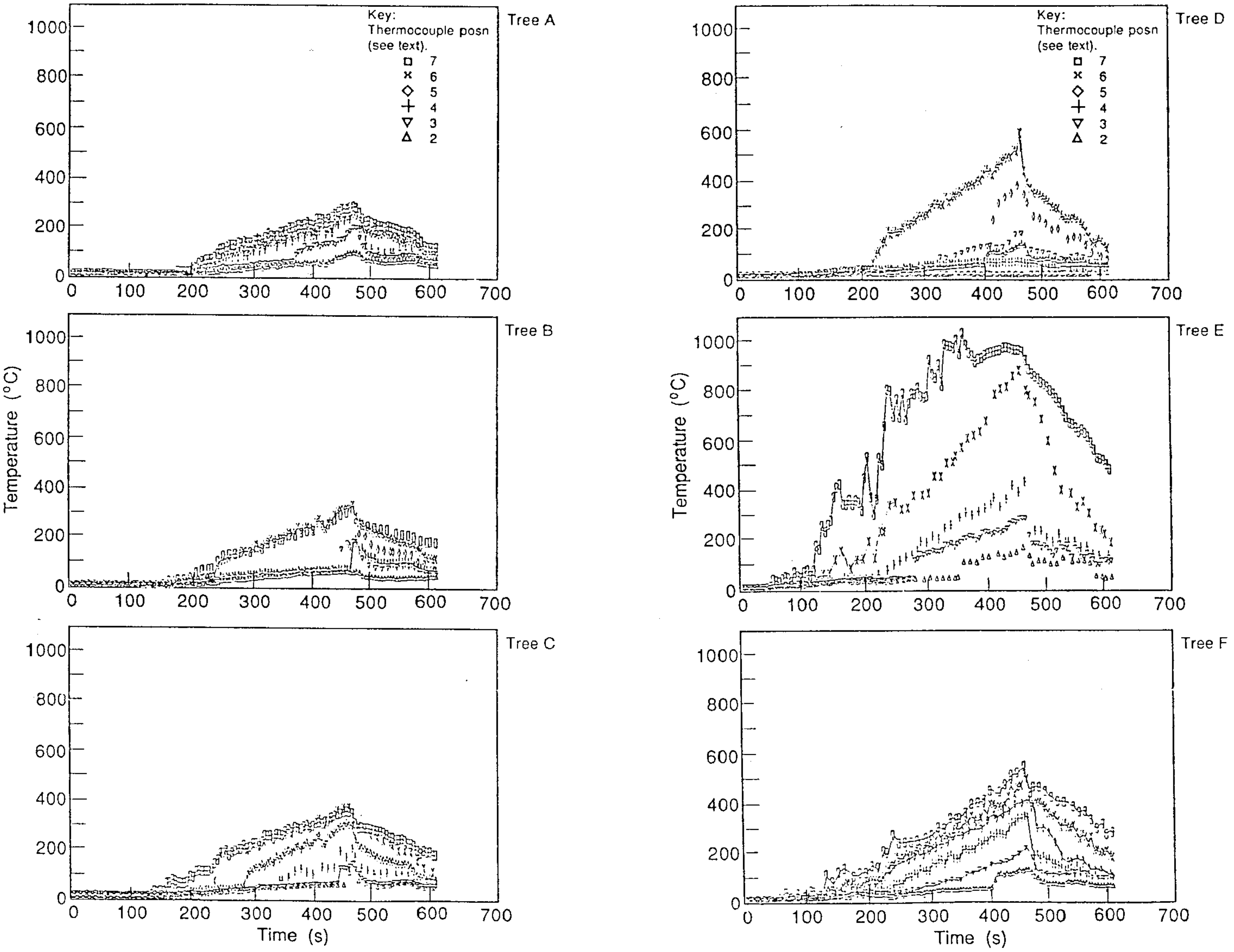


Figure C2 Fuselage centre-line temperatures - Test CFT2

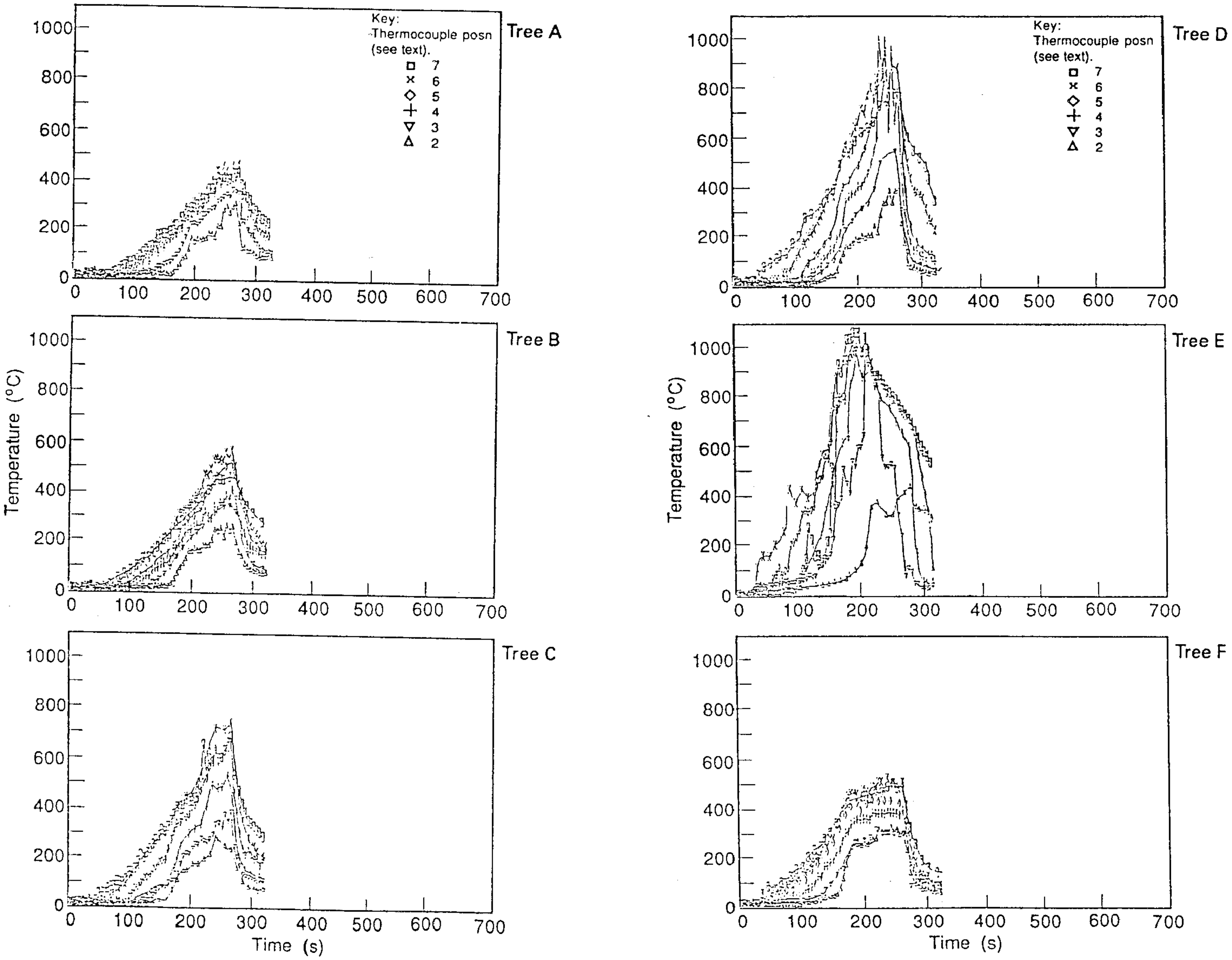


Figure C3 Fuselage centre-line temperatures - Test CFT3

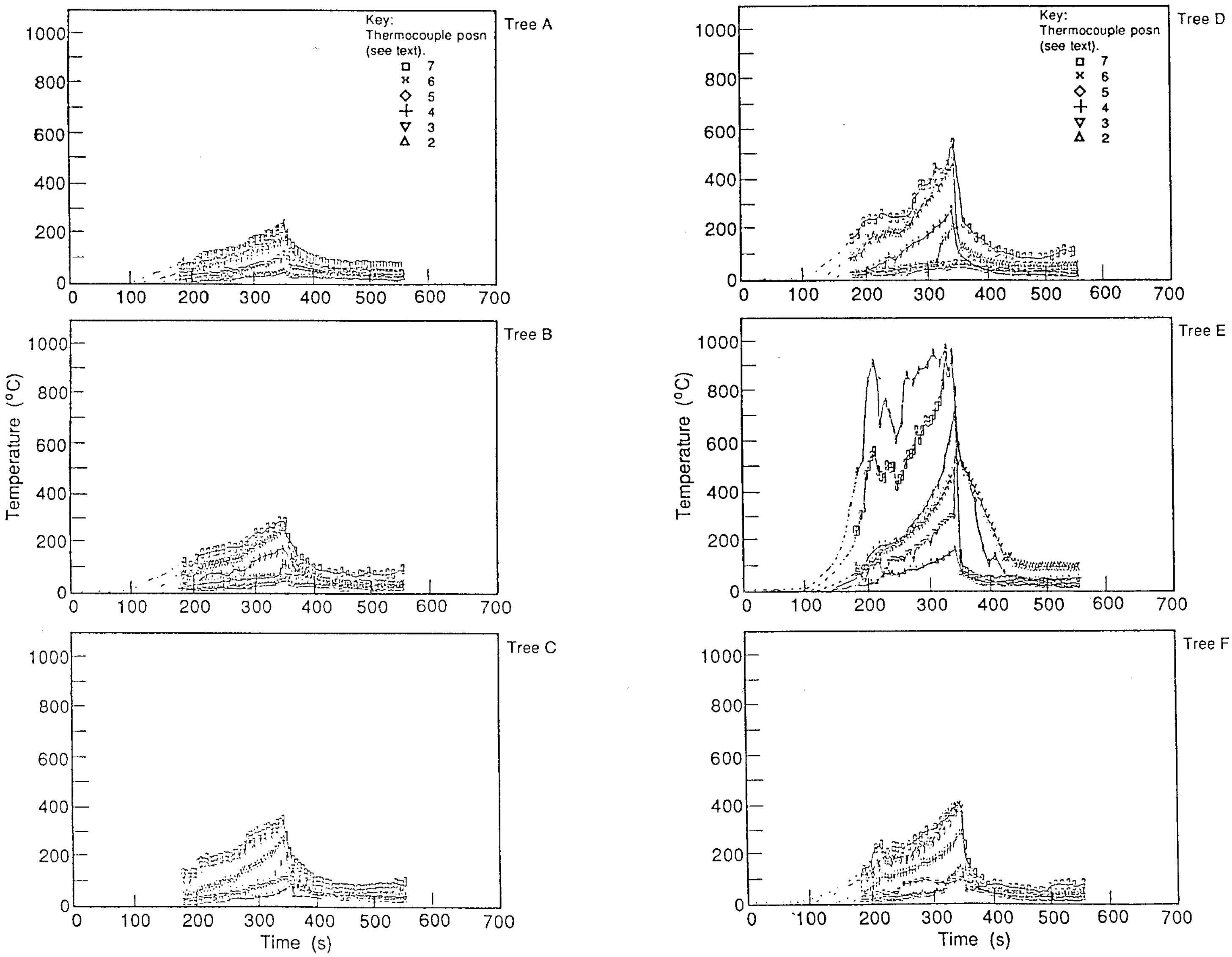


Figure C4 Fuselage centre-line temperatures - Test CFT4

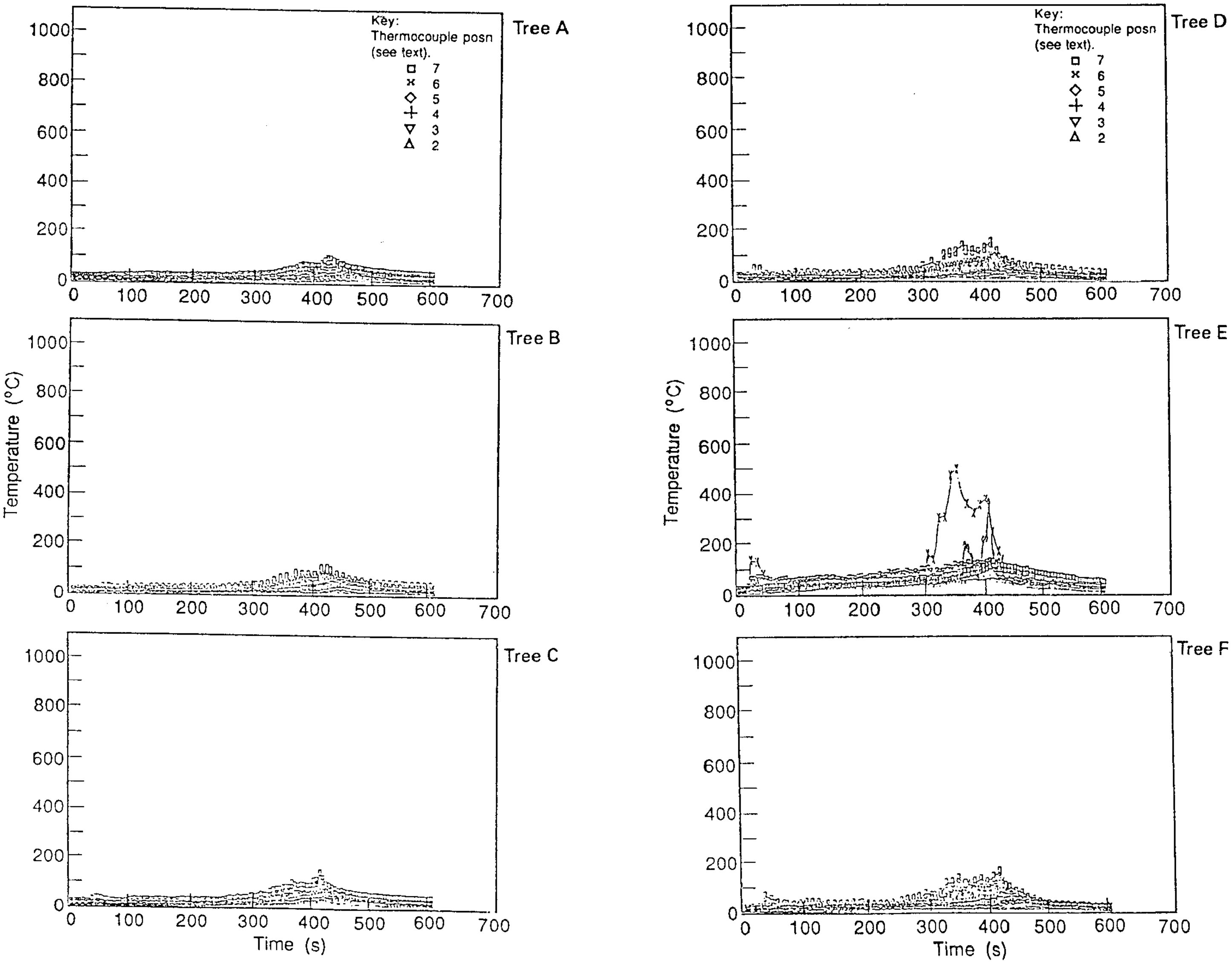


Figure C5 Fuselage centre-line temperatures - Test CFT5

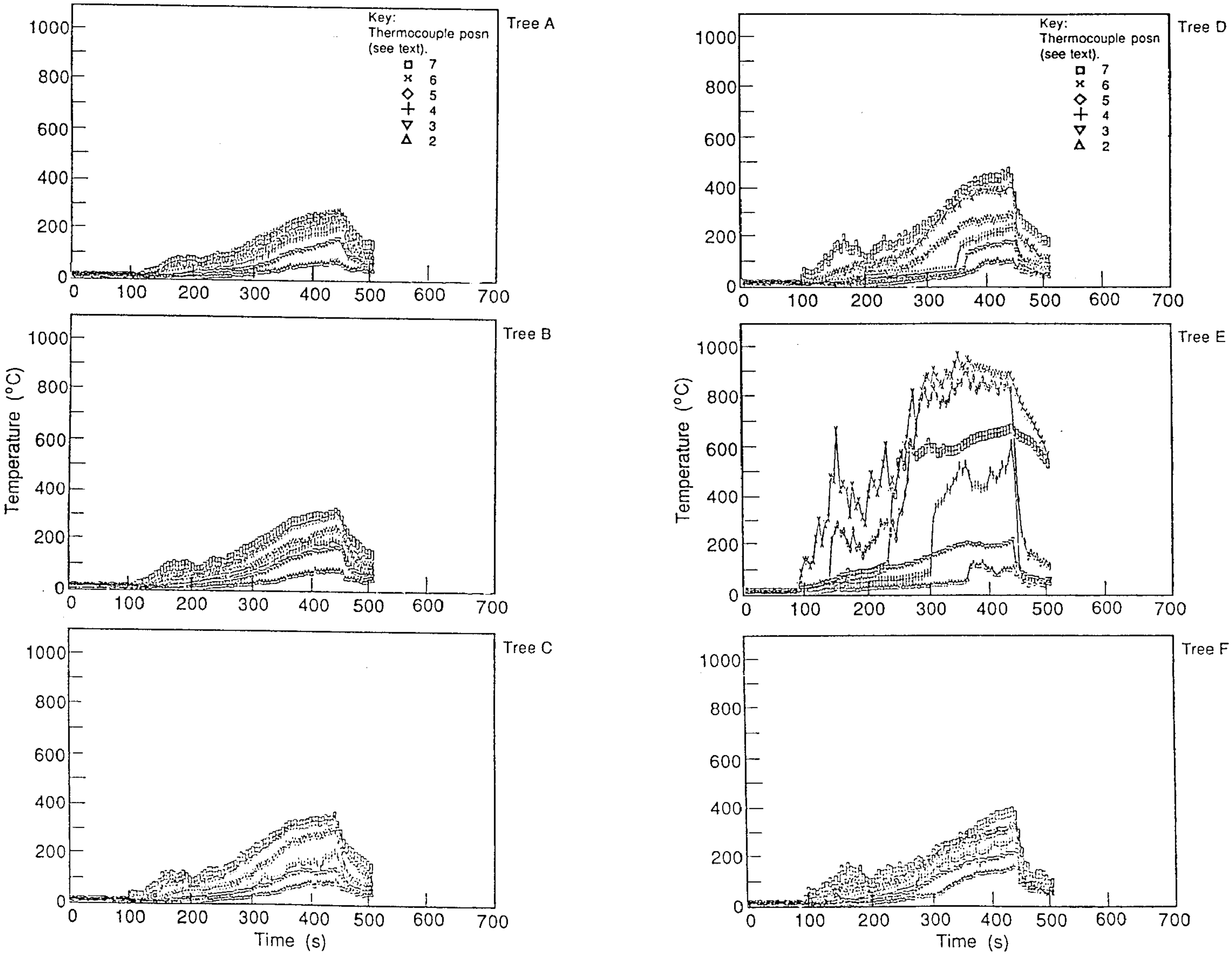


Figure C6 Fuselage centre-line temperatures - Test CFT6

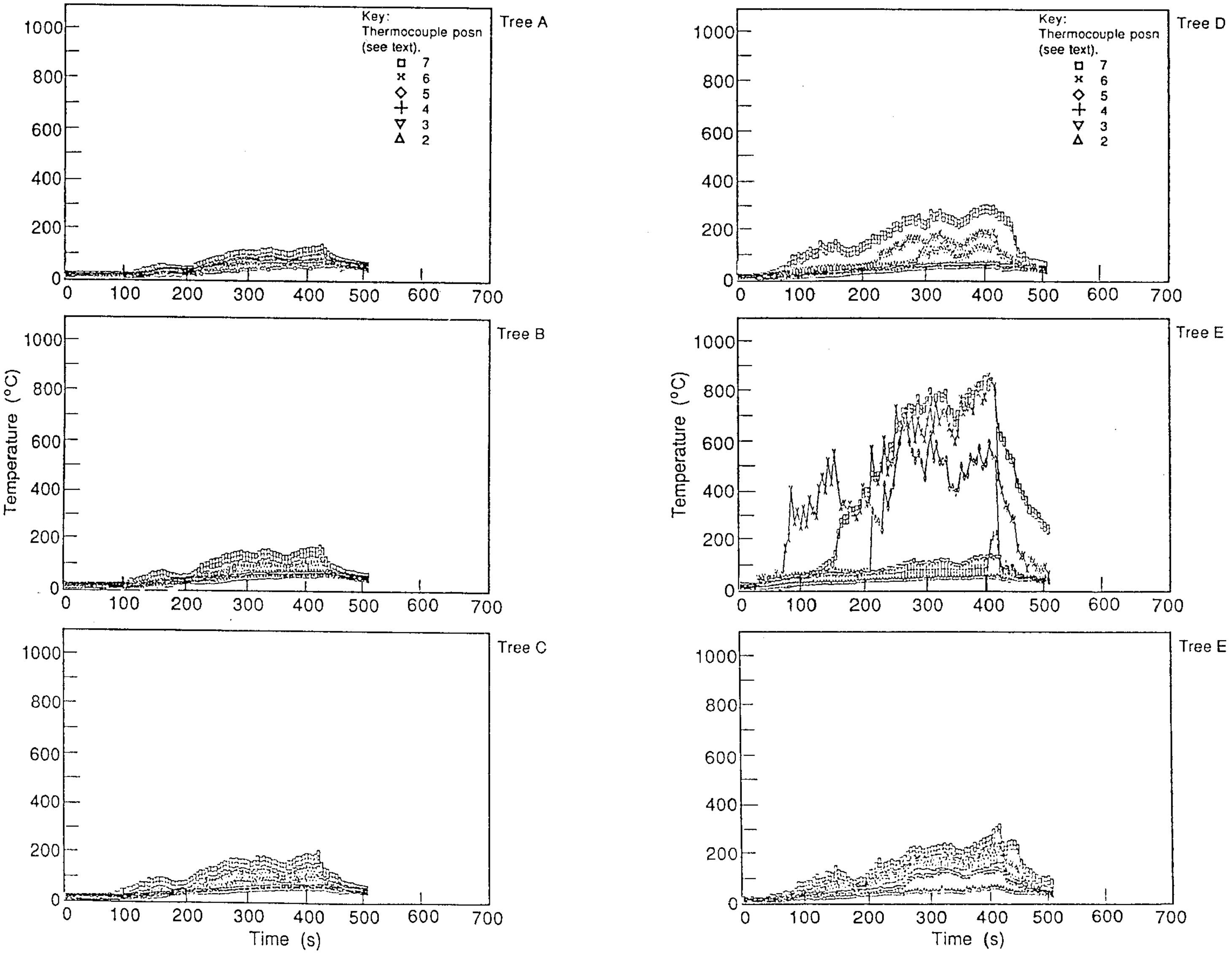


Figure C7 Fuselage centre-line temperatures - Test CFT7

APPENDIX D - SMOKE MEASUREMENTS

This appendix shows, for tests CFT1, CFT2, CFT3, CFT5, CFT6 and CFT7, the results of smoke opacity measurements made at measuring stations A and C (Figure 14). At each measuring station smoke opacity was measured at three heights - 1.7 m (top), 1.1 m (middle) and 0.3 m (bottom). Results are shown as optical density (OD) as defined in equation 1.

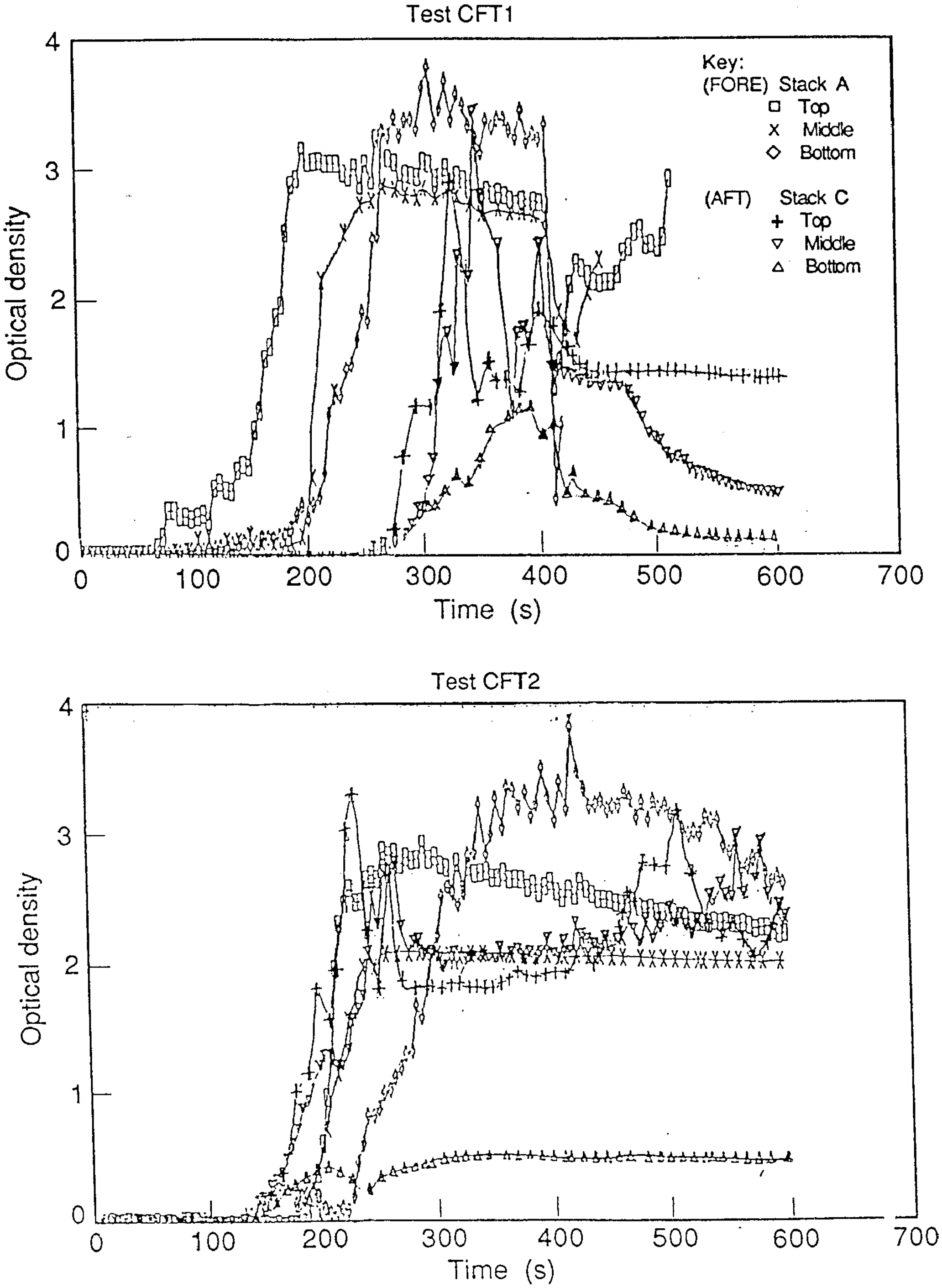
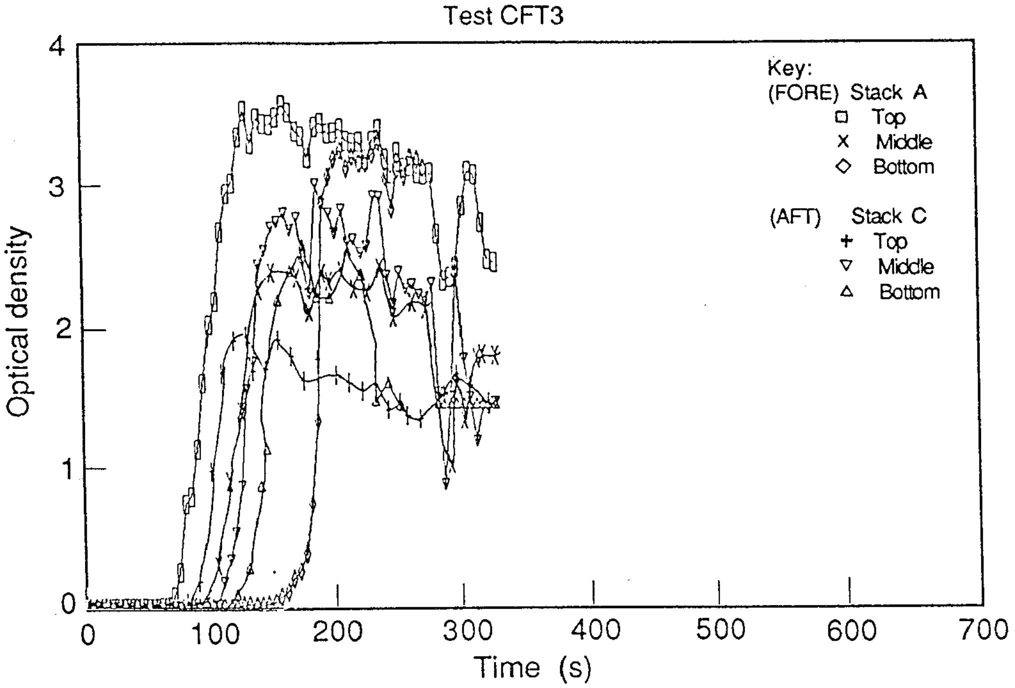


Figure D1 Measurements of smoke opacity - Tests CFT1 and CFT2



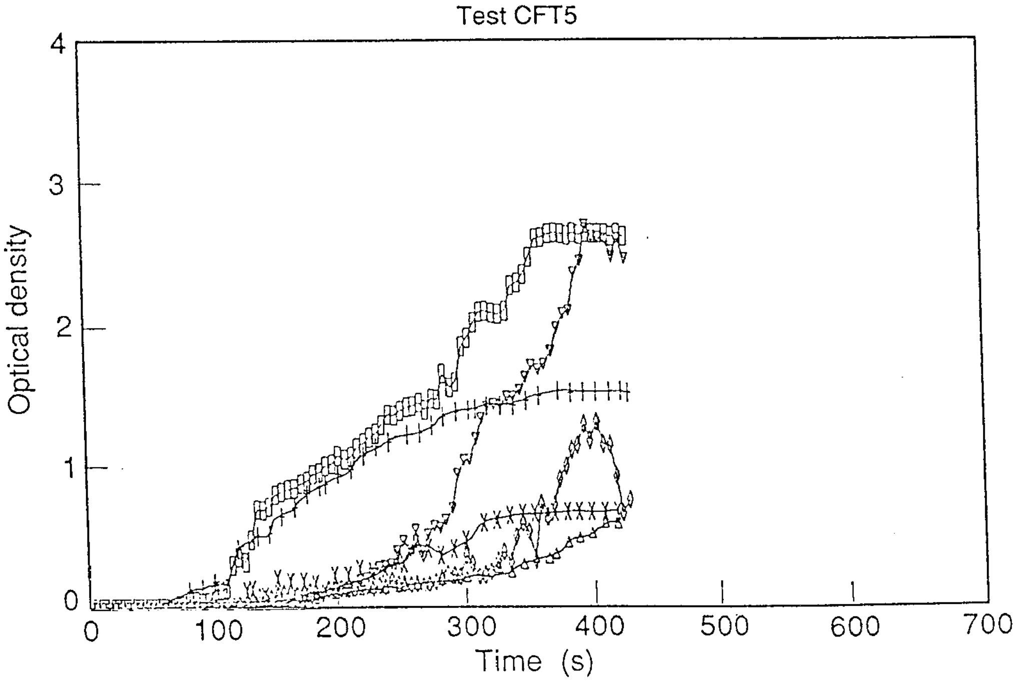


Figure D2 Measurements of smoke opacity - Tests CFT3 and CFT5

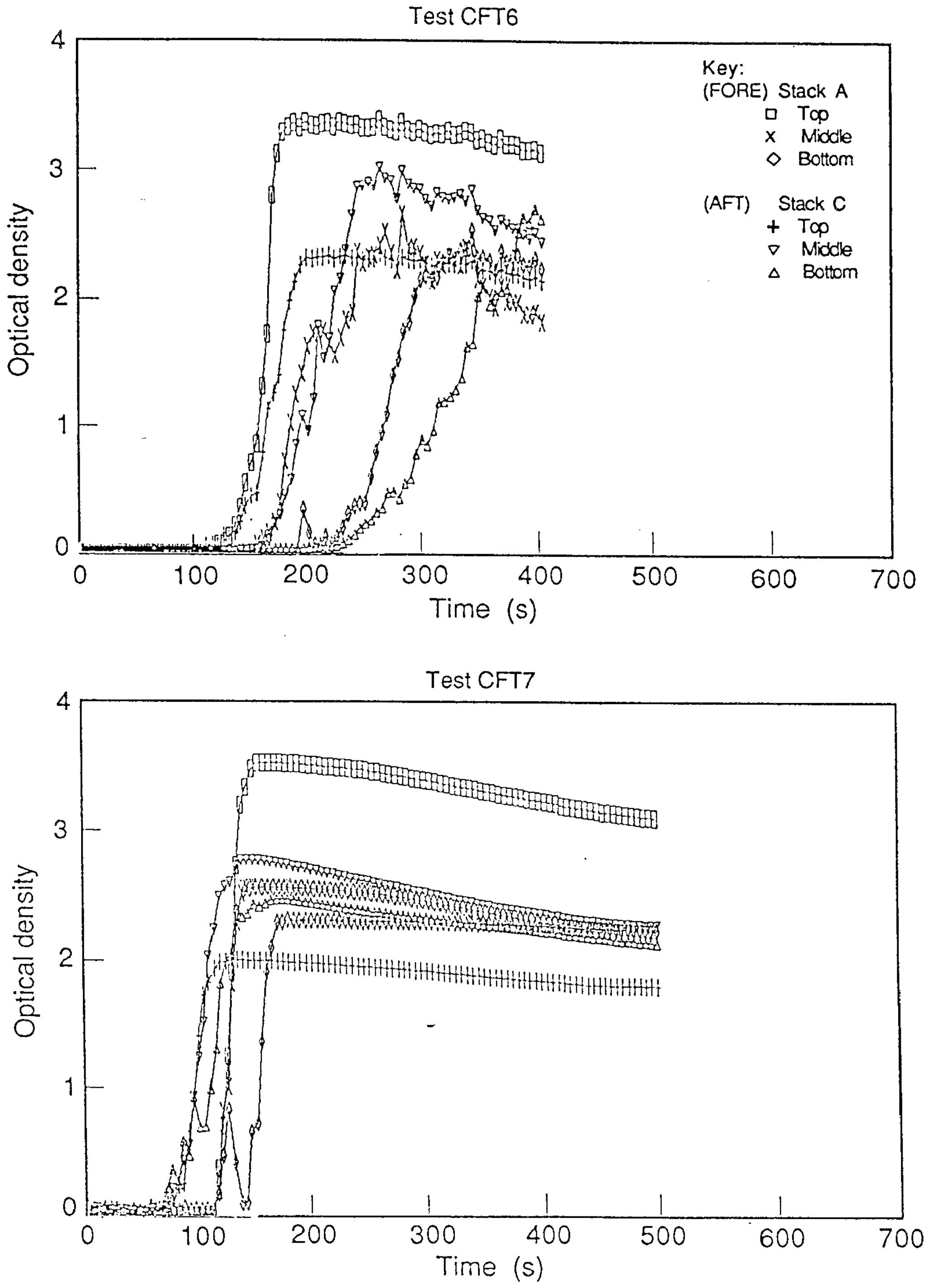


Figure D3 Measurements of smoke opacity - Tests CFT6 and CFT7

APPENDIX E - THERMAL RADIATION MEASUREMENTS

This appendix shows, for tests CFT1 to CFT7, the results of the measurements of thermal radiation at the four measuring positions RD1, RD2 and RD3, as shown in Figure 14.

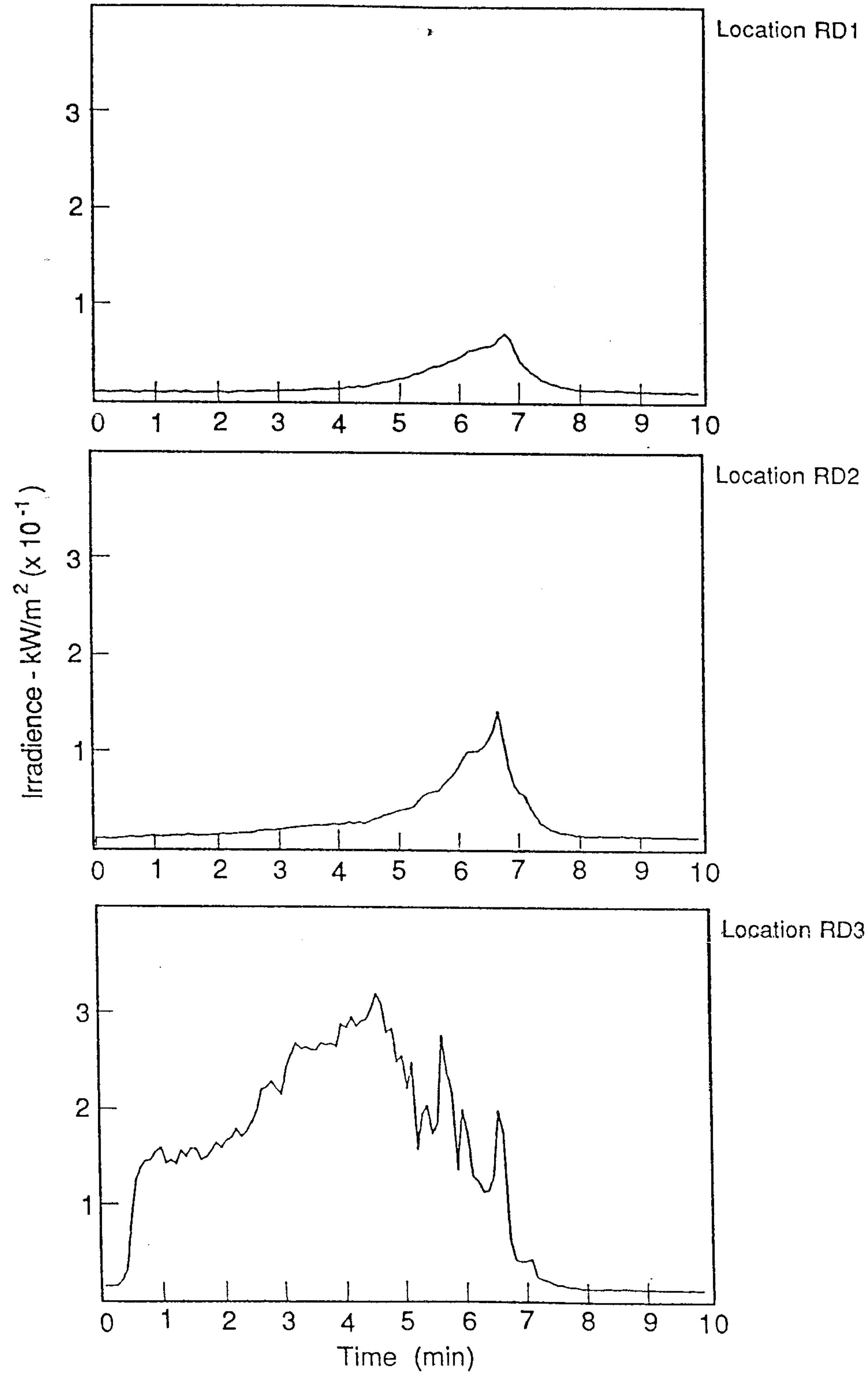


Figure E1 Thermal radiation measurements - Test CFT1

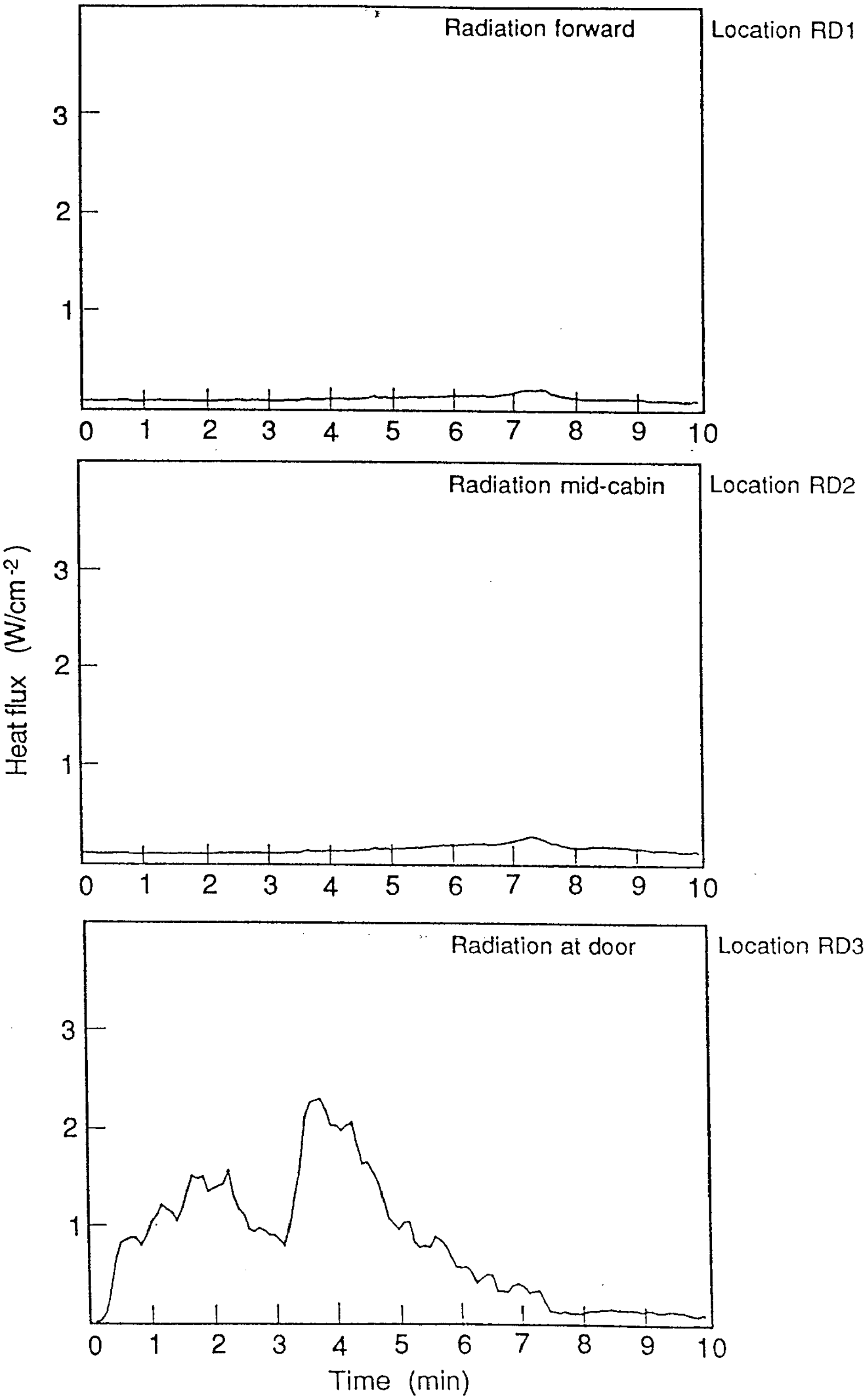


Figure E2 Thermal radiation measurements - Test CFT2

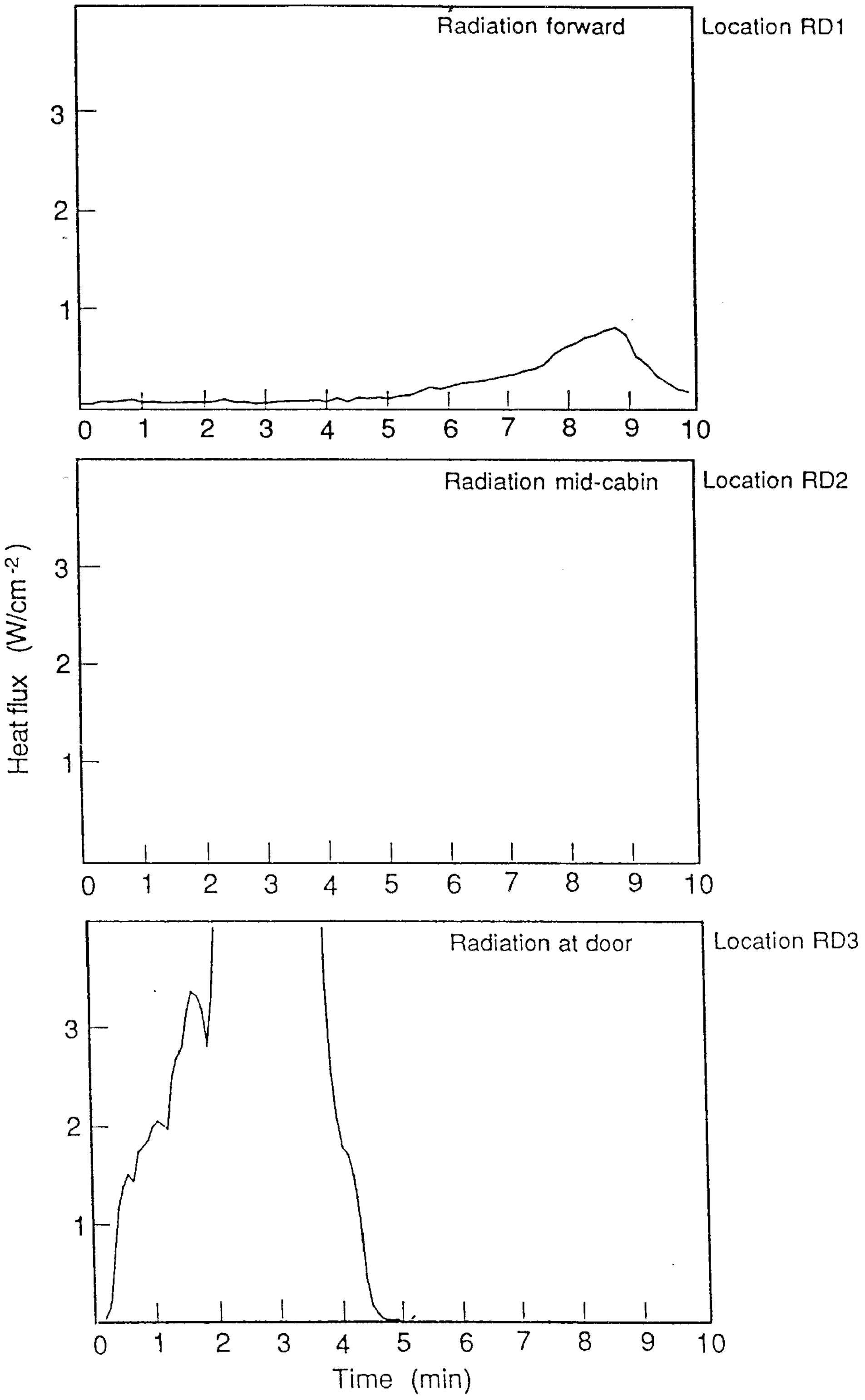


Figure E3 Thermal radiation measurements - Test CFT3

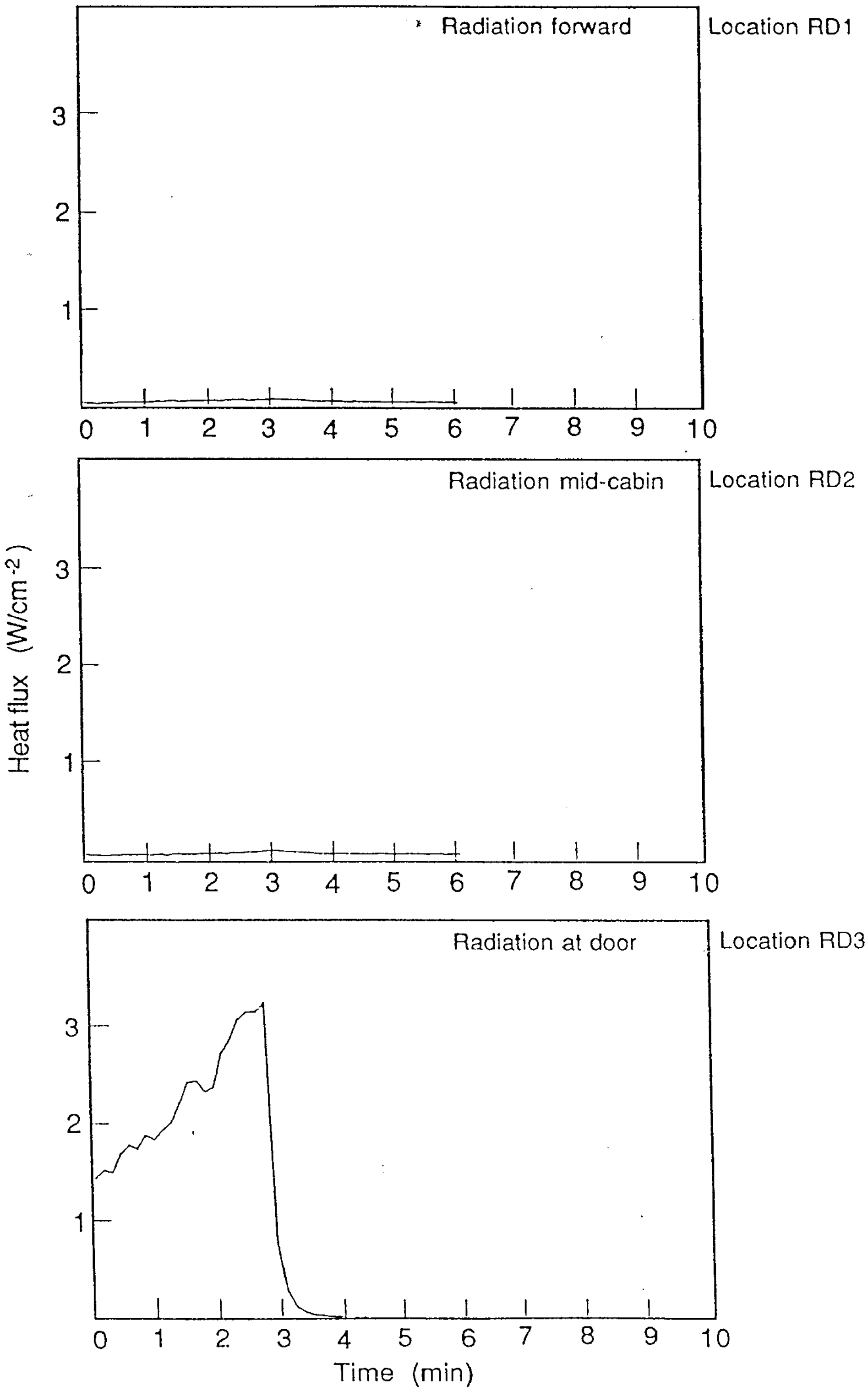


Figure E4 Thermal radiation measurements - Test CFT4

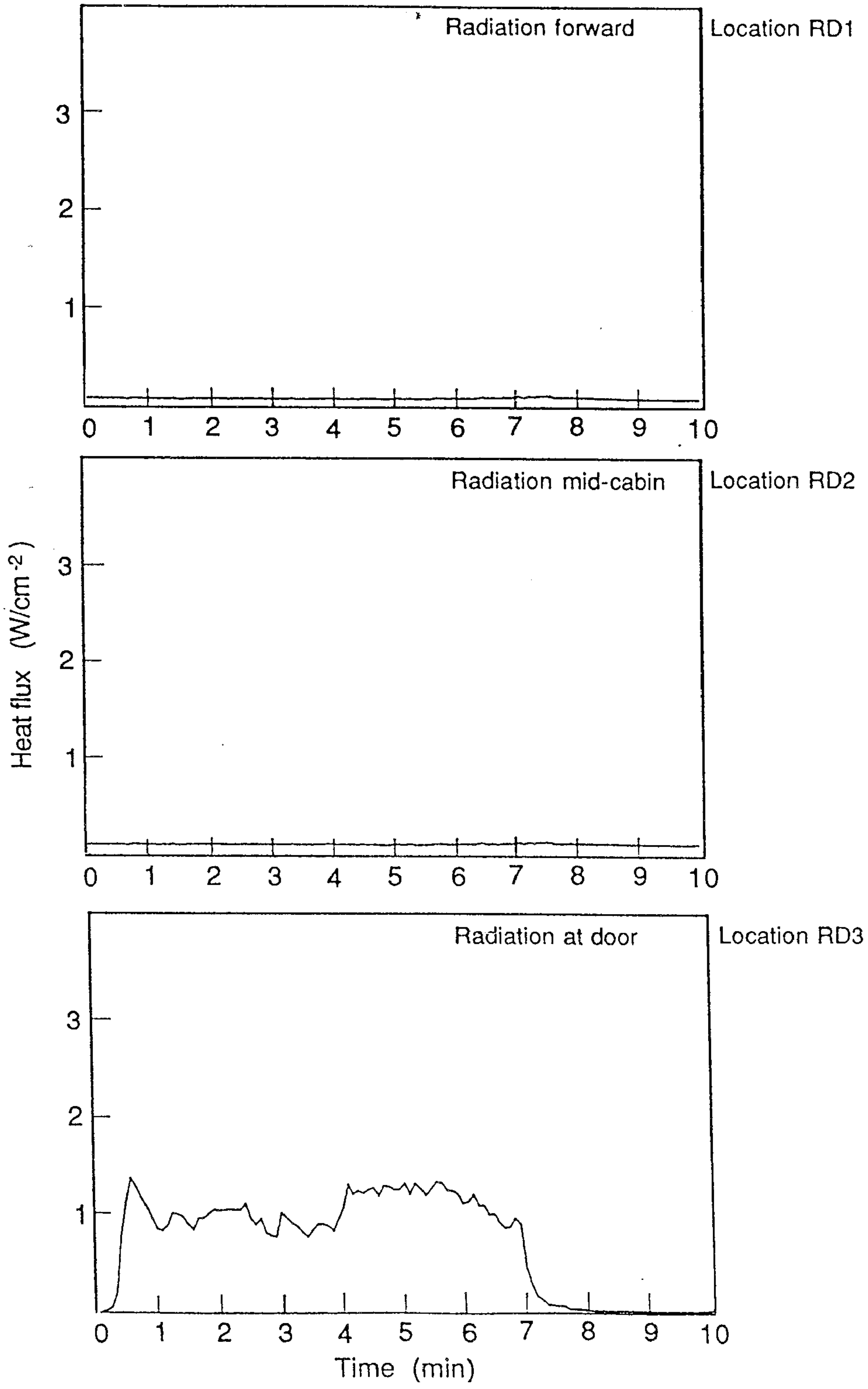


Figure E5 Thermal radiation measurements - Test CFT5

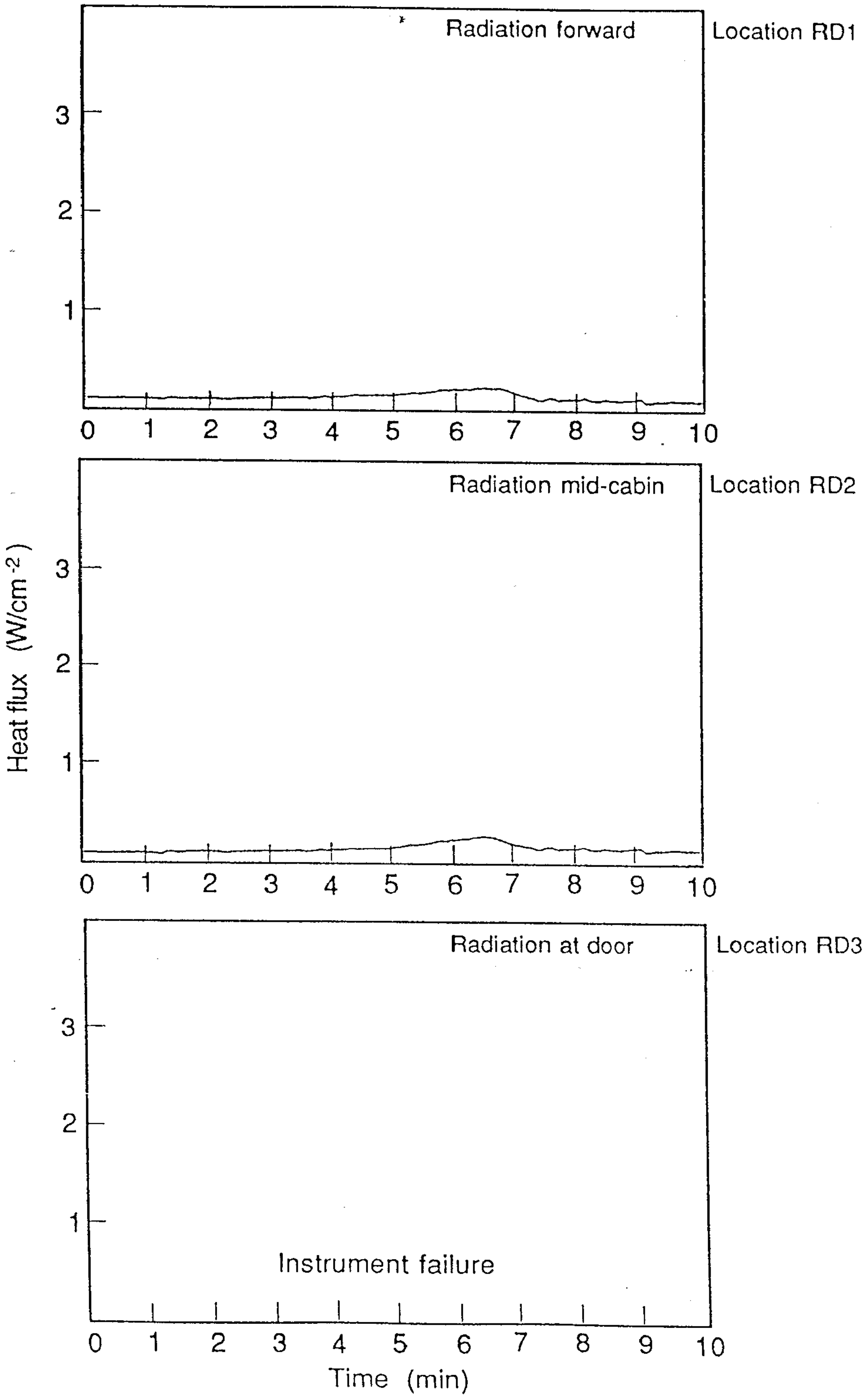


Figure E6 Thermal radiation measurements - Test CFT6

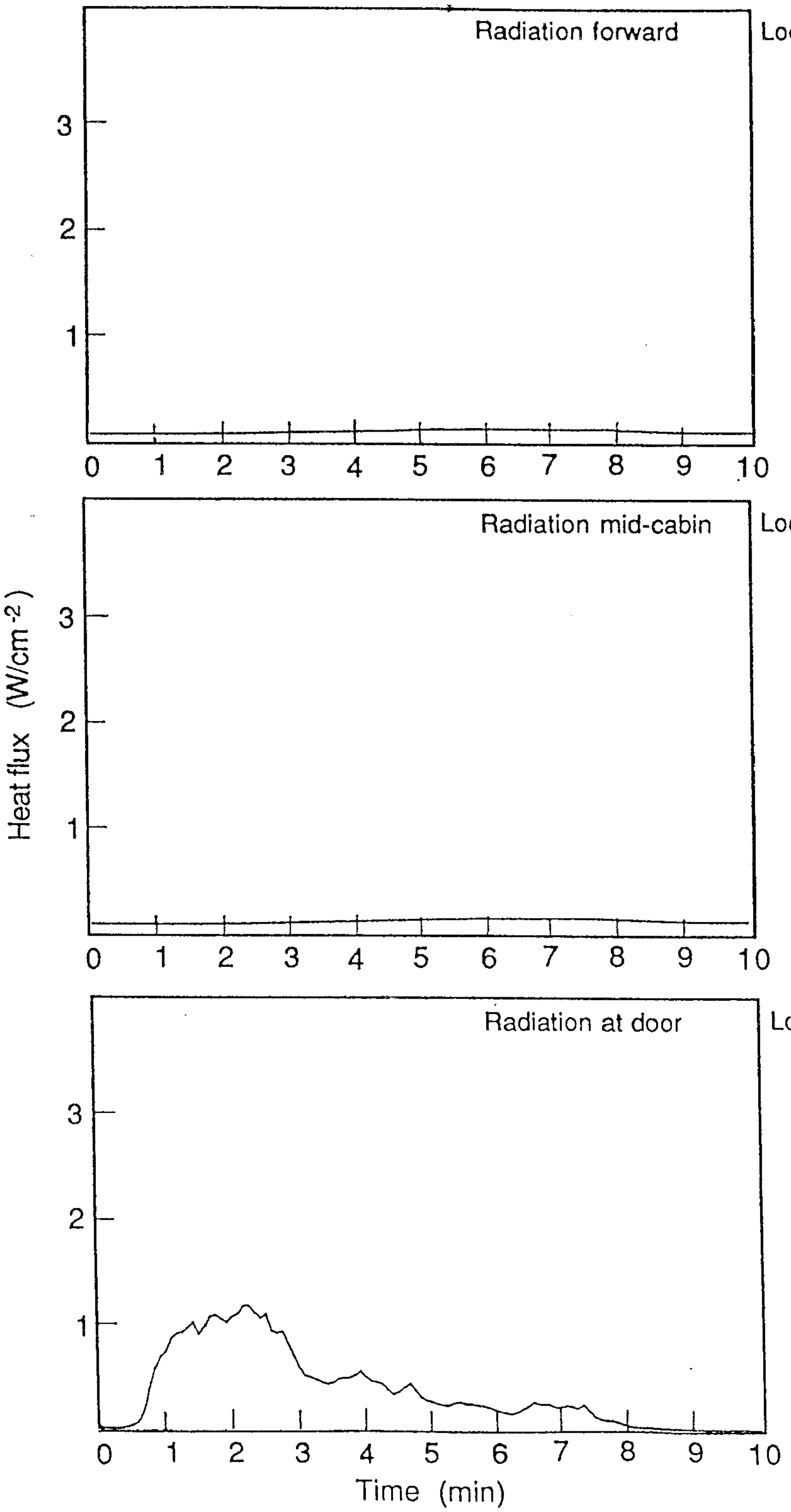


Figure E7 Thermal radiation measurements - Test CFT7

APPENDIX F - OBSERVATIONS OF FIRE DEVELOPMENT

It was not possible to directly observe the internal fuselage cabin conditions during each experiment. However, use of the recorded video signals allows the reconstruction of general actions within the cabin for each experiment. It must be borne in mind that the camera visibility does not necessarily give a guide to human eye reaction to conditions internally. Hence the observations can only be used to give a guide.

Test CFT1

Time		Observations
min	sec	
-	17	Flames entering fuselage through doorway.
-	26	Smoke layer at level of bottom of overhead bin structure.
-	53	Flames intermittently to centreline of fuselage.
1 -	20	Smoke layer deepening.
1 -	55	Smoke layer to approximately half cabin height.
2 -	05	Flames across width of fuselage at fire entry point.
3 -	10	Front camera vision obscured.
3 -	15	Flame entry into cabin progressing deeper. Rear camera vision obscured.

Test CFT2

Time		Observations
min	sec	
-	12	Flames entering fuselage through doorway.
-	30	Smoke mixing with spray.
-	49	Flames intermittently rolling under ceiling towards centreline of cabin.
1 -	00	Visibility along cabin reduced from rear camera position.
1 -	10	Visibility effectively ended.

* Note: For this test the full length of spray in the cabin seriously impeded the front camera visibility at ignition.

Test CFT3

Time		Observations
min	sec	
-	15	Flames entering fuselage through doorway.
-	31	Smoke layer established at level with bottom of overhead bin units.
-	45	Seats A's of middle and rear rows involved in burning. Smoke layer deepening along length of fuselage.
1 -	00	General area of flaming involving triple seat units side of aisle, flaming across ceiling.
1 -	11	Flaming below falling from ceiling and overhead bin panels.
1 -	29	Seats of front row being subjected to falling flaming debris.
1 -	52	Vertical face of overhead bin opposite the opening ignited, flaming debris falling onto double seat unit.
2 -	00	Smoke layer to height of seat backs.
2 -	33	Ignition of seat squabs of front row, flame running across from seat A to C.
2 -	40	Smoke layer to seat squab height.
2 -	57	Smoke layer effectively at floor level, vision from front camera obscured.

Test CFT4

Time		Observations
min	sec	
-	14	Flames entering fuselage through doorway.
-	27	Smoke mixing in spray, generally affecting depth to bottom of overhead bin units.
-	36	Section A of middle row burning.
-	55	Smoke layer spreading along fuselage.
1 -	15	Smoke layer in furnished area to approximately height of seat backs.
1 -	28	Seats B and C of middle row giving off copious amounts of smoke.
2 -	00	Vision obscured.

Test CFT5

Time		Observations
min	sec	
	25	Flames entering fuselage through doorway.
	38	Smoke mixing in spray zone, generally layer of smoke level with bottom of overhead bin.
	58	Seat A of middle row of seating burning well, smoke layer at seat top height in zoned area.
1	20	Rear camera vision obscured. Smoke layer generally at bottom of overhead bin level along length of fuselage.
2	00	Flames from seat A not spread to other seating.
2	20	Smoke layer in cabin gradually deepening.
2	50	Front camera vision only possible at floor level.
3	20	Vision from front camera position effectively obscured.

Test CFT6

Time		Observations
min	sec	
	23	Flames entering fuselage through doorway.
	30	Smoke mixing in spray zone.
	44	Smoke layer at level of bottom of overhead bin.
	50	Seat A of middle row burning well.
1	15	Rear camera obscured.
1	30	Flames pulsing across ceiling of cabin in area opposite fire opening.
1	43	Flames ignited further material of ceiling/overhead bin assembly, flaming debris falling on double seat unit.
1	50	Smoke layer within cabin deepening to approximately half total cabin height.
2	30	Smoke layer almost totally extending from ceiling to floor level.
2	50	Front camera position obscured.

Test CFT7

Time			Observations
min		sec	
	-	40	Flames entering fuselage through doorway.
	-	45	Smoke from external fire mixing with spray in cabin.
1	-	10	Rear camera vision obscured.
1	-	50	Smoke spreading forward through cabin.
2	-	10	Front camera position effectively obscured.

APPENDIX G - FIRE DAMAGE TO CABIN SEATING

This appendix shows diagrams of the damage to the cabin seating caused by exposure to the fire. The results for tests CFT4, CFT5, CFT6 and CFT7 are shown in each case alongside the results of Test CFT3 for purposes of comparison. The layout of the seating is shown in Figure 17.

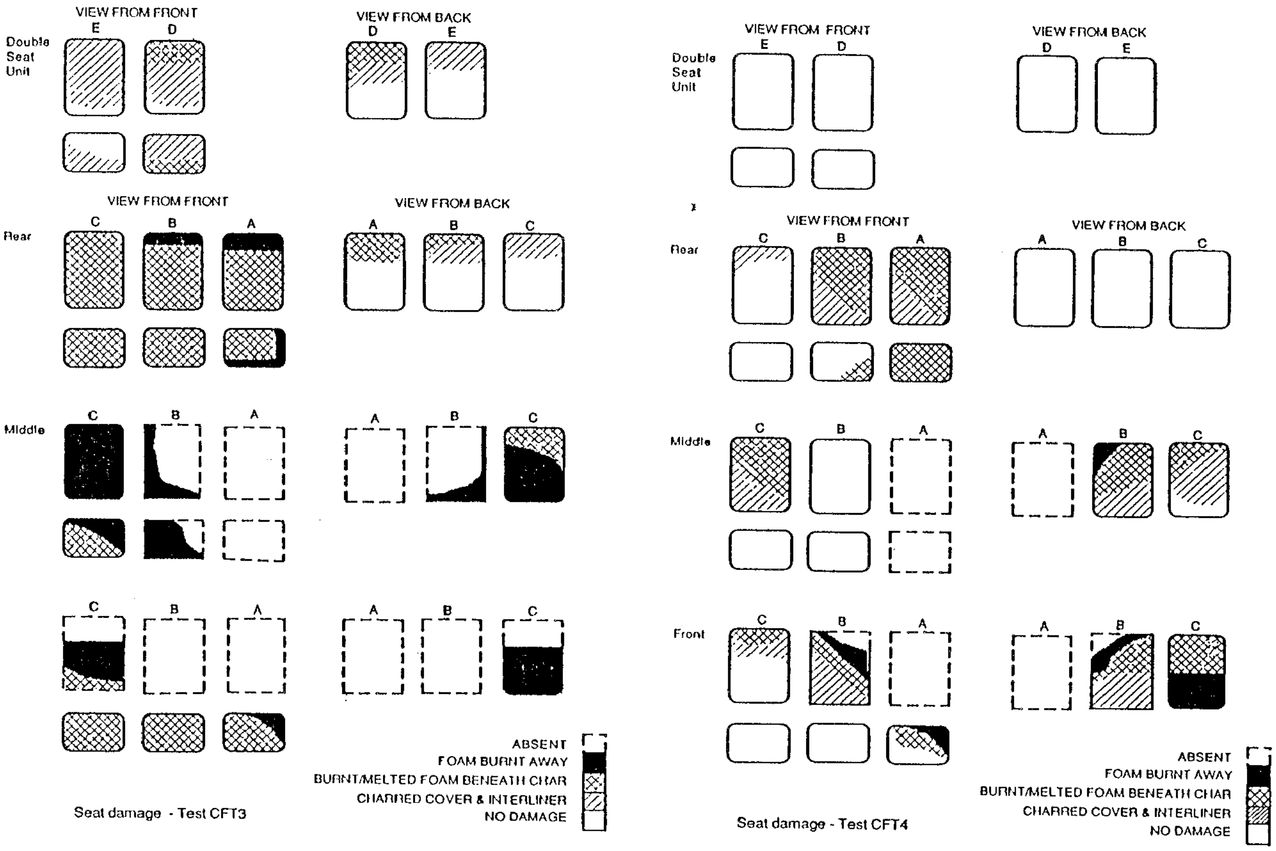


Figure G1 Seat damage — Test CFT4 (with CFT3 for comparison)

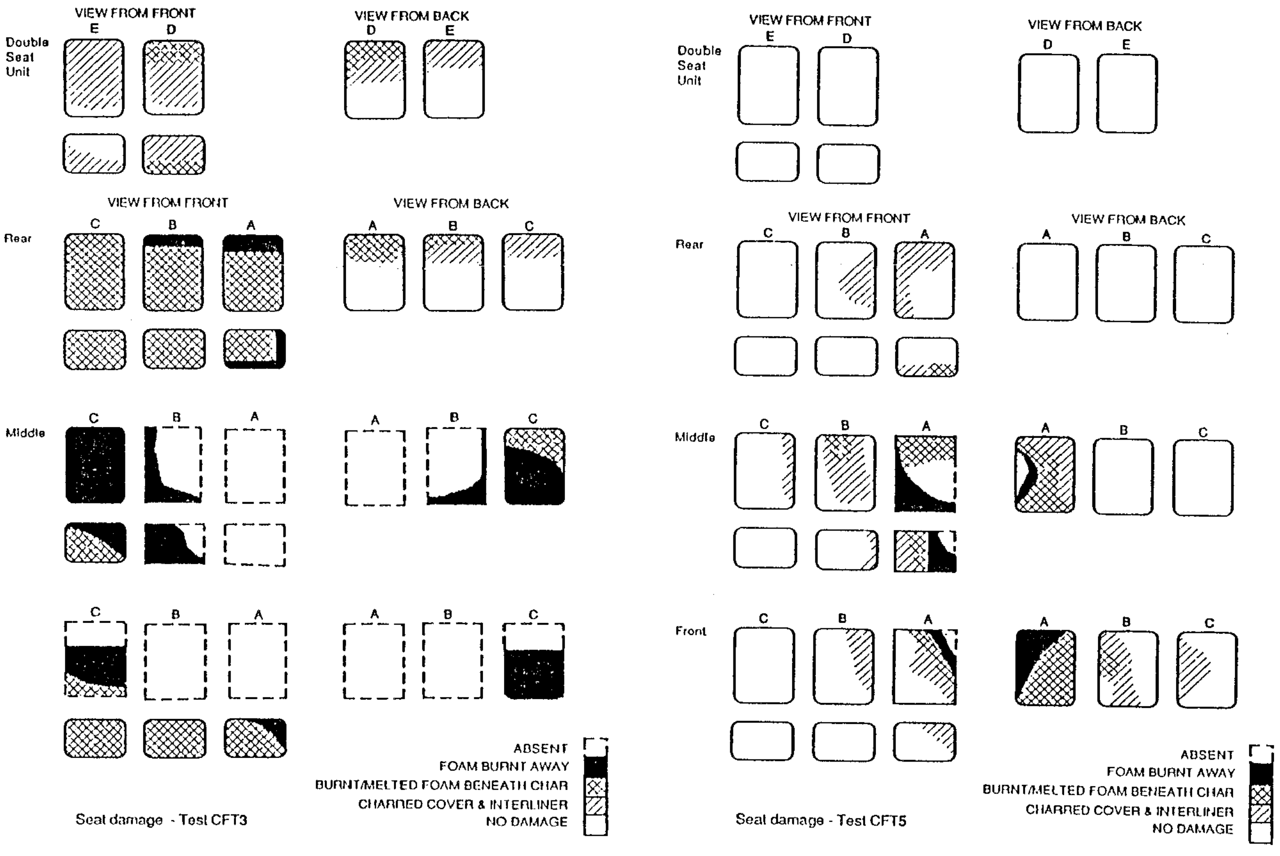


Figure G2 Seat damage — Test CFT5 (with CFT3 for comparison)

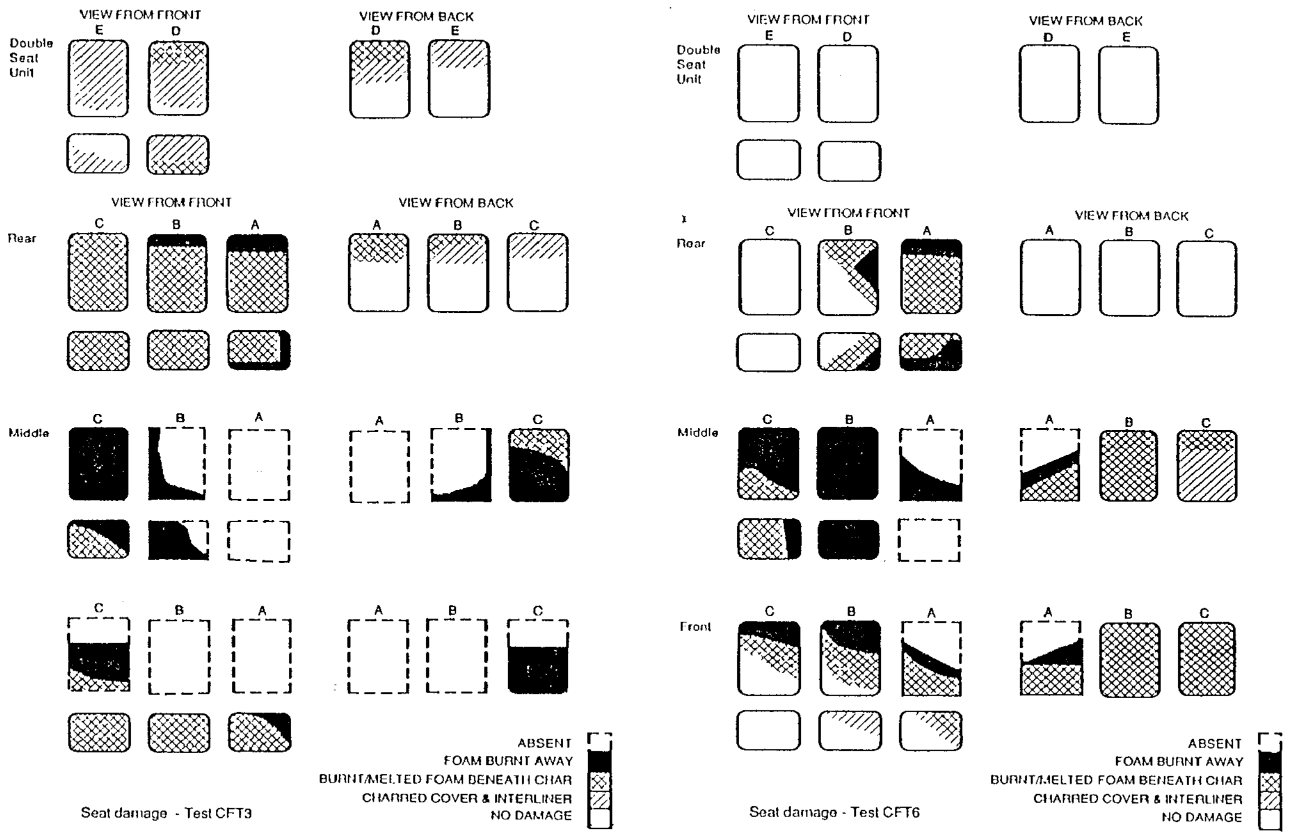


Figure G3 Seat damage — Test CFT6 (with CFT3 for comparison)

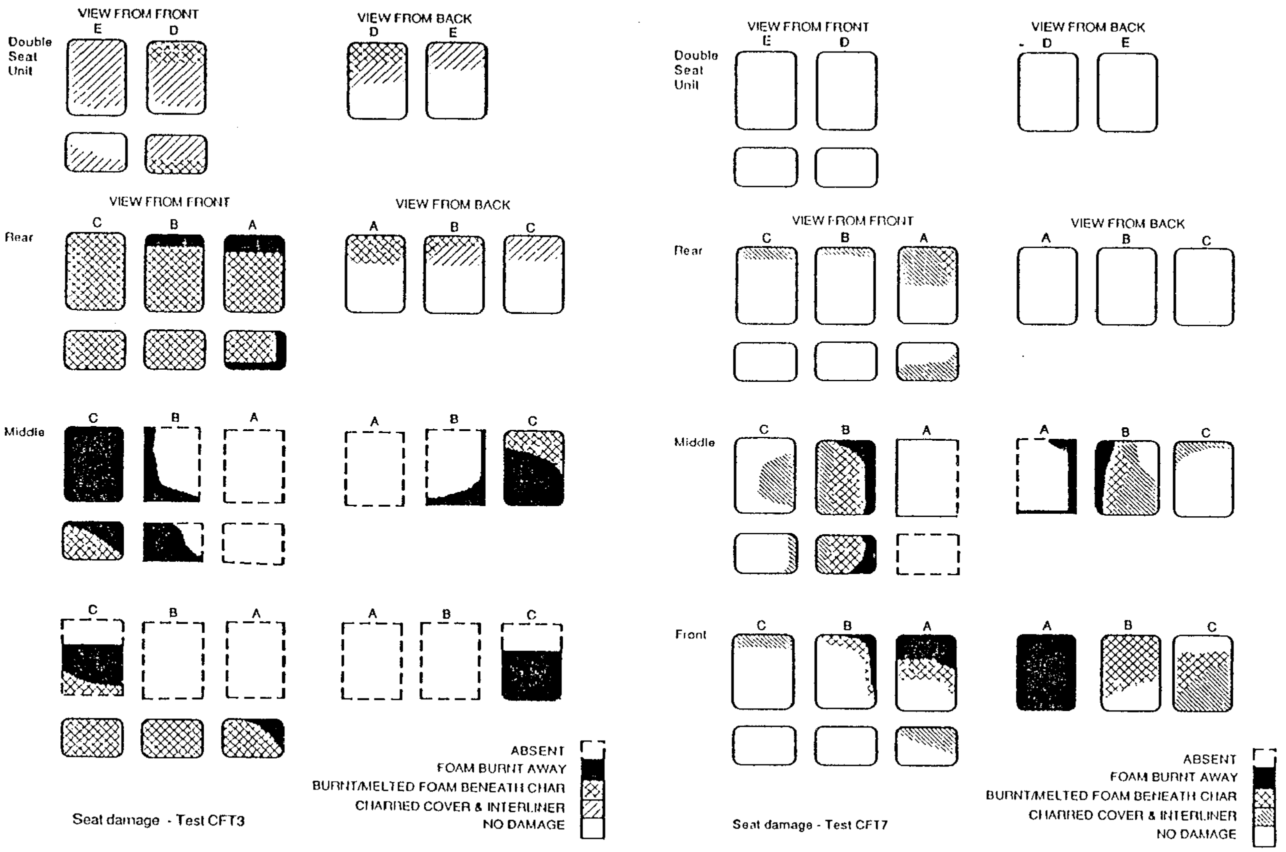


Figure G4 Seat damage — Test CFT7 (with CFT3 for comparison)