

**FIRES IN PASSENGER AIRCRAFT: THE EFFECTS OF WATER SPRAYS ON
LIFE THREAT HAZARDS FROM TOXIC PRODUCTS, SMOKE AND HEAT**

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SUMMARY

Study design:

A series of large scale tests were carried out which were designed to study the effect of water spray on the tenability of the atmosphere produced in the passenger cabin during aviation fuel fires external to an aircraft fuselage.

Two test rigs were used - a mock narrow bodied fuselage and an actual full size Boeing 707 fuselage.

Both rigs were instrumented to measure parameters relevant to life threat, including temperature and radiant heat, smoke optical density and toxic products associated with the gas, liquid and solid particulate phases of the smoke during fires with and without spray application.

Results:

1. When the water spray was not used the fire grew rapidly and produced a dense smoke containing very high concentrations of hydrogen cyanide and carbon monoxide capable of causing loss of consciousness in exposed persons after a few minutes exposure, by which time the cabin temperature was also high enough to cause incapacitation. The smoke was rich in oily particles which are predicted to be very irritant because they were of a size capable of deep penetration into the lung, and because of the high concentrations of acid gases associated with them.
2. The use of the water spray was found to cause a considerable reduction in the concentrations of toxic gases and particles present during the first four minutes of the fire, increasing the time available for escape by approximately three minutes or more in different tests. The sprayed tests also had much lower concentrations of acid gases and both solid and liquid particles of respirable size, as well as lower cabin temperatures and a longer time to smoke obscuration. The main effects were felt to be due to retardation of fire growth, with some evidence for washing out of acid gases.
3. There was evidence for some increase in the amount of larger particles present in some of the sprayed tests, and it is considered that this represents trapped water droplets. However, the acid gas content of these droplets was low, and because only small amounts were found and their size was too large for them to penetrate into the lung, they are considered to present a much less serious hazard of lung damage than that of the smoke from the unsprayed fire.

Conclusions:

1. The tests showed that the use of a fine water spray improved the survivability time of aircraft cabin fires by at least several minutes.
2. There was a considerable reduction in the production of heat, toxic and

irritant gases and smoke particles, resulting from a reduction and penetration into the cabin and the washing out of a proportion of the acid gases and particles from the smoke.

3. Although a small amount of larger droplets in the smoke may have been due to the water spray, these had a low acid gas content and are considered not to present any additional hazard.
4. Far from increasing the risk of lung damage 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.
5. Although the results obtained from the experiments performed so far are extremely encouraging, it is recommended that further research should be conducted on the effects of water sprays on fires. Particular aspects that require further study are the degree of penetration into the human lung of fine water spray droplets, the biological effects of droplets contaminated with acid gases and the thermal capacity of hot smoke containing water sprays

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1. BACKGROUND

1.1 GENERAL DESCRIPTION OF WORK

- The work reported here represents one aspect of a study of the affect of a fine water spray mist on the development of fire atmospheres in an aircraft cabin. The cabin fires examined were those resulting from the application against an open doorway of an external fuel fire consisting of 50 U.S. gallons of aviation fuel.
- Part of this work is to measure the rate of development and extent of the fire atmosphere in the aircraft cabin, particularly in terms of its content of toxic fire products, and to estimate the developing life threat hazard. The smoke atmosphere was characterised in terms of the content of narcotic gases (carbon monoxide, hydrogen cyanide, carbon dioxide and reduced oxygen), acid gases (hydrogen halides) and organic products.
- One other aspect of this work was to determine the composition of the smoke atmosphere in terms of solid particulate and liquid droplets, the particle size range and composition of the solid particles and droplets, and their possible effects on the human respiratory system if inhaled.
- In addition to the toxic hazards, measurements were also made of physical hazards in terms of smoke optical density, temperature and radiant heat flux.

1.2 MAIN POINTS OF INVESTIGATION

- In particular it was hoped that information would be obtained on the following points:
 1. > The extent to which the application of water spray to the fire reduces the overall concentration of permanent toxic gases (carbon monoxide (CO), carbon dioxide (CO₂) and reduced oxygen (O₂)) by impeding the rate of fire development.
 2. The extent to which the application of water spray to the fire reduces the overall concentration of smoke particulate in the cabin atmosphere;
 - a) by impeding the rate of fire development, particularly by inhibiting combustion of cabin furnishings.

- b) by washing smoke particulate out of the fire atmosphere in the cabin.
3. The extent to which the application of spray reduces the concentration of acid gases (particularly hydrogen chloride (HCl) and hydrogen cyanide (HCN)) in the smoke by either impeding the fire or washing the smoke.
 4. 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 (deep lung).
 5. The extent to which water droplets, if created, pick up significant concentrations of acid gases from the smoke, and are therefore likely to present a greater inhalation hazard than the original smoke atmosphere created when no spray is used
 6. 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.
 7. The effect that the use of the spray has on the optical density of the atmosphere in the cabin.

From this information, an assessment has been made of the effect of water spray on the survivability of aircraft cabin fires.

The evaluation of the fire atmosphere in terms of the above parameters presents a considerable technical challenge, since it consists of a very complex mixture of gases, liquid droplets and solid particles. The smoke contains vapours and particulate.

The particulate consists of both solid carbonaceous material (bearing adsorbed gases and organic condensates), and organic and aqueous liquid droplets, covering a range of particle sizes, mostly in a respirable range (i.e. less than 5 μm mass median aerodynamic diameter (MMAD)).

The water droplets are initially too large to be inhaled (greater than 100 μm MMAD), but are likely to evaporate in the hot fire atmosphere, producing water vapour, steam and/or small droplets of varying sizes, depending upon the decomposition conditions. However, it has been suggested that water droplets at sizes below 35 μm MMAD may evaporate rapidly and cannot exist for more than a few seconds. Acid gases such as HCl and HCN will partition between vapour and adsorption to solid and liquid particles.

1.3 TOXIC EFFECTS OF EXPOSURE TO FIRE ATMOSPHERES

Combustion products cause incapacitation and death in fires by two main toxic mechanisms - narcosis and irritancy (1).

1.3.1 Calculation of time to incapacitation due to effects of narcotic gases

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

Time to incapacitation (loss of consciousness) in a fire occurs when a critical dose of narcotic gases has been inhaled. This dose 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, and these fractional effective doses (FEDs) are summed through the fire until the FED reaches unity, when incapacitation is predicted to occur.

An algorithm has been developed by Purser (2) for calculating the FEDs for each narcotic gas and the interactions between them, according to the formula:

$$F_{IN} = [(F_{Ico} + F_{Icn}) \times VCO_2 + F_{Io}]$$

or $F_{IN} = F_{Ico2}$, whichever is the greater

Where:

F_{IN} = fraction of an incapacitating dose of all narcotic gases
 F_{Ico} = fraction of an incapacitating dose of carbon monoxide
 F_{Icn} = fraction of an incapacitating dose of hydrogen cyanide
 VCO_2 = multiplication factor for carbon dioxide induced hyperventilation
 F_{Io} = fraction of an incapacitating dose of low oxygen hypoxia
 F_{Ico2} = fraction of an incapacitating dose of carbon dioxide

1.3.2 Evaluation of the effects of irritants

Smoke irritants consist of inorganic acid gases (such as hydrogen chloride) and organic compounds, particularly low molecular weight aldehydes (formaldehyde and acrolein). More than twenty irritant substances have been detected in smoke and it is considered that others remain to be identified (2). As opposed to the narcotic gases, which have little effect until a well defined endpoint (loss of consciousness) occurs, the 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. This is important as it impedes escape attempts due to effects on vision and breathing, and it 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.

The other important effect of irritants is that a proportion of those inhaled penetrate into the deep lung. If a sufficient dose is inhaled a lung inflammatory response can occur, usually some hours after exposure. This may cause respiratory failure and death, 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 into the lung, so that lung inflammation is the major effect.

If hydrogen chloride, however, 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 microns diameter) water droplets from the spray, then they will impact in the upper respiratory tract, or not be inhaled at all, thereby protecting the lung from damage that would otherwise have occurred.

In general, particles of a diameter less than approximately 5 microns will penetrate into the lung, while particles between 5 and approximately 15 microns 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 to occur in an emergency situation, may suffer penetration of somewhat larger particles. As Figure 1 shows it is possible that some particles up to as much as 200 microns diameter may deposit in the mouth, although it is unlikely that particles greater than 10 microns diameter will penetrate significantly into the smaller airways or deep lung.

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

2. EXPERIMENTAL ARRANGEMENTS

2.1 OVERVIEW

Two experimental series were used.

In the first, relatively small fires were carried out with "fuels" of aviation kerosine with and without typical aircraft passenger compartment interior materials. The test rig (Figures 2-5) was a mock section of a narrow-bodied aircraft cabin fitted with water spray nozzles and was connected to an extract hood where measurements of rate of heat release were made (reported elsewhere).

Sampling of the gas and particulate atmosphere was achieved close to (but not in) the fire and at a point several metres "downstream" at standing and crouching height. Particulate sizing equipment was also used.

The second series of tests and the main scenario considered, involved a large fuel fire close to an open entrance to the fuselage of a full size 707 aircraft cabin test rig.

For these tests four main toxic gas measurement points were installed (Figure 6). These were positioned close to the fire at the rear of the fuselage, near the centre (two points) and near the front. At the centre position, more detailed measurements of gas, liquid and solid phase partitioning of the toxic gases and their size distribution were made.

2.2 INSTRUMENTATION.

2.2.1 Choice of sampling methods

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

1. 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
2. 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.

3. 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.
4. 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 analysers.
5. 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 to some extent in the methods employed.

2.2.2. General description of methods used

Details given in this section refer particularly to the main test series using the Boeing 707 fuselage. The same general methods were also used for the preliminary experiments on the mock narrow-bodied aircraft rig.

1. Permanent gases

Continuous concentration measurements of permanent gases (carbon monoxide, carbon dioxide and oxygen) were made using infra-red analysers for carbon oxides and a paramagnetic analyser 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.

Sampling lines were passed into a mobile laboratory in which were placed the gas analysers.

2. Elutriators

During preliminary large scale experiments at FRS Borehamwood, 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. Total smoke traps - open face filters and gas bubblers

The aim was 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 (3.7 cm diameter circular glass fibre filters) placed horizontally, facing downwards (i.e. sampling vertically upwards) or vertically (i.e. sampling horizontally), in the smoke, at a rate of 1 litre/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.

The solid deposit was weighed, and the filter paper was then placed in 0.01 M NaOH solution for extraction and analysis of any acid gases adsorbed to the particulate.

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, two devices were used that are designed to trap particles within several different size ranges.

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 7) samples at a rate of 1.4 litres/minute, and traps particles above $5.5 \mu\text{m}$ on the first stage, and respirable particles ($<5.5 \mu\text{m}$) on the subsequent stages.

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

The sampler was placed to point vertically into the smoke, 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 stated in the literature, but is likely to be approximately $10\text{--}20 \mu\text{m}$.

Liquid droplets will also be fractionated by the sampler, and will 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.

The other 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 (Figures 8 and 9) 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 litres/minute.

The main reason for using this device in this study is that at this sampling rate the upper stage of the device is stated to trap large 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 $40 \mu\text{m}$. Particles above $50 \mu\text{m}$ up to $100 \mu\text{m}$ should mostly be trapped, and a smaller percentage up to a maximum of $200 \mu\text{m}$. 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 may not be trapped by the other devices.

At the high sampling rate of 17.5 litres/minute it was not practicable to place a gas bubbler after the Cascade Impactor, but it should trap all 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.

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 plates did not facilitate analysis for adsorbed acid gases. For this reason a further particle sizing device, the May Multistage Impinger (Figure 10), 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 litres/minute vertically downwards through an orifice in the top of the device. 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. Respirable particles are trapped in the middle and lower stages down to approximately 0.5 μm . Smaller particles are trapped by a glass fibre filter placed in series with the device.

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 water 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 area of liquid in the bottom stage in a swirl, whereas the opportunity for contact with the liquid interface is reduced in the upper stages.

6. Acid gases

Acid gases both in the vapour phase and attached to particulate were trapped in the various filters, impactors and gas traps described above. In addition, grab samples were taken into evacuated vessels from the continuous atmosphere 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 analysed by High Performance Ion Chromatography (HPIC).

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 of organic smoke constituents. These were analysed by gas-chromatography/mass spectrometry.

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 the 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.

9. Temperature and humidity measurements

A number of thermocouples were placed throughout the fuselage including one at the particulate sampling point at head height (1.7 metres).

In order to estimate the humidity in the cabin two thermocouples were placed at a height of 0.8 metres. Cotton tape soaked in water, with one end in a small vial of water, was wrapped around the end of one thermocouple, to provide wet and dry thermocouples. The temperature difference between these was then used as an approximate indication of the relative humidity during the test.

To measure radiant heat flux a number of radiometers were positioned in the fuselage facing forward. Details of results from these are reported elsewhere although some of these data have been used for this report.

10. Smoke optical density measurements

Data on smoke optical density are reported elsewhere although use is made of this data in this report.

These various devices were therefore employed to obtain as good a characterisation of the fire atmosphere as possible. As described, none of the methods used can fully separate and characterise vapour, liquid and solid atmosphere constituents throughout the desired size range, but it was determined from the preliminary experiments that a reasonable degree of assessment could be performed, and at least sufficient to detect major differences between sprayed and non-sprayed fires.

2.2.3 Details of design of mock narrow-bodied aircraft tests.

Figure 2 is a schematic of the test rig showing the two sampling positions. At each position, fire gases were extracted through stainless steel tubing (8.0 mm. O.D.), at 3 litres/min, to a mobile laboratory. These sampling lines were electrically heated to prevent condensation of products and were internally lined with a proprietary epoxy compound to minimise surface adsorption of sampled gases and vapours. Moisture and particulate filters were positioned inside the mobile laboratory at the end of each sampling line prior to entry into gas analysers.

A 'take-off' point for collection of samples for hydrogen cyanide, hydrogen chloride and the gas chromatography - mass spectrometry analyses was

positioned before these filters.

Carbon monoxide and carbon dioxide concentrations were measured continuously using non-dispersive infra-red analysers sampling from the main line stream at 1.0 l/min. Oxygen was monitored continuously using paramagnetic analysers.

All output was fed to a data logger scanning each data channel every five seconds.

In addition, "grab" samples could be extracted from these lines to provide "snapshot" concentrations of the effluent gases at certain times during each test. This was achieved using evacuated glass sampling vessels of nominal capacity 170 ml, attached when required to a "tee" piece in the main sampling line. By releasing the vacuum through a hand operated clip, a sample of the fire gases were drawn into the vessel for later analysis (3).

Hydrogen cyanide and hydrogen chloride were also collected in this way by adding 20 ml. of 0.01 M NaOH solution to the vessels prior to evacuation. These "wet" samples were then analysed using High Performance Ion Chromatography (HPIC).

The "dry" samples were analysed for organic species by gas chromatography, and in addition in some cases mass spectrometry.

Gravimetric smoke data were obtained by collecting smoke particulate on open face surface filters (polycarbonate membrane, 25 mm diameter, 2 micron pore size).

Samples for particulate analysis were taken from a point close to the heated line sampling point at the end of the rig furthest from the fire, at a height of approximately 1.9 metres. The samples were drawn continuously into two 25 mm diameter copper pipes, which passed up through the roof of the rig and turned through 90°, passing horizontally through a further metre of copper tubing (designed to act as an elutriator to remove large water droplets) before passing to the sampling devices.

At the end of one elutriator was placed the May impinger and filter, through which smoke was sampled at a rate of 10 l/min. At the end of the other elutriator was placed a device used for trapping and particle sizing of solid particles, the Marple cascade impactor. This is a similar device to the Andersen cascade impactor used for the aircraft tests, except that it had more stages. Also at the end of the second elutriator was a take off point for a total particulate filter.

After both the Marple and the total filter were placed two bubblers in series, to trap acid gases. The Marple and total particulate filter were sampled at a rate of 2 l/min.

Four tests are reported here, designated C74, C75, C76 and C77. In tests C74 and C75 there were 4 filter units at high level (0.15m. from the ceiling). In C76 and C77 two more units were added at low level (1.10m. from the ceiling). Figure 3 shows the arrangement for C76 and C77.

The units were connected with solenoid valves for remote operation of any required sampling head and the method of installing the bubbler sampling

vessels. Figure 4 shows the set up of the filter heads in detail. All filters were operated horizontally facing downwards. The aluminium hoods shown were used on all sampling lines to protect the measurement point from water spray. By drawing the fire atmosphere through the filter pads at 1.0 l/min and weighing the deposits collected over time intervals the concentration of smoke particles could be estimated.

Bubbler sample vessels downstream of these filters contained 150ml. of 0.01M sodium hydroxide to trap hydrogen chloride and hydrogen cyanide in solution for HPIC analysis. During sprayed tests water was collected in containers placed on the floor inside the test rig for subsequent analysis of hydrogen cyanide and hydrogen chloride and pH. (These containers are designated "floor pots" in the results section). The source of water for the sprays was subjected to a similar analysis.

Four thermocouples (T1, T2, T3, T4) were provided to give temperatures at the sampling points as shown in Figure 5. T1 and T2 were furthest from the fire, T1 by the upper gravimetric smoke filters (1,3 and 5) and T2 by the inlet to the gas sampling line. T3 and T4 were closest to the fire, T3 at the sampling line inlet and T4 at smoke filter 6.

2.2.4 Details of design of 707 Fuselage Tests.

Toxic gas analysis for these full scale studies carried out at Cardington was facilitated with similar apparatus to that used in the mock narrow bodied aircraft studies (see 2.2.3.). Four heated and epoxy-lined gas sampling lines were used, complete with particulate filters and vapour traps, carbon monoxide, carbon dioxide and oxygen analysers. The sampling points are shown in Figure 6, and all were along the centre line (in plan) of the fuselage. Point G1 was at standing height (1.7m), adjacent to the fuselage opening used for the fire entry. Points G2 and G3 were half way along the fuselage, G2 at standing height (1.7m.) and G3 at crouching height (0.7m.). Point G4 was furthest from the fire entry door adjacent to the front crew cabin bulkhead and at standing height (1.7m.). 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 (see 2.2.1). Particulate was collected on open face surface filters using 25mm glass fibre filters in an 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 (see 2.2.1). The filter pads were positioned horizontally, facing the floor.

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.

2.3 PROCEDURE.

2.3.1. Mock Narrow Bodied Aircraft Tests.

Tests C74, C75, C76 and C77 are reported here. Table 1 gives brief details of the fuels used and the timings for water spray on/spray off.

Carbon monoxide, carbon dioxide and oxygen were measured continuously at both sampling points for the whole duration of every reported test. "Wet" and "dry" grab samples, gravimetric smoke samples and particulate samples were taken at relevant time intervals. For details see the results section (3.1).

2.3.2. 707 Fuselage Aircraft Tests.

2.3.2.1 General

Seven tests were carried out and were designated CFT1 through CFT7. Table 2 summarises the test conditions. Data logging was started one minute before each test to check correct operation of all instrumentation. Tests generally lasted seven minutes and carbon monoxide, carbon dioxide and oxygen were measured continuously at all four sampling points (see Figure 6).

"Wet" grab samples (for hydrogen chloride and hydrogen cyanide analysis) were taken consistently at 1,2,3,4,5 and 6 minutes after ignition for every test. "Dry" grab samples (for organic species analysis) were taken on the half minute, starting at 30 seconds after ignition and ending usually at 6 min 30 sec.

The smoke filter and bubbler units 1,2,3 and 4 were switched on for a three minute period during each test starting at 1 minute and finishing at 4 minutes after ignition. Units 5 and 6 were on for the period 4 minutes to 7 minutes.

2.3.2.2 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.

2.3.2.3. Operating characteristics of particle sizing samplers

Open face filter

The samples were drawn through, at a rate of 1 litre/minute, a weighed glass fibre filter (Whatman GF/A - collection surface area 7 cm²). The material collected on the filter was weighed and the filter was then placed in 0.01 M NaOH solution for further analysis.

The atmosphere extracted from the filter was passed through two bubblers in series, each containing 0.01 M NaOH solution. These solutions were analysed for chloride, bromide and cyanide content.

Andersen Mini Sampler

The particle size distribution of solid and, to some extent, liquid particulate was determined using the Andersen Mini Sampler (see Section 2.2.2, Figure 7). The material collected on each stage of the sampler was weighed, and then extracted with 0.01 M NaOH solution for further analysis.

At a sampling rate of 1.4 litres/minute the collection characteristics of the sampler are:

- 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.

The upper particle size limit for the device is likely to be approximately 10-20 µm.

The atmosphere extracted from the sampler was passed through two bubblers in series, each containing 0.01 M NaOH solution. These solutions were analysed for chloride, bromide and cyanide content.

Casella Cascade Impactor

The particle size distribution of solid and to some extent also liquid particles was also determined using a Casella Cascade Impactor (see Section 2.2.2, Figures 8 and 9). The material collected on each stage of the sampler was weighed, and then extracted with 0.01 M NaOH solution for further analysis.

At a sampling rate of 17.5 litres/minute the collection characteristics of the sampler are:

- 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.

May Multistage Impinger

The particle size distribution of liquid droplets and solid particles was determined using a May Multistage Impinger (4)(see Section 2.2.2, Figure 10). This device differs from the other devices in that liquid droplets and solid particles, and a proportion of vapours, are trapped in solution. The solution in each stage was analysed for chloride, bromide and cyanide content. A Whatman GF/A filter was placed in the extract line after the Impinger to trap small particles.

At a sampling rate of 10 litres/minute the collection characteristics of the sampler are:

- 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.

The upper particle size limit for capture by the device is not published, but considering the relatively high sampling rate and vertically downward sampling orientation, it is likely that relatively large particles would be trapped, perhaps up to 50 μm a.d. or more.

Temperature and humidity measurements

The outputs from the thermocouple placed at the sampling point at a height of 1.7 metres, and from the wet and dry thermocouples placed at a height of 0.8 metres, were displayed at the monitoring point outside the aircraft hold. The readings were recorded at approximately 30 second intervals throughout each test (tests CFT4-CFT7 only).

The relative humidity reading, based on wet thermocouple temperature depression, was taken from tables supplied with wet and dry bulb hygrometers.

Procedure

All devices except the Casella Cascade Impactor were run from 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 "shakedown" 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.

3. RESULTS

3.1 MOCK NARROW BODIED AIRCRAFT TESTS

Details of test conditions are shown in Table 1.

3.1.1 Continuous Measurements-Carbon Monoxide, Carbon Dioxide, Oxygen, Temperature and Smoke Optical Density.

Figures 11 and 12 show plots of the carbon monoxide, carbon dioxide and oxygen measurements in test C74 (wood crib and PVC sheet, no spray) at the "near" sampling point (i.e. the point nearest the fire) and "far" sampling point (i.e. the point furthest from the fire).

Figures 13 and 14 give the temperature (both points) and optical density (far point) measurements respectively.

Figures 15 to 18 give the equivalent data for test C75 (wood and PVC sheet, sprayed between 9 and 12 minutes; i.e. between 540 and 1080 seconds).

Figures 19 to 27 give the equivalent data for tests C76 (mixed fuels, spray on between 2 and 5 minutes; i.e. between 120 secs and 300 secs) and C77 (mixed fuels, spray on between 5 and 8 minutes; i.e. between 300 secs and 480 secs).

3.1.2. Timed measurements - particulate and gas phase hydrogen cyanide and hydrogen chloride.

The times during tests C 74 and C 75 when the various sampling devices were started and stopped are shown in Table 3. Details of the results from the various devices in terms of particulate mass, hydrogen chloride and hydrogen cyanide concentration are shown in Appendices 1 to 7. The salient points are summarized in Table 4.

It is not possible from the results obtained, to determine whether the total amount of smoke particulate was reduced by the spray. However, when the concentration of small particles ($< 1.55 \mu\text{m}$) was considered, in both sets of tests the mass concentration in the sprayed tests was a factor of 3.5-4.5 less than that in the unsprayed tests as follows:

Tests	C74/C75	C76/C77
Without spray	0.21 mg/l	0.32 mg/l
With spray	0.06 mg/l	0.07 mg/l

During both fire types the amount of smoke particulate trapped by the Marple impactor was small, there being no deposits on the top two stages (greater than $6 \mu\text{m}$). This result agreed with the May impinger, in that for all tests except the unsprayed fire containing polyurethane (C77), smoke was trapped almost entirely in the bottom stage (less than $1.55 \mu\text{m}$). For test C77 the upper stages of the May also contained particulate, and the proportion of particles larger than $1.55 \mu\text{m}$ was greater in the Marple than with the other unsprayed fire.

The total particulate deposits on the Marple were mostly greater than on the surface filters. It is therefore considered that there was probably not much loss of smoke particulate deposited in the pipe elutriators. Also, neither the surface filters nor the particle size analysers became wet during the spray tests, suggesting that the spray did not form a mist of small droplets capable of deposition, for example, in the less than 30µm range.

In all cases the main deposits were of small particles capable of penetration into the deep lung (<1.55 µm).

When the spray was on, for the first fire there was a slight increase in both the size and total amount of particulate trapped, but no evidence for water droplets.

For the second fire, with the spray off, there were both larger (6 µm) as well as smaller particles, but the total deposits for the sprayed fire were too small and are therefore considered unreliable.

The May impinger gave similar results to the Marple, in that for all fires except the last test (C77 unsprayed, large load) the smoke deposits were almost entirely on the bottom stage.

With regard to HCl recovery, the highest levels were in the grab samples. All other devices gave much lower recoveries, which suggests that these failed to give a true measure. In particular, the Marple and total filter samples gave low figures on most occasions, as did the surface filters. The May impinger also gave rather low results, but these were more consistently closer to the grab sample levels. For all devices, the point where HCl was trapped in liquid occurred after the atmosphere had passed some distance down unheated copper and/or plastic pipes, and this may account for the low HCl recoveries. The total particulate samples taken from the end of the elutriator pipe were generally low in both particulate and HCl recovery, and the bubblers appeared not to be trapping all the HCl vapour.

Where usable data were obtained, the HCl concentration in smoke from sprayed fires was less than that from non-sprayed fires. This effect may have been partly or mainly due to dilution (especially when the smoke layer was deepened by the spray during the first test). However, spray water collected from the ground was more acidic after passing through the fire (Appendix 7).

3.1.3 GAS CHROMATOGRAPHY/MASS SPECTROMETRY

Those samples which met the criterion "greater than 200 ppm carbon monoxide" were subjected to chemical analysis by gas chromatography and (sometimes) mass spectrometry. Figure 28 displays two chromatograms produced from samples obtained in test C76. The left hand chromatogram is that from 3 minutes into the test (after the sprays had been activated for one minute) and the right hand chromatogram is that from 2 minutes into the test (immediately prior to activation of the spray).

3.2. 707 FUSELAGE TESTS

3.2.1 Continuous Measurements - Carbon monoxide, Carbon Dioxide, Oxygen.

Figures 29 to 35 are plots of this data for tests CFT1 to CFT7 respectively. Each plot contains the measurements of these gases for each of the four sampling points.

3.2.2 Particulate and Gas Phase Hydrogen Cyanide and Hydrogen Chloride

Since the acid gases hydrogen cyanide and hydrogen chloride were expected to partition between the vapour phase and particulate phase (solid and liquid) of the smoke it was necessary to analyse both the soot deposits on the horizontal and vertically sampling open face filters and the various stages of the cascade impactors, and also the gas traps placed in the lines behind them. These therefore give integrated samples of the total acid gas content of the smoke over the period 1-4 minutes. Details of the recoveries of particulate, HCl and HCN from the various stages of the various devices and from the grab samples are given in Appendices 8 - 17, as follows;

- Appendix 8 - Andersen filter analysis - concentrations of HCl and HCN associated with particulate
- Appendix 9 - Andersen filter bubblers - concentrations of HCl and HCN in the gas phase
- Appendix 10 - Total particulate filter (open face - sampling horizontally) concentrations of HCl and HCN associated with particulate
- Appendix 11 - Total particulate filter (open face - sampling horizontally) bubblers - concentrations of HCl and HCN in the gas phase
- Appendix 12 - Tests CFT1 to CFT3: "Grab" sample analysis for HCN and HCl
- Appendix 13 - Tests CFT4 to CFT7: "Grab" sample analysis for HCN and HCl
- Appendix 14 - Tests CFT1 to CFT7: Total particulate filters (open face - sampling vertically) concentrations of HCl and HCN associated with particulate
- Appendix 15 - Tests CFT3 to CFT7: Total particulate filters (open face - sampling vertically) bubblers - concentrations of HCl and HCN in the vapour phase
- Appendix 16 - Tests CFT3 to CFT7: May impinger concentrations of HCl and HCN, and filter particulate
- Appendix 17 - Tests CFT3 to CFT7: Casella - concentrations of HCl and HCN associated with particulate

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 36 gives plots of hydrogen cyanide and hydrogen chloride analysis from the timed "grab" samples during tests CFT3 to CFT7 (not CFT7 in

the case of hydrogen chloride) 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 Appendix 18.

Tables 5 and 6 present the HCl and HCN data in a slightly reduced form, while the salient features are summarized in Table 7. 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 or water droplets. In almost all cases HCl was recovered almost entirely from particulate traps and stages (Tables 5 and 7). The highest recoveries were obtained from the May impinger particularly the middle stage (associated with particles 0.5-1.5 μm 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 171 and 287 ppm respectively. Taking the two devices with the best recoveries (May and horizontal open face filter), the fully sprayed tests (CFT4 and CFT7) showed an average 53-81% reduction in HCl concentration at G2 (mid cabin 1.7 metres) compared to the unsprayed test, while the zone sprayed tests showed an even larger reduction of 93-96% 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 94-98% 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.

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 6 and 7). 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 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 96% for both fully sprayed and zone sprayed tests.

3.2.3 Smoke particulate and water droplets

Appendices 8 - 17 give details of particulate recoveries from the various sampling devices where appropriate, as well as acid gas data.

Table 8 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) which was included because it should trap some of the larger particles or water droplets up to 200 μ m diameter, 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, 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 37, and the particle size distribution data from the Andersen sampler are illustrated in Figure 38.

The fuel only fire (CFT1) produced a light sooty particulate, 76% of which was respirable. The furnished, unsprayed fire (CFT3), produced approximately 4 times as much particulate, which left an oily deposit on the collection plates and contained some larger particles, 64% being respirable according to the Andersen sampler (Figure 38) and 61% according to the Casella data. The total deposit on the Andersen was similar to that on the horizontal open face filter (Figure 37). As stated above, the particulate contained high 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 38), but the total particulate deposited on the horizontal open face filters was greater than that in the unsprayed test (Figure 37). 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 CFT4 some water was found on the first stage of the Casella, while for CFT7, the horizontal open face filter 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.

For the zone sprayed tests there was a difference between CFT6 and CFT5. CFT6 produced a fire of similar, or perhaps slightly greater size than that in the full sprayed tests, and the total particulate trapped by the Andersen, and the lower stages of the Casella sampler were somewhat similar to that collected in the fully sprayed tests. The deposit on the upper two stages of the

Casella 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.

3.2.4 TESTS CFT1 TO CFT7 - GAS CHROMATOGRAPHY/MASS SPECTROMETRY

Many samples were obtained during this study but only those 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 measured.

Figure 39 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 40 Shows a plot summarising the results from gas chromatography for tests CFT3 to CFT7 for each sampling time.

4. RESULTS OF LIFE THREAT HAZARD ANALYSIS - FRACTIONAL EFFECTIVE DOSE CALCULATIONS

As explained in the Background Section, estimates of the likely tenability time for passengers in the cabin, in terms of predicted time to incapacitation, were made using the data from the Boeing 707 fuselage fires CFT3 - CFT7. This was carried out using the algorithms developed by Purser (2) and applied to previous aircraft cabin fire test data from a wide bodied jet test facility (5).

This life threat modelling technique uses the cumulative dose of a range of selected 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 dose 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 a detailed examination is made of two situations to give a basic comparison of the conditions in an unsprayed (CFT3) and fully sprayed (CFT7) fire. The analysis is made for conditions in the mid passenger cabin at head height (1.7 metres) (Sampling point G2, 23.7 metres from the front of the fuselage).

4.1 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 9. 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 HCN.

ASPHYXIATION
BURNS

Approximately 30 seconds later incapacitation due to convected heat from pain and burns is predicted, with the level of radiant heat becoming unbearably painful at the same time.

Earlier in the fire some degree of incapacitation is predicted from the effects of irritant 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 (5), and the fact that PVC is known to release HCl at low 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 and 1.5 minutes. 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.

IMPAIRMENT
OF SENSES

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. Although the smoke was thick and irritant it is considered that a subject breathing it for up to 4 minutes would not receive a dose capable of causing fatal lung inflammation, although some degree of lung damage in survivors might be expected.

In summary, passengers in the mid cabin region would become exposed to a visually 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.

SUMMARY

4.2 DETAILED EXAMINATION OF LIFE THREAT HAZARD FOR A FURNISHED, FULLY SPRAYED FIRE TEST (CFT7)

Details of the life threat hazard analysis for a furnished, fully sprayed cabin fire test (CFT7) are shown in Table 10. 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 10 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.

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.

Similarly, the level of radiant heat does not reach the tenability limit of 0.25 w/cm^2 , at any time. The maximum level 0.12 w/cm^2 , reached during the sixth minute of the fire.

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 concentrations 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, however, is that the tenability for visual obscuration was exceeded early in the fire at 1 minute 30 seconds, slightly earlier than in the unsprayed fire. Although this would have some effect on escape capability it is considered not to present a serious hazard, based upon the video recording of the fire.

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 (approximately 1 minute 30 seconds) no serious hazard develops until 5 minutes 30 seconds, when loss of consciousness is predicted, mainly due to the combined effects of carbon monoxide and hydrogen cyanide. It is 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) by approximately 3.25 minutes, from 2.25 minutes to 5.5 minutes.

ASPHYXIATION

BURNS

IMPAIRMENT
OF SENSES

SUMMARY

COMPARISON

5.2 707 FUSELAGE TESTS

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.

In particular, the work was designed to examine the effectiveness of a fine water spray in reducing the concentrations of smoke and toxic gases and heat in the aircraft cabin, due to three beneficial processes:

- 1) Delay of penetration of the fire into the cabin and inhibition of the overall fire growth and combustion of the cabin furnishings.
- 2) Washing out of smoke particulate and acid gases (principally hydrogen chloride and hydrogen cyanide) from the fire atmosphere in the cabin.
- 3) Reduction of the temperature in the cabin.

Against these anticipated beneficial effects there was some concern about possible injurious effects of sprays, in particular:

- 1) The possibility that water spray droplets contaminated by smoke irritants might be inhaled and cause lung injury.
- 2) The possibility that water spray droplets would evaporate, and although they may reduce the temperature of the smoke, they may form steam, which when inhaled would also cause lung injury.

In practice, irritant products in unsprayed smoke exist partly as gases and partly attached to small solid particles and liquid droplets. All of these are capable of penetrating into and damaging the lungs. Water spray droplets are too large to be inhaled into the lung and it is considered likely that the water spray could be beneficial in scrubbing these gases and particles from the smoke, and thereby preventing them from being inhaled. There was, however, a slight possibility that the contaminated water spray droplets may themselves become small enough to penetrate into the lungs and increase the quantity of toxic products deposited in the delicate small airways and alveolar region.

5.2.1 Effects of water sprays on survivability in terms of time to incapacitation

The key point to determine was whether the water spray improved survivability in terms of predicted time to incapacitation, where incapacitation is defined as a state where the subject is alive but unable to escape by their own efforts.

The two major mechanisms of incapacitation during a fire exposure are narcosis and heat exposure, while exposure to visually obscure smoke and irritants initially inhibit and slow escape attempts, and at high levels may themselves prevent escape. It is quite clear that, in the tests performed, the water sprays were beneficial in all these areas, giving on average an increase of approximately three minutes or more in the predicted time to incapacitation.

4.2 EXAMINATION OF LIFE THREAT HAZARD FOR THE REMAINING FIRE TESTS (CFT1, CFT2, CFT4-CFT6) AT THE MID CABIN POINT (G2)

FED analyses have also been carried out for the other cabin fire tests, at the same point (mid cabin, 1.7 metres height) and these are illustrated graphically in Figures 41 and 42. These diagrams show the accumulating fractional incapacitating dose with time. Incapacitation is predicted when the FED equals unity, and reaches the FED1 line in the diagrams.

Figure 41 shows the situations for the first two tests, fuel only, unsprayed (CFT1) and fuel only, sprayed (CFT2). As Figure 29 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 5.75 minutes.

In contrast, the sprayed, fuel only fire (CFT2) showed little penetration of fire gases until about 8 minutes, so that incapacitation is not predicted.

Figures 43 and 44 show the FEDs for convected heat for CFT1 and CFT2, for 4 positions in the fuselage, G1 near the fire at 1.7 metres height, G2 and G3 at mid cabin, 1.22 and 1.7 metres height, and G4 near the front of the fuselage at 1.22 metres height. For the unsprayed fire CFT1, at point G2, the FED for convected heat is reached after approximately 4.5 minutes, so for this fire temperature was the limiting factor for tenability rather than toxic gases as in the furnished fire tests. The diagram 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 (Figure 43), although the temperature profile near the door is similar to that in the unsprayed test, further into the cabin the use of the spray increases the tenability time for convected heat by a minute or so.

Figure 42 shows the narcotic gas FEDs for the various furnished cabin tests. The diagram clearly illustrates the dramatic difference between the unsprayed test (CFT3) and the sprayed tests, all of which improve tenability by approximately 3 minutes or more. The vertical take off of the FED line for CFT3 is almost entirely due to the high HCN concentration in the fire at that time (see Figure 36), while the more gradual increase in the other tests reflects the more gradually increasing concentrations, particularly of CO and HCN. Results for the two fully sprayed tests CFT4 and CFT7 are similar, but surprisingly the zone sprayed tests gave better protection. This was especially true of the zone sprayed test CFT5, for which the atmosphere was tenable throughout the test.

With regard to convected heat, Figure 45 shows the results for the unsprayed test (CFT3), illustrating the rapidly increasing FED at point G2 approximately half a minute after the rapidly increasing HCN FED. The diagram also illustrates the approximate one minute tenability near the door, and the slightly increased tenability in the middle and front of the cabin at the lower level above the floor. Figure 46 shows the exceptionally good result for CFT5, while Figures 47 and 48 show the results for CFT6 and CFT7. The results for the second zone sprayed test (CFT6) are rather disappointing when compared to the first (CFT5) and compared to the fully sprayed test CFT7.

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. Approximately half a minute later, with the mid-cabin temperature at head height in excess of 200°C, and a radiant heat flux in excess of 0.25 w/cm², incapacitation by heat and burns is predicted, with death soon afterwards due to burns in any subject not already dead due to the effects of cyanide.

Also important are the conditions earlier in the test in terms of smoke, irritant acid gases and organic products, and particulate. For test CFT3 the smoke tenability limit of 2 metres visibility was exceeded at 1 minute 40 seconds, and it is considered that the smoke present at this time, and probably between 1 and 1.5 minutes, would have been extremely irritant.

Unfortunately, the grab samples taken at intervals for HCl measurement gave poor recoveries, but the integrated samples taken between 1 and 4 minutes show very high average HCl and HBr concentrations, with a combined concentration of over 2000 ppm. 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 (5), HCl and HF concentrations were high within half a minute of ignition, and became very high after 1.5 minutes. 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 one 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.

When this fire is compared to the fully sprayed fire test (CFT7) (see Tables 9 and 10) there is clearly a great improvement. Narcotic gas concentrations, particularly those of hydrogen cyanide, are not only very much lower, but occur several minutes later in the fire, so that the atmosphere is tenable until nearly 6 minutes. The cabin temperatures are also much lower, only just reaching 100°C after 7 minutes, with low radiant fluxes, so that heat incapacitation is not predicted at any stage of the fire at the mid-cabin point. Similarly the concentrations of acid gases are considerably lower, by approximately 53-80% in the fully sprayed tests, and 93-96% in the zone sprayed tests. The concentrations present during 1-4 minutes in the sprayed tests are considered to be irritant, but not unbearable, while those in the zone sprayed tests would be even less irritant.

The only obvious drawback of the sprayed tests is that the spray lowered the smoke layer and restricted visibility from an early stage in the tests. After consideration of the videos, however, it is considered that this would not be a major problem. The other fully sprayed test was similar to CFT7, and the zone sprayed tests gave even better protection. This is especially true of CFT5, where the atmosphere remained tenable throughout the test.

5.2.2 Mechanisms of tenability improvement

Of the three beneficial mechanisms postulated, it is considered that the major benefit of the spray was in preventing or delaying the fire from entering the cabin and consuming the cabin furnishings. This greatly reduced the toxic gas growth curve, and also kept the temperature in the cabin down. This effect occurred even when the cabin was unfurnished, so that the lower temperatures probably resulted from abstraction of heat by the spray and reduction in heat release from fuel in the cabin.

With regard to the possible benefits by washing out smoke particles and acid gases, the benefits are less clear. It is difficult to assess any such effect because decreased acid gas concentrations can result from inhibition of the fire and increases of the depth of the smoke layer, as well as washout. However, since the floor pots collected acidic water, it seems likely that some acid was washed out.

5.2.3 Effects of spray on particulate and possible hazards from water droplets

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. It must also be remembered that the cabin was only partly furnished, so that much higher concentration of irritant gases would probably be released from a fire in a fully furnished cabin.

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 ($< 5 \mu\text{m}$ 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 less than $200 \mu\text{m}$ 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; i.e. capable of penetrating into the mouth and possibly 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 inhaled (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.

5.2.4 Possible hazards from heat and steam

There is no doubt that the use of the water spray considerably reduced the heat hazard by reducing the temperature and heat flux in the cabin. However, if this heat was abstracted by raising the water spray to steam, it is possible that a hazard to the lung might be created, since steam is known to be extremely damaging to the deep lung, due to latent heat release as it condenses.

It is considered that for this hazard to arise the temperature would need to be above 100°C , since the capacity of the atmosphere for water would be too small below this temperature. Above 100°C , the presence of a serious problem would depend upon how much water was in the gas phase; i.e. how many mg of water per litre of air were present. It is suggested that this should be assessed by measuring the latent heat in the fire atmosphere by taking it through a condenser.

In the present study an attempt to obtain some estimate of the size of this problem was made by placing wet and dry thermocouples in the cabin at 0.8 metres height. In practise the temperature even at 1.7 metres remained below 100°C throughout most of the sprayed tests at mid-cabin, and the 0.8 metre wet bulbs also showed some degree of depression relative to the dry bulbs through most of the tests.

Although it is considered that this aspect would benefit from further study, it is considered that a serious "steam" hazard did not occur in the sprayed tests.

6. REFERENCES

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TABLE 1. MOCK NARROW BODIED AIRCRAFT TESTS - FUELS AND SPRAY TIMINGS			
TEST	FUEL	SPRAY ON (minutes)	SPRAY OFF (minutes)
C74	Wood crib (9 Kg) PVC sheet (6.75 Kg) Avtur fuel (0.5 litres)	No spray used	
C75	Wood crib (9 Kg) PVC sheet (6.0 Kg) Avtur fuel (0.5 litres)	9	12
C76	Wood crib (11.25 Kg) Polyurethane (1.5 Kg) Other materials (2 Kg) Avtur Fuel (1.0 litre)	2	5
C77	Wood crib (11.25 Kg) Polyurethane (1.5 Kg) Other materials (2 Kg) Avtur fuel (1.0 litre)	5	8

TABLE 2. 707 FUSELAGE TESTS - EXPERIMENTAL CONDITIONS

TEST	FUEL	SPRAY ON/OFF	REMARKS
CFT1	Kerosine only	OFF	'Shakedown' proving test
CFT2	Kerosine only	ON	For fuel 'background'
CFT3	Kerosine + furniture	OFF	Baseline test
CFT4	Kerosine + furniture	ON	Spray throughout cabin - burst pipe
CFT5	Kerosine + furniture	ON	Zoned spray - only in fire region
CFT6	Kerosine + furniture	ON	Zoned spray - different nozzle design
CFT7	Kerosine + furniture	ON	Repeat of CFT4 with leak corrected

TABLE 3. TESTS C74 AND C75 - TIMINGS FOR PARTICULATE SAMPLES					
	May	Marple	Total Particulate	Filter A	Filter B
Start time (min.)	2	2	2	2	5
Stop Time (min.)	5	5	5	5	8
Total Sampling Time (min.)	3	3	3	3	3 (6 for continuous)
Flow Rate (l/min.)	10	2	2	1	1

TABLE 4. TESTS C74 AND C75 - EFFECTS OF SPRAY ON SMOKE FROM PVC FUEL

	C74 UNSPRAYED		C75 SPRAYED	
	Particulate	HCl (ppm)	Particulate	HCl (ppm)
May	majority 0.05-1.55 μm	97.6	majority 0.05-1.55 μm	35.1
Marple	0.22 mg/l, 97% less than 1.55 μm	9.6	0.106 mg/l, 57% less than 1.55 μm	18
Total (in line)	0.049 mg/l	7.2	0.011 mg/l	8.7
Total (surface)	0.133 mg/l	269	0.071 mg/l	35.7
Grab		858		400

TESTS C76 AND C77 EFFECT OF SPRAY ON SMOKE FROM PVC AND PUF FUEL

	C 77 UNSPRAYED		C76 SPRAYED	
	Particulate	HCl (ppm)	Particulate	HCl (ppm)
May	wide size range to 9 μm	173	majority 0.05-1.55 μm , filter damp	118
Marple	0.575 mg/l, 56% less than 1.55 μm	45	0.075 mg/l, 98% less than 1.55 μm	nd
Total (in line)	0.13 mg/l	9.8	0.12 mg/l	16.4
Total (surface)	0.2 mg/l	1.9	0.566 mg/l	3.9
Grab		925		92

TABLE 5. TESTS CFT1 TO CFT7: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	28	0	10	16
Open face filters						
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		22.4	2.3	nd	0.4	nd
Stage 2		22.4	1.1	nd	0.4	1.1
Stage 3		4.9	9.0	0.2	6.0	18.1
Stage 4		-	nd	nd	0.4	2.6
Filter		51.4	5.6	1.4	1.9	1.9
Total		101.1	18.0	1.6	9.1	23.7

TABLE 6. 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						
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	2.70	0.00	nd	tr
Total		16.40	2.72	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 7. HYDROGEN CYANIDE - CONCENTRATIONS 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 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 8. TESTS CFT 1 TO CFT 7: PARTICULATE CONCENTRATIONS 1-3 MINUTES
(g/m³)

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

TABLE 9
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							
FID _{CO}	0.00	0.00	0.00	0.02	0.06	0.16	0.38
FID _{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
FID _O	0.00	0.00	0.00	0.00	0.00	0.00	0.01
FID/30s	0.00	0.00	0.00	0.10	10.10	>10	>10
ΣFID	0.00	0.00	0.00	0.11	11.10	>10	>10
Fractional effective dose of convected heat							
Temp °C	12	14	28	81	156	274	408
FID/30s	0.00	0.00	0.01	0.03	0.20	4.96	>10
Σ FID	0.00	0.00	0.01	0.04	0.24	5.20	>10

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 smoke 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. However it is unlikely that sufficient irritants would be inhaled up to 4 minutes to cause life-threatening post-exposure lung damage.

TABLE 10
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							
FID _{CO}	0.01	0.02	0.03	0.05	0.09	0.14	0.16
FID _{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
FID _O	0.00	0.00	0.00	0.00	0.00	0.00	0.01
FID/30s	0.01	0.03	0.04	0.14	0.45	0.96	1.21
Σ FID	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
FID/30s	0.00	0.01	0.01	0.02	0.02	0.03	0.04
Σ FID	0.00	0.01	0.02	0.04	0.06	0.09	0.13

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: no heat incapacitation
Time to tenability limit for radiant heat limit not exceeded, maximum 0.12 w/cm²

Effects of irritants:
Over period between 1 and 4 minutes: average respirable particulate 2.2 mg/l
average total particulate
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 through to represent trapped water spray droplets, too large to penetrate into the lung.

TABLE 11. TESTS CFT1 TO CFT7: TIME TAKEN (SECONDS) FOR FED TO REACH UNITY FOR DIFFERENT HAZARDS

TEST	SAMPLING POSITION AND HAZARD								
	G1		G2			G3		G4	
	CO, CO2, O2	TEMP	CO, CO2, O2	TEMP	CO, CO2, O2, HCN	CO, CO2, O2	TEMP	CO, CO2, O2	TEMP
CFT1	318	218	400	291	400	NR	336	346	336
CFT2	NR	186	NR	355	NR	NR	NR	NR	409
CFT3	190	191	195	155	150	209	186	195	186
CFT4	345	-	336	-	273	NR	-	345	-
CFT5	NR	NR	NR	NR	NR	NR	NR	NR	NR
CFT6	NR	104	NR	296	382	NR	356	NR	396
CFT7	NR	241	377	NR	327	441	NR	NR	NR

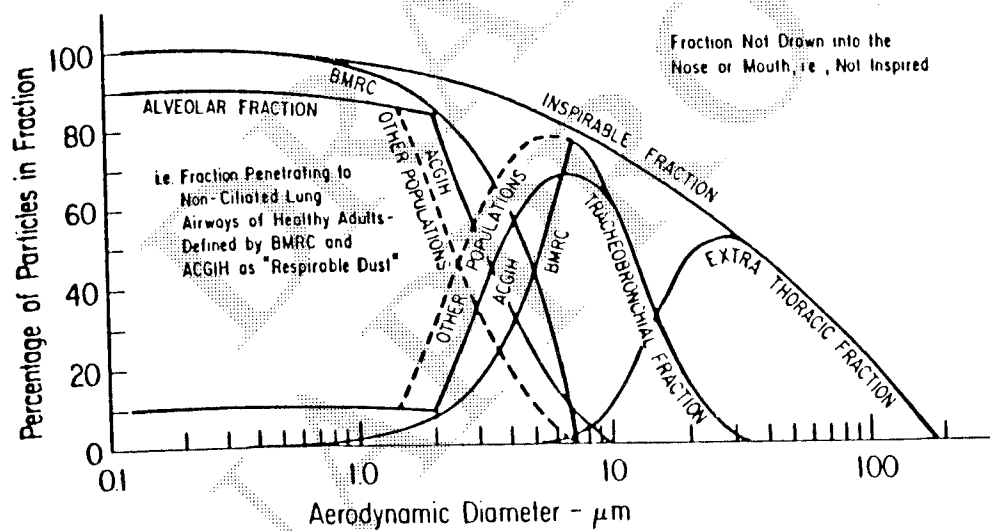
Notes:- NR FED did not reach unity during course of test
 - No data available

TABLE 12. TESTS CFT1 TO CFT7: TIME TAKEN (SECONDS) FOR
RADIATION LEVELS TO REACH 0.25 W/CM2

TEST	RADIOMETER POSITION			
	RAD1	RAD2	RAD3	RAD4
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

Figure 1

Depth of penetration of airborne particles of different sizes into the respiratory tract



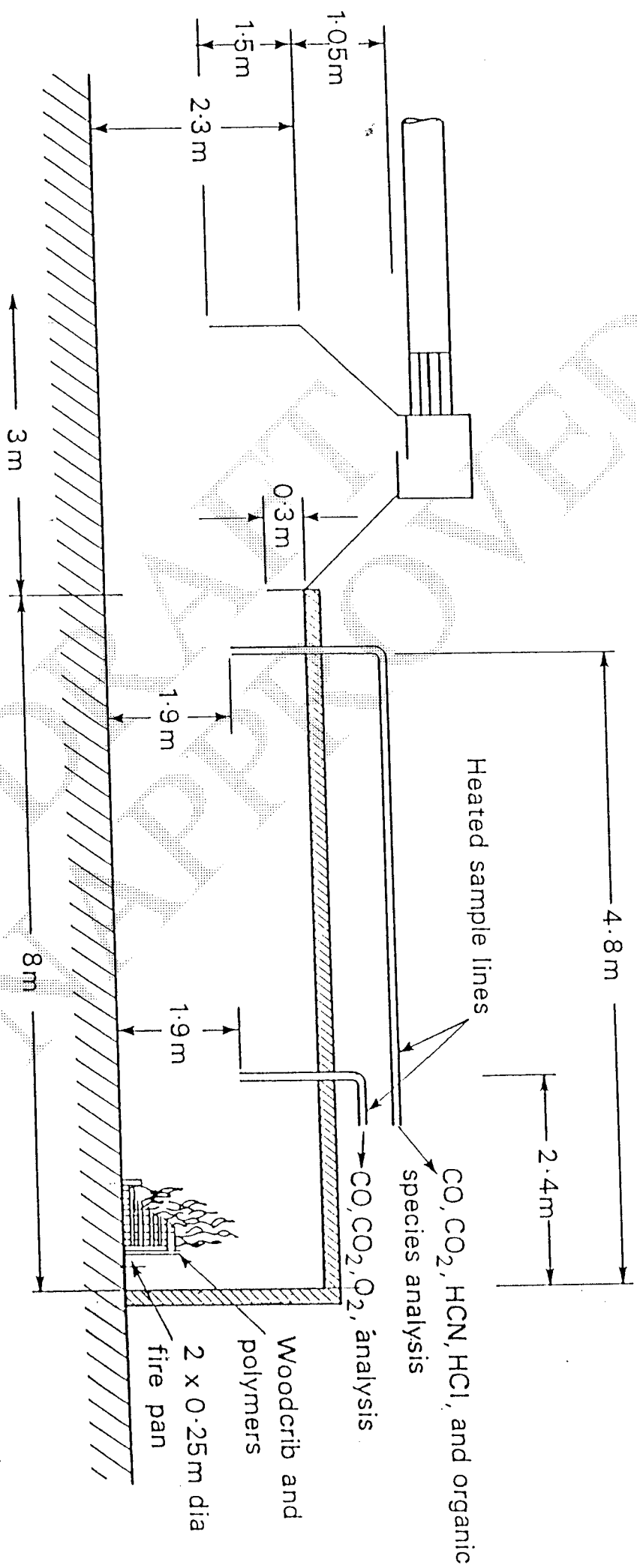


Figure 1. Location of mobile laboratory heated sample lines in the mock narrow bodied aircraft tests

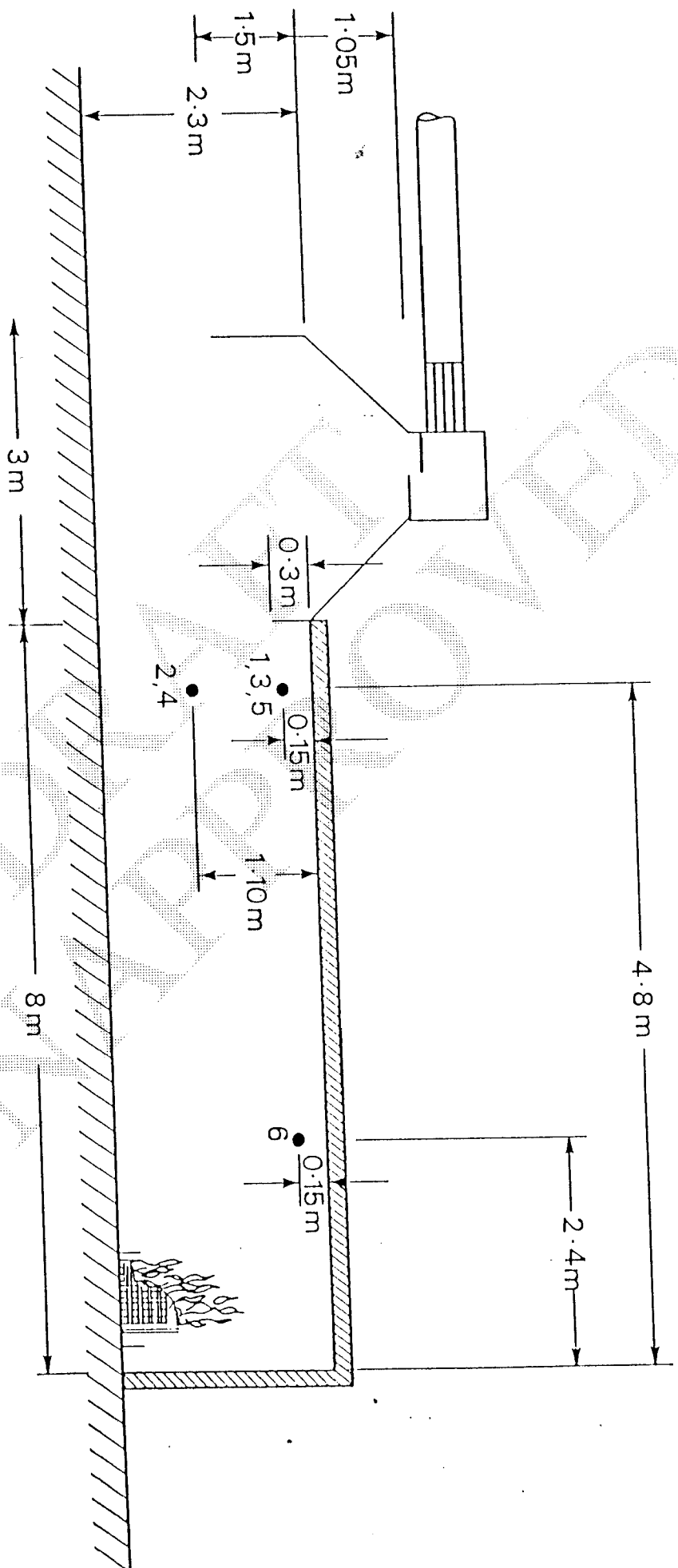


Figure 2. Position of smoke particulate filters 1 to 6 in the mock narrow bodied aircraft tests

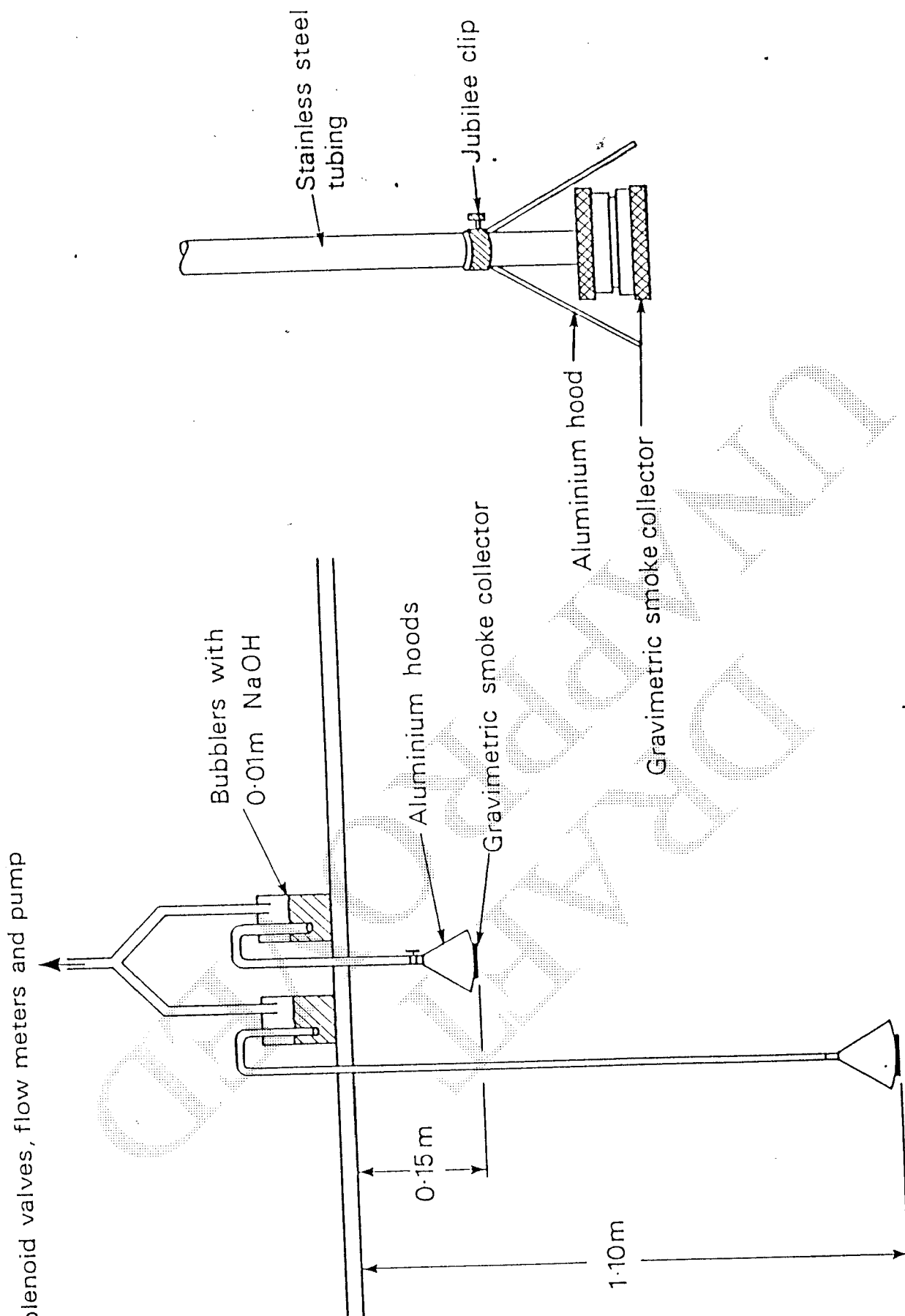


Figure 3. Detail of smoke particulate filters as used in the mock narrow bodied aircraft tests

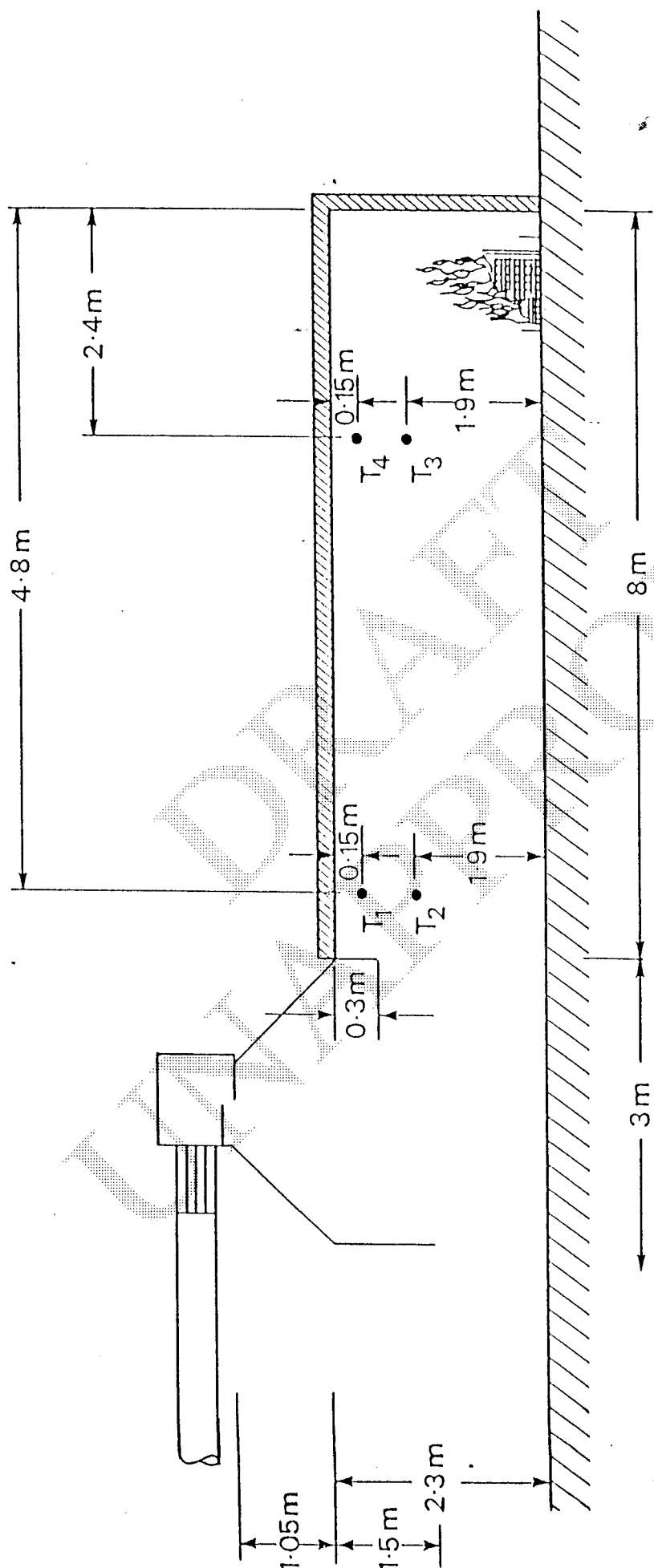


Figure 4. Location of thermocouples T_1 to T_4 in the mock narrow bodied aircraft tests

- Key:
- x Sampling point of mobile laboratory heated line
 - o Sampling point of particulate filter/bubblers unit
 - Sampling point of particulate sizing apparatus

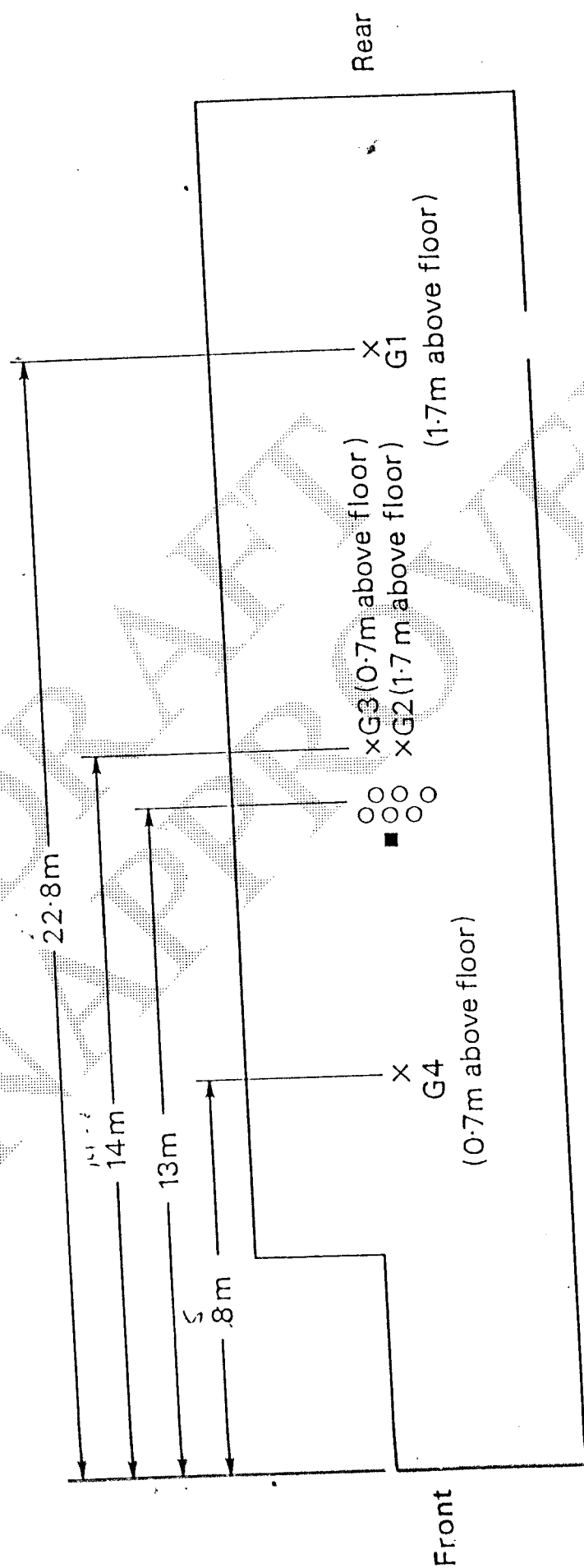
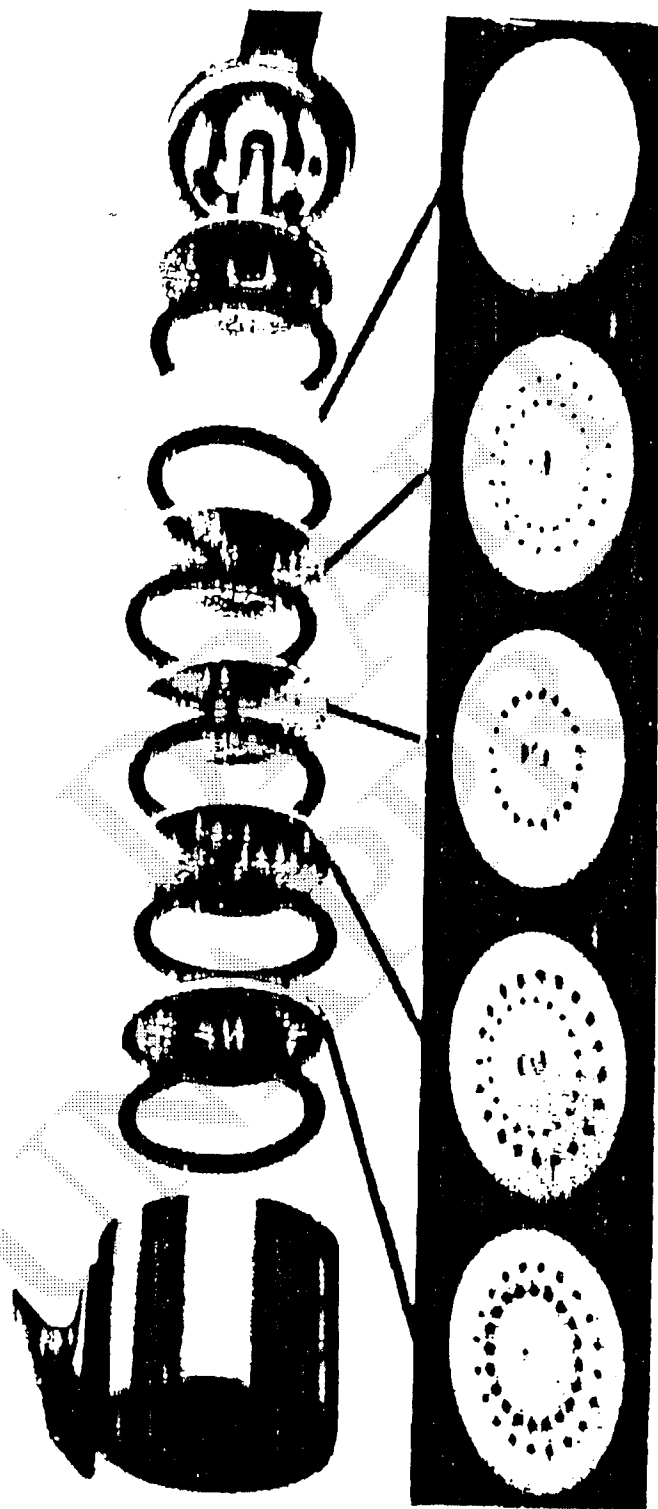


Figure 5. Plan view of 707 fuselage showing gas/smoke sampling points

ANDERSEN MINI SAMPLER - PARTICLE SIZE ANALYSER FOR DRY AEROSOLS



1	2	3	4	5
4.7 and up	4.7 to 3.3	3.3 to 2.1	2.1 to 0.65	below 0.65 micron

Micron particle sizes

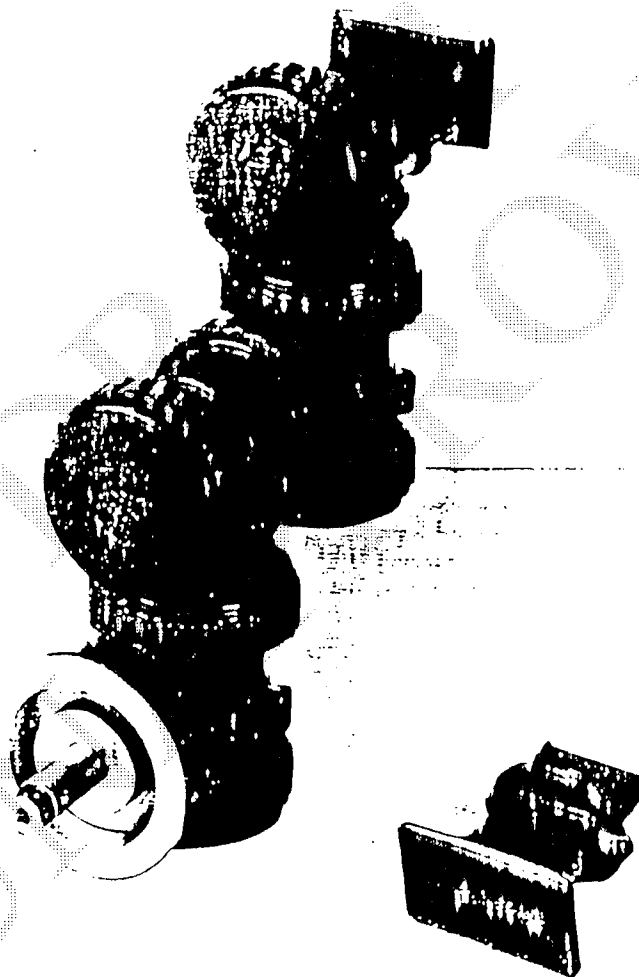
All size and percentage figures are calibrated at 1.4 litres per minute air flow

This instrument collects and sizes airborne particles for subsequent gravimetric and/or chemical analyses or immediate visual evaluation.

HRC

Figure 1.

Figure 8.



The Cascade Impactor samples liquid or solid particles from 0.5 to 50 μ diameter without in any way altering them. This is of particular value when sampling a liquid droplet cloud, since even large drops are not shattered. A very wide range of materials can be sampled with suitable techniques. Low as well as high concentrations can be sampled, whilst evaluation is made easier by the separation during samp-

ling into four size fractions on separate glass discs.

This is one of the few samplers capable of dealing with liquid droplet clouds, both volatile and non-volatile. It is therefore widely used to

7
Figure 3.

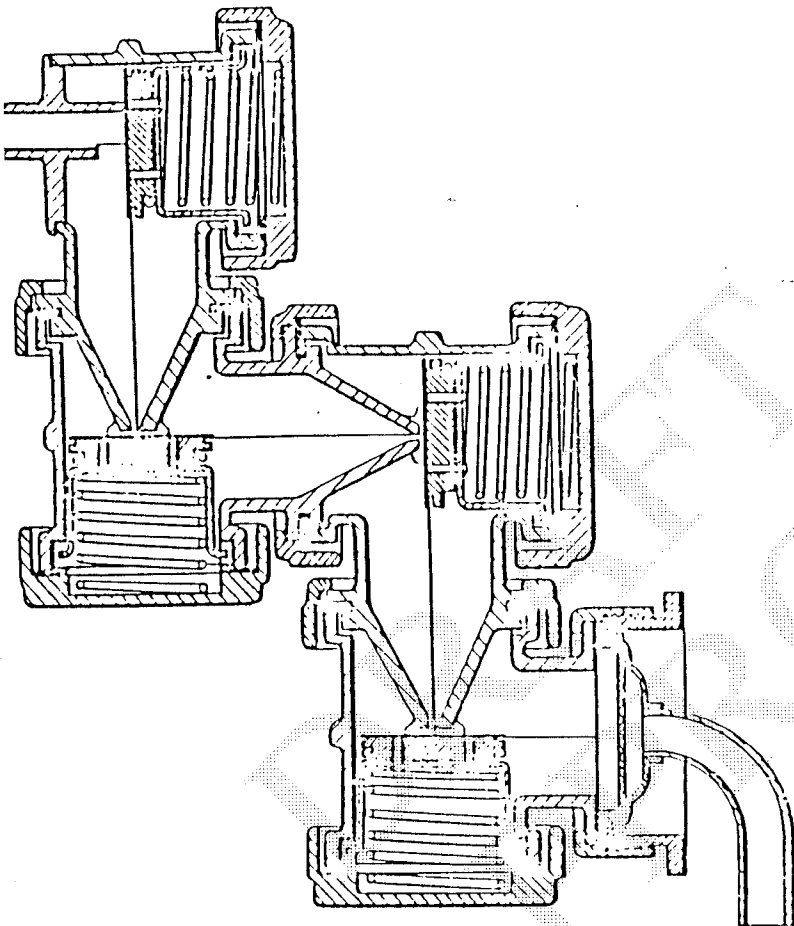
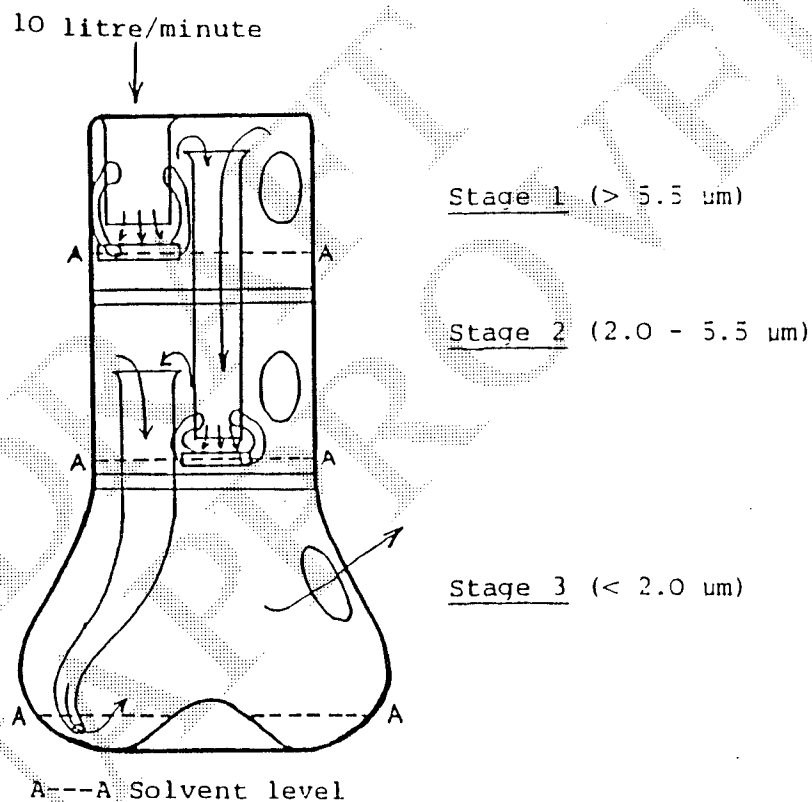


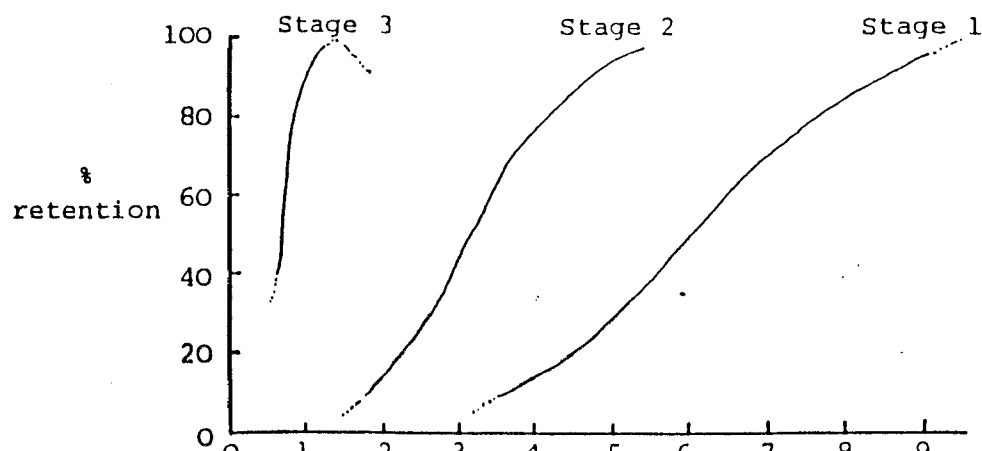
Fig. 1

FIGURE A

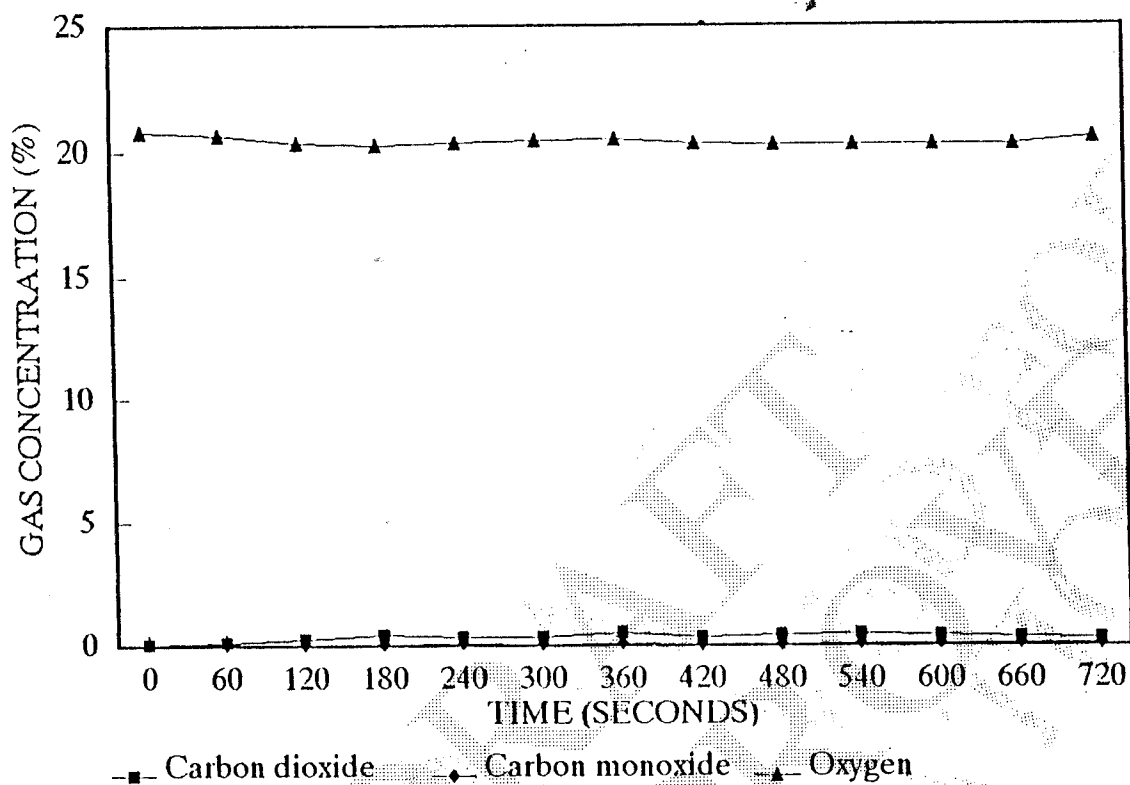
May multistage impinger for liquid aerosols



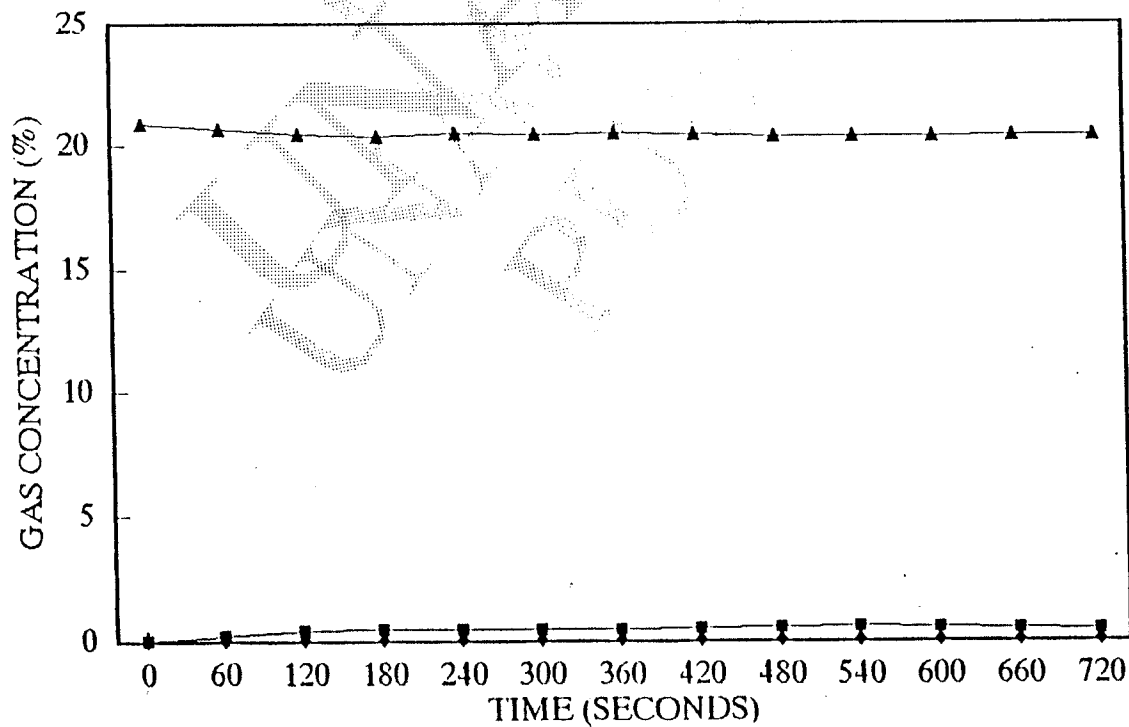
Individual stage cut-off curves (after May K.R. 1966 Bacteriological Reviews Vol 30 No. 3)



11
FIGURE 6. TEST C74 - GAS CONCENTRATIONS
NEAR FIRE

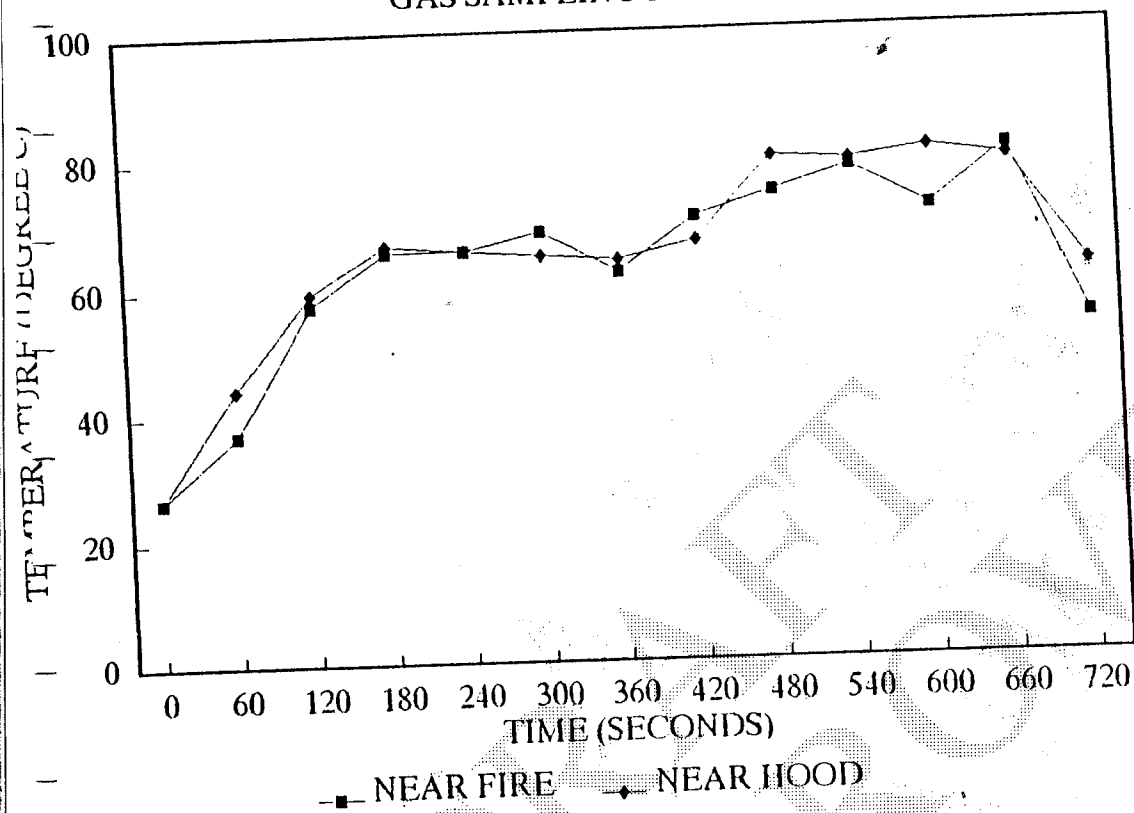


12
FIGURE 7. TEST C74 - GAS CONCENTRATIONS
NEAR HOOD



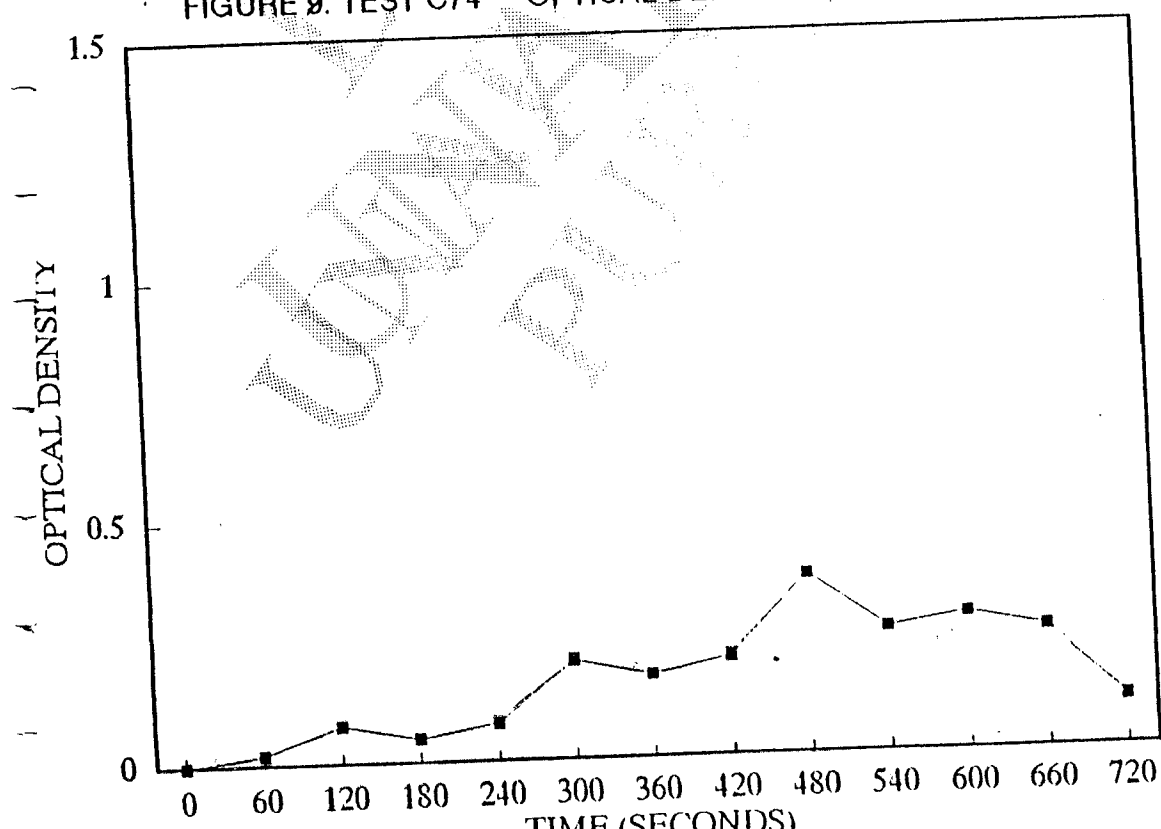
13

FIGURE 8. TEST C74 - TEMPERATURE MEASUREMENTS
GAS SAMPLING POSITIONS



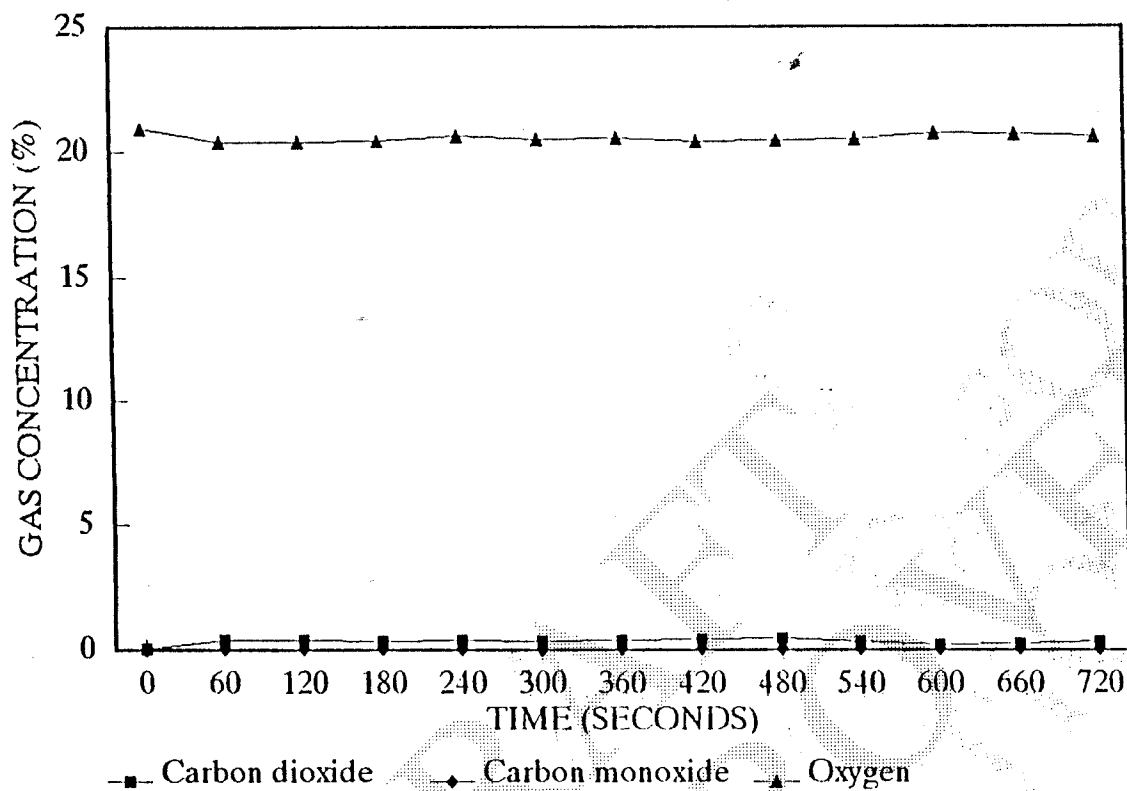
14

FIGURE 9. TEST C74 - OPTICAL DENSITY MEASUREMENTS



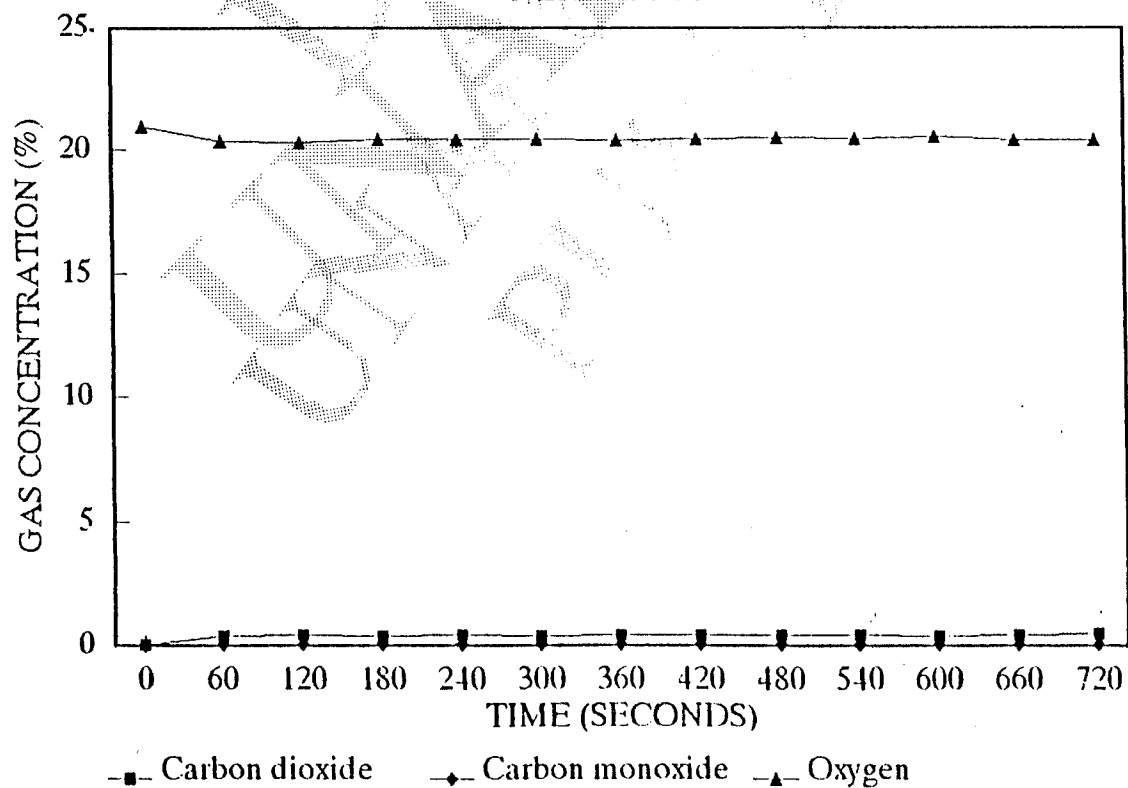
15

FIGURE 10. TEST C75 - GAS CONCENTRATIONS
NEAR FIRE

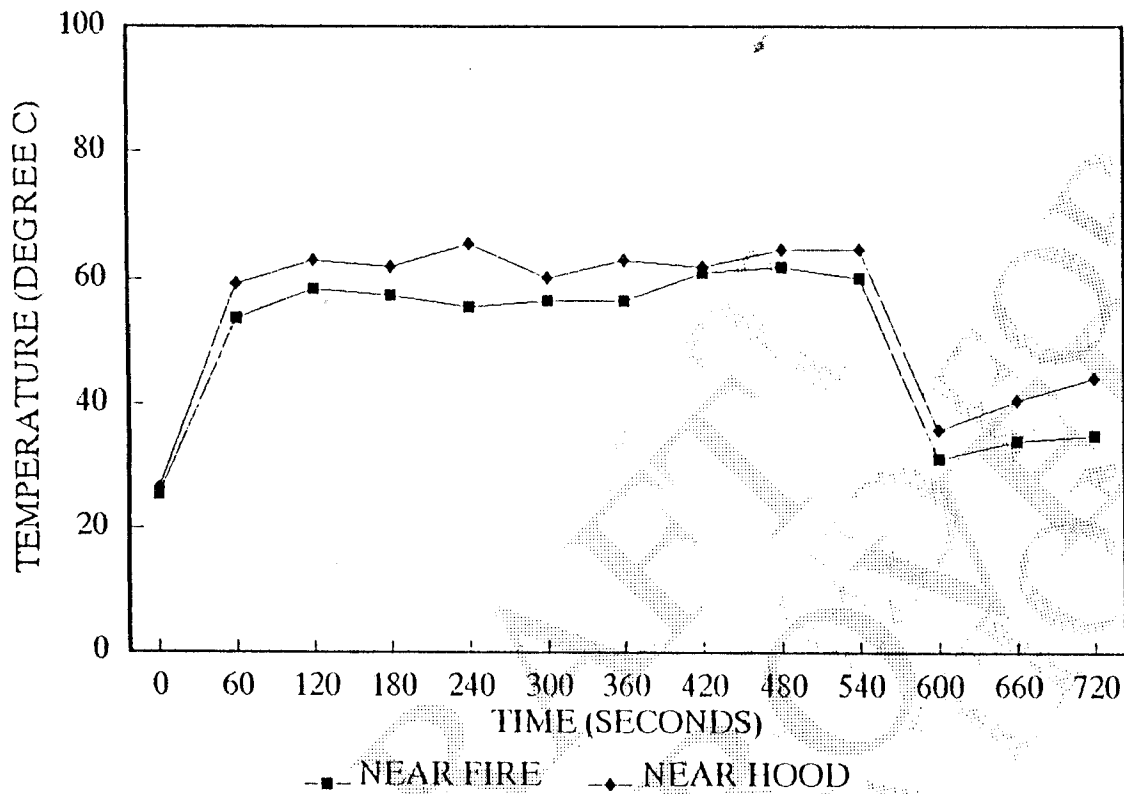


16

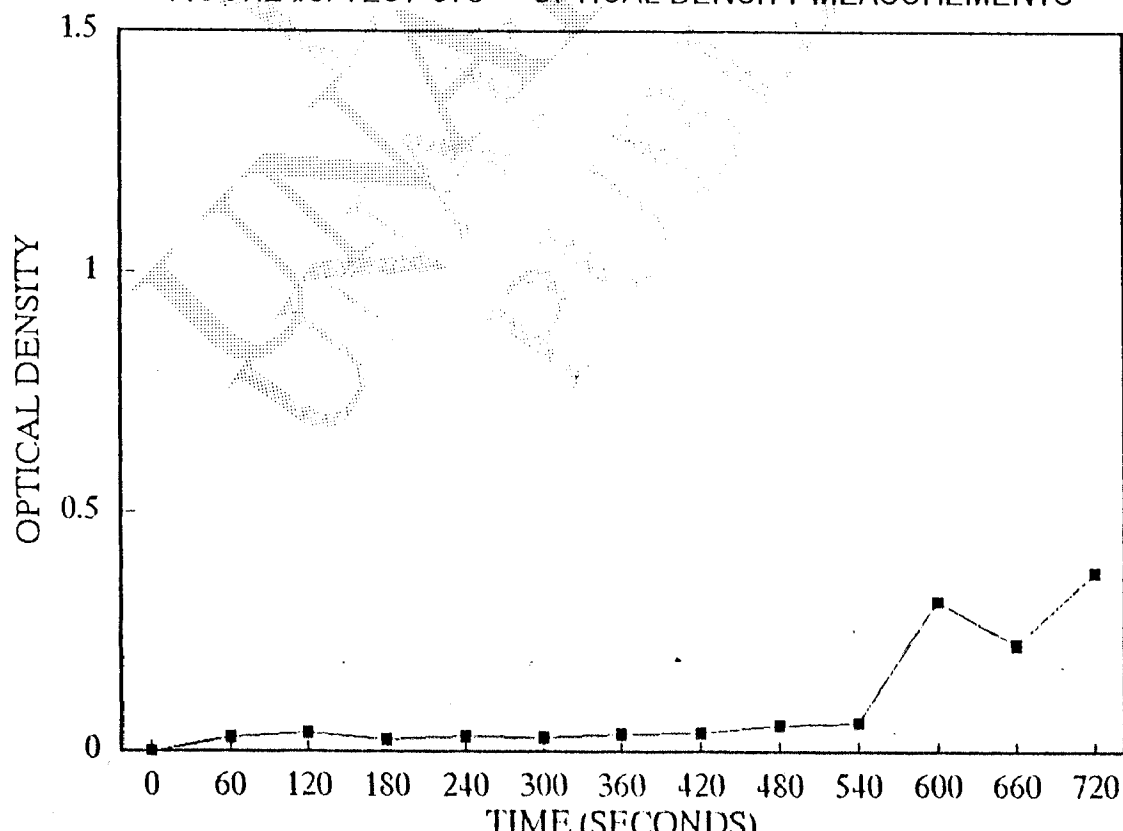
FIGURE 11. TEST C75 - GAS CONCENTRATIONS
NEAR HOOD



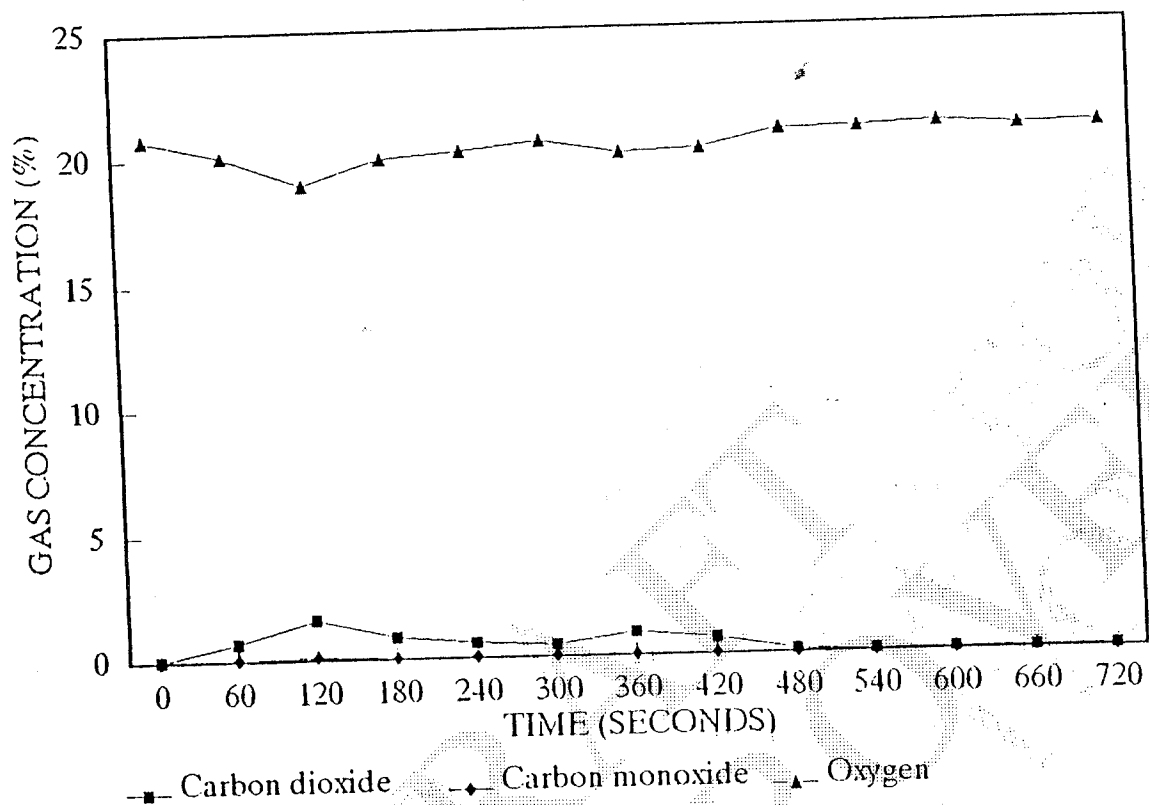
17
FIGURE 12. TEST C75 - TEMPERATURE MEASUREMENTS
GAS SAMPLING POSITIONS



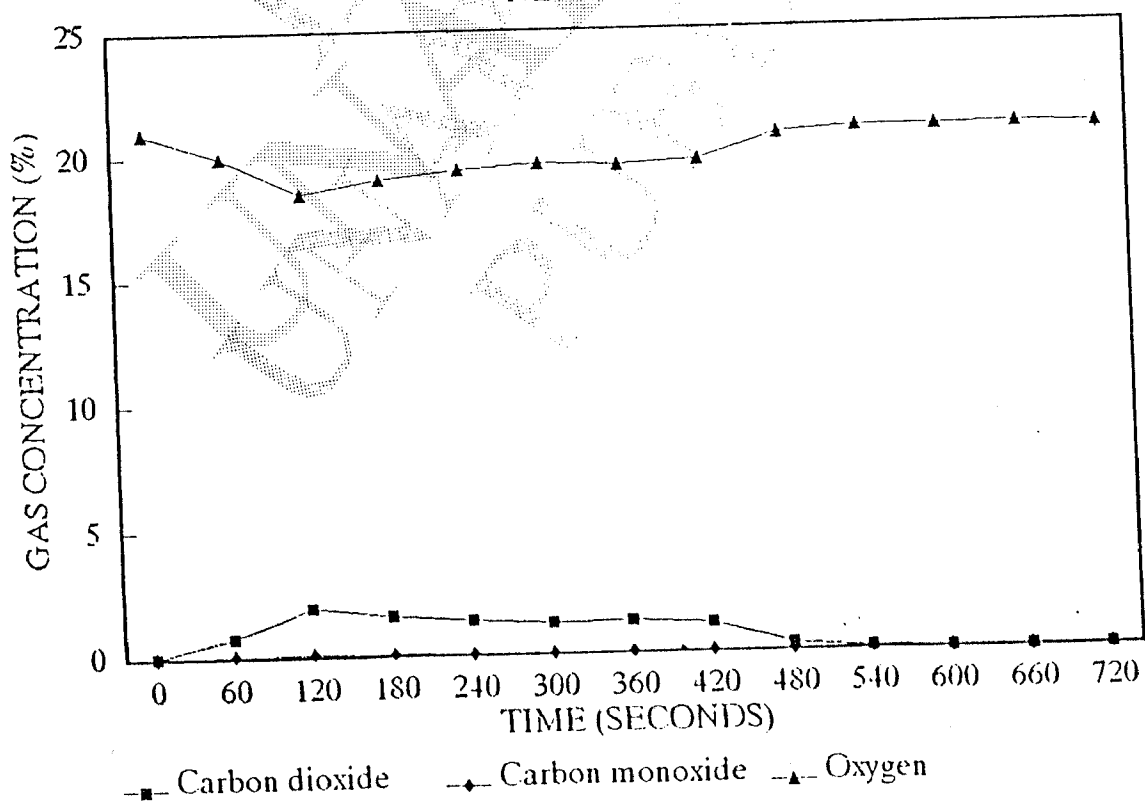
18
FIGURE 13. TEST C75 - OPTICAL DENSITY MEASUREMENTS



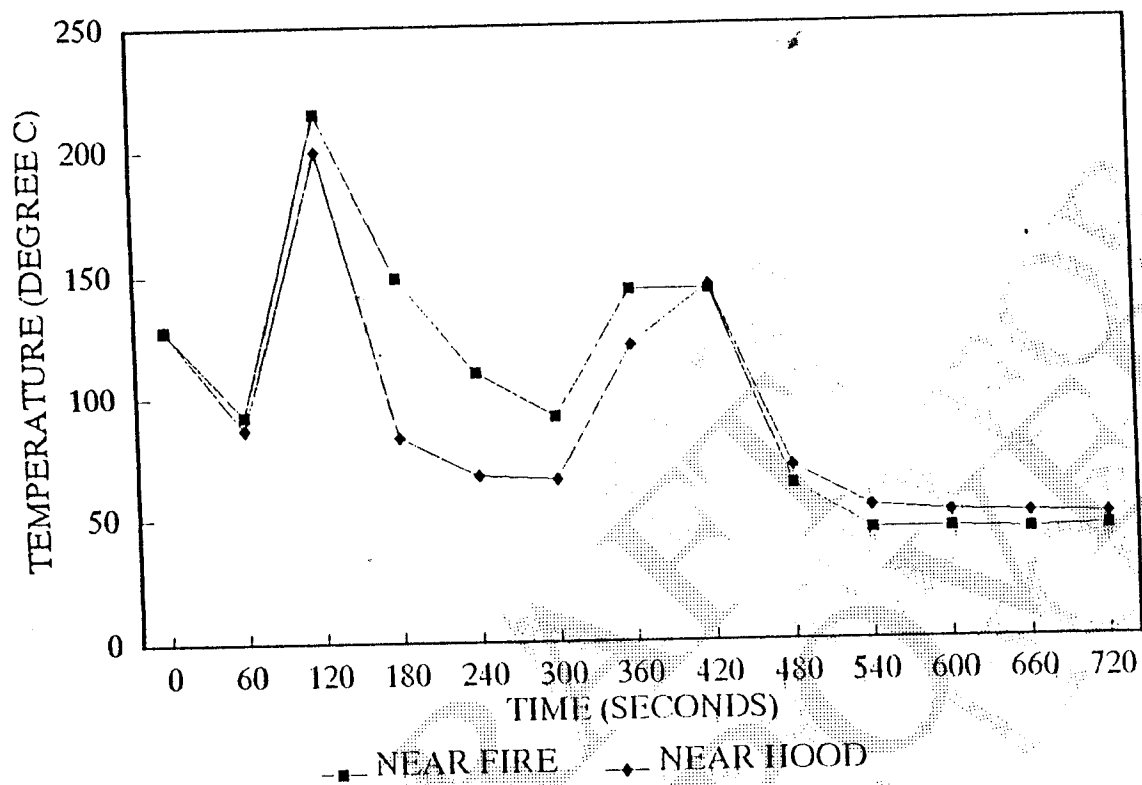
19
FIGURE 14. TEST C76 - GAS CONCENTRATIONS
NEAR FIRE



20
FIGURE 15. TEST C76 - GAS CONCENTRATIONS
NEAR HOOD



21

FIGURE 16. TEST C76 - TEMPERATURE MEASUREMENTS
GAS SAMPLING POSITIONS

22

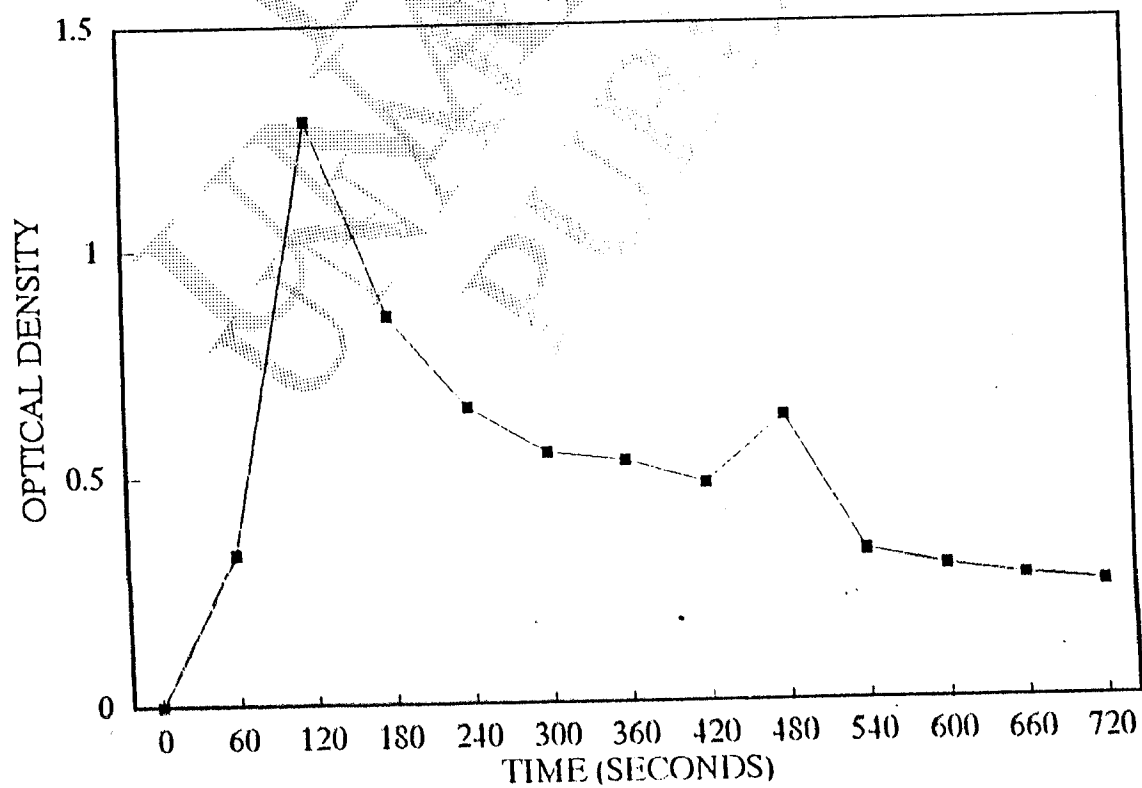
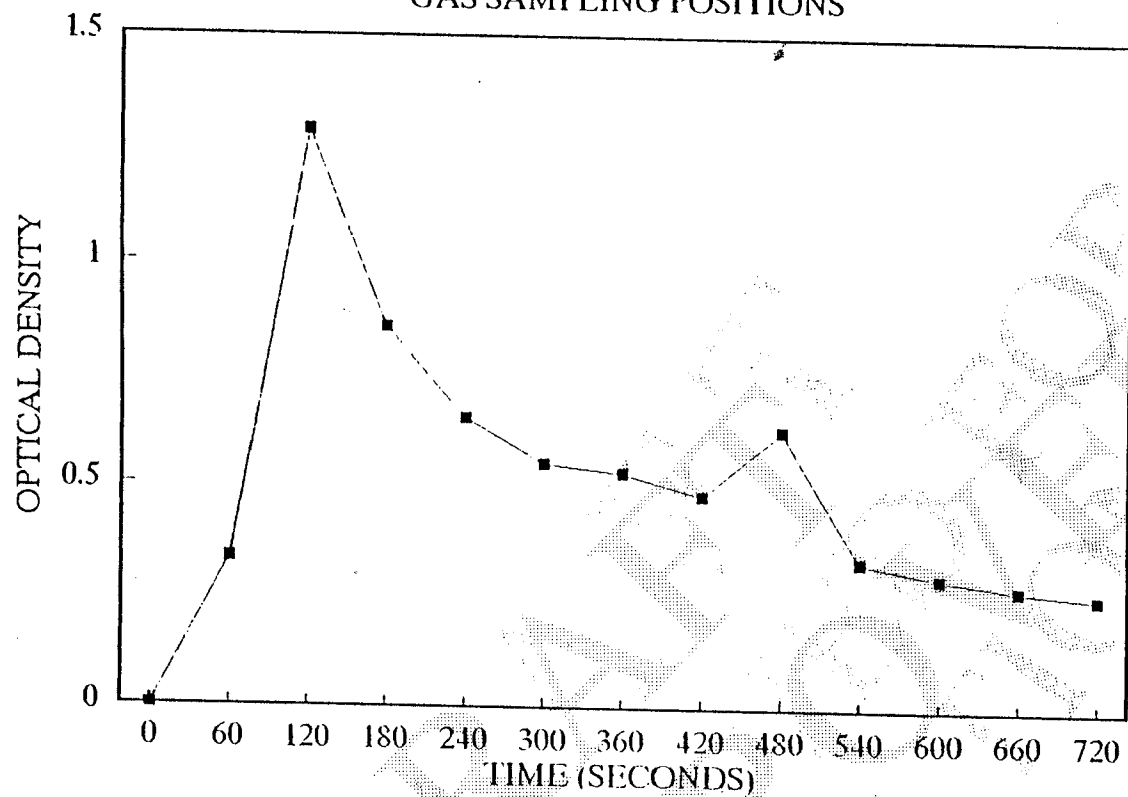
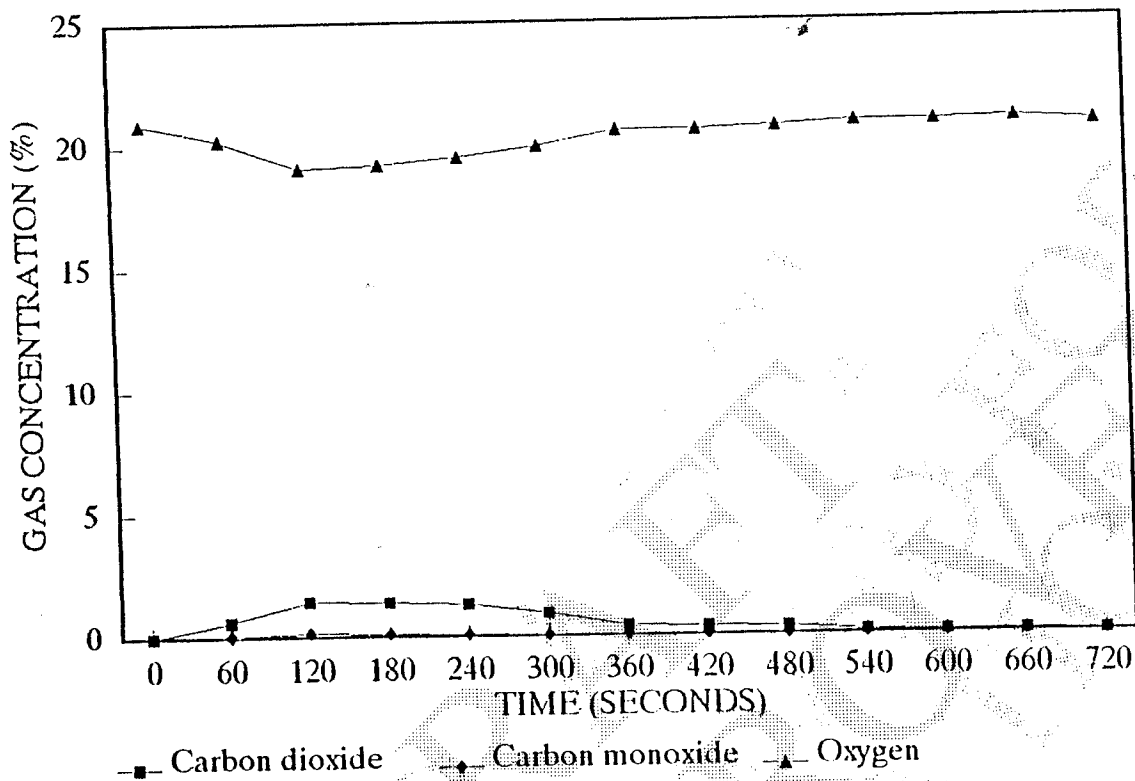
FIGURE 17. TEST C76 - OPTICAL DENSITY MEASUREMENTS
GAS SAMPLING POSITIONS

FIGURE 17. TEST C76 - OPTICAL DENSITY MEASUREMENTS
GAS SAMPLING POSITIONS



24

FIGURE 18. TEST C77 - GAS CONCENTRATIONS
NEAR FIRE

25

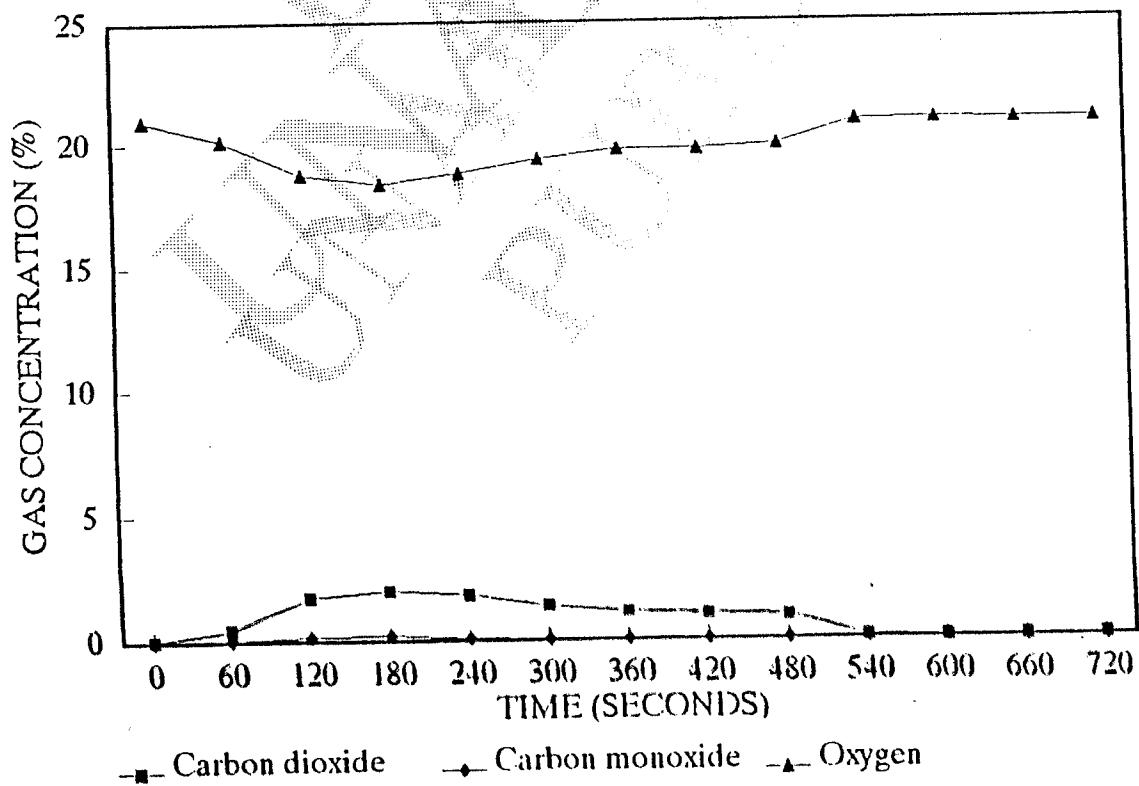
FIGURE 19. TEST C77 - GAS CONCENTRATIONS
NEAR HOOD

FIGURE 20. TEST C77 - TEMPERATURE MEASUREMENTS
GAS SAMPLING POSITIONS

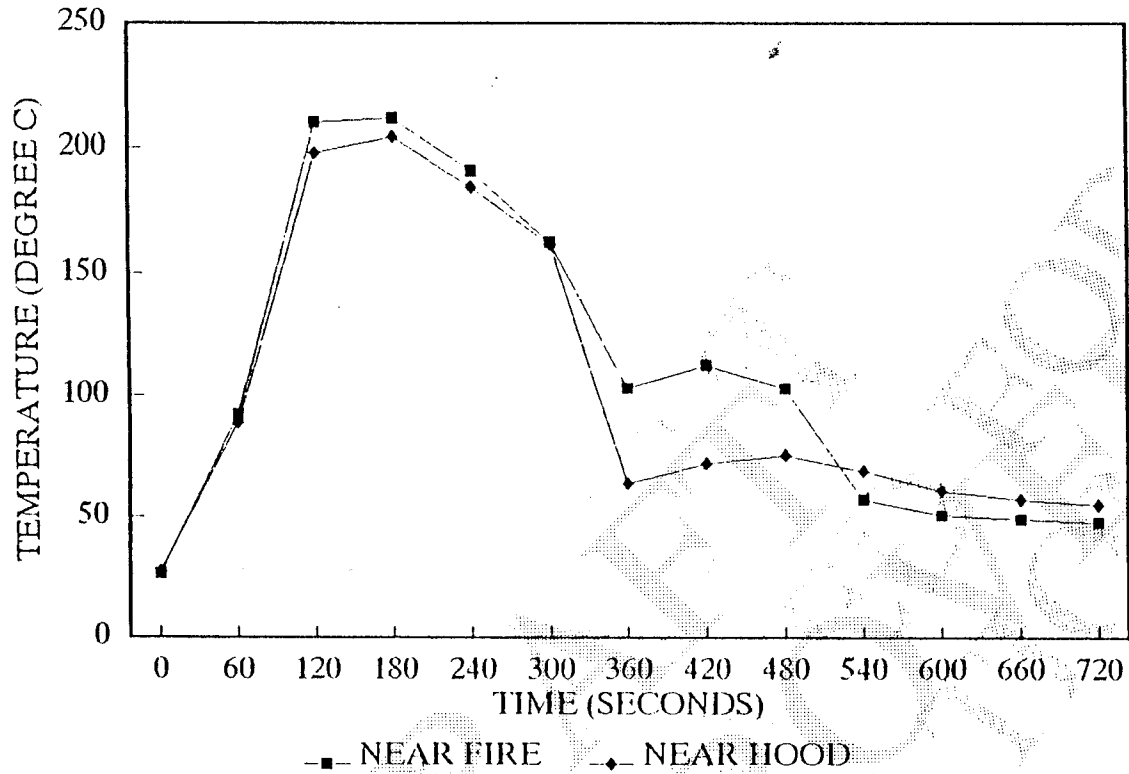
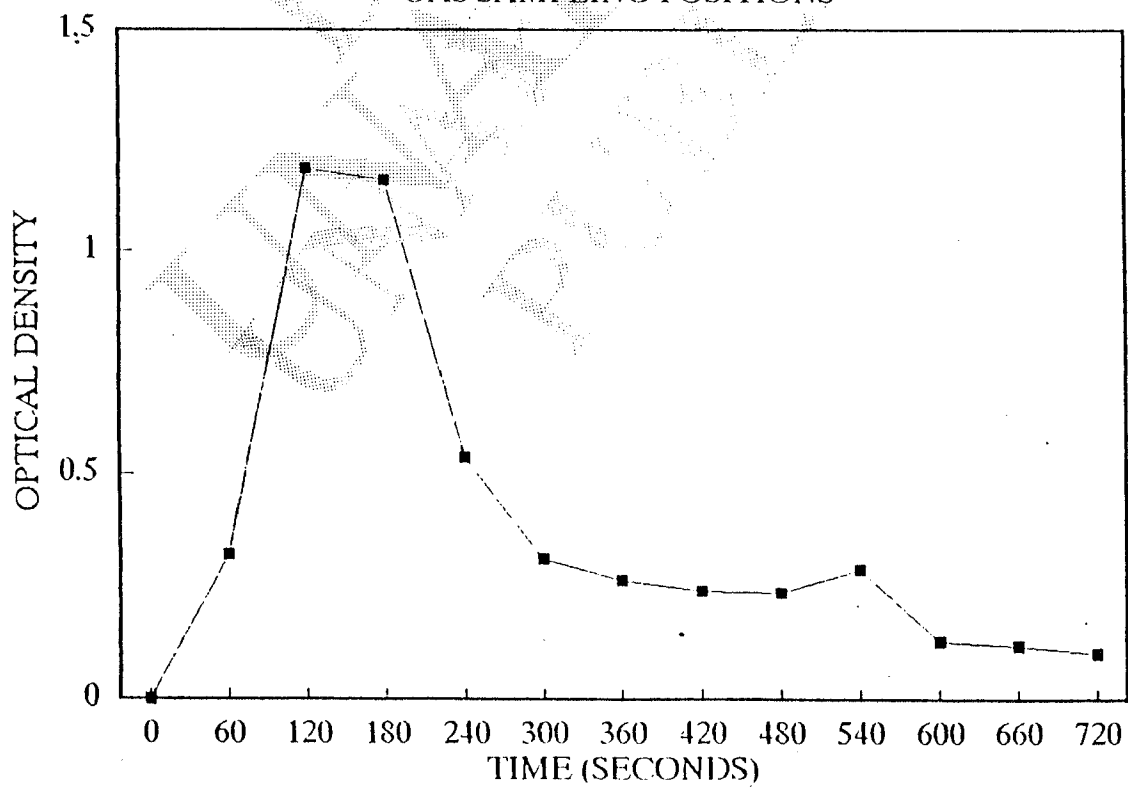


FIGURE 21. TEST C77 - OPTICAL DENSITY MEASUREMENTS
GAS SAMPLING POSITIONS



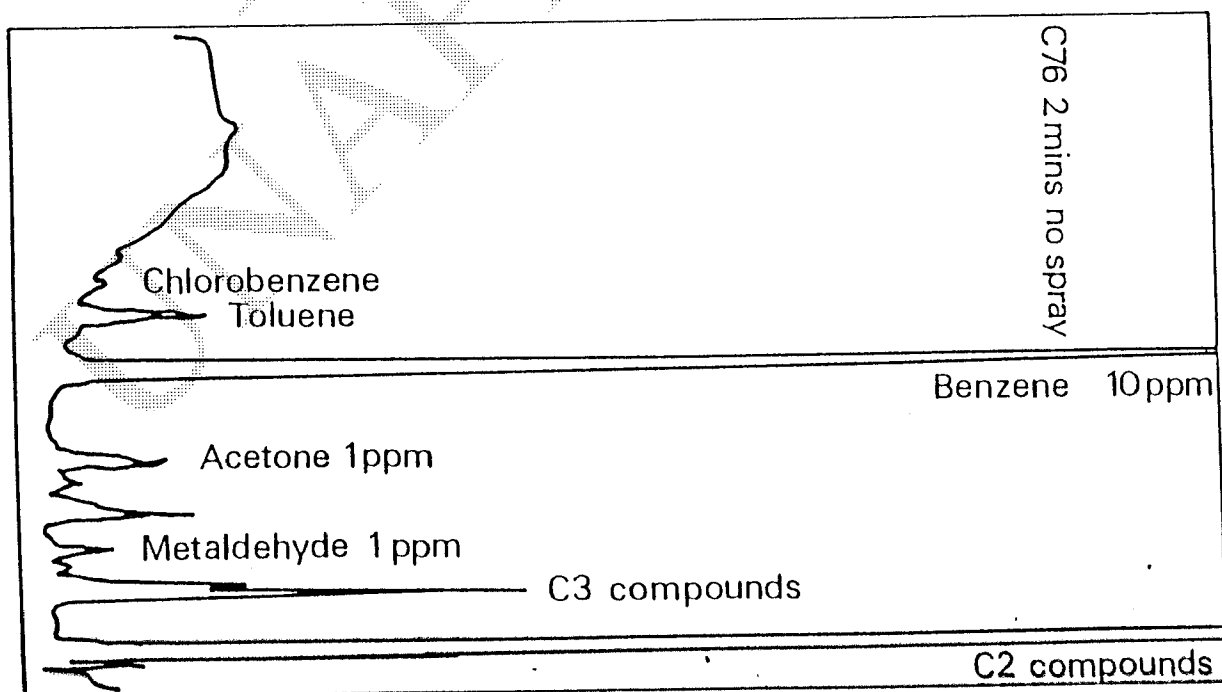
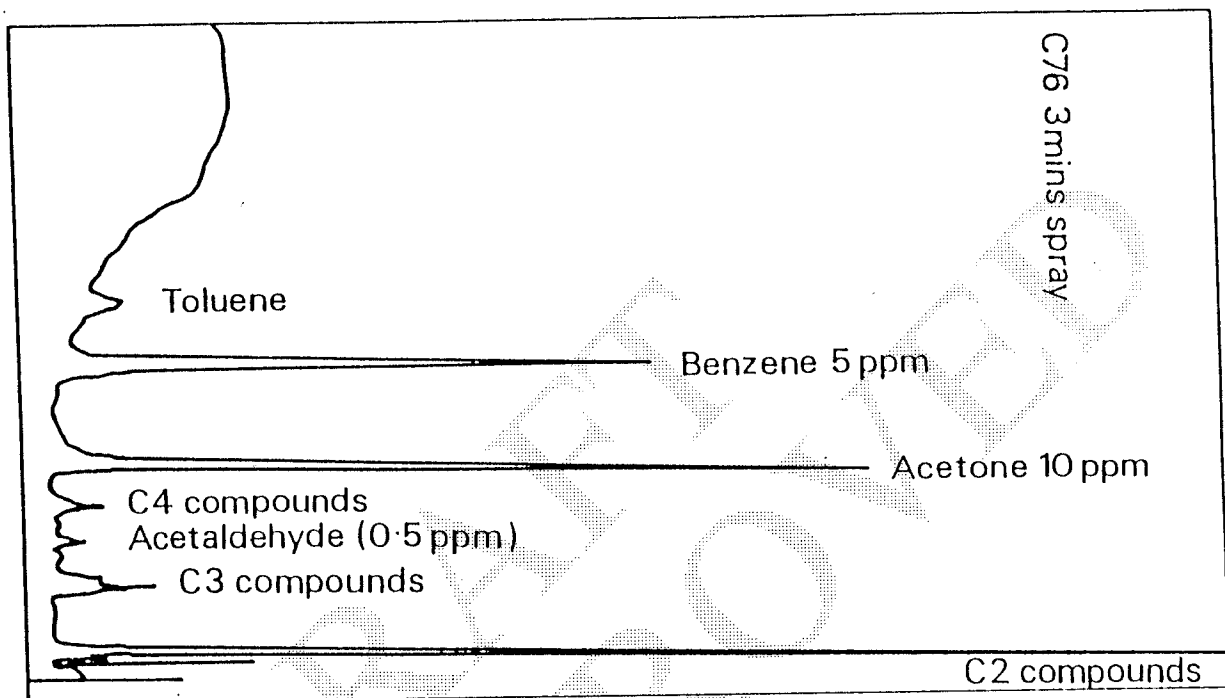
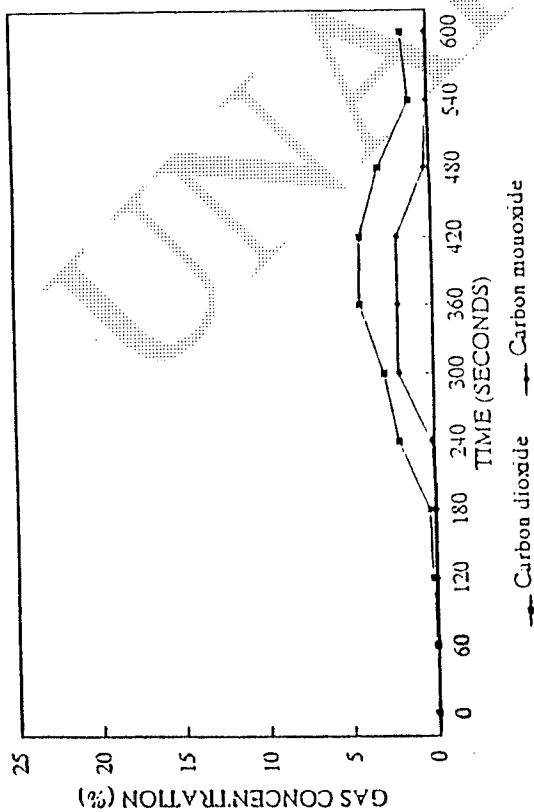
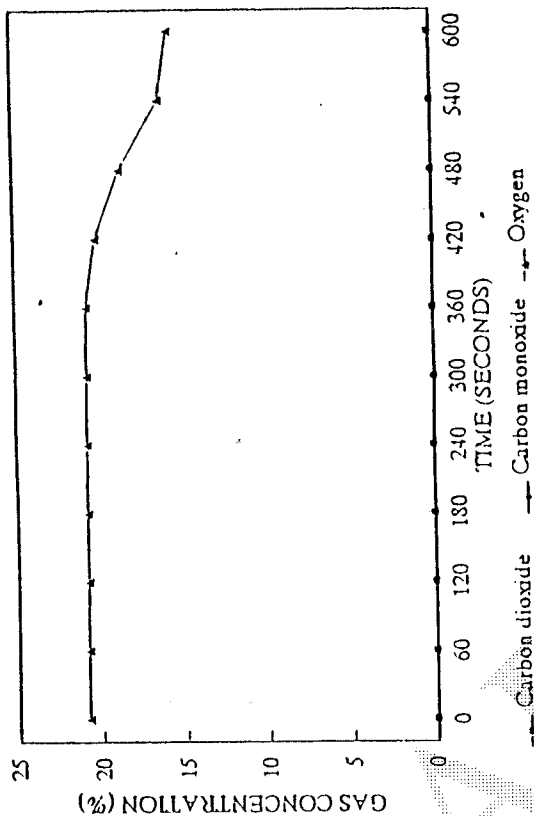


Figure 22. Test C76, Gas Chromatograms

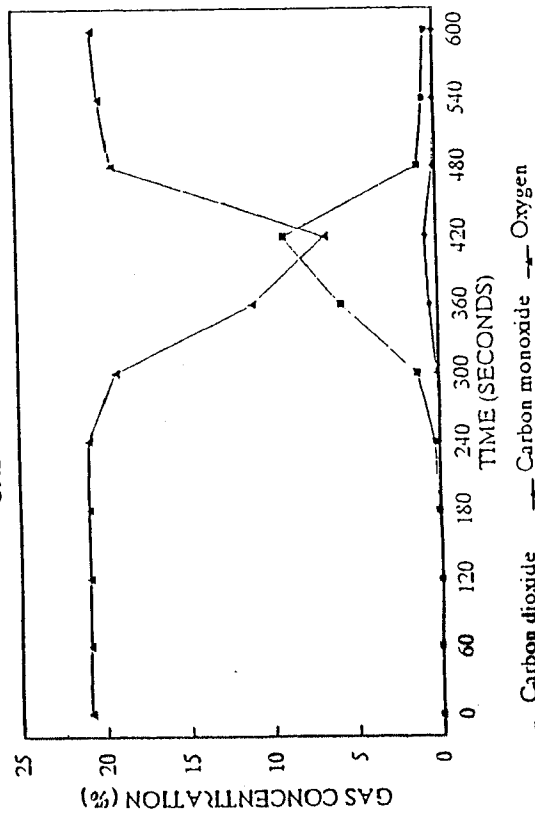
CFT1 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT1 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT1 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT1 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

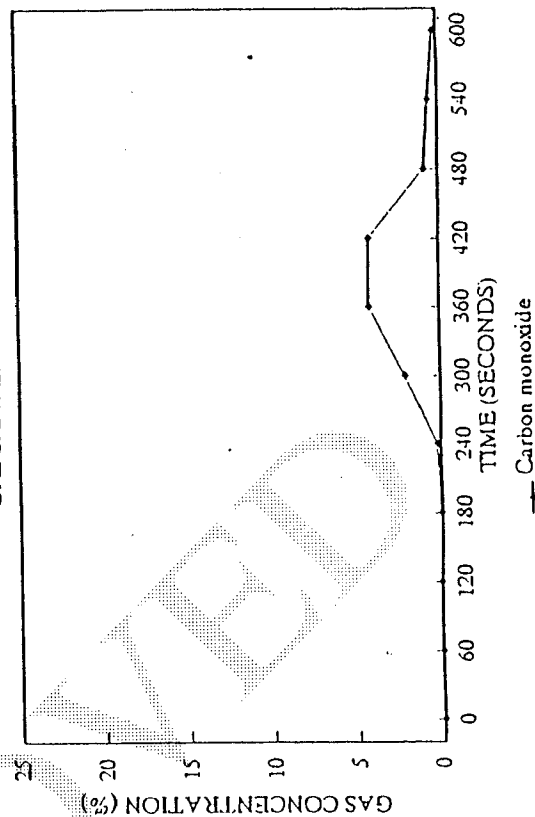
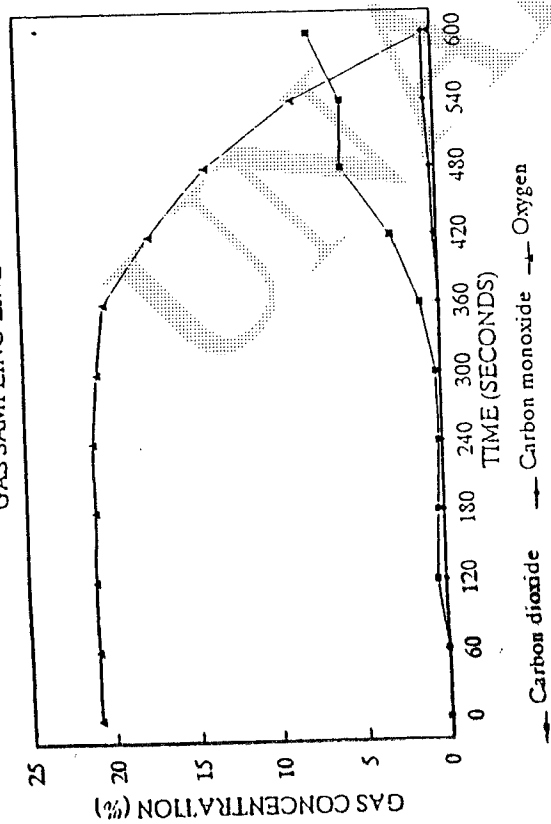
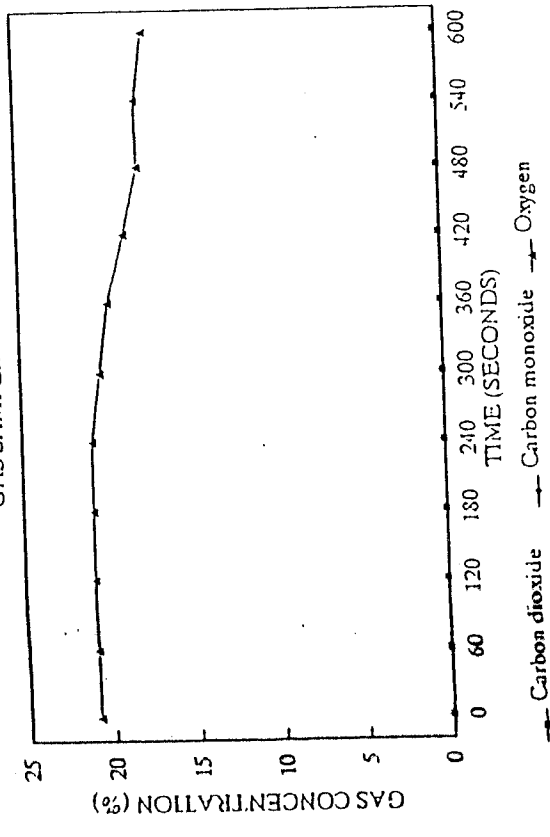


Figure 23.

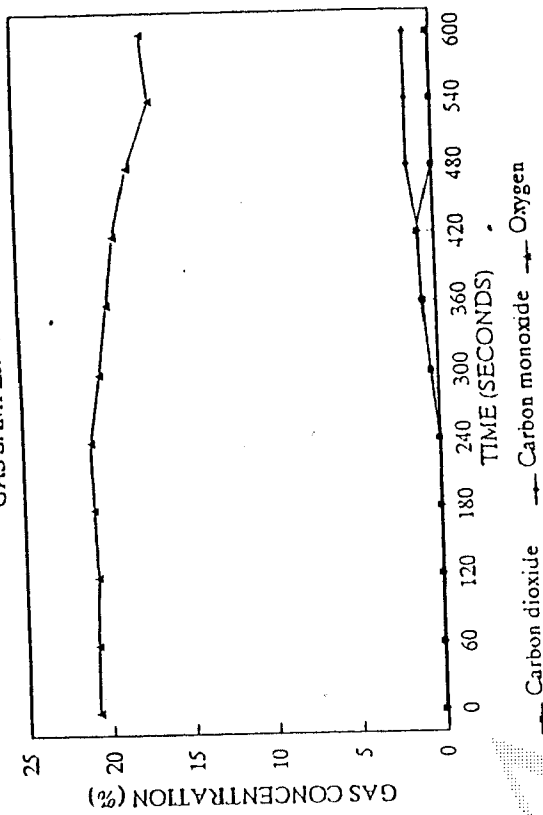
CFT2 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT2 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT2 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT2 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

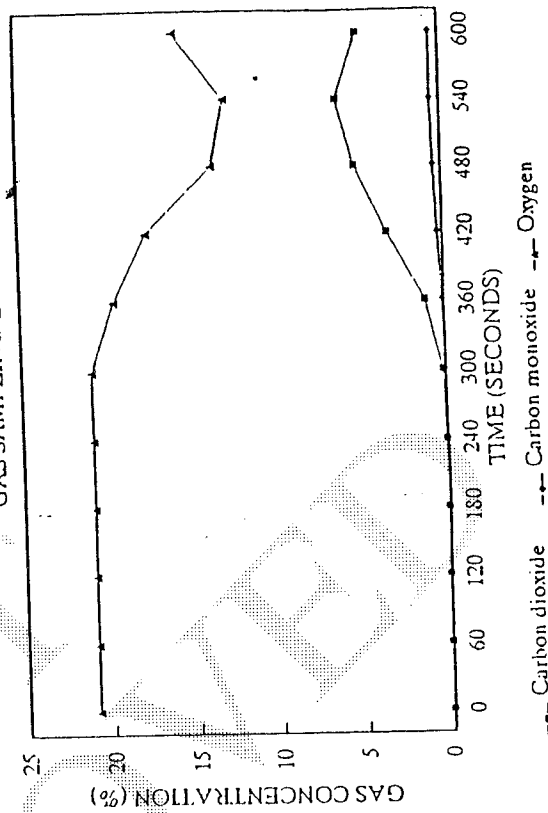
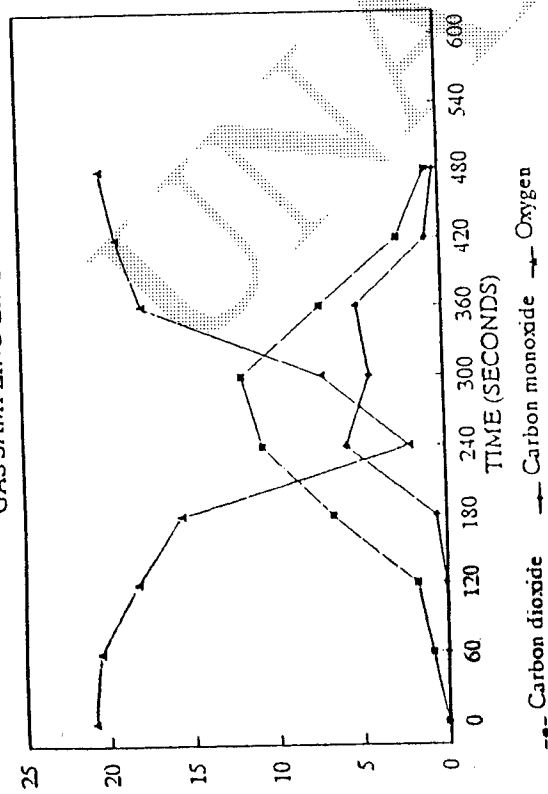
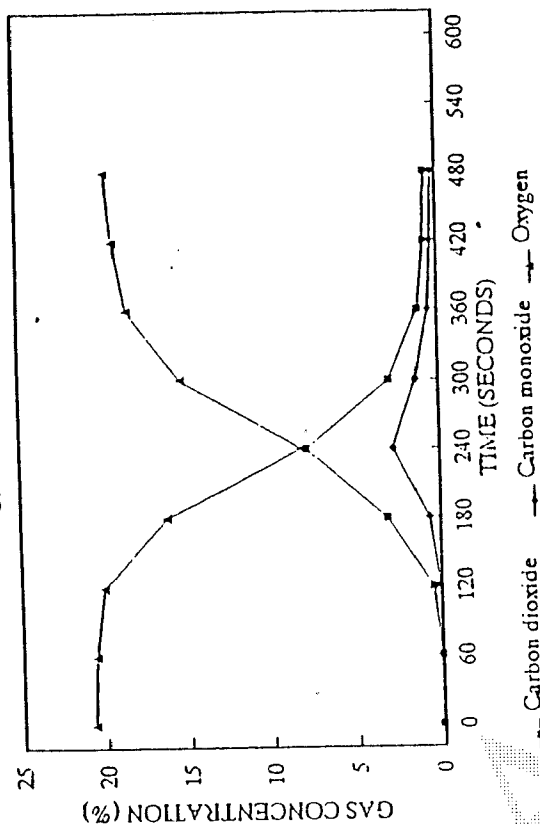


Figure 24.

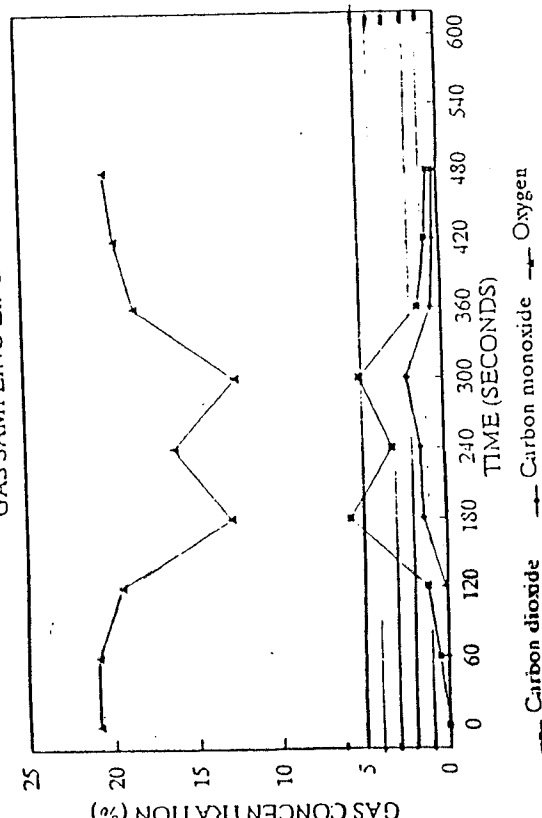
CFT3 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT3 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT3 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT3 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

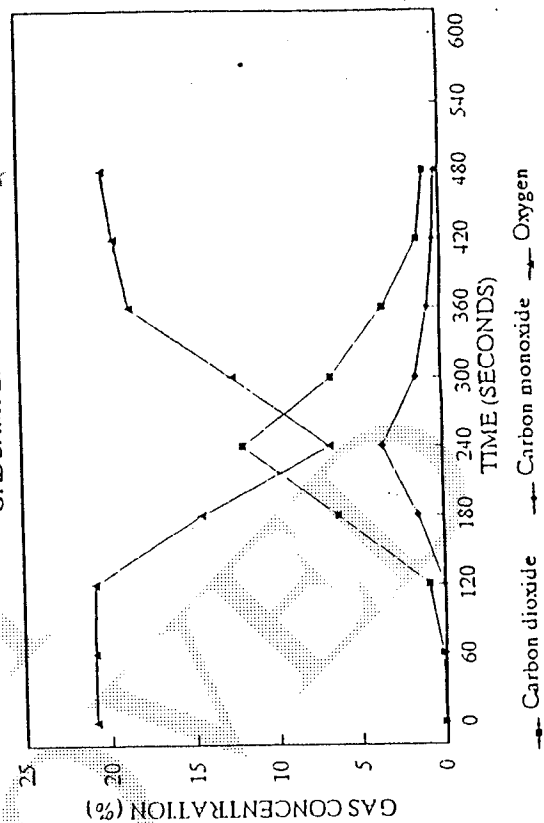
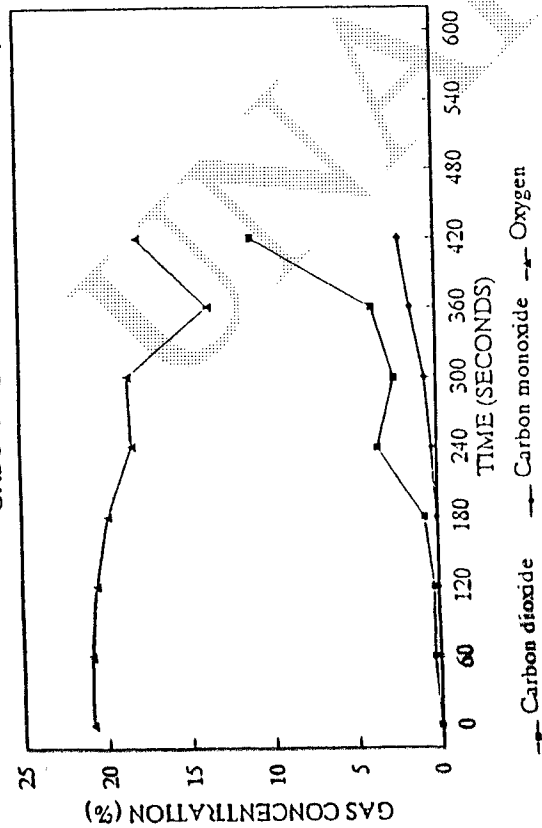
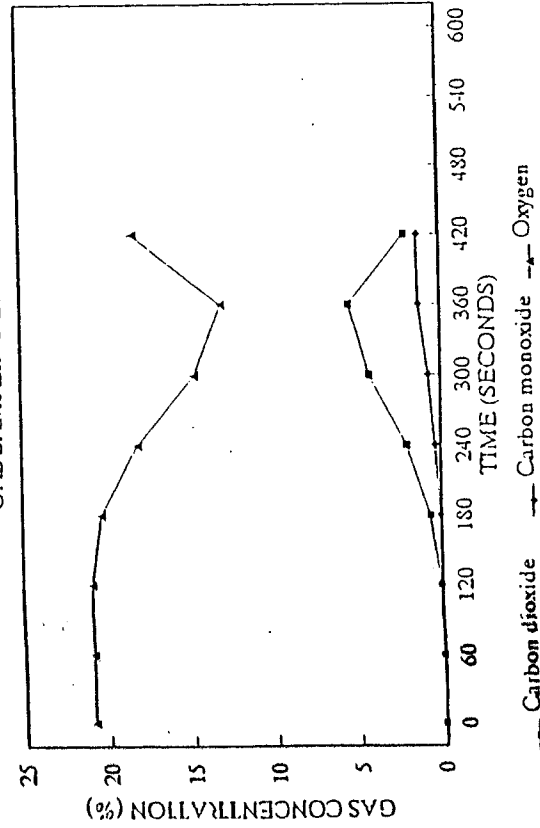


Figure 25.

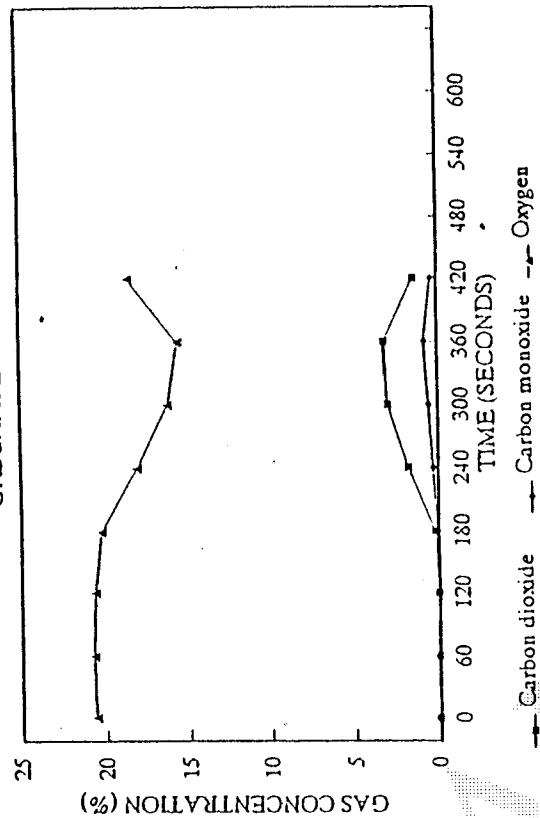
CFT4 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



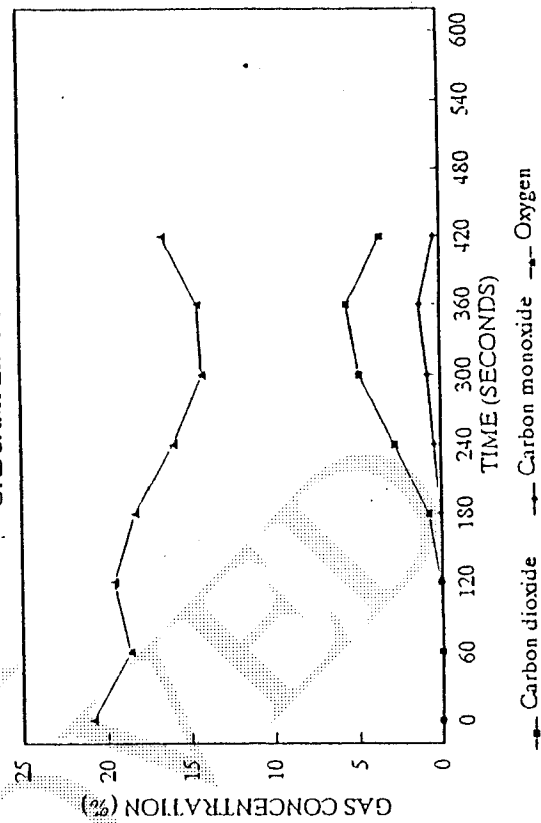
CFT4 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



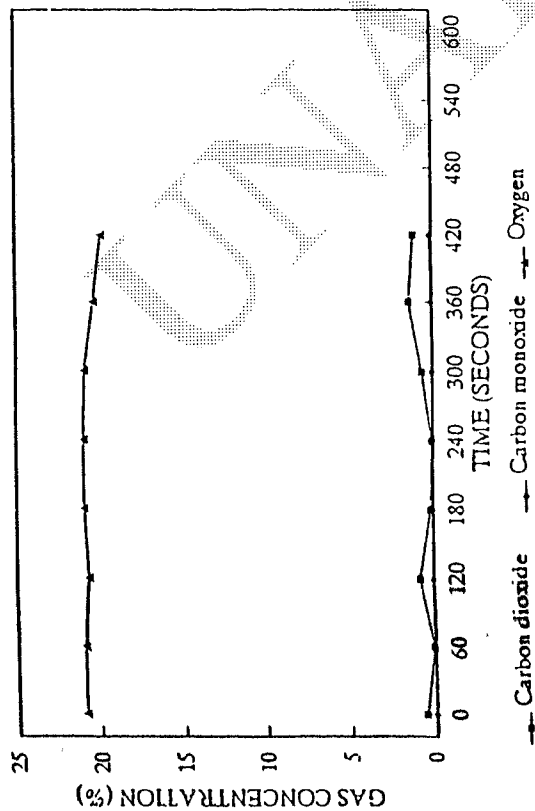
CFT4 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



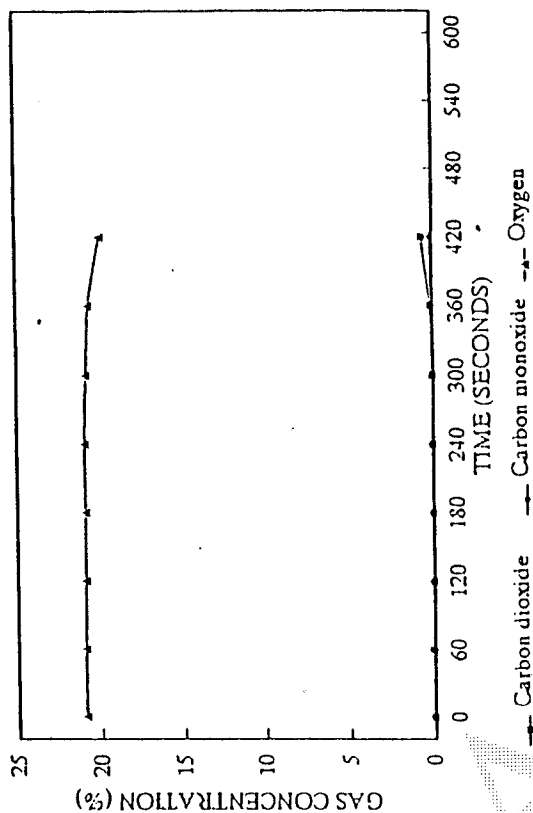
CFT4 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4



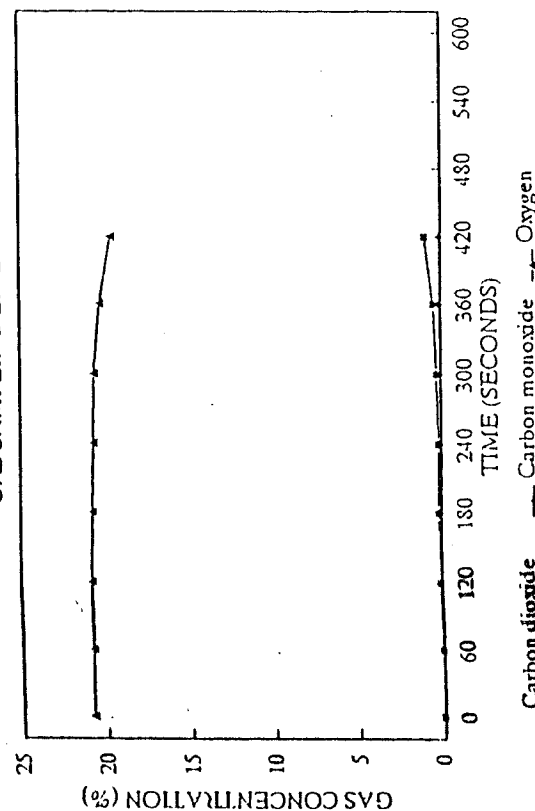
CFT5 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT5 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT5 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT5 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

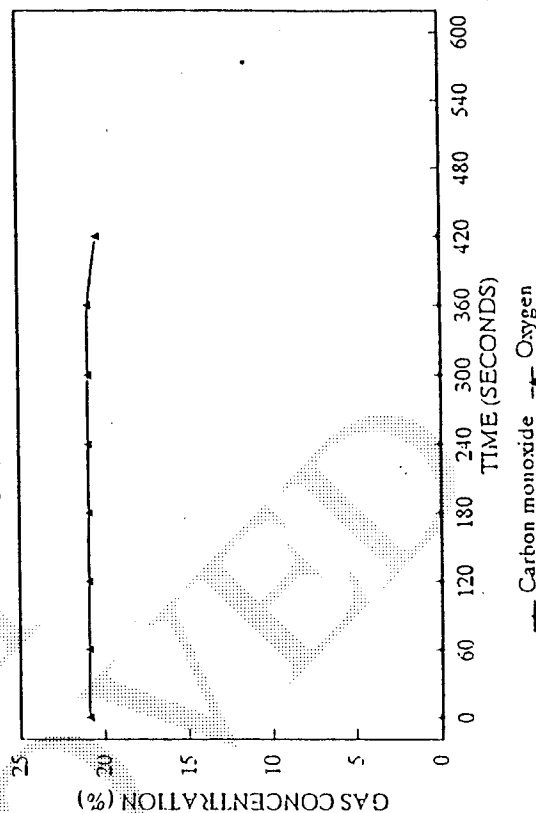
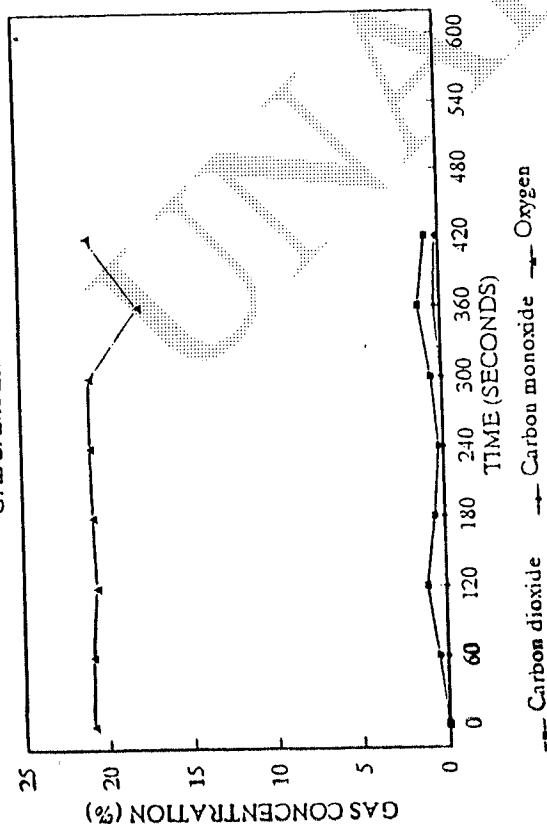
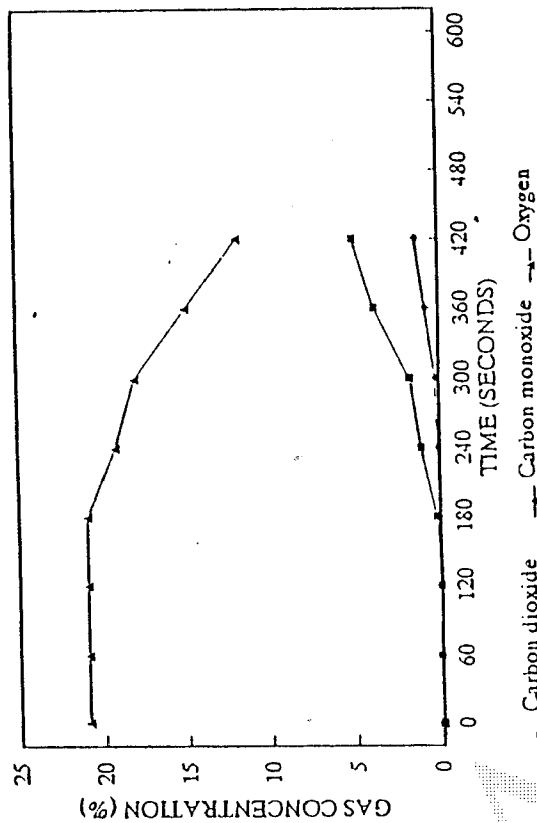


Figure 27.

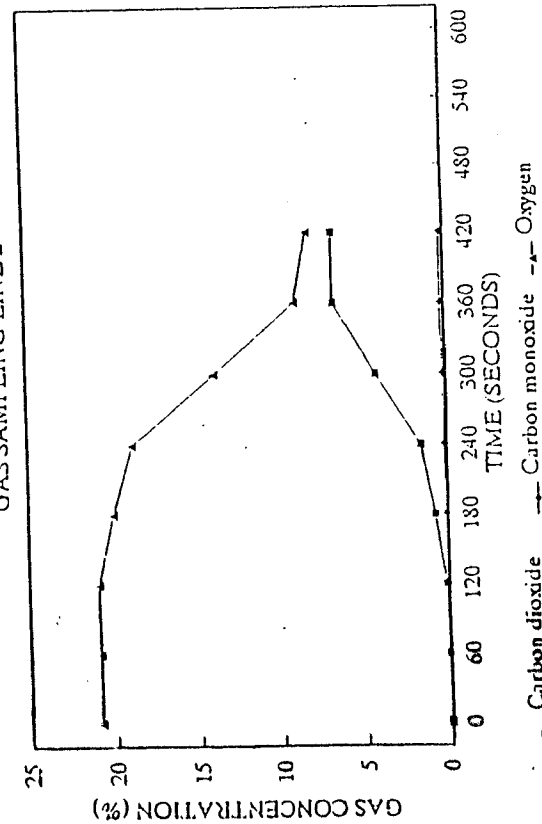
CFT6 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT6 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT6 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT6 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

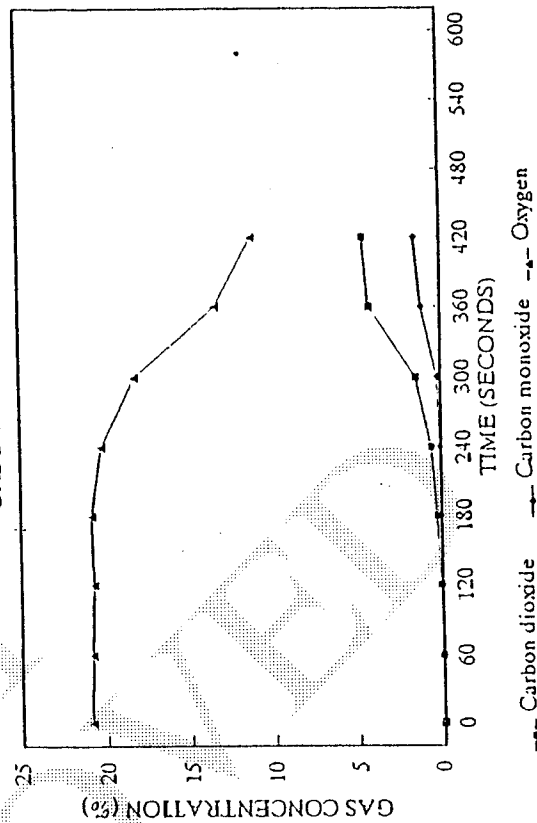
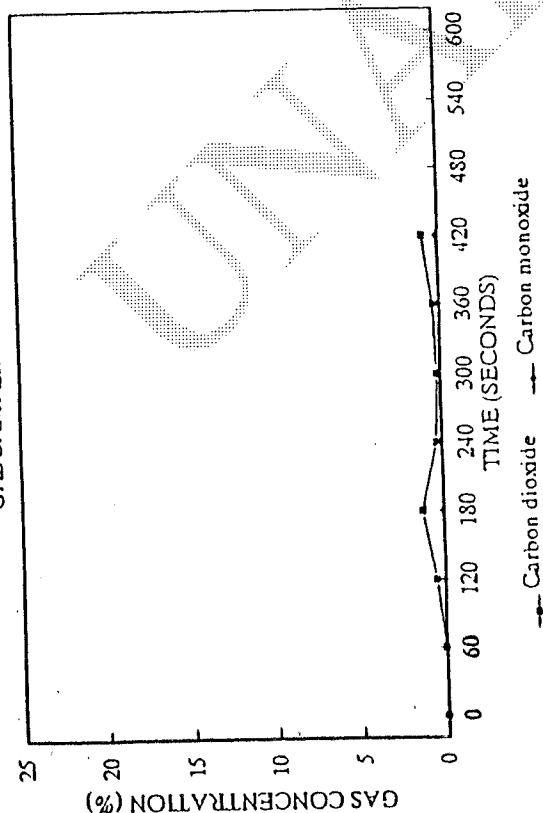
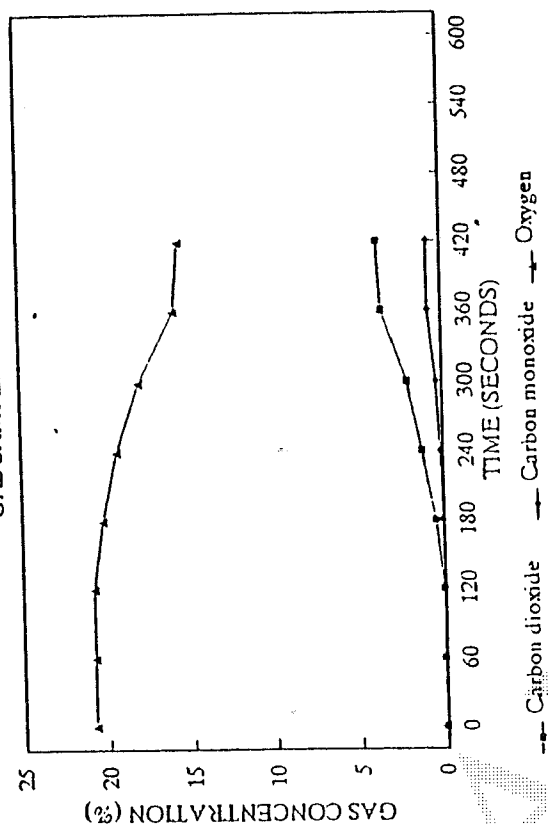


Figure 28.

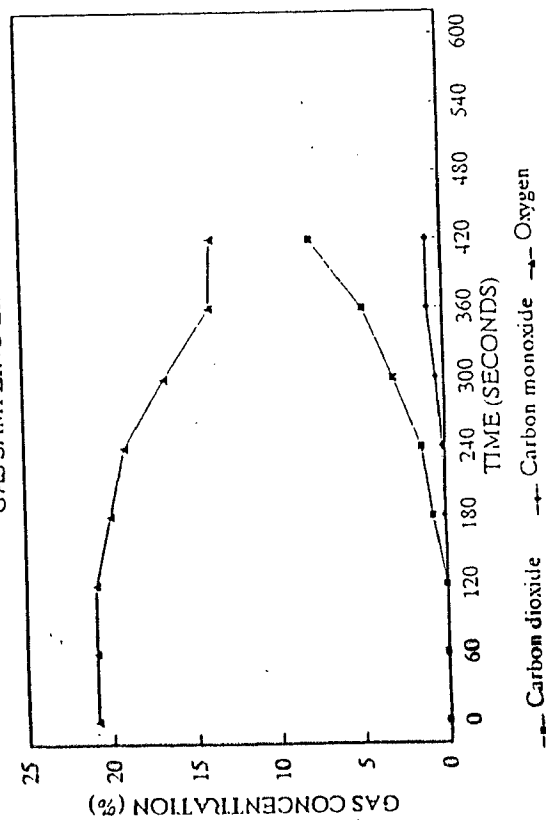
CFT7 - GAS CONCENTRATIONS
GAS SAMPLING LINE 1



CFT7 - GAS CONCENTRATIONS
GAS SAMPLING LINE 3



CFT7 - GAS CONCENTRATIONS
GAS SAMPLING LINE 2



CFT7 - GAS CONCENTRATIONS
GAS SAMPLING LINE 4

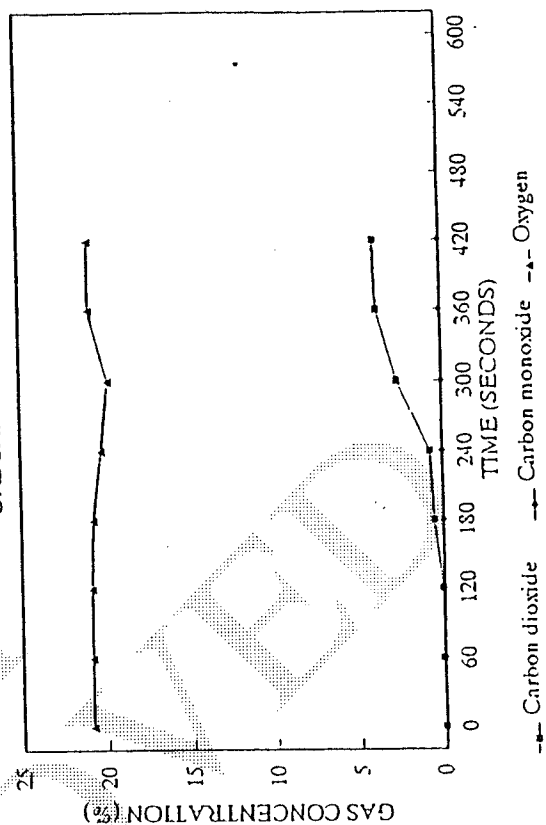
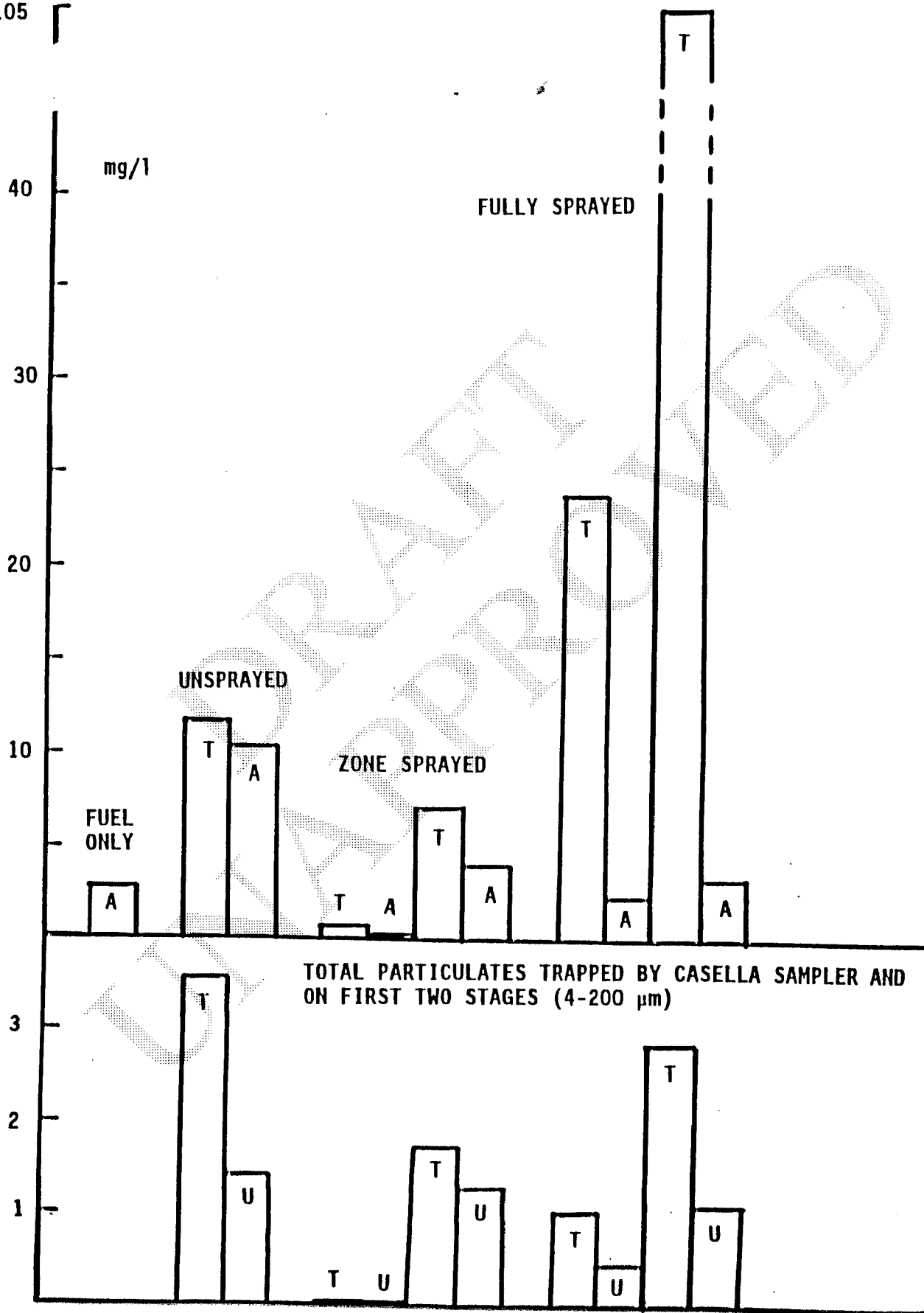


Figure 29.

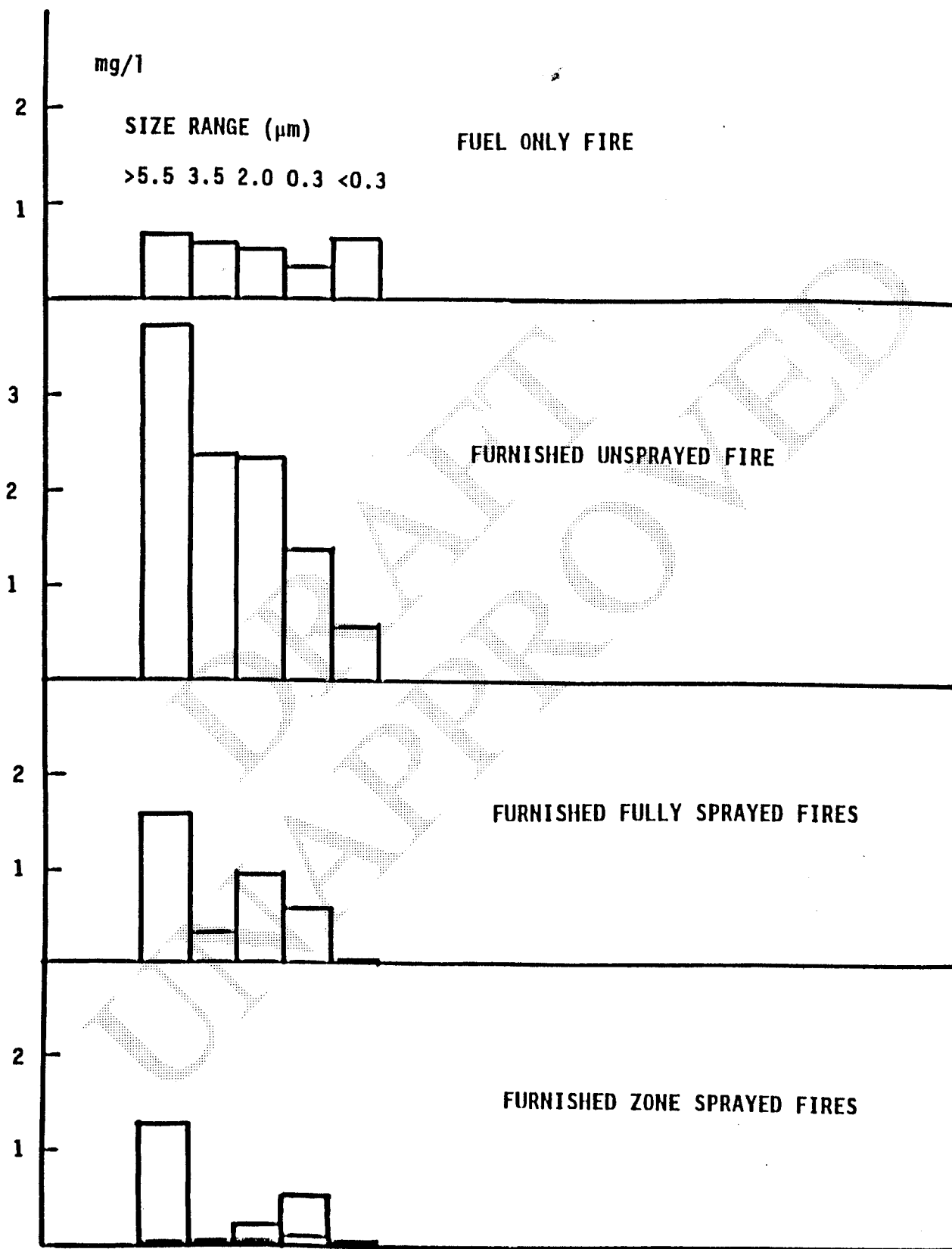
36
37
105

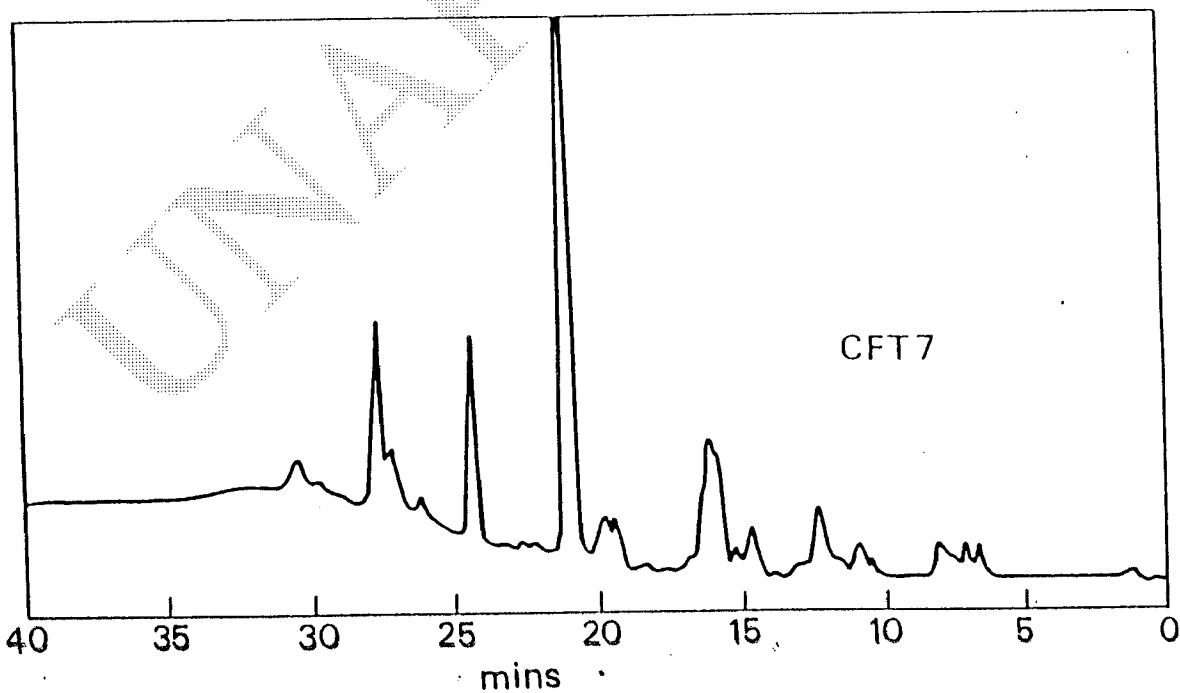
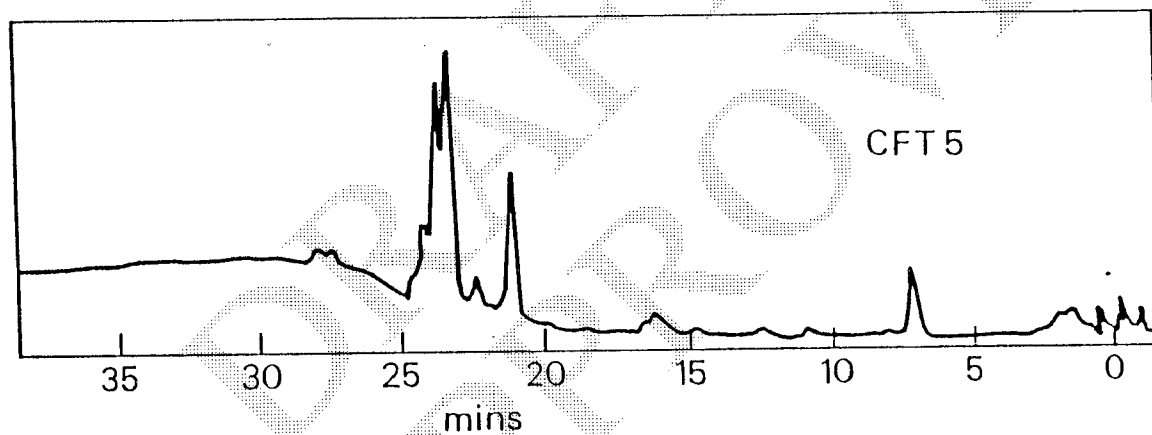
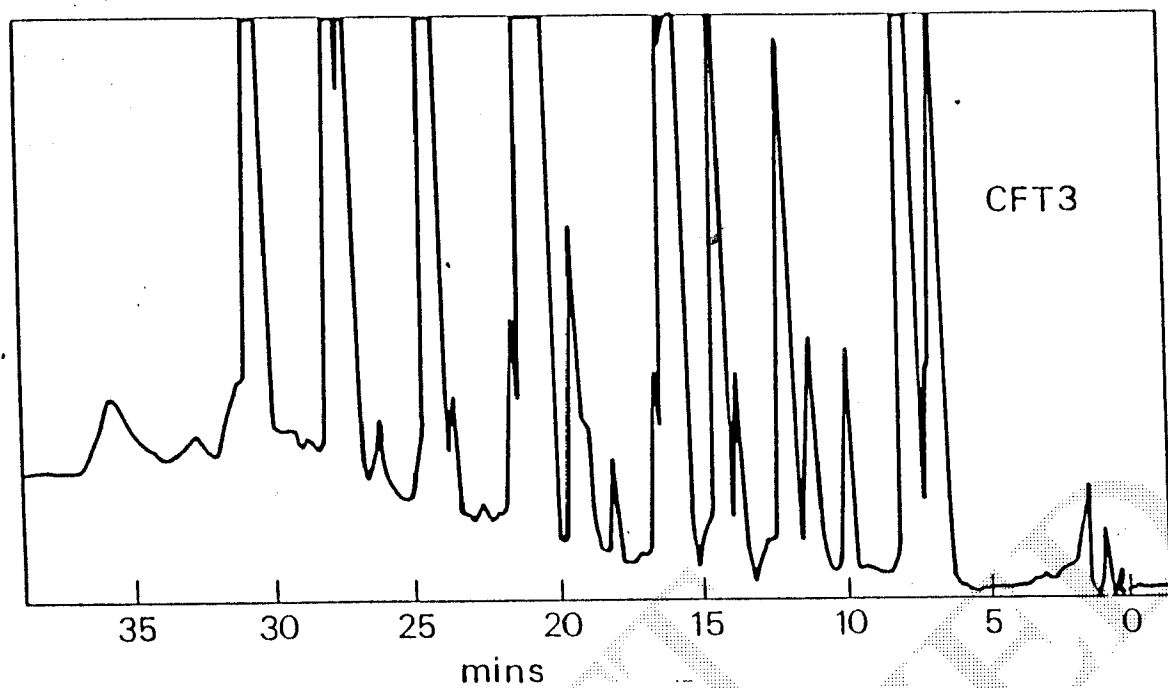
TOTAL PARTICULATE CONCENTRATIONS (mg/l) ON OPEN FACE FILTER
AND TOTAL TRAPPED BY ANDERSEN SAMPLER



37
38

PARTICLE SIZE DISTRIBUTION OF FIRE ATMOSPHERES IN AIRCRAFT CABIN DATA FROM ANDERSEN SAMPLER





40
FIGURE 32. CFT TESTS - TOTAL ORGANICS

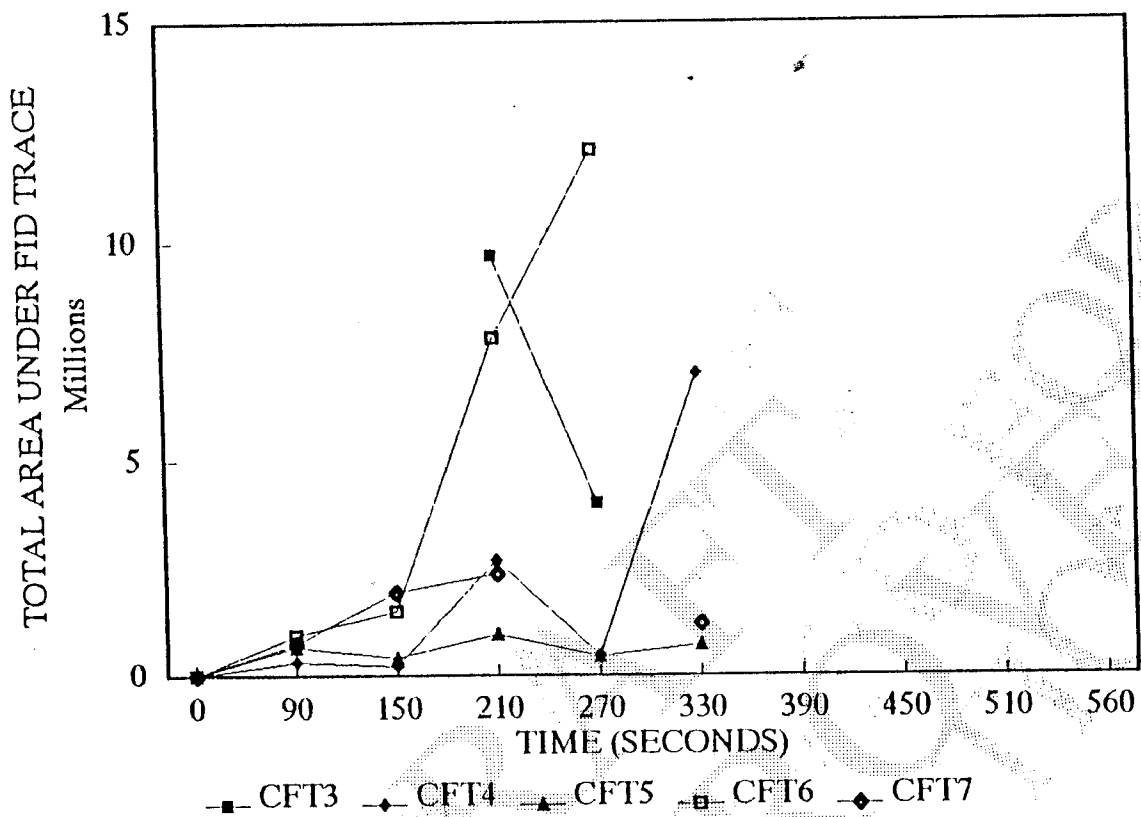


FIGURE 41. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(CO, CO₂, O₂, HCN) – GAS SAMPLING LINE 2

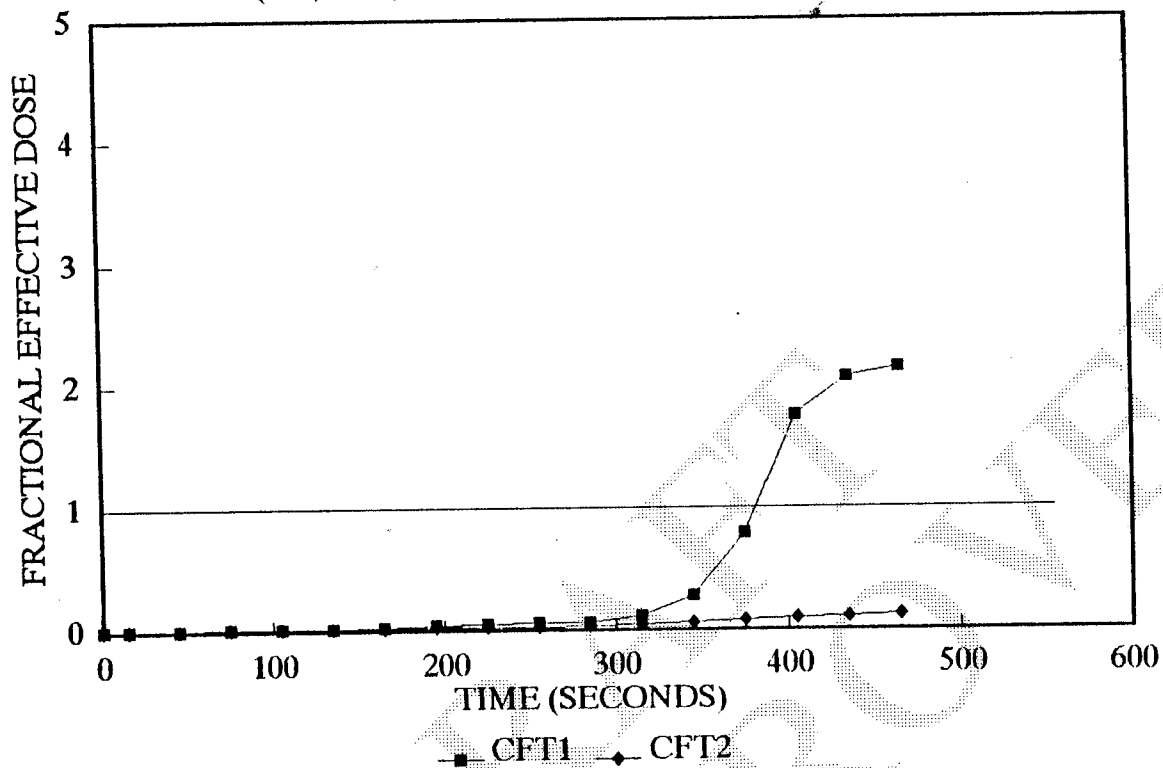


FIGURE 42. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(CO, CO₂, O₂, HCN) – GAS SAMPLING LINE 2

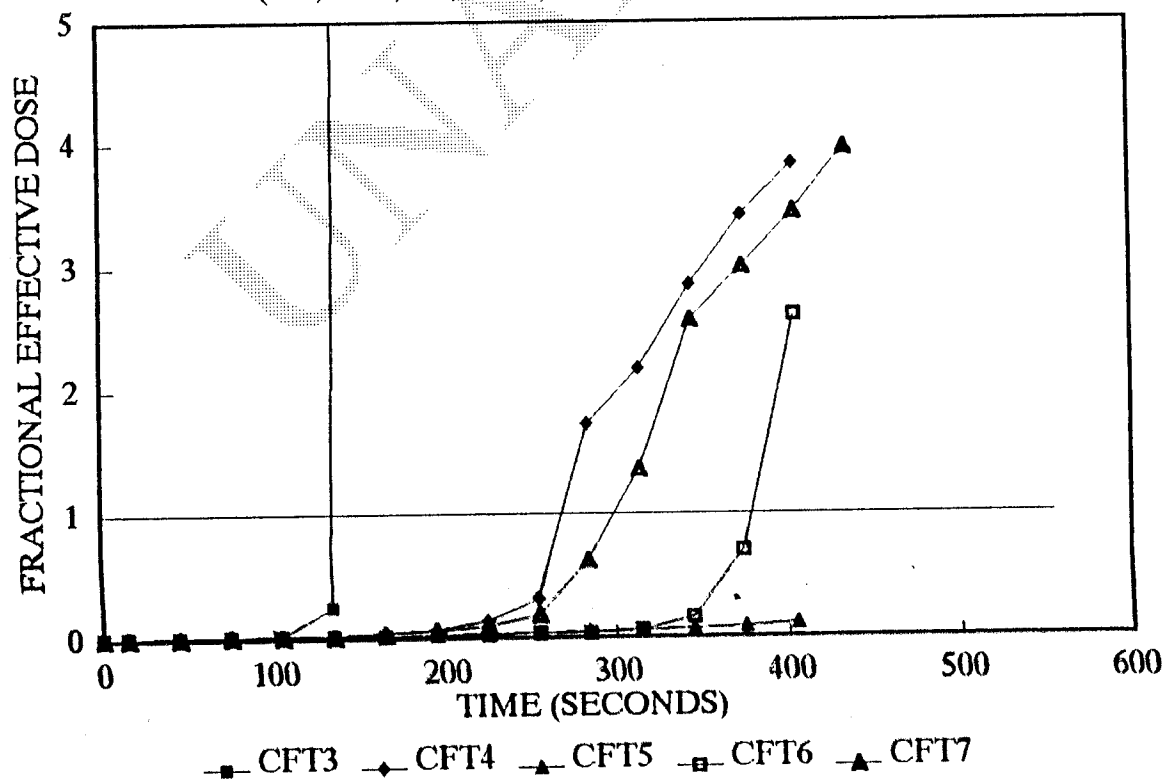


FIGURE 53. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO₂, O₂)
CFI5

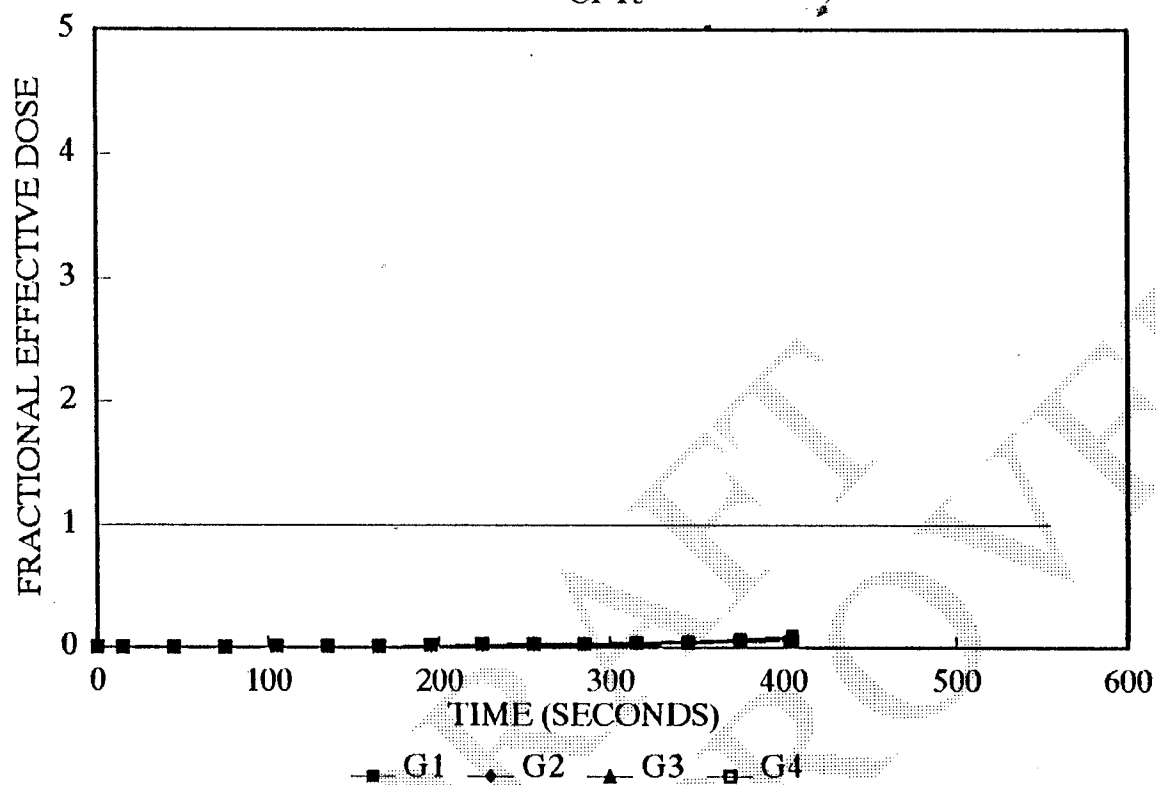


FIGURE 54. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO₂, O₂)
CFI6

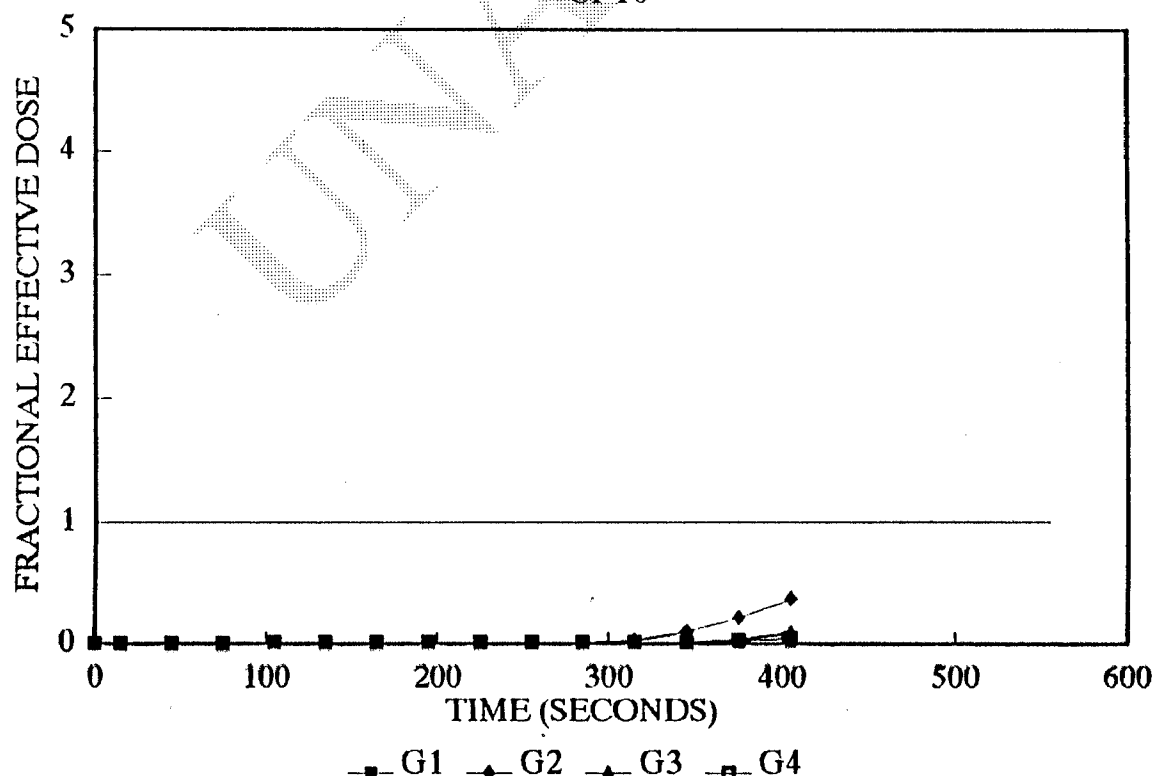


FIGURE 51. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO2, O2)
CFT3

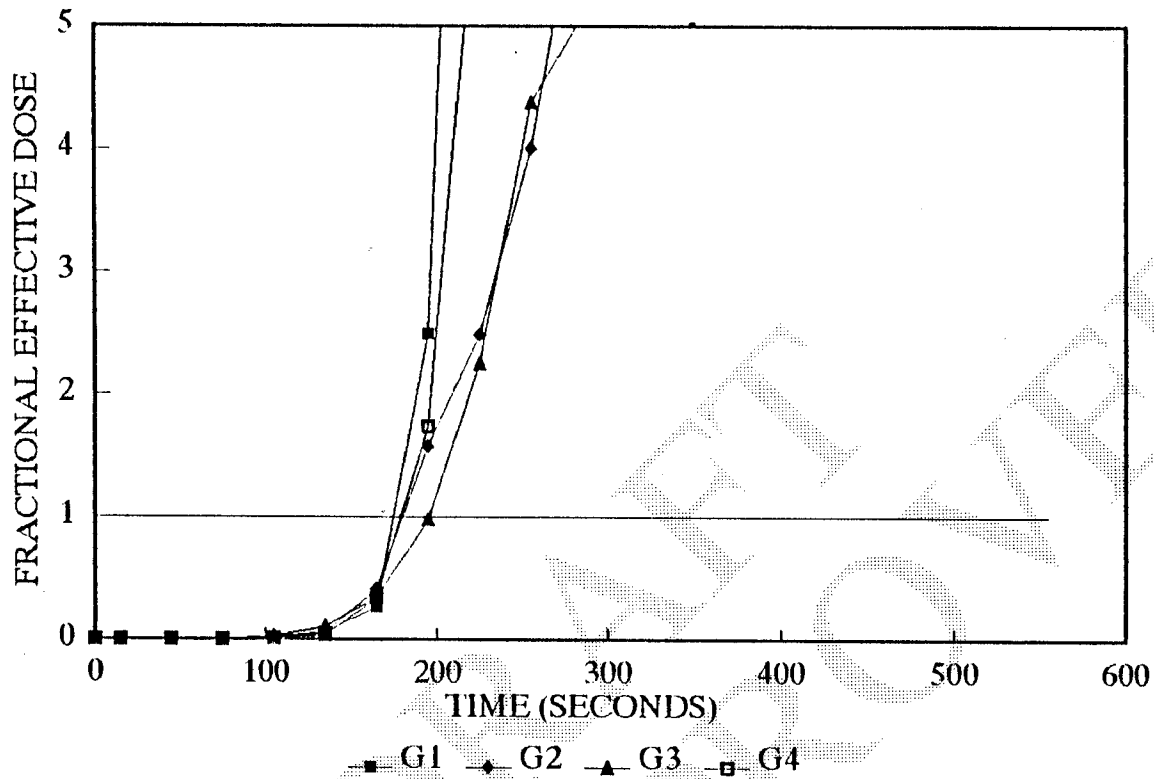


FIGURE 52. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO2, O2)
CFT4

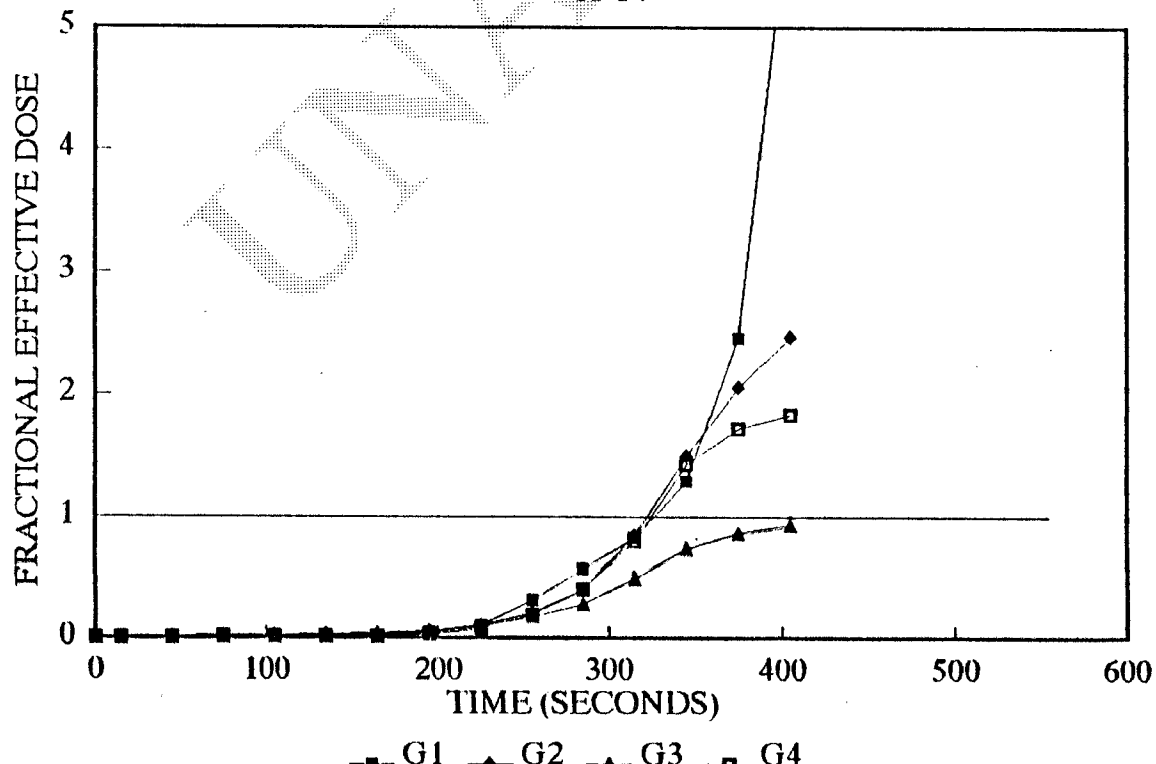


FIGURE 49. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO2, O2)
CFT1

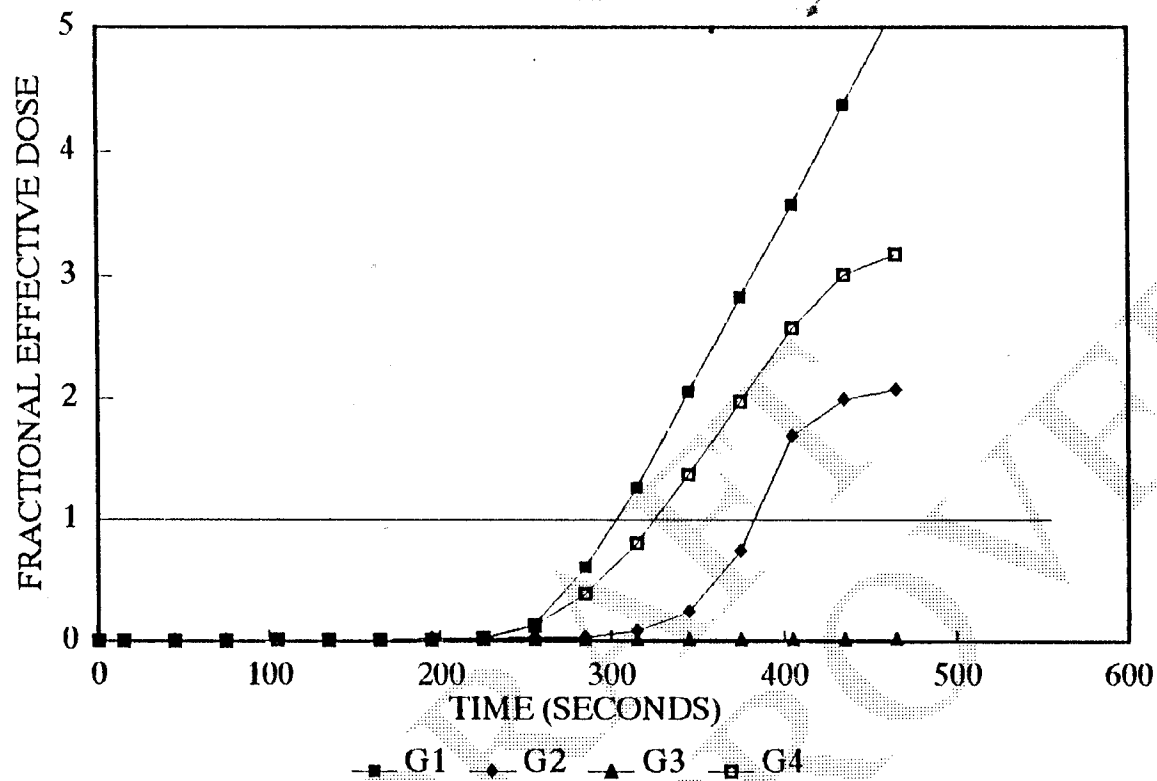


FIGURE 50. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO2, O2)
CFT2

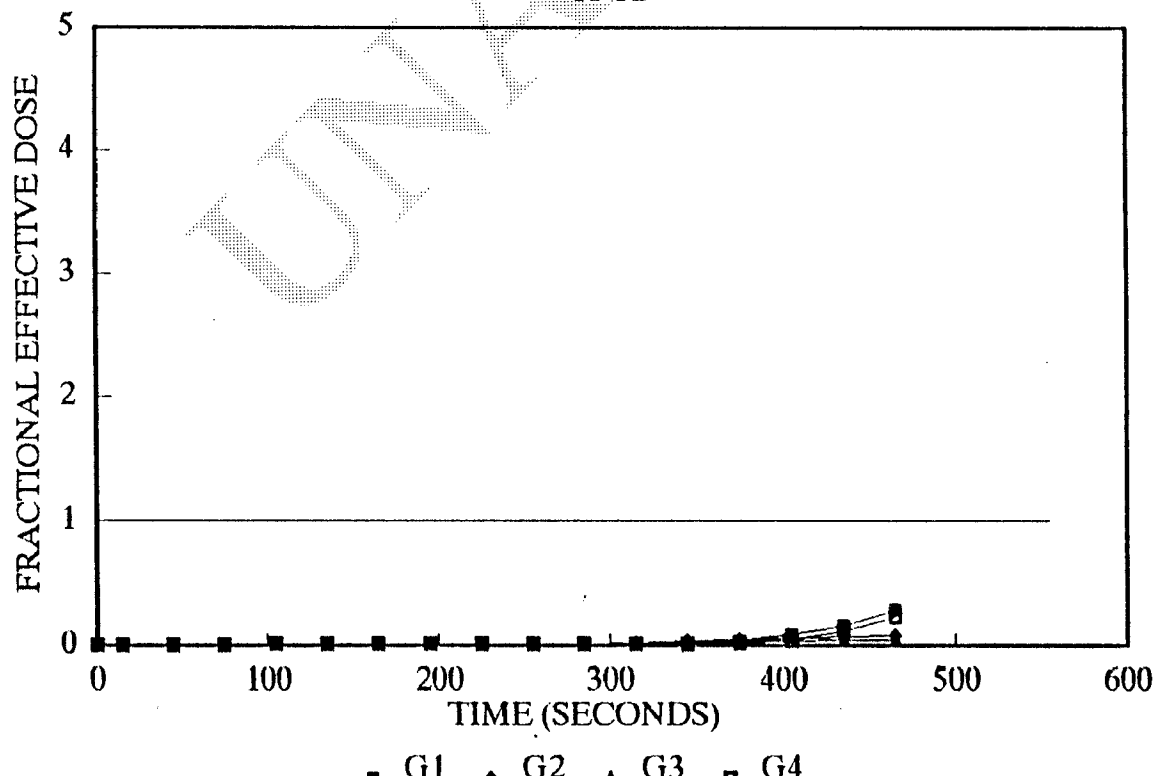


FIGURE 47. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT6

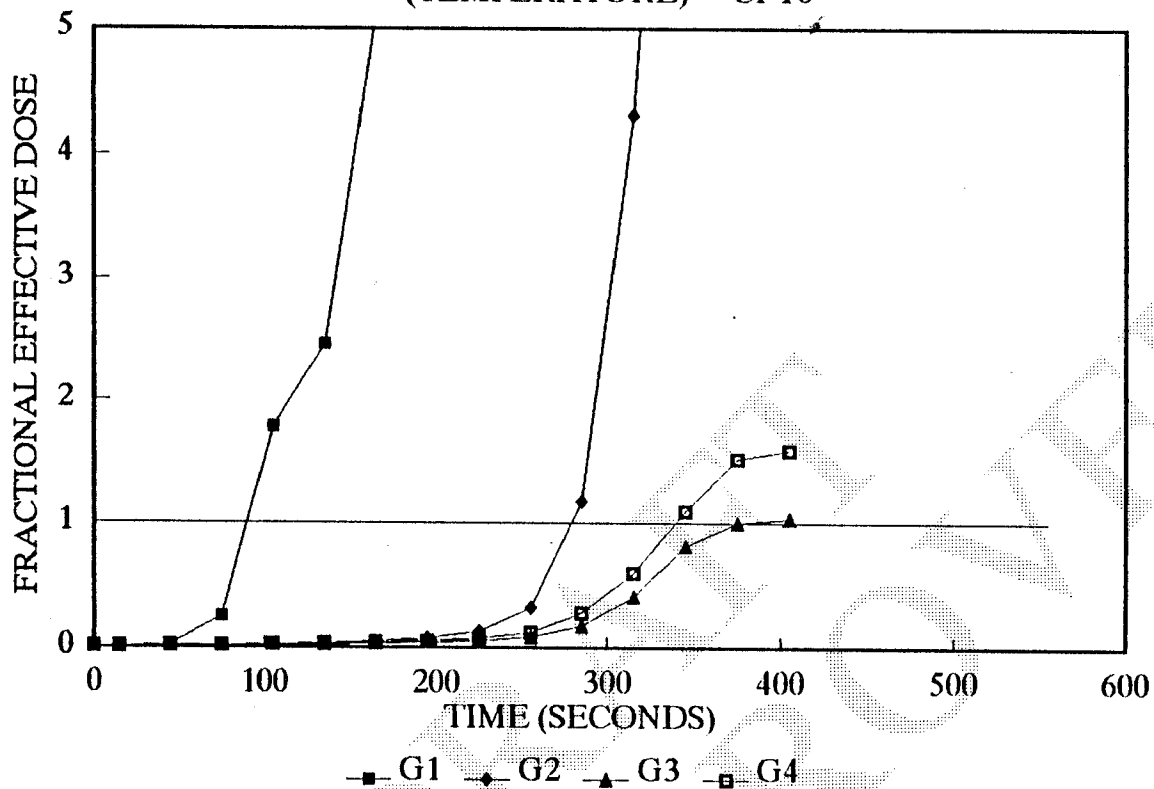


FIGURE 48. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT7

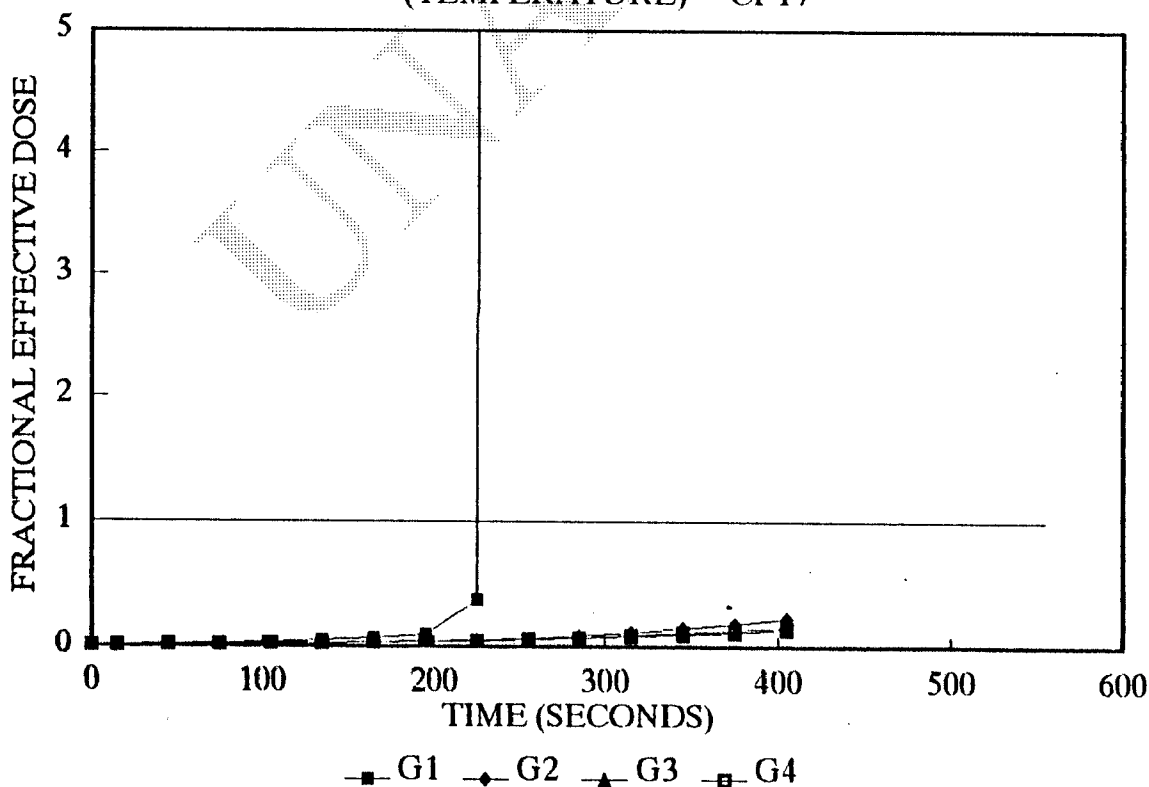


FIGURE 45. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT3

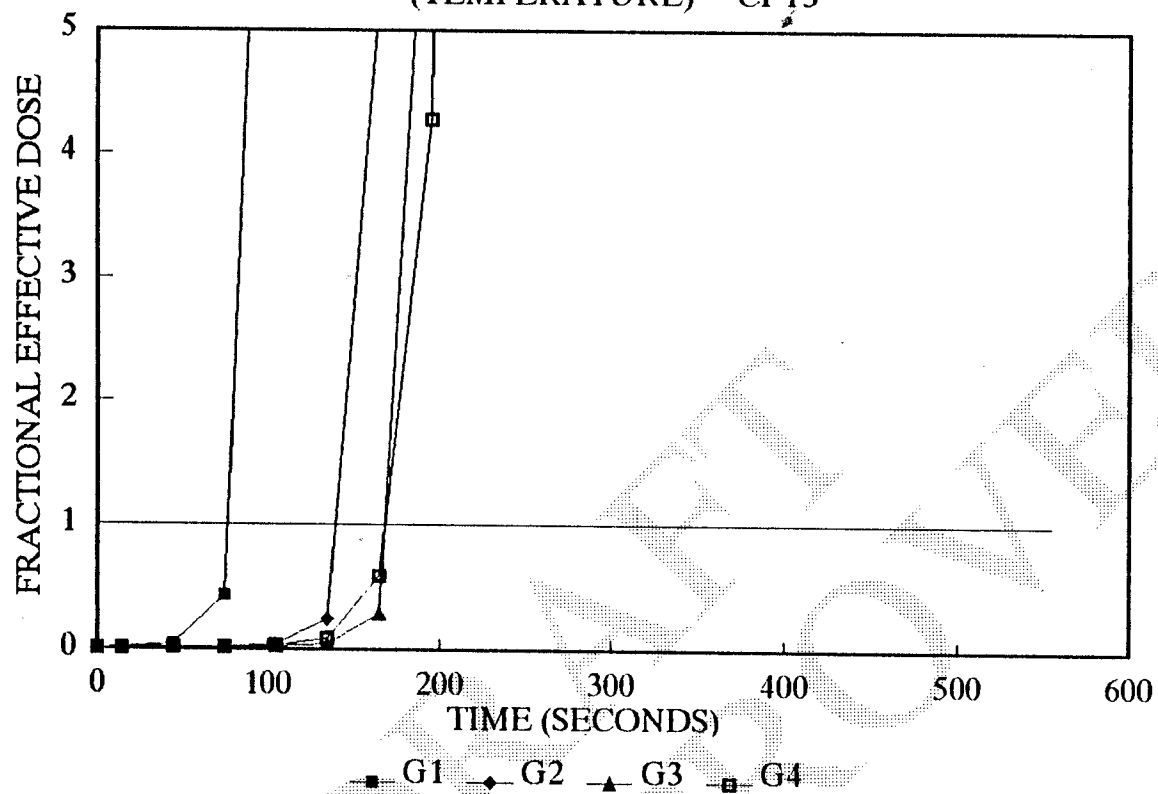


FIGURE 46. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT5

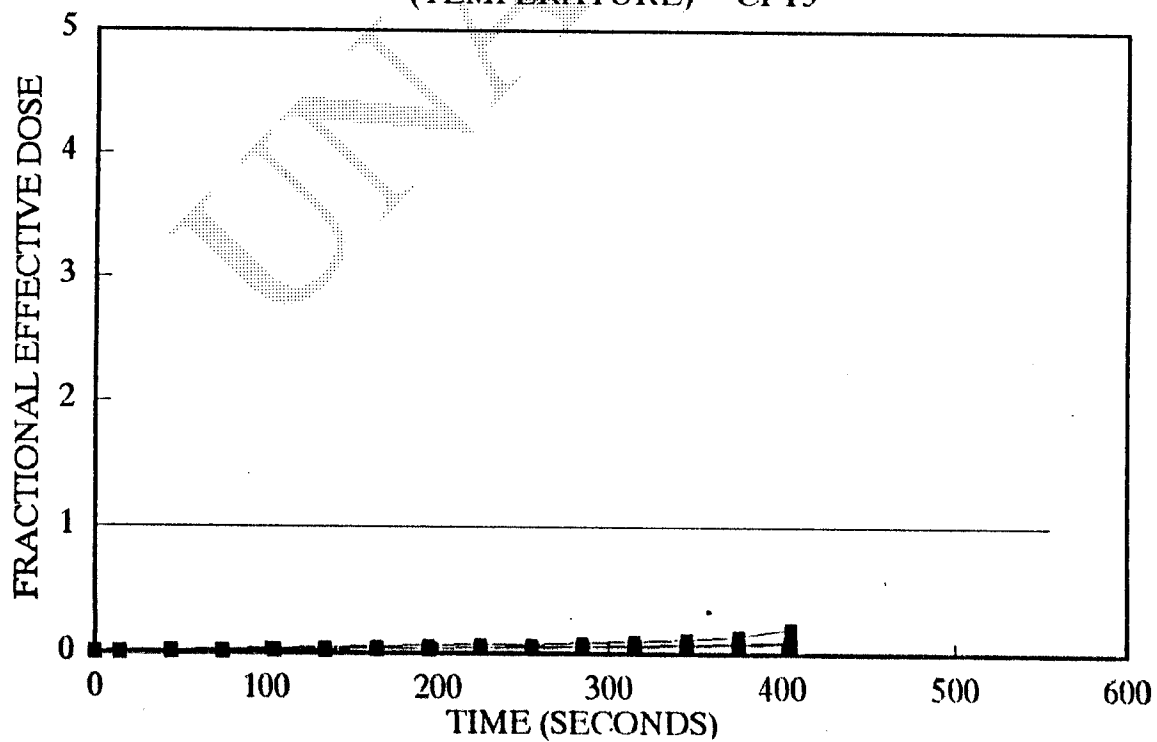


FIGURE 43. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT1

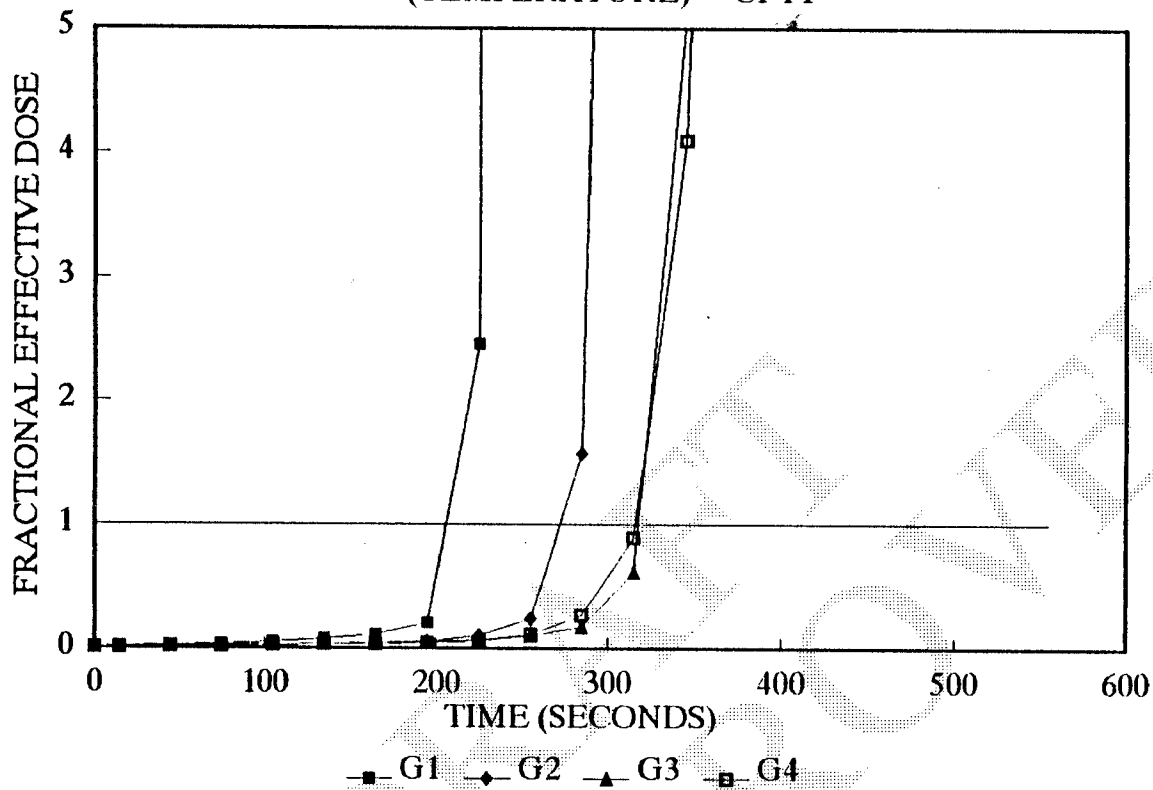


FIGURE 44. FRACTIONAL EFFECTIVE DOSE ANALYSIS
(TEMPERATURE) – CFT2

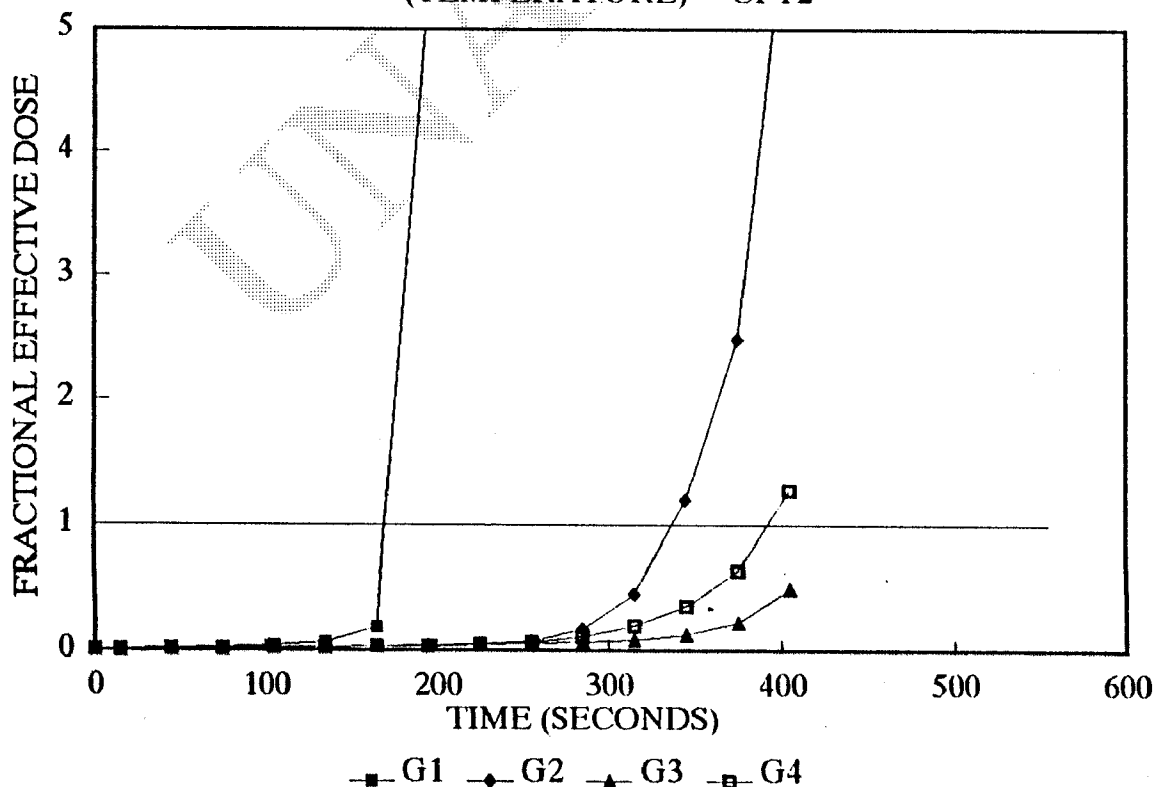
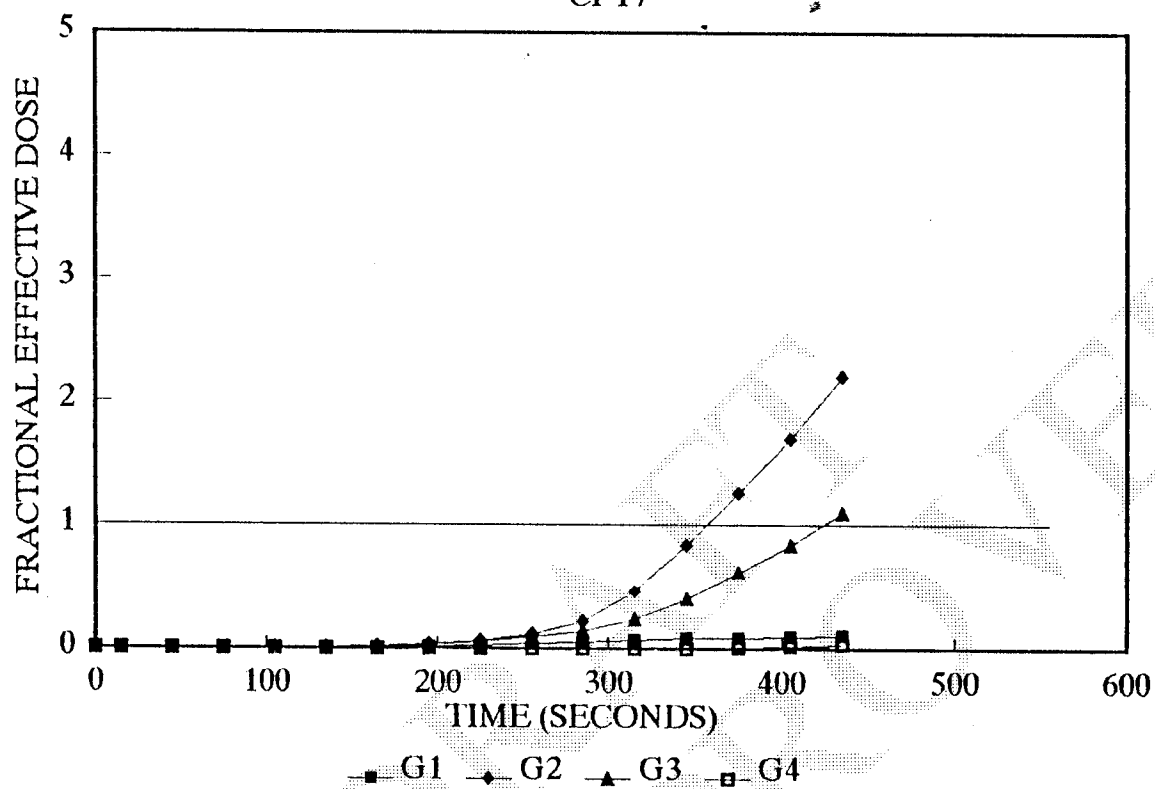


FIGURE 55. FRACTIONAL EFFECTIVE DOSE ANALYSIS (CO, CO2, O2)
CFT7



APPENDIX 1. TESTS C74, C75, C76 AND C77: MARPLE FILTER ANALYSIS						
		Mass Particulate Collected mg	HCl mg/g soot	HCl µg/l atm	HCN mg/g soot	HCN mg/l atm
C 7 4	Filter	1.63	76	20.7	NA	NA
	S3	0	nd	nd	NA	NA
	S4	0	nd	nd	NA	NA
	S5	0.05	34	0.3	NA	NA
	S6	0.05	36	0.3	NA	NA
	S7	0.29	20	1.0	NA	NA
	S8	0.70	27	3.2	NA	NA
	S9	0.52	28	2.5	NA	NA
C 7 5	Filter	0.33	270	15.0	NA	NA
	S3	.003	2700	1.4	NA	NA
	S4	0.18	13	0.4	NA	NA
	S5	0.03	170	0.9	NA	NA
	S6	0.04	50	0.3	NA	NA
	S7	0.001	15000	2.6	NA	NA
	S8	0.004	2600	1.8	NA	NA
	S9	0.004	2100	1.4	NA	NA
C 7 6	Filter	0.11	-	-	-	-
	S3	0.00	-	-	-	-
	S4	0.00	-	-	-	-
	S5	4.04	-	-	-	-
	S6	0.01	-	-	-	-
	S7	0.09	-	-	-	-
	S8	0.07	-	-	-	-
	S9	0.12	-	-	-	-
C 7 7	Filter	1.12	98	0.018	T	T
	S3	0	-	0.002	nd	nd
	S4	0.05	340	0.004	nd	nd
	S5	1.16	54	0.01	nd	nd
	S6	0.30	240	0.012	T	T
	S7	0.43	140	0.01	T	T
	S8	0.19	120	0.004	nd	nd
	S9	0.20	110	0.004	T	T

Notes: All values refer to HCl or HCN associated with soot particles.

nd none detected

NA not applicable

APPENDIX 2. TESTS C74, C75, C76 AND C77: TOTAL PARTICULATE ANALYSIS

Test	FILTERS					BUBBLERS	
	Mass soot mgs	HCl* mg/g soot	HCl* mg/l atm	HCN* mg/g soot	HCN* mg/l atm	HCl gas phase + mg/l atm	HCN gas phase + mg/l atm
C74	0.73	76.7	0.010	NA	NA	0.008	NA
C75	0.01	4.0	0.004	NA	NA	0.007	NA
C76	0.72	70.8	0.017	nd	nd	0.010	nd
C77	0.80	55.0	0.015	nd	nd	0.008	nd

Notes: * Values refer to HCl or HCN associated with soot particles.

+ values refer to gas phase HCl or HCN

nd none detected

NA not applicable.

**APPENDIX 3. TEST C74,C75,C76,C77 "GRAB" SAMPLE ANALYSIS FOR HCN
AND HCL**

Time (mins)	HCN							
	C74		C75		C76		C77	
	mg/l	ppm	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	-	-	-	-	0.002	1.7	0.005	4.0
2	-	-	-	-	0.075	64	0.038	33
3	-	-	-	-	0.056	4.8	0.020	17
4	-	-	-	-	0.002	1.9	0.002	1.9
5	-	-	-	-	0.001	0.6	0.001	0.4
6	-	-	-	-	T	T	T	T
7	-	-	-	-	-	-	-	-
	HCL							
	C74		C75		C76		C77	
	mg/l	ppm	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	-	-	-	-	0.273	184	1.36	898
2	-	-	-	-	2.47	1630	4.40	2900
3	-	-	-	-	0.226	149	2.62	1720
4	-	-	-	-	0.126	83	0.953	628
5	0.63	410	0.40	267	0.066	43	0.645	425
6	-	-	-	-	0.209	138	0.229	151
7	-	-	-	-	-	-	-	-
8	1.8	1190	0.73	478	-	-	-	-
9	-	-	-	-	-	-	-	-
10	1.48	975	0.17	112	-	-	-	-
11	-	-	-	-	-	-	-	-
12	-	-	0.18	116	-	-	-	-

Notes: T Trace

- no sample taken

**APPENDIX 4. TESTS C74, C75, C76 AND C77: SMOKE FILTERS - CONCENTRATION
OF HCL AND HCN ASSOCIATED WITH PARTICULATES**

	Position	Sampling time minutes	Mass soot mg	HCL mg/g soot	HCl mg/l atm	HCN ug/g soot	HCN ug/l atm
C 7 4	1.HOOD	0-10.3	2.6	15.4	0.004	NA	NA
	2.HOOD	3-10.3	1.0	30.0	0.004	NA	NA
	3.FIRE	0-10.3	1.8	22.0	0.004	NA	NA
	4.FIRE	3-10.3	0.3	33.0	0.001	NA	NA
C 7 5	1.HOOD	0-12.4	0.8	38.0	0.002	NA	NA
	2.HOOD	9.5-12.4	0.2	50.0	0.006	NA	NA
	3.FIRE	0-12.4	4.4w	0.7w	0.001	NA	NA
	4.FIRE	9.5-12.4	1.1w	2.7	0.001	NA	NA
C 7 6	1.HOOD	2-8	1.2	24.0	0.005	T	T
	2.HOOD	5-8		T	T	nd	nd
	3.HOOD	5-8	0.3	30.0	0.003	T	T
	4.HOOD	2-5	0.6	47.0	0.009	T	T
	5.HOOD	2-5	1.7	15.0	0.008	T	T
	6.FIRE	2-8	Did not survive fire				
C 7 7	1.HOOD	2-8	1.2	12.5	0.003	T	T
	2.HOOD	2-5	0.0	T	T	nd	nd
	3.HOOD	2-5	0.6	10.0	0.002	nd	nd
	4.HOOD	5-8	0.1	40.0	0.001	T	T
	5.HOOD	5-8	0.8	23.8	0.006	T	T
	6.FIRE	2-8	2.4	Not analysed			

Notes: w Filter wet
NA Not applicable
nd none detected

**APPENDIX 5. TESTS C74, C75, C76 AND C77: SMOKE FILTER BUBBLERS
- CONCENTRATIONS OF HCL AND HCN IN THE GAS PHASE**

TEST	POSITION	SAMPLING TIME (minutes)	HCl mg/l atm	HCN ug/l atm
C74	1.HOOD	0 - 10.3	0.68	NA
	2.HOOD	3 - 10.3	0.43	NA
	3.FIRE	0 - 10.3	0.46	NA
	4.FIRE	3 - 10.3	0.09	NA
C75	1.HOOD	0 - 12.4	0.24	NA
	2.HOOD	9.5 - 12.4	0.05	NA
	3.FIRE	0 - 12.4	<0.01	NA
	4.FIRE	9.5 - 12.4	<0.01	NA
C76	1.HOOD	2 - 8	0.01	2
	2.HOOD	5 - 8	0.03	nd
	3.HOOD	5 - 8	0.01	4
	4.HOOD	2 - 5	0.01	4
	5.HOOD	2 - 5	0.01	1
	6.FIRE	2 - 8	<0.01	2
C77	1.HOOD	2 - 8	0.04	1
	2.HOOD	2 - 5	0.03	nd
	3.HOOD	2 - 5	0.01	1
	4.HOOD	5 - 8	0.02	nd
	5.HOOD	5 - 8	0.03	nd
	6.FIRE	2 - 8	0.01	1

Notes: NA Not applicable
nd None detected

**APPENDIX 6. TESTS C74, C75, C76 AND C77: MAY IMPINGER
CHEMICAL ANALYSIS**

Position		Mass soot mg	HCl mg/g soot	HCl mg/l atm	HCN ug/g soot	HCN ug/l atm
C 7 4	upper	NA	NA	0.050	NA	NA
	middle	NA	NA	0.123	NA	NA
	lower	NA	NA	0.207	NA	NA
	filter	0.27	520	0.005	NA	NA
C 7 5	upper	NA	NA	0.003	NA	NA
	middle	NA	NA	0.003	NA	NA
	lower	NA	NA	0.045	NA	NA
	filter	0.20	450	0.003	NA	NA
C 7 6	upper	NA	NA	0.006	NA	0.002
	middle	NA	NA	0.014	NA	0.003
	lower	NA	NA	0.163	NA	0.026
	filter	.21	230	0.002	nd	nd
C 7 7	upper	NA	NA	0.008	NA	0.002
	middle	NA	NA	0.063	NA	0.007
	lower	NA	NA	0.197	NA	0.030
	filter	0.13	520	0.002	nd	nd

Notes: nd None detected
 NA Not applicable

**APPENDIX 7. TESTS C74, C75, C76 AND C77: ANALYSIS OF SPRAY
WATER AND "FLOOR POTS"**

Test	HCl in spray reservoir mg/L	HCl (floor pot) mg/L(mean)	HCN in spray reservoir mg/L	HCN (floor pot) mg/L(mean)
C74	62	NA	0	NA
C75		12000		NA
C76		15000		nd
C77		123000		nd

Notes: nd None detected

NA Not applicable

APPENDIX 8. TESTS CFT 1 TO CFT 7: ANDERSEN FILTER ANALYSIS - CONCENTRATIONS OF HCL AND HCN ASSOCIATED WITH PARTICULATES

		Mass soot mg	Conc soot mg/l atm	HCl mg/g soot	HCl mg/l atm	HCl ppm	HCN ug/g soot	HCN ug/l atm	HCN ppm
C F T 1	A1	5.86	1.40	-	-	-	-	-	-
	A2	5.17	1.23	-	-	-	-	-	-
	A3	4.56	1.06	-	-	-	-	-	-
	A4	2.86	0.67	-	-	-	-	-	-
	FILTER	5.52	1.31	-	-	-	-	-	-
C F T 3	A1	15.66	3.73	4.5	0.15	99	4.5	0.02	0.02
	A2	9.99	2.38	33.0	0.08	53	8.0	0.02	0.02
	A3	9.79	2.33	9.2	0.02	13	ND	ND	ND
	A4	5.73	1.36	10.5	0.01	7	ND	ND	ND
	FILTER	2.36	0.56	101.7	0.06	40	38.1	0.02	0.02
C F T 4	A1	2.86	0.68	24.5	0.02	13	10.5	0.01	0.01
	A2	1.80	0.43	-	-	-	-	-	-
	A3	3.91	0.93	33.2	0.03	20	23.0	0.02	0.02
	A4	0.97	0.23	113.4	0.03	20	61.9	0.01	0.01
	FILTER	0.18	0.04	111.1	T	T	333	0.01	0.01
C F T 5	A1	0.17	0.04	ND	ND	ND	3412	0.14	0.12
	A2	0.11	0.03	ND	ND	ND	727	0.02	0.02
	A3	0.23	0.05	43.5	T	T	304	0.02	0.02
	A4	0.48	0.11	166.7	0.02	13	292	0.03	0.03
	FILTER	0.20	0.05	313.4	0.01	7	ND	ND	ND
C F T 6	A1	10.70	2.55	5.6	0.01	7	ND	ND	ND
	A2	0.29	0.07	ND	ND	ND	ND	ND	ND
	A3	1.59	0.38	44.0	0.02	13	ND	ND	ND
	A4	3.89	0.93	51.4	0.05	33	ND	ND	ND
	FILTER	0.33	0.08	90.9	0.01	7	ND	ND	ND
C F T 7	A1	5.27	1.25	9.5	0.01	7	T	T	T
	A2	1.09	0.26	18.3	T	T	ND	ND	ND
	A3	4.14	0.99	31.4	0.03	20	T	T	T
	A4	3.74	0.89	50.8	0.05	33	26.7	0.02	.02
	FILTER	0.12	0.03	83.3	T	T	T	T	T

Notes:- T Trace
ND None detected

**APPENDIX 9. TESTS CFT3 TO CFT7: ANDERSEN FILTER BUBBLERS -
CONCENTRATIONS OF HCL AND HCN IN THE GAS PHASE**

TEST	HCl gas phase mg/l	HCl gas phase ppm	HCN gas phase mg/l	HCN gas phase ppm
CFT3	0.01	6	0.64	565
CFT4	nd	nd	0.17	153
CFT6	nd	nd	0.05	41
CFT7	nd	nd	0.03	24

**APPENDIX 10. TESTS CFT 1 TO CFT 7: TOTAL PARTICULATE FILTERS -
CONCENTRATIONS OF HCL AND HCN ASSOCIATED WITH PARTICULATES**

Test	Mass soot mg	HCl mg/g soot	HCl mg/l atm	HCl ppm	HCN ug/g soot	HCN ug/l atm	HCN ppm
CFT3	34.80	74.4	0.86	566	11.2	0.13	0.12
CFT4	71.97	21.4	0.51	336	2.1	0.05	0.04
CFT5	1.95	76.8	0.05	33	ND	ND	ND
CFT6	21.39	3.7	0.03	20	3.7	0.03	0.03
CFT7	316.35w	2.8	0.30	198	0.3	0.03	0.03

Notes: ND None detected

**APPENDIX 11. TESTS CFT3 TO CFT7: TOTAL PARTICULATE BUBBLERS -
CONCENTRATIONS OF HCL AND HCN IN THE GAS PHASE**

TEST	HCl gas phase mg/l	HCl gas phase ppm	HCN gas phase mg/l	HCN gas phase ppm
CFT3	0.03	23	0.90	797
CFT4	ND	ND	0.01	11
CFT5	-	-	-	-
CFT6	ND	ND	0.03	30
CFT7	ND	ND	0.01	13

APPENDIX 12. TESTS CFT1 TO CFT3: "GRAB" SAMPLE ANALYSIS FOR HCN AND HCL

Time minutes	HCN					
	CFT1		CFT2		CFT3	
	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	nd	nd	-	-	nd	nd
2	nd	nd	-	-	0.07	59
3	nd	nd	nd	nd	0.58	513
4	nd	nd	-	-	2.18	1937
5	nd	nd	nd	nd	0.43	381
6	0.01	9	-	-	-	-
Time minutes	HCL					
	CFT1		CFT2		CFT3	
	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	-	-	-	-	0.02	12
2	-	-	-	-	0.03	22
3	-	-	-	-	0.04	29
4	-	-	-	-	0.03	21
5	-	-	-	-	0.05	35
6	-	-	-	-	-	-

APPENDIX 13. TESTS CFT4 TO CFT7: "GRAB" SAMPLE ANALYSIS FOR HCN AND HCL

Time minutes	HCN							
	CFT4		CFT5		CFT6		CFT7	
	mg/l	ppm	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	nd	nd	nd	nd	nd	nd	nd	nd
2	nd	nd	T	0.5	nd	nd	T	T
3	0.01	13	T	3.0	nd	nd	0.02	21
4	0.09	79	0.01	9.0	nd	nd	0.05	45
5	0.34	300	0.01	8.0	nd	nd	0.22	197
6	-	-	-	-	0.26	231	0.25	225
7	-	-	-	-	0.27	242	-	-
Time minutes	HCL							
	CFT4		CFT5		CFT6		CFT7	
	mg/l	ppm	mg/l	ppm	mg/l	ppm	mg/l	ppm
1	0.05	36	nd	nd	0.05	41	nd	nd
2	0.01	9	nd	nd	nd	nd	nd	nd
3	0.03	29	nd	nd	nd	nd	0.03	22
4	0.05	36	nd	nd	nd	nd	0.07	43
5	0.03	22	nd	nd	0.10	64	0.07	49
6	-	-	-	-	0.06	39	0.07	43

APPENDIX 14. TESTS CFT 1 TO CFT 7: TOTAL PARTICULATE FILTERS - CONCENTRATIONS OF HCL AND HCN ASSOCIATED WITH PARTICULATE

Position number		Mass soot mg	Conc. soot mg/l atm	HCl mg/g soot	HCl mg/l atm	HCl ppm	HCN ug/g soot	HCN ug/l atm	HCN ppm
CFT 1	1	0.1	<0.1	-	-	-	-	-	-
	2	5.8	1.9	-	-	-	-	-	-
	3	1.1	0.4	-	-	-	-	-	-
	4	wet	wet	-	-	-	-	-	-
	5	7.9	2.6	-	-	-	-	-	-
	6	15.3	5.1	-	-	-	-	-	-
CFT 3	1	20.0	6.7	16.0	0.11	72	T	T	T
	2	11.9	4.0	36.1	0.14	92	T	T	T
	3	14.2	4.7	16.3	0.09	59	T	T	T
	4	13.4	4.5	37.3	0.17	112	T	T	T
	5	10.6	3.5	22.6	0.08	53	-	-	-
	6	12.2	4.1	39.3	0.16	105	T	T	T
CFT 4	1	3.6	1.2	88.9	0.11	72	T	T	T
	2	2.1	0.7	76.2	0.05	33	-	-	-
	3	1.8	0.6	161.0	0.10	66	T	T	T
	4	3.1	1.0	51.6	0.05	33	T	T	T
	5	21.9	7.3	55.3	0.40	263	T	T	T
	6	17.6	5.9	73.3	0.43	283	T	T	T
CFT 6	1	6.5	2.2	50.8	0.11	72	2100	4.6	4.0
	2	3.7	1.2	67.6	0.08	53	T	T	T
	3	7.2	2.4	54.2	0.13	86	208	0.5	0.4
	4	4.0	1.3	75.0	0.10	66	nd	nd	nd
	5	46.6	15.5	20.6	0.32	211	15	0.2	0.2
	6	37.3	12.4	52.3	0.65	428	-	-	-
CFT 7	1	2.0	0.7	145.0	0.10	66	T	T	T
	2	1.6	0.5	144.0	0.08	53	T	T	T
	3	1.9	0.6	153.0	0.01	7	T	T	T
	4	1.9	0.6	147.0	0.09	59	T	T	T
	5	19.6	6.5	59.2	0.39	257	T	T	T
	6	18.7	6.2	64.7	0.40	263	T	T	T

**APPENDIX 15. TESTS CFT3 TO CFT7: TOTAL PARTICULATE FILTER BUBBLERS -
CONCENTRATIONS OF HCL AND HCN IN THE VAPOUR PHASE**

Test	Position number	HCl gas phase mg/l	HCl gas phase ppm	HCN gas phase mg/l	HCN gas phase ppm
CFT3	1	0.328	215	0.612	544
	2	0.147	96	0.312	277
	3	0.170	112	0.417	371
	4	0.130	85	0.376	334
	5	0.094	62	0.212	188
	6	0.014	9	0.333	295
CFT4	1	0.025	16	0.017	15
	2	0.021	14	0.005	5
	3	0.004	3	0.015	14
	4	0.023	15	T	T
	5	T	T	0.192	170
	6	0.027	18	0.171	152
CFT6	1	nd	nd	0.027	24
	2	nd	nd	0.016	14
	3	nd	nd	0.030	27
	4	nd	nd	0.002	2
	5	0.091	60	0.485	430
	6	0.042	28	0.320	285
CFT7	1	T	T	0.013	11
	2	T	T	0.005	4
	3	T	T	-	-
	4	T	T	0.001	1
	5	T	T	0.109	97
	6	0.021	14	0.126	112

Notes:- T Trace
nd None detected
- No sample taken
No data available for CFT5

APPENDIX 16. TESTS CFT 3 TO CFT 7; MAY IMPINGER - CONCENTRATIONS HCL, HCN AND FILTER PARTICULATE								
Position		Mass soot mg	HCl mg/g soot	HCl mg/l atm	HCl atm ppm	HCN mg/g soot	HCN mg/l atm	HCN atm ppm
C F T 3	upper	NA	NA	0.50	329.3	NA	0.40	0.36
	middle	NA	NA	0.70	461.0	NA	10.50	9.35
	lower	NA	NA	0.34	223.9	NA	7.50	6.68
	filter	157.20	3.2	0.02	13.2	NA	NA	NA
C F T 4	upper	NA	NA	0.04	26.3	NA	T	T
	middle	NA	NA	0.15	98.8	NA	0.01	0.01
	lower	NA	NA	0.04	26.3	NA	0.01	0.01
	filter	3.99	17.5	T	T	T	T	T
C F T 5	upper	NA	NA	T	6.6	NA	0.27	0.24
	middle	NA	NA	0.01	13.2	NA	0.70	0.62
	lower	NA	NA	0.02	T	NA	0.27	0.24
	filter	0.99	20.2	T	32.2	nd	nd	nd
C F T 6	upper	NA	NA	0.05	85.6	NA	-	-
	middle	NA	NA	0.13	85.6	NA	0.07	0.06
	lower	NA	NA	0.02	13.2	NA	0.03	0.03
	filter	-	-	-	-	-	-	-
C F T 7	upper	NA	NA	0.03	19.8	NA	0.77	0.68
	middle	NA	NA	0.11	72.4	NA	2.60	2.31
	lower	NA	NA	0.01	6.6	NA	0.73	0.65
	filter	1.23	24.4	T	T	T	T	T

Notes:- T Trace
NA Not applicable

**APPENDIX 17. TESTS CFT3 TO CFT7: CASELLA - CONCENTRATIONS OF
HCL AND HCN ASSOCIATED WITH PARTICULATES**

Position		Mass soot mg	Conc soot mg/l atm	HCl mg/g soot	HCl mg/l atm	HCl ppm	HCN ug/g soot	HCN ug/l atm	HCN ppm
C F T 3	C1	26.09	0.50	52.25	0.026	17	-	-	-
	C2	48.46	0.92	28.06	0.026	17	3.92	T	T
	C3	18.32	0.35	16.38	0.006	4	3.28	T	T
	C4	26.88	0.51	-	-	-	-	-	-
	Filter	71.51	1.36	43.63	0.060	40	6.15	-	-
C F T 4	C1	7.51	0.43	2.66	0.001	<1	-	-	-
	C2	0.33	0.02	30.30	0.001	<1	nd	nd	nd
	C3	5.71	0.33	14.01	0.005	3	674	0.22	0.2
	C4	4.95	0.28	nd	nd	nd	778	0.22	0.2
	Filter	0.00	0.00	T	T	T	-	-	-
C F T 5	C1	0.30	0.02	nd	nd	nd	nd	nd	nd
	C2	0.18	0.01	nd	nd	nd	nd	nd	nd
	C3	1.37	0.08	2.92	T	T	nd	nd	nd
	C4	0.65	0.04	nd	nd	nd	nd	nd	nd
	Filter	2.17	0.12	13.82	0.002	1	nd	nd	nd
C F T 6	C1	6.20	0.35	1.61	0.001	<1	nd	nd	nd
	C2	16.50	0.94	0.61	0.001	<1	nd	nd	nd
	C3	7.40	0.42	21.62	0.010	7	nd	nd	nd
	C4	0.30	0.02	33.33	0.001	<1	nd	nd	nd
	Filter	0.23	0.01	217.4	0.003	2	nd	nd	nd
C F T 7	C1	4.11	0.23	nd	nd	nd	nd	nd	nd
	C2	17.33	0.99	1.73	0.002	1	nd	nd	nd
	C3	25.25	1.44	19.01	0.027	18	3.96	T	T
	C4	0.81	0.05	86.42	0.004	3	T	T	T
	Filter	2.17	0.12	23.04	0.003	2	nd	nd	nd

Notes:- T Trace
nd None detected

**APPENDIX 18. 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

APPENDIX 19. SUMMARY OF DATA USED FOR FED CALCULATIONS

TEST	POSITION			
	G1	G2	G3	G4
CFT1	CO ₂ , CO	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO
CFT2	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂
CFT3	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂
CFT4	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂
CFT5	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO, O ₂
CFT6	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂
CFT7	CO	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂	CO ₂ , CO, O ₂