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Performance of Fire Detectors in Residential Buildings

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Preface

This work is an extension of earlier research, which has shown that computer fire models are able to predict, within certain defined limits, fire spread in a typical New Zealand house.

A literature survey on the available types of smoke alarms has identified their respective performance characteristics. Experimental trials have confirmed the smoke alarm responses and also demonstrated the subsequent hazard development. Modelling occupant responses to alarms and developing fire hazards has identified the circumstances where life is most at risk, providing data in support of fire safety promotions.

Acknowledgments

This work was supported by the Public Good Science Fund of the Foundation for Research, Science and Technology, and the Building Research Levy.

The author wishes to thank Home and Safety (NZ) Ltd for the generous supply of BRK/First Alert smoke alarms and technical advice and the New Zealand Fire Service for sponsorship of a portion of this work relating to carbon monoxide alarms.

Readership

This report is intended for code writers, fire safety promoters, fire safety engineers and designers.

PERFORMANCE OF FIRE DETECTORS IN RESIDENTIAL BUILDINGS

BRANZ Study Report No. 76 **P.C.R. Collier**

REFERENCE

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KEYWORDS

Alarms; Detection; Escape; Egress; Fire; Life Safety; Smoke.

ABSTRACT

The effectiveness of smoke alarms in providing early warning of developing fire hazards is demonstrated by comparing experimental results on various early fire development scenarios of both smouldering and flaming fire types and combinations of doors open or closed.

A combination fire scenario, including a prolonged smouldering phase and subsequent full development, is compared with a computer model for various installations of smoke alarms to determine probable occupant responses and survival.

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1. INTRODUCTION

New Zealand statistics (Cropp, 1991) show that of an annual average of 30 deaths by fire in buildings, 90% occur in residences. Of these a disproportionately high number occur in rented accommodation. Also contributing significantly to the statistics are fire deaths occurring in rest homes for the elderly. In all situations the greatest cause of death is smoke inhalation. In over 80% of fatal fires the alarm was raised by someone other than the occupant. In 70% of fatal fires it was thought that a smoke detector would have helped victims to escape, because the circumstances suggested that someone could have been alerted to the fire earlier and warned others before the build-up of smoke and heat reached lethal levels.

For the remaining 30%, it was thought that the spread of fire was too rapid or there were very young children alone who would have been unable to respond to an alarm.

The experimental results of this study show that smoke alarms of the correct type, installed in suitable location(s) and maintained regularly, perform effectively to give very early warning of developing fire hazards. Maintenance and regular testing of the devices cannot be over-emphasised and are the key to continuing protection.

Modelling of selected scenarios confirmed the early warning potential of smoke alarms. Provided occupants could first hear the alarm and then take action, survival was very likely. The factors inhibiting survival were found to be a low sound level and/or an occupant in deep sleep or under the influence of drugs or alcohol.

2. LITERATURE REVIEW

While the potential benefits of smoke alarms are widely recognised, two reasons for their unsuccessful operation were consistently identified throughout the literature review. They are:

1. Maintenance and power supply problems.
2. Combinations of type of fire and detection mechanism as well as geometry, ie doors open, closed or ajar.

2.1 Early Detection of Fire

There is no doubt that the early detection of fire, in particular by smoke detectors, is the single most effective means of reducing fire deaths and damage. Since 90 to 95% of fire deaths occur in residential buildings (NZFS, 1993), targeting this area will achieve the most cost-effective results.

The experience internationally where concerted smoke alarm campaigns have been conducted such as in the USA (Hall, 1988), the UK (FPA, 1994) and Australia (Bibby, 1995) have all achieved reductions in fire deaths, particularly in dwellings. However, in the USA (Hall, 1988) it is evident that over a period of time (15 to 20 years since the campaign began) a complacency in attitude develops, and this results in a rise in fire deaths. The reasons for this may range from simply a lack of maintenance of detection and alarm devices to the initial impetus and enthusiasm of the campaign not being maintained. These two reasons fall outside the scope of this study, but from a technical viewpoint the regular maintenance of smoke alarms, periodic testing and battery replacement and cleaning, all in accordance with manufacturers' recommendations, cannot be over-emphasised.

This study investigates various combinations of types of fire from smouldering to flaming, slow growth to fast growth, and the response of different detection mechanisms. The influence of building geometry, for example doors open, closed or ajar, is also considered.

To make optimum use of fire detection devices, in this case smoke detectors, it is necessary to understand the mechanisms of fire growth, or more importantly, the products which evolve from a developing fire which the device is designed to detect. Smoke consists of solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion, together with the quantity of air that is entrained or otherwise mixed into the mass. The products of combustion usually include particulates, unburnt fuel, water vapour, carbon monoxide and some other toxic and corrosive gases (NFPA 1988). The study by Bright (1975) considered the various fire signatures, how they are distributed in the various types of fire and the most effective methods of detection. Any fire releases a very large number of solid and liquid particles which range in size from 5×10^{-4} microns to 10 microns. These particles suspended in air are called aerosols. The aerosols resulting from a fire represent two different fire signatures. Those particles measuring less than 0.3 microns do not scatter light and are therefore classified as invisible. Those which are larger than 0.3 microns scatter light and are therefore classified as visible. The invisible aerosol signature is generally referred to as the "products of combustion" and the visible aerosol signature as "smoke".

The invisible aerosol is the earliest appearing fire signature noted to date (Bright, 1975). Heating of materials during the pre-ignition stage of a fire produces submicron particles ranging in size from 5×10^{-4} to 1×10^{-3} microns. These are generated at temperatures well below ignition temperatures. The temperatures at which submicron-size particles are generated is defined as the thermal particulate point.

As heating of a material progresses toward the ignition temperature, the concentration of invisible aerosol increases to the point where larger particles are formed by coagulation. As this process continues, the particle size distribution changes upward to the range between 0.1 and 1 microns. The production of visible aerosols can occur prior to ignition and is usually initiated at temperatures several hundred times higher than the thermal particulate point.

The aerosol size distribution for smouldering and flaming combustion of various materials has been determined by Scheidweiler (Bright, 1975). The results are shown in Figure 1. It can be seen that smouldering fires produce more large particles than flaming fires. It is important, however, to note that for both fire types the maximum relative particle concentration appears to be in the range of particle sizes smaller than

0.3 microns (not shown in Fig 1). This indicates that invisible aerosol signals can provide early detection in the immediate vicinity of either fire type. The detection mode best suited for the invisible aerosol signature is the ionisation chamber type. Photoelectric units with light sources having a major spectral component in the near ultraviolet and blue-green wavelengths and a suitable photocell should also respond to the larger invisible aerosols, since the best scattering of energy occurs when the particle diameter approaches the wavelength of the incident radiation.

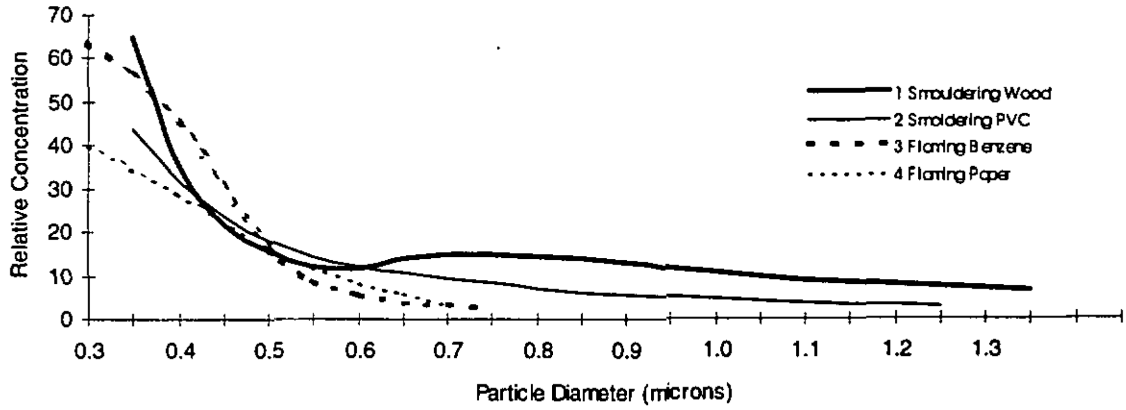

Figure 1: Particle size and distribution of various types of smoke.

Smouldering fires produce more large particles than flaming fires so the sensitivity of ionisation or photoelectric detectors to a particular fire will depend on particle size.

2.2 Types of Smoke Detector and Response

- Ionisation suitable for detecting small particles and products of combustion, rapidly developing clean-burning, flaming fires, and those producing invisible particles which do not effectively scatter light. Sensitive to particle size less than 0.3 micron. Prone to nuisance alarms from steam and sources of invisible ionised particles eg. cooking.

- Photoelectric - suitable where there are larger particles, more visible smoke, smouldering slow developing fires producing smoke which effectively scatters light. Sensitive to particles larger than 0.3 microns. Not very sensitive to flaming fires producing mainly invisible smoke.

Studies of various smoke detector/alarm types, in particular ionisation and photoelectric types, show that, depending on the source of the smoke one type will be expected to perform better than the other. Notarianni (1993) concludes from simulated fires in two-bed hospital patient rooms that ionisation detectors activate before photoelectric detectors in flaming wood crib fires. However, both ionisation and photoelectric detectors activated before the patient's life would be threatened.

Chow and Wong (1994) conducted an experimental study to assess the sensitivity and response times of four types of fire detectors: ionisation, optical smoke, infra red and rate of heat-rise detectors. The detectors were installed in a fire chamber and subjected to 10 trials covering five different types of fire under a controlled environment. The types of fire were: pool fire (4), smouldering cellulose/plastic (3), flaming cellulose/plastic (2) and gas (1). Comparing the ionisation and photoelectric detectors, in flaming fires (5) the ionisation detectors activated first and in smouldering fires (3) photoelectric detectors activated first. In two trials with clean burning methanol and natural gas both the ionisation and photoelectric detectors failed to operate after 240 seconds.

Johnson and Brown (1986) conducted various tests comparing the operation of detectors with smouldering fires and artificial smoke in low/medium/high outputs (hot and cold) in a typical Melbourne dwelling. Adequate warning was given when the smoke detectors were situated as follows:

1. Photoelectric and ionisation detectors sited in bedrooms with doors partly ajar provided adequate detection of smouldering smoke only when it originated in the same room, and generally provided poor escape times from smoke originating in other areas of the dwelling.

2. Photoelectric detectors sited in the hallway were more effective for detecting smouldering smoke than ionisation detectors, and provided adequate escape times for most conditions of size and location of smoke sources.

3. Ionisation detectors sited in the hallway generally provided inadequate escape times unless smoke movement into the hallway was restricted by doors ajar 120 mm, causing a slower loss of visibility, or unless they were sited close to the smoke source.

4. An acceptable arrangement for protection against smouldering fires under the conditions investigated appeared to be photoelectric detectors located at each end of the hallway.

Visibility in escape routes may determine whether escape is possible and this will be a function of the time at which the alarm is raised.

Kennedy et al (1978) conducted a series of full-scale tests of smoke detectors installed in bedrooms and corridors of residential institutions. Their conclusions were that ionisation detectors often give inadequate warning in smouldering fires and, once they have activated, the time available for escape is reduced and escape routes may be heavily smoke-logged.

Reis and Solomon (1979) caution that although photoelectric detectors may provide earlier warning of smouldering fires and ionisation detectors perform better in flaming fires, a combination smoke detector may not offer any greater degree of protection. Combination smoke detectors are only as good as their individual parts. There is a risk that inferior combination detectors may be produced due to desensitising the individual ionisation and photoelectric components (using AND-type logic to eliminate unwanted alarms).

Sultan (1984) reports similar conclusions to Reis. In addition he comments that there are problems with hearing detectors against background noise and behind closed doors and that air conditioning/ventilation systems will transport smoke around buildings.

Bukowski (1977) concludes that it is safer to sleep with the bedroom door open. Experiments conducted with fires in closed bedrooms resulted in lethal conditions occuring in the bedrooms before detectors located outside the bedrooms responded. Thus, the person in the room of fire origin would not be warned in time to escape unless the detectors were in the bedroom or the bedroom door was open. Since there was no increased hazard to the occupants from fire originating outside the bedroom when the bedroom door was open, and since the open bedroom door would greatly increase the chances of saving the occupant from a fire starting in the bedroom, it might be safest to sleep with the bedroom door open when detectors are present in the home.

Budnick (1984) provides a qualitative assessment of early warning devices in residential occupancies and concludes that hazardous conditions in escape routes may occur before smoke reaches a detector to activate it. This has important implications in the location and spacing of smoke detectors.

2.2.1 Domestic smoke alarms - guide for specifiers Fire Prevention 281, July/August 1995

Advice over the choice and location of domestic smoke alarms is given in the periodical Fire Prevention (FPA, 1995) as follows:

Optical (or photoelectric) smoke alarms are designed to react to smoke produced typically by slow smouldering fires rather than the small burnt particles produced by a fast-flaming flash fire. The optical alarm is therefore less likely to react to the results of cooking and this makes it far more suitable for installation near kitchens or in confined spaces, such as bedsits where false alarms with ionisation types of smoke alarm could be a problem.

Fires occurring when the household is asleep may start anywhere, but locating the smoke alarm where it is most likely to awaken the sleeping occupants obviously gives a heavy sleeper behind a closed bedroom door a far greater chance of escape than if the alarm was out of earshot.

The minimum UK Home Office recommendation for locations of smoke alarms in a typical two-storey house is that an optical smoke alarm should be fitted downstairs in the hall with an ionisation alarm upstairs on the landing. If only one smoke alarm can be installed in a dwelling, then it should be installed either just outside a bedroom(s) or at the top of the stairs. Although domestic fires may start in the kitchen, it is more likely that when they do, the tenant or householder will be present and aware of the fire even before the smoke alarm responds.

2.3 Testing of Household Smoke Detectors

Harpe and Christian (1979) describe the development of a test method based on a hot plate generating smoke from a smouldering source (dry timber on 300 °C hot plate). A similar method was used to generate smoke in the experimental phase of the project reported here.

2.4 Modelling the Response of Smoke Detectors and Alarms

For modelling purposes Evans and Stroup (1986) and NIST (1989) treat smoke detectors as low-temperature heat detectors with no thermal lag (RTI = 0) and, on the basis of a wood crib fire, an actuation temperature 13 °C above ambient. This assumes, in the absence of an understanding of the many processes affecting smoke detector response, that a small temperature rise at a detector location must be due to the arrival of smoke (heated air, products of combustion) etc. This correlates well with the actuation of smoke detectors (ionisation anyway) shown experimentally by Collier (1997) where a measured temperature rise of 2 to 3 °C (behind a closed door) coincided with the actuation of a smoke alarm. The requirement for a 13°C temperature rise would therefore appear to be a conservative assumption.

2.5 Problems in the Unsuccessful Operation of Detectors

A study of US statistics (Willey, 1979) highlights some of the factors in the unsuccessful operation of smoke alarms. Broadly speaking, these factors are incorrect installation and lack of maintenance, including battery replacement and not keeping the smoke alarms clean, as recommended in the manufacturers' instructions.

Problems also occur in the evacuation phase, - people problems include re-entry into the burning structure, ignoring the alarm signal and fire-fighting actions.

In other cases arousal problems due to alcohol or drugs prevented people responding to smoke detector alarms. In one fatal case a child awakened by a smoke alarm could not arouse the victim, who had been drinking. In other cases unrelated to alcohol one 74-year-old victim was deaf and would not have heard the alarm. In another case, the victim's bedding was the first material ignited, and a smoke alarm alerted other occupants of the building. It needs to be appreciated that residential smoke detectors will not always save lives in situations where clothing and bedding ignitions are directly related to occupants.

In summary, the factors which cause unsuccessful operation of smoke alarms are:

1. Detector location/level of protection.
2. Power supply impaired/smoke alarm removed.
3. Post-ignition people factors (evacuation problems).
4. Pre-ignition people factors (arousal problems).
5. Clothing/bedding ignitions.

Hall (1988 and 1993) reports that subsequent to successful campaigns in the USA where smoke alarms were installed in 92% of homes, the proportion of non-operational alarms showed an increase in the period following the campaign. The main reasons for non-performance of detectors were power supply problems, with dead or missing batteries being the principle element. Reasons range from neglect, theft of batteries and nuisance alarms resulting in removal of battery to lack of maintenance. These problems are being addressed by wired-in detection systems which include battery backup.

Proper location of alarms will reduce nuisance alarms, as will correct selection of alarm type (ionisation or photoelectric). Updating to more modern alarms will also improve performance and manufacturers often recommend complete replacement after a period of 10 years or so.

3. EXPERIMENTAL TRIALS

3.1 Apparatus

A plan view of the BRANZ test house in Figure 2 shows the five compartments (shaded grey) which were used in the experimental trials. This house is typical of New Zealand single storey dwellings. Each compartment was instrumented with thermocouple trees (eight thermocouples per tree) and measurements of oxygen and carbon monoxide were taken at the kitchen ceiling. Additional records of alarm activation times, fire temperatures and fuel mass loss were also recorded, for comparison with the models. A specification of the house is included as Appendix A.

Smoke alarms, both ionisation and photoelectric types, as well as carbon monoxide alarms, were connected to the data logger to record activation times. Smoke alarms were located in pairs (ionisation and photoelectric) in the lounge (5), hallway (4) and bedroom (2). Carbon monoxide alarms were located in the kitchen (5) and hallway (4).

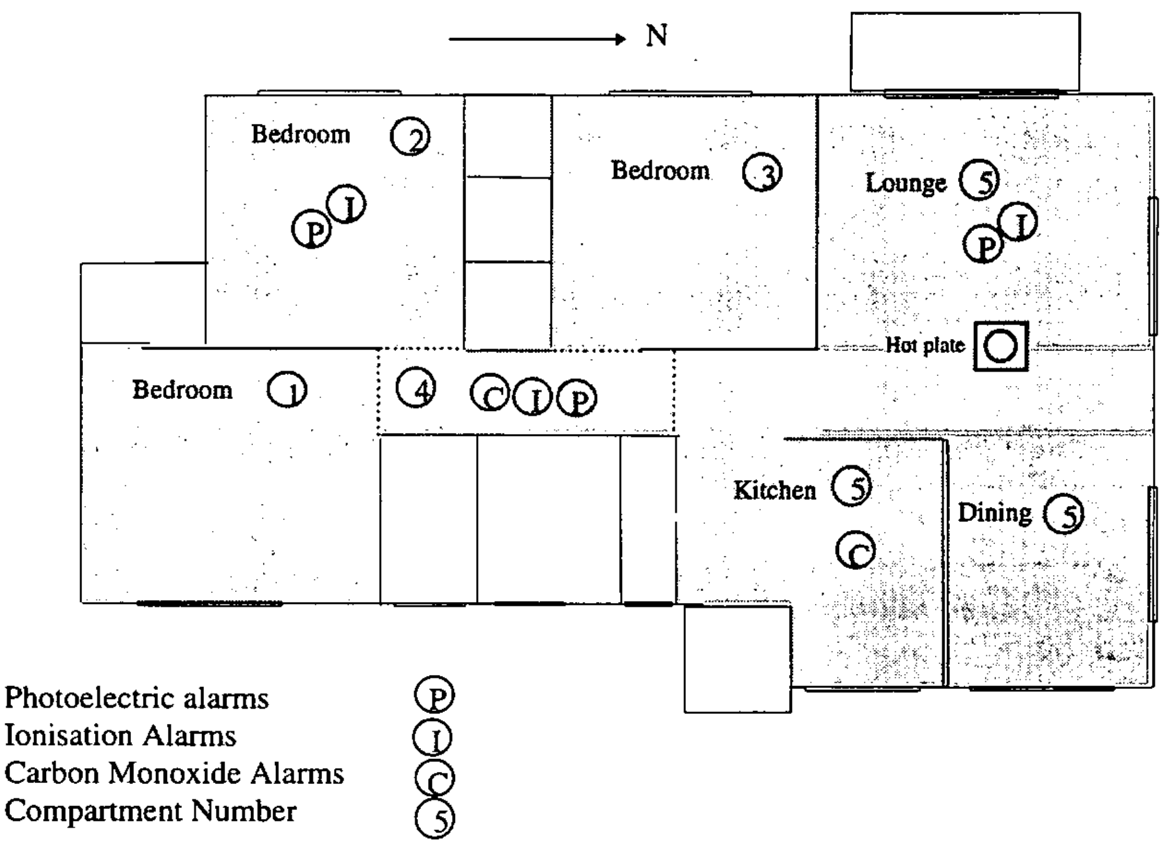

Figure 2: Plan of house as set up for smoke tests.

3.2 Fire Types

Trials with smouldering and flaming fires as listed in Table 1 were conducted to monitor the response of the smoke alarms.

Table 1: Types of Fire

Fuel	Smouldering	Flaming
Paper	#	#
Wood	#	#
Carpet	#	
Methylated spirits		#
Hexane		#

3.3 Smouldering Fires

For the smouldering fires the fuel was placed on a 1.1kW electric hotplate in the lounge, the temperature of which increased from ambient to greater than 500 °C. This apparatus is similar to that used by Harpe (1979), and 14 trials were conducted using wood cribs or paper as the smoke-producing medium. Exterior windows were closed to prevent draughts. Smoke generation was slow at first and dependent on the hotplate temperature, the heat generated by the hotplate was sufficient to generate a thermal plume which entrained the surrounding air. The smoke plume rose to the ceiling, from where it filled downwards to form a low intensity haze. Temperatures close to the ceiling rose by approximately 5°C, while temperatures at the floor remained constant. On this basis it was considered that a hot and cold layer interface was established which had the potential to cause flow between rooms.

For the trials using wood as the source, a pyramid of 14 rectangular sticks of wood measuring 17 x 12 x 90 mm, with a total weight of approximately 130 grams and moisture content of 12%, was placed on the hotplate. The bottom two layers were four sticks wide and the top two layers three sticks wide. Spacing between sticks was 4 mm.

For the carpet trials a 200 x 200 mm sample was placed on the hotplate and for the paper trial 50 pages from the Yellow Pages section of the telephone directory was used. Paper and carpet were included in the results as their behaviour was very similar

The individual trial results are presented in Tables 2, 3 and 4, depending on the ventilation between rooms. The minimum, average and maximum times are included and these latter times are graphed on the bar charts (Figures 3 to 5) as an indication of the trends.

In cases where an alarm did not activate the time is recorded as a nil result, and similarly a column on the bar chart is omitted.

Windows to the outside (except that in bedroom 1) were closed to reduce the influence of any wind. In all tests the wind was from a northwesterly direction and varied in strength from 2 to 10 knots. Three separate internal venting scenarios were used:

1. All internal doors between the 5 compartments under consideration (see Figure 2) were open;
2. The door between the lounge and hallway (door 4/5) was closed;
3. All doors between the 5 compartments were ajar 100 mm.

A fourth ventilation scenario with door 4/5 and door 4/2 closed was trialed, but is not reported because the alarms in bedroom 2 (compartment 2) had not activated after the expiry of a considerable time and well after the fuel source was consumed.

Similarity between trials was achieved by starting to record data when the temperature of the hotplate was close to and moving towards 300°C (temperature rises typically peaked above 500 °C). The times of alarm activation were corrected back to elapsed time from when the hotplate exceeded 300°C. The selection of 300°C was on the basis that charring of wood, and smoke development, is considered to commence at this temperature. Visual observations during the trials confirmed that smoke production increased more rapidly above 300°C than below. This procedure was adopted so that a similar level of smoke development occurred at the same times between trials. Once a reliable smoke production pattern was established, carpet and paper was used in some trials instead of wood. Tables 2 to 4 list the corrected data, grouped according to each ventilation condition. The times to alarm activation are averaged and the mean, maximum and minimum times are plotted in Figures 3 to 5.

Table 2: Smouldering wood, carpet or paper, all doors open

Times to activation of alarms (sec)						
Fuel	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
wood	163	666	263	963	466	993
wood	367	719	441	976	575	1037
wood	391	826	475	1010	676	1206
wood	553	800	614	995	744	1350
wood	579	875	634	1080	821	1274
carpet	183	417	162	1006	257	1634
carpet	189	681	188	687	240	1033
paper	520	729	570	964	756	1073
********						
Min	163	417	162	687	240	993
Average	368	678	401	918	533	1223
Max	579	875	634	1080	821	1634

Table 3: Smouldering wood or paper, door 4/5 closed

Times to activation of alarms (sec)						
Fuel	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
wood	444	450	1861	-	-	-
wood	528	828	1708	-	-	-
wood	524	759	2038	2554	3263	-
paper	714	713	1757	3244	-	-
********						
Min	444	450	1708	2554	3263	-
Average	553	688	1841	2899	3263	-
Max	714	828	2038	3244	3263	-

Table 4: Smouldering wood, all doors 100 mm ajar

Times to activation of alarms (sec)						
Fuel	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
wood	402	601	636	1669	1561	-
wood	330	567	475	850	755	-
********						
Min	330	567	475	850	755	-
Average	366	584	556	1260	1158	-
Max	402	601	636	1669	1561	-

In all three ventilation scenarios, activation of the photoelectric alarms preceded that of the ionisation alarms. This is in accordance with the findings of Johnson (1986), Kennedy (1978) and Scheidweiler (Bright, 1975) for smouldering type fires, where photoelectric alarms are expected to activate sooner due to the larger particle sizes in the smoke, a result of the incomplete combustion. The ionisation alarms eventually activated, but the time elapsed was approximately twice as long. The conditions prevailing when the ionisation alarms activated, under smouldering fire conditions, were far from what could be considered serious, and vision across the width of the building, (6 m for the lounge/dining room), was not significantly impeded.

For the three ventilation conditions in the smouldering fires the results are displayed in Tables 2 to 4 and Figures 3 to 5, where the columns show the range of activation times and the trend line the mean. Figure 3, where all doors were open, shows the consistently earlier operation of the photoelectric alarms ahead of the ionisation alarms in each compartment. The significance of this difference extends to the activation of the photoelectric alarms in the hallway and bedroom at the end of the hallway, in many cases preceding that of the ionisation alarm in the room of fire origin. While the time differences are significant this is somewhat mollified when considering that the rate of fire development (smouldering) or smoke production is slow and therefore development of the hazard is slow.

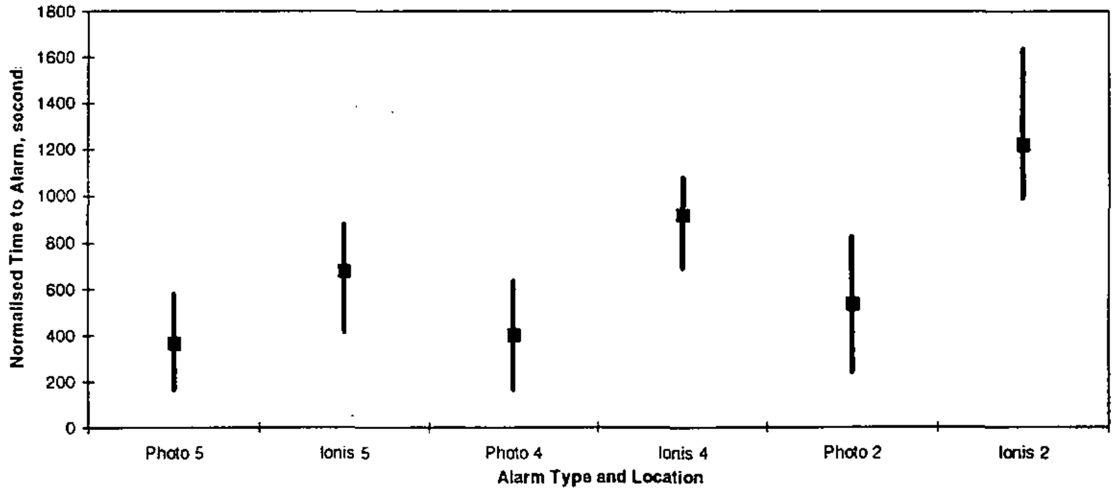

Figure 3: Mean and range of activation times for photo-electric and ionisation alarms in smouldering fire conditions with all compartment doors open.

Restricting air and smoke movement from the lounge by closing the hallway door will increase the activation times of alarms in the hallway and bedroom(s). Figures 4 and 5 show the trend. If the door from the lounge to the hallway is shut and the others previously open remain open, then the operation of alarms downstream of the closed door is seriously impeded. But the established trend of the photoelectric alarms activating earlier is repeated, and the intervals between alarms is increased, to the extreme where non-operation results in some cases. In the four trials of this scenario (Figure 4) the alarms in bedroom 2 activated as follows: photoelectric 1/4 (1 out of 4 times) and ionisation 0/4. At the same time the alarms in the room of fire origin operated slightly earlier, due to the containment of smoke in that room. The carbon monoxide alarm in the kitchen activated in two of the trials, and this was the only occasion that activation was achieved in the smouldering tests. Details of the carbon monoxide alarm responses are covered in a later section.

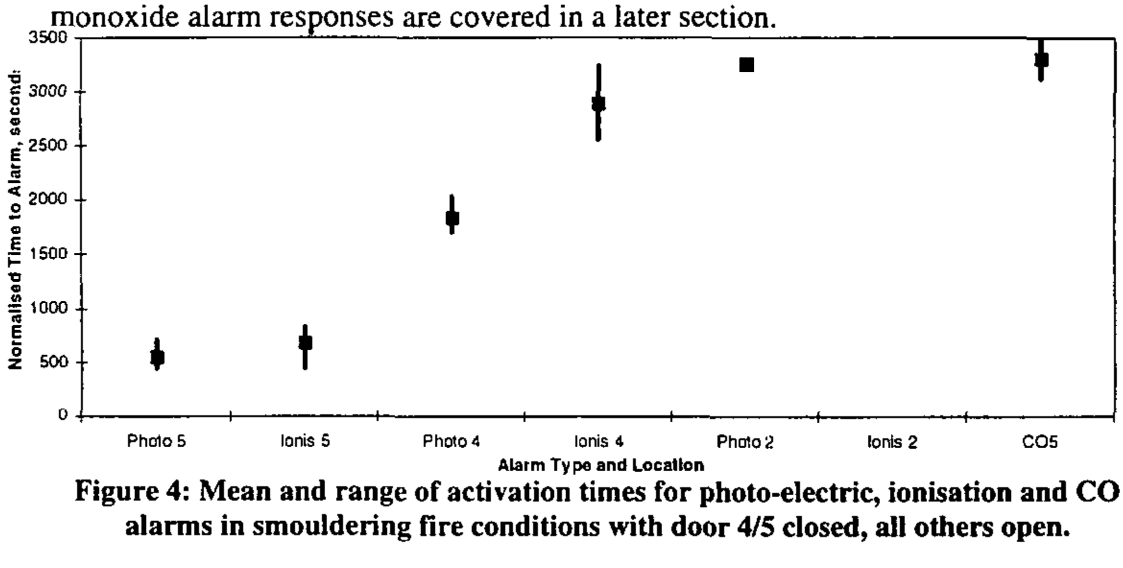

Figure 4: Mean and range of activation times for photo-electric, ionisation and CO alarms in smouldering fire conditions with door 4/5 closed, all others open.

When all the doors are ajar 100 mm (Figure 5) the alarm response is similarly retarded in the downstream rooms, although not as marked as when one door is firmly closed. The differences between the maximum and minimum response times at points further away are also increased. The ionisation alarm in bedroom 2 did not activate at all when smoke movement was restricted by two doors 100 mm ajar.

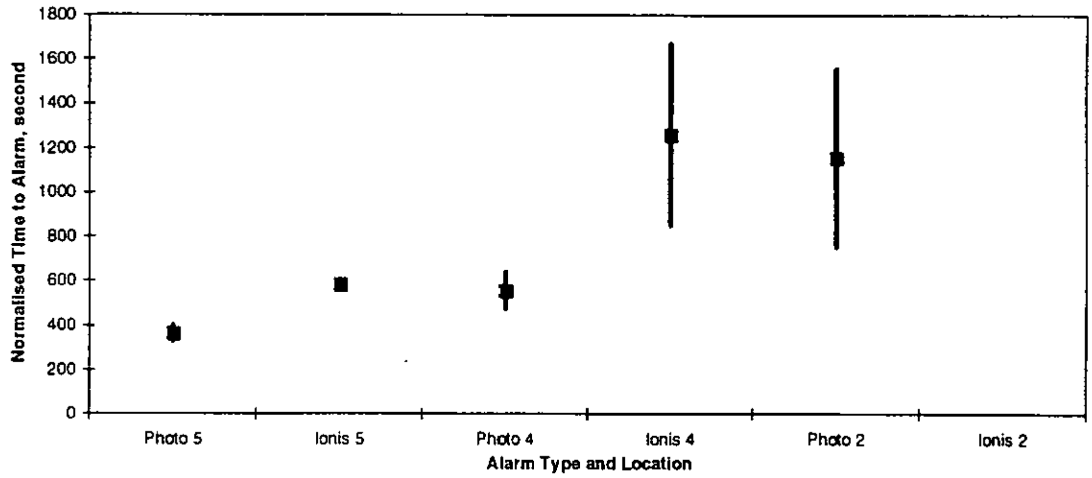

Figure 5: Mean and range of activation times for photo-electric and ionisation alarms in smouldering fire conditions with all compartment doors open 100 mm.

In conclusion, in the trials with the smouldering-type fires, photoelectric alarms quite clearly give a significantly earlier warning of a potential fire problem or, more correctly, of a smouldering situation which may develop into a serious fire. With the earliest warning of a developing fire situation, human intervention may occur in sufficient time so that an early developing and still smouldering fire can be safely extinguished without any property damage. This scenario precedes the situation (later alarm relying on ionisation alarms) where occupants only have time to evacuate the premises due to more advanced fire development. While it is acknowledged that life safety is of prime importance and occupants should always vacate a building on alarm as a matter of instinct, investigation of the cause of an alarm may then take place should it not be obvious. Quite often property may then be saved should it be safe to extinguish a fire prior to fire service attendance.

3.3.1 Smouldering trials with cool smoke

In addition to the trials using the hotplate to create smoke, two further trials using cooler smoke to check the response of the alarms were conducted. The source of smoke was a strip of smouldering newspaper 100 mm wide by 3000 mm long which had been soaked in a sodium nitrate solution and allowed to dry. When ignited this produced a constant source of cool smoke as the strip burnt from one end to the other. While the source produced some heat it was only that due to the smouldering of the paper, as the purpose of the sodium nitrate was to provide a source of oxygen, when heated, to assist the burning. The thermocouple data confirmed that temperature rises in the building were negligible.

Heat output of the treated paper was estimated as 0.2 kW on the basis of the heat of combustion of the paper and the duration of burning.

3.3.2 Observations on smouldering fires with cool smoke

From the centre of the lounge the smoke plume from the smouldering newspaper rose vertically in a laminar flow to a height of approximately 750 mm, where the flow regime became turbulent and the smoke mixed with the surrounding air. The smoke, now cooler due to mixing with air, accumulated in the region between 750 mm elevation and the ceiling. Smoke accumulation, over this large volume, was slow and considerable time elapsed until smoke density or obscuration level was sufficient to activate either alarm. When the alarms did activate their response was intermittent rather than continuous. This intermittent operation continued for 8 to 16 minutes. During this time the smoke was slowly obscuring vision across the lounge/dining room, but at no time did vision become significantly poor to the extent that escape would be impeded. Eventually the alarms sounded continuously when the level of smoke had homogeneously filled the compartment(s) from top to bottom. At this time the building was entered and the extent of smoke filling could only be described as a nuisance, but it was obvious by the smell that smoke was present.

Comparing the trials with warm (hotplate generated) and with cool smoke, the heat (temperature) in the smoke makes a significant difference in the time taken for an alarm to be raised. The former generates a much earlier alarm response. A typical real life scenario could be a heater or fire too close to a combustible surface; the heat source contributes to the convective mixing of the smoke and assists in driving it towards the ceiling where smoke alarms would be installed. A smouldering cigarette in contact with a combustible material could generate cool smoke for a considerable time, slowly filling a compartment before alarms activate. Even then the response could be intermittent, which is less likely to wake an occupant in a deep sleep.

In general, the response of the detectors in the above two trials using cool smoke was inconsistent with previous trials. This can be explained by variations in sensitivity between devices of the same type and outside influences such as wind (measured at 8 to 10 knots from a north-westerly direction) causing air currents within the building to play a significant role in distributing the smoke. The windows, although closed, did not provide a perfect seal against the outside environment due to damage from a previous fire. External environmental effects did not appear to impact on earlier experimental results (when windows were closed). This can be attributed to a stronger plume action from the fire or smoke source pumping smoke to the ceiling level and further providing currents to transport smoke and combustion products between compartments. This finding reinforces manufacturers' recommendations that smoke detectors are installed away from the influence of ventilation duct outlets, which may blow smoke away from the detector.

Table 5: Cool smoke trials

Times to activation of alarms (sec)							
Fuel	Doors	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
paper	all open	1621	-	492	1814	1065	-
paper	4/5 closed	-	1038	-	-	-	-

The variation between all doors being open and door 4/5 (between lounge and hallway), being closed in Table 5 shows that the response of the alarms in the lounge/dining/kitchen areas is quite different. The outside wind was a gusting northwesterly of up to 10 knots, and although all windows were closed (except bedroom 1) gaps in the window seals could have influenced the movement of the smoke within and between compartments and also into the alarm sensor chambers. Problems were also experienced with the smoke source in the second trial where the source eventually extinguished itself and the trial was abandoned at 1700 seconds. It was also observed that in both tests the operation of the alarms was intermittent, indicating that a randomness in the movement of the smoke coupled with a lack of convective flow, as would not be expected in a fire with a greater heat input, resulted in unreliable operation of smoke alarms. These two tests illustrate the lower boundary of operation of these devices and give an indication of their sensitivity and early warning capability, albeit intermittent.

3.3.3 Pan of fat on hotplate

A pan containing a mixture of mutton and chicken fat was placed on the hotplate and allowed to heat, with the objective of starting a fat fire. After a time of 36 minutes (2830 seconds) the fat had risen to a steady temperature of 271 °C (551K) (Figure 6), without ignition. Reference to SFPE Handbook (Society of Fire Protection Engineers, 1995) shows that for lard oil the temperature of auto ignition at atmospheric pressure is 546K, so although a fat fire did not start it is very likely one would have if the temperature had risen further, or a source of ignition had been available. Of more significance, all the smoke alarms, except the ionisation alarm in the bedroom furthest from the kitchen, had activated at various stages as the temperature of the fat (at 40 °C when the test commenced) increased.

Although a fire did not occur in this trial the alarms responded to the conditions. As the fat was heated, increasingly dense vapour and fumes were evolved and circulated throughout the house, driven primarily by the heat from the hotplate (about 1.1 kW).

The presence of carbon monoxide was not detected and neither was any decrease in the level of oxygen, which is the expected result given that combustion did not occur.

The nearest alarms were in the lounge adjoining the kitchen. The photoelectric alarms responded before the ionisation alarms (Table 6), which is contrary to the findings in the literature search. This suggests that photoelectric alarms are the preferred option in kitchens where cooking fumes are often responsible for false alarms.

This unexpected result could be explained by acknowledging that other sources of cooking fumes, such as from burning toast to roasting/grilling were not used in these trials. Particles from these types of combustion processes are more likely to be responsible for false alarms in kitchen/cooking situations and the photoelectric detecting mechanism is less sensitive and thus more suitable, especially in confined spaces.

Table 6: Fat on hotplate

Times to activation of alarms (sec)							
Fuel	Doors	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
fat	all open	1292	1841	1288	1538	2264	-

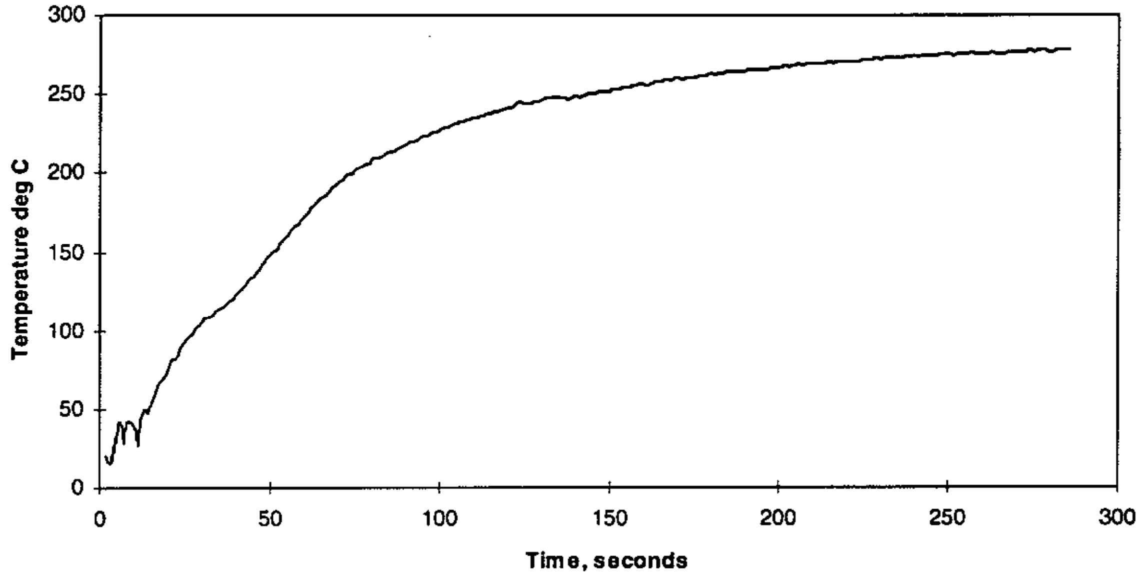

Figure 6: Temperature of fat in pan.

To complete the kitchen/cooking scenario, a pan of water was boiled for 30 minutes without any response from the smoke alarms. It was, however, determined that with a relative humidity of 60%, 0.5 kg of water would have had to have been introduced to the air in the lounge/dining/kitchen areas (excluding leakage through vents) to reach 100% humidity and possibly activate the alarms. Further attempts to activate the alarms by cooking activities were abandoned.

3.4 Flaming Fires

With flaming type fires (and more rapid heat production) the activation of alarms would be expected to favour the ionisation alarms ahead of the photoelectric type, but the time difference to activation between the two types would be significantly reduced.

Three flaming fire scenarios were trialed. Each comprised a fuel source on a load cell to determine mass loss rate and hence heat output. For each trial all doors to the five compartments being monitored were open.

3.4.1 Pan of methylated spirits

A 250 mm x 250 mm square pan containing 0.75 kg methylated spirits on a load cell in the lounge was ignited, producing a steady heat output of approximately 30 kW. A maximum temperature of 80°C was reached in the lounge and correspondingly smaller temperature rises were recorded throughout the building (all doors open) and without any response from the smoke alarms. This negative result from the smoke alarms is consistent with the findings of Chow and Wong (1994) using clean-burning fuels. An additional trial using a bottled LPG (liquefied petroleum gas) heater was omitted from the programme as it too would have failed to activate any alarms.

3.4.2 Pan of hexane

The same pan containing 0.488 kg of hexane was ignited and reached an early plateau of 40 kW and then increased to a maximum heat output of 116 kW before decay, as shown in Figure 7. The heat output was calculated on the basis of the product of the mass loss rate and heat of combustion.

The responses of the alarms are shown in Table 7. The high rate of heat output of the hexane fire caused the rapid development of a hot upper layer and transport of combustion products throughout the house, resulting in the early activation of the smoke alarms. Temperatures in the house rapidly increased to 150 °C in the lounge and 60°C in the bedrooms, indicating the free movement of combustion products.

Table 7: Hexane pool fire

Times to activation of alarms (sec)							
Fuel	Doors	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
hexane	all open	54	22	80	59	111	73

Figure 8 shows that oxygen consumption is minimal, at only 1 to 2 % of the 20.9% available. Similarly, the production of carbon monoxide is minimal, peaking at approximately 15 ppm, due to the oxygen availabilty and its accessibility to the fuel surface. In this scenario the carbon monoxide alarms did not activate.

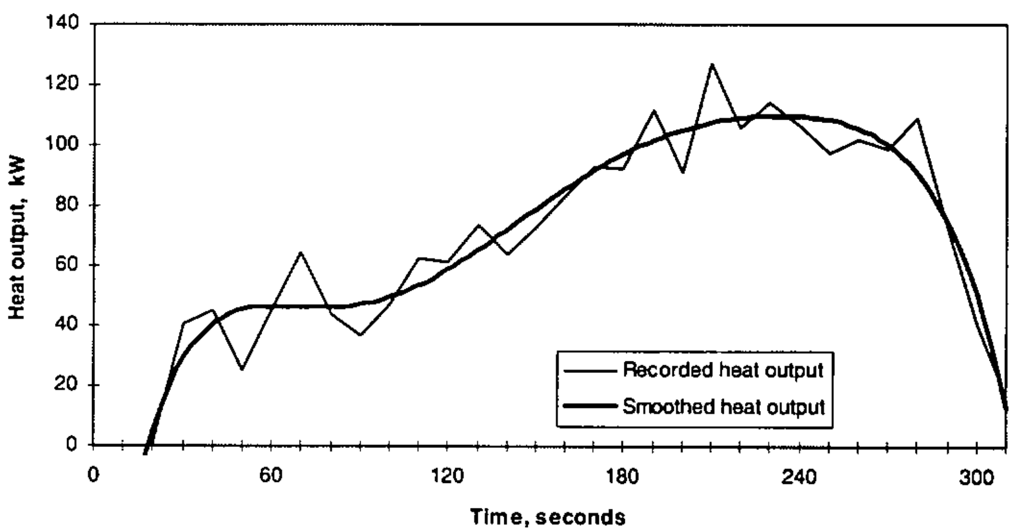

Figure 7: Heat output of hexane fuel fire, pan 250 mm x 250 mm.

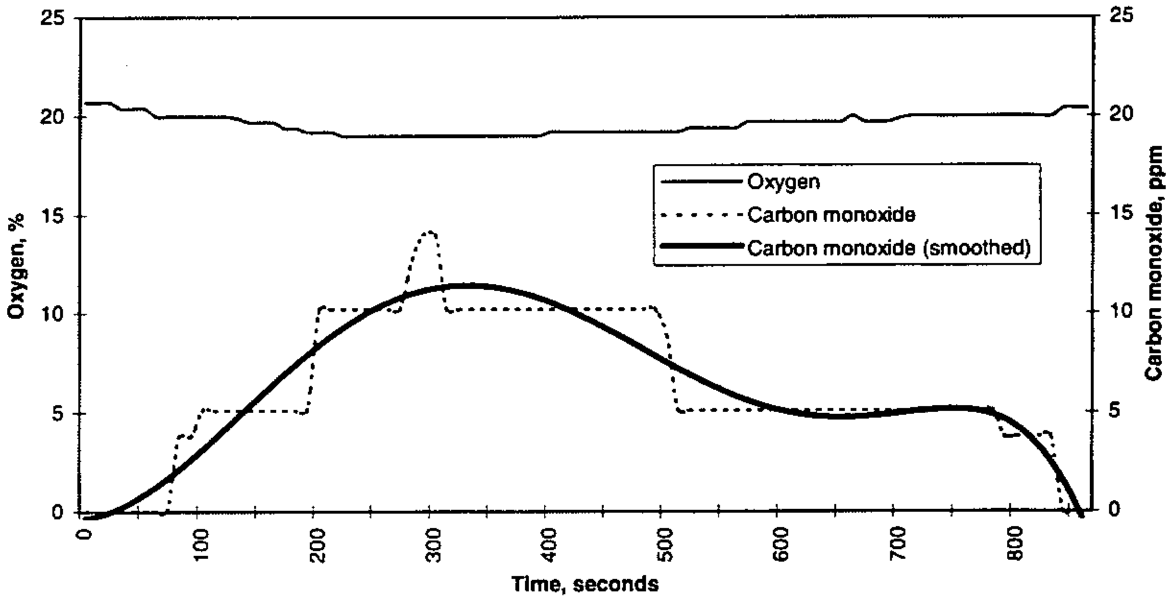

Figure 8: Oxygen and carbon monoxide produced from hexane pool fire.

3.4.3 Wooden crib

A wooden crib constructed of 25 mm x 25 mm sticks of radiata pine in a pyramid shape eight levels high and weighing 3.65 kg (mc 11%) was ignited on the load cell. Figure 9 shows the heat output produced on the basis of mass loss and an assumed effective heat of combustion of 13 MJ/kg (Hadvig, 1981), as well as the corresponding maximum temperature recorded on a thermocouple tree 0.8 m from the centre of the fire plume. The estimated maximum heat output was approximately 55 kW, occurring about 450 seconds after ignition, after which the fire decayed to a mass of glowing embers. The responses of the smoke alarms are shown in Table 8. The carbon monoxide level (Figure 10) recorded in the kitchen peaked in the early stages of the fire at 150 seconds, when the crib fire was in the early stages of growth. Observations at this time confirmed that the fire was within the crib and probably starved somewhat of air, before strong air currents were established to drag in a fresh supply. The carbon monoxide level dropped significantly to a level of 60 ppm once the fire established itself, and was flaming vigorously, and remained at this level until the fire was reduced to a pile of glowing embers. Carbon monoxide then began to rise again, peaking at 178 ppm. The exposure time at this level was sufficient to activate the two carbon monoxide alarms situated in the kitchen and hallway, at times of 1290 and 1366 seconds respectively.

Table 8: Wooden crib fire

Times to activation of alarms (sec)							
Fuel	Doors	Photo 5	Ionis 5	Photo 4	Ionis 4	Photo 2	Ionis 2
wood	all open	110	70	160	175	226	228

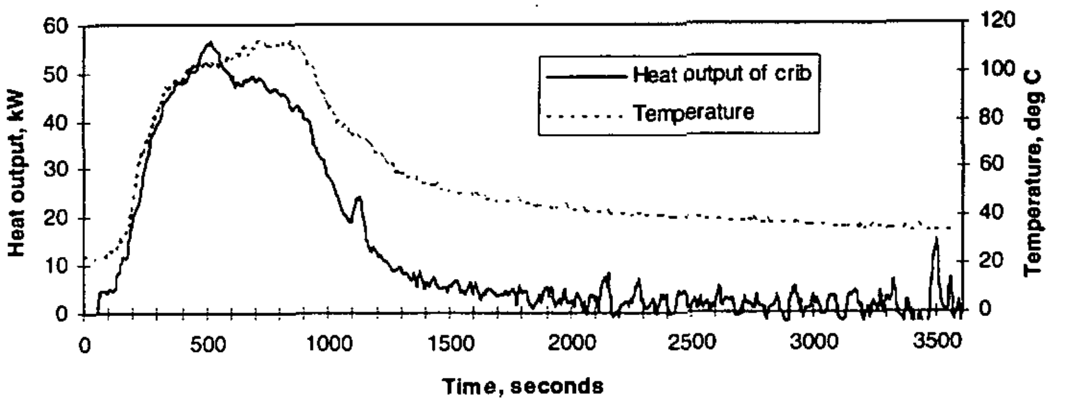

Figure 9: Heat output from wooden crib.

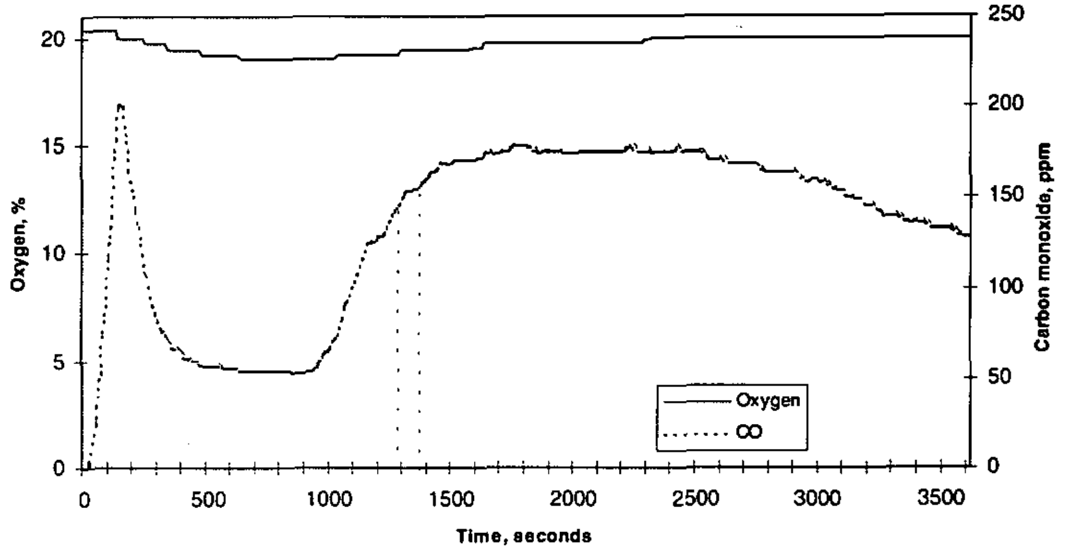

Figure 10: Oxygen and carbon monoxide levels in wood crib fire.

4. DISCUSSION

Photoelectric detectors were shown to give extremely early warning of the occurrence of smouldering-type fires, which were used in the trials conducted and are very slow developing. The hotplate (used approximately 1 kW and sitting on the floor) unfortunately created some artificial draught upwards which assisted the movement of smoke towards the ceiling-mounted smoke alarms. This mixing is not realistic as smouldering fires will typically start from carelessly discarded cigarettes or hot coals from a fireplace deposited on carpet. To confirm that a low heat input smouldering fire is also capable of triggering smoke alarms a consistently smouldering low heat output source was required. Newsprint soaked in sodium nitrate solution and then dried was found to be an excellent source of cooler smoke (in the absence of the hotplate) for evaluating the performance of the smoke alarms. Cut into strips 100 mm wide, it smouldered at a constant rate and was found to be a reliable means of smoke production. Generally alarm times were later than with those produced using the hotplate, but not by a significant amount. Such a comparison is difficult because of the constant rate of smoke production for the smouldering strip compared with the increasing rate as the hotplate heated up and produced more smoke. The photoelectric alarms preceded the ionisation alarms for both hot and cool smoke from a smouldering source.

4.1 Flaming Fire Results

Alarm responses in the trials involving flaming fire sources differed significantly from those with smouldering fires. Not unexpectedly, the ionisation alarms operated first, but more importantly, the time lapse between the two alarm types was reduced due to the more rapid development of the fire. However, this benefit was countered by the hazard developing faster and less time being available for action/escape.

4.2 Review of a Fully Developed Fire from an Earlier Research Programme

In a previous experimental series (Collier, 1997) a fire originating in the lounge/dining/kitchen area with the door to the hallway closed was allowed to develop to a flashover condition before extinguishment by the fire service. An ionisation smoke alarm on the ceiling in the hallway was activated by smoke leakage through the gaps in the door frame. At the time of smoke alarm activation (140 seconds) the temperature in the hallway, at the ceiling, had risen only 2 to 4°C and only the slightest smokey haze was visible. At the same time the stage of fire development in the lounge had progressed from the rubbish bin to the curtains and onto the sofa, which were all close together. Smoke was filling the compartment and the temperature in the upper layer had risen to 150°C but a rapid rise in temperature and the shattering of glass in the windows had not yet commenced. Although escape from the hallway through the lounge/dining/kitchen areas, where the two external doors are, would be unlikely due to the smoke level, the closed hallway door afforded sufficient protection for escape from ground-level windows.

4.3 Carbon Monoxide Alarms

Activation of the CO alarms to smouldering fires was achieved in two trials with a large wooden crib and with a telephone directory comprising 500 leaves of paper placed on the hotplate. The lounge to the hallway was closed, allowing the smoke to accumulate in the one compartment. Alarm times in the kitchen were 3124 and 3497 seconds respectively, in each case well beyond the activation times of the photoelectric and ionisation alarms in the same compartment. The peak concentration of CO was 128 ppm, recorded at 5300 seconds in the trial with the paper on the hotplate. The integrated product of CO concentration by time was computed at alarm time and compared with the specified alarm level of the device. The results from the smouldering crib trial are shown in Figure 11.

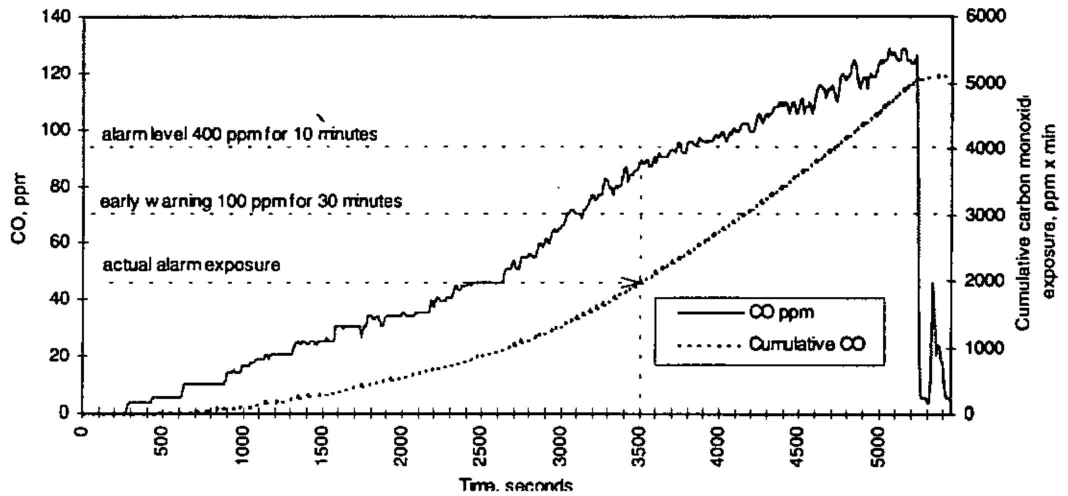

Figure 11: Carbon monoxide alarm response to smouldering crib fire.

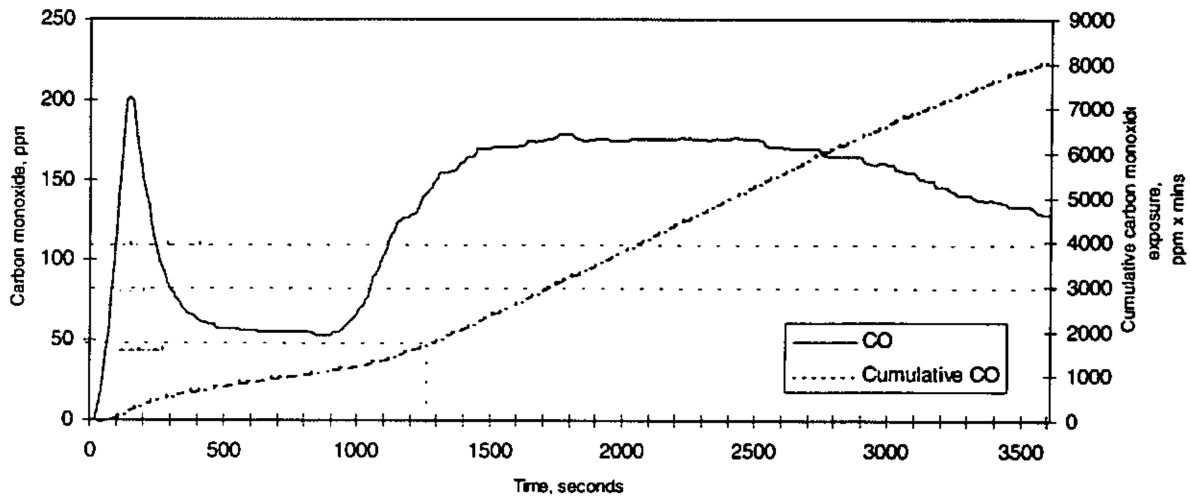

Figure 12: Carbon monoxide alarm response to flaming crib fire.

Figures 11 and 12 show the carbon monoxide levels recorded beside the carbon monoxide alarm located in the kitchen. The right-hand vertical axis is the cumulative carbon monoxide level, the same basis on which the alarms operate. This method of CO exposure in the sensor mechanism mimics the accumulation of COHb (carboxyhaemoglobin) in the blood of humans (and other animals), which is a stable compound preventing oxygen uptake in the lungs. The operating mechanism of the detector involves the passage of light through sensor discs to a receiver. When no CO is present light passes through the discs freely, but when the sensor is exposed to CO the discs darken and, once a critical amount of light is blocked, the alarm sounds. The sensor mechanism regains transparency with reducing levels of CO exposure. The alarm levels of the devices used in these trials were set at factory levels to activate before a 10% level of COHb could typically accumulate in the blood of persons exposed.

The alarm levels required by UL (Underwriters Laboratories Inc, 1992) Standard 2034 are exceeded by the CO alarms under trial and equate to (sourced from manufacturers' specifications) the following:

Full alarm level:

400 ppm CO in 10 minutes	(or 4000 ppm x minutes) (UL 2034 time 15 minutes)
200 ppm CO in 25 minutes	(or 5000 ppm x minutes) (UL 2034 time 35 minutes)
100 ppm CO in 60 minutes	(or 6000 ppm x minutes) (UL 2034 time 90 minutes)
40 ppm CO in 1 to 6 days	(or 57600 to 345,600 ppm x minutes)

Early warning level:

100 ppm CO in 30 minutes (or 3000 ppm x minutes)

The lowest cumulative full alarm level of 400 ppm in 10 minutes and the early warning level of 100 ppm in 30 minutes are included in Figures 11 and 12 for comparison with the actual measured alarm conditions. In each case the alarm activated before the early warning level was reached, but it should be remembered that the alarm levels are the minimum requirements and are therefore set conservatively to allow for any drift that may occur as the detector ages, although aging may actually make the detector mechanism more sensitive.

4.4 General Advice on Use

Carbon monoxide alarms are NOT intended as an alternative to smoke alarms. Their function is entirely different and they are designed to detect an accumulating hazard over time, such as from gas heaters and gas hot water cylinders. The devices on trial performed this function conservatively, giving an early warning of the development of carbon monoxide before a hazard to life developed from that species (CO). The smoke alarms had activated well in advance and the smoke hazard was very apparent and irritating at this stage.

5. COMPUTER MODELLING OF OCCUPANT RESPONSE AND SURVIVABILITY

Using a series of limited fires of various types, the performance of ionisation and photoelectric smoke alarms, as reported by the literature cited, has been verified. What the trials could not verify is the benefit to life safety that early warning by smoke alarms would have if the fires progressed further. To do this the Hazard 1.2 (NIST 1994) model has been used to extrapolate some likely scenarios to determine under which conditions smoke alarms would prevent loss of life and pinpoint situations where lives are more at risk.

For the purposes of modelling the response of smoke alarms the assumptions outlined in the literature survey of this report will be followed.

Smoke alarms can be treated as low-temperature heat detectors with no thermal lag (RTI = 0) where a measured temperature rise of 2 to 3 °C (Collier, 1997) is required for activation. The basis for this is, if the passage of hot gases from a fire source to a smoke alarm has caused a temperature rise then smoke or combustion products must be present. Selection of this temperature rise was found to agree more closely with the actual alarm times in the trials, than if a 13°C rise was used as suggested by Evans and Stroup (1986), which would have given a conservative estimate of alarm time. Unfortunately, making a distinction between the two to determine whether an ionisation or a photoelectric alarm will activate first is not so straight forward and has not been attempted in this study.

Hazard 1.1 (NIST, 1991) in its EXITT module for occupant response, escape, tenability and survival uses optical density as the basis for alarm activation. The critical level is OD = 0.015 (units m^{-1}) and a layer depth of 0.15 m assumed at the ceiling. Therefore, the greater the OD, the shorter distance it is possible to see through the smoke. When attempting to model a fire scenario the dependence of the OD on the soot yield of the fuel is of prime importance while the selection of the C/CO_2 ratio for the fuel makes a significant difference to the OD and to when the alarms will activate. If $C/CO_2 = 0$ in the fire input then EXITT will not activate the smoke alarms at all.

Figure 21 in Appendix C shows a layout of the house with the various EXITT nodes and connections which escaping occupants can follow.

EXITT files (with extension .BLD) describe the building layout in terms of Figure 21. Alarm locations and noise levels (alarm and background) are included, as are the occupants of the building using the parameters of age, sex, state of awakedness and location. Typical occupant responses are included based on documented human behaviour. Survivability is also assessed according to exposure to narcotic gases and heat, based mainly on animal studies. The second part of the file is the occupant responses and outcome. A typical EXITT input file (as used in the following trials) is included in appendix D.

5.1 Trial Fire to Assess Occupant Responses and Survivability

For the purposes of these trials to determine the likely outcome of a fully developed fire the following combined scenario was selected:

- A smouldering fire originating in the lounge spreads after a significant development time to fully involve the contents of the lounge/dining and, eventually, the kitchen areas.

- The scenario begins with the heat and smoke release typical of the hotplate trials reported earlier and shown in Figure 4, and with the door between the lounge and hallway closed.

- The second part of the scenario is based on the fully developed scenario reported by Collier (1997). Such a scenario could begin with a radiant heater left on after the occupants had retired for the night. The heater is situated close enough to furniture or other combustibles so that a considerable period of smouldering occurs (in this case 2200 seconds, 37 minutes) before ignition.

- Once ignition occurs the fire develops rapidly, spreading across articles of furniture to a flashover situation, peaking at approximately 1500 kW.

The CFAST file for this scenario is listed in Appendix B. Graphs of the temperatures, hot layer levels, carbon monoxide, optical density, heat input, oxygen and carbon dioxide are shown in Figures 13 to 20. The door to the hallway prevents fire spread for a limited time; initially hot gases open up passages around the edges before the door is burnt through. At this stage hot gases fill the remainder of the house, except bedroom 2 and the bathroom where the doors are closed.

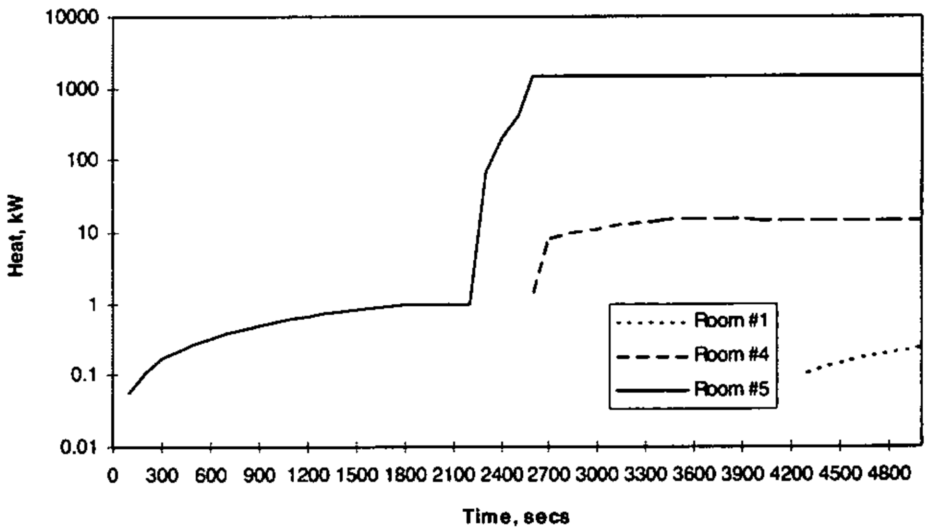

Figure 13: Heat output of fire(s).

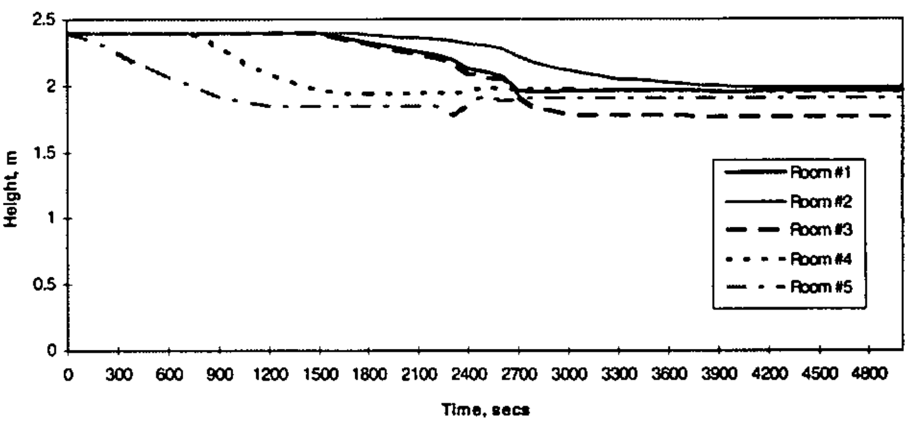

Figure 14: Hot layer height.

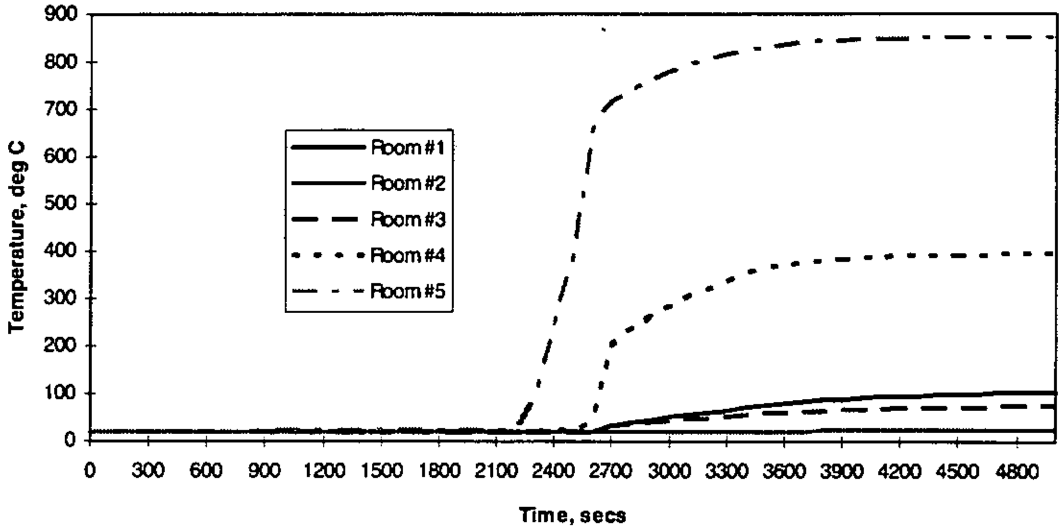

Figure 15: Upper layer temperature.

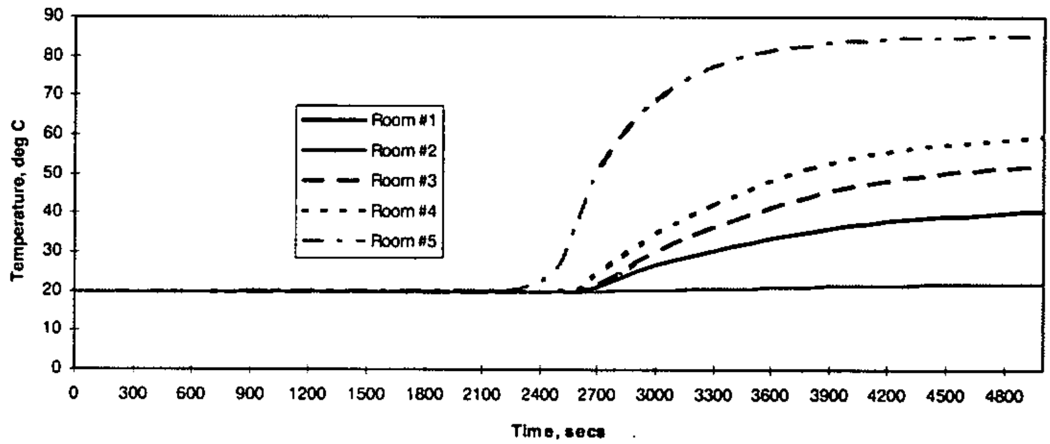

Figure 16: Lower layer temperature.

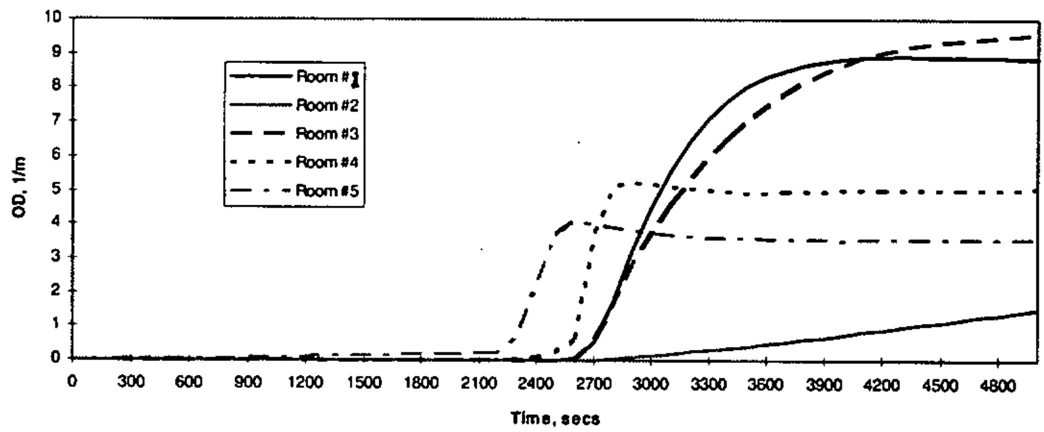

Figure 17: Optical density.

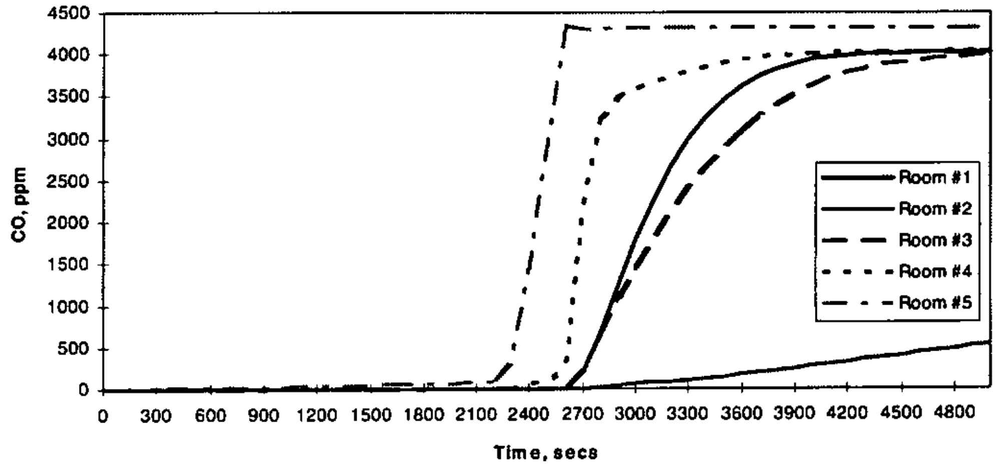

Figure 18: Carbon monoxide in upper layer.

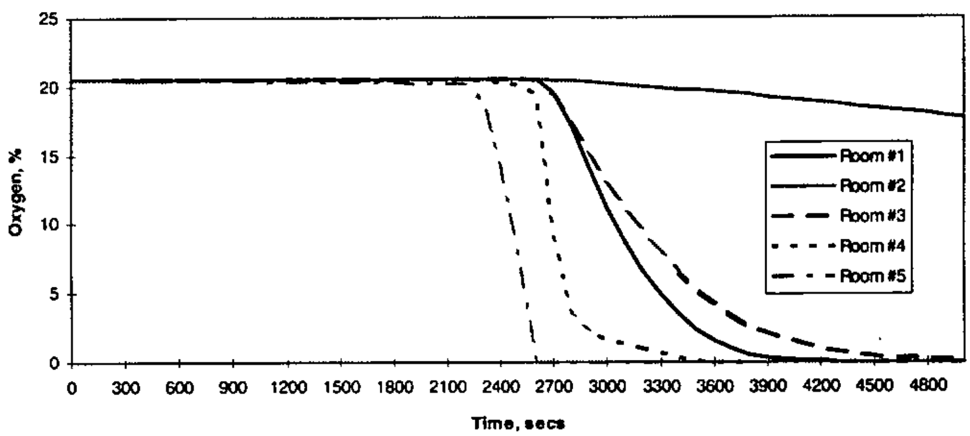

Figure 19: Oxygen in upper layer.

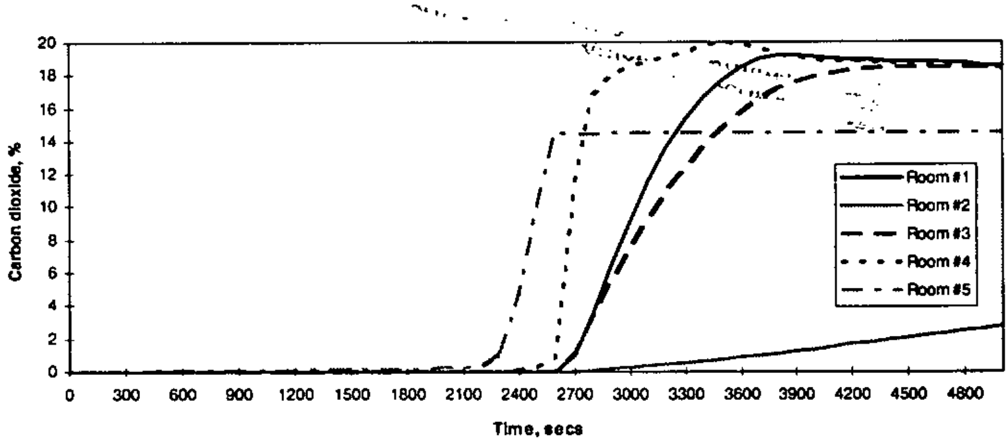

Figure 20: Carbon dioxide in upper layer.

The effects of the fire on occupant response were modelled assuming four occupants of the house are all sleeping, as described in Table 9. The locations refer to the EXITT node numbers in Figure 21 and the sleeping penalties of 0 for average sleepers and 50 for deep sleepers. A scenario where the occupants are sleeping at night time was chosen on the basis that this is the time and circumstance where most deaths occur (Cropp, 1991) and it is more challenging for EXITT to handle. In a daytime scenario the fire may be discovered before a smoke alarm is activated and escape is more likely.

Table 9: Occupants in house

Person	Location	Age	Sex	State	Sleep Penalty	Require Assistance	Travel Speed
1	1	41	Male	Asleep	50	No	1.3
2	1	41	Female	Asleep	0	No	1.3
3	2	12	Male	Asleep	50	No	1.3
4	3	3	Female	Asleep	50	Yes	1.3

The outcomes of the fire scenario described, with a single smoke alarm in the various locations listed in Table 10 (refer to the Figure in Appendix C for EXITT - node number and alarm locations) are summarised as follows. A typical output file can be found in Appendix E.

The most favourable outcome is a smoke alarm in the lounge, as 151 seconds alarm time provides adequate time for escape through the door at node (7). This favourable outcome depends on the alarm being heard by occupant (2) (female 41) through the closed lounge/hallway door.

Had she, as well as the other occupants, been a deep sleeper then the occupants would awake at the same time had there been no alarms - that is 2614 seconds. At this time escape along the hallway and out through the doors is no longer possible due to smoke. The occupants are then trapped in the building with the only means of escape being through windows, which fortunately in this case are at ground level. Escape is not assumed as windows may be fitted with burglar-proof catches, so occupants 1, 2 and 4 continue to be exposed to the products of a developing fire which eventually burns through the hallway door. The occupants die at approximately 3750 seconds. The twelve year old male in bedroom 2 behind a closed door remains asleep and unaffected at 5000 seconds. The other occupants are unable to reach bedroom 2 due to smoke in the hallway.

A hallway-mounted smoke alarm activating at 2182 seconds wakes the female 41, in time to permit entry into the hallway before the smoke is too bad. In this instance the parents are successful in reaching the children, but then are still unable to exit the building. Two occupants are trapped in bedroom 3 with the door open and die at 3750 seconds. The other two occupants in bedroom 2 with the door closed remain alive but still trapped at 5000 seconds. Although the model does not make the decision it is reasonable to assume that the occupants in bedroom 3 would close the door and survive to 5000 seconds as well.

Table 10: Summary of outcomes, survival

Alarms, no of (in compartment)	First alarm	Occupants	Awakened	Trapped	Dead	File*
none	-		2614s	3	1,2,4	SAN.SRV
1 (4)	2182s		2192s	3	1,2,4	SA4.SRV
1 (5)	151s	all escaped	161s	-	-	SA5.SRV
1 (1)	2536s		2616s	3	1,2,4	SA1.SRV
1 (2)	2686s		2614s	3	1,2,4	SA2.SRV
1 (3)	2523s		2616s	3	1,2,4	SA3.SRV

Given the above outcomes it appears that, in order to give occupants the most favourable chances of escape, interconnected alarms offer a significant advantage. Interconnected alarms reduce the delays in alerting occupants which may be caused by closed doors which both prevent smoke getting to alarms and reduce the sound level of those alarms in a room of fire origin some distance away.

Smoke alarms producing 88dB at 3 m sound level were used throughout this analysis. Adjustments to the sound level at nodes remote from alarms were then made on the basis of reducing the sound level by 6dB each time the distance away from alarms is doubled and reducing a further 12dB for sound transmission through closed doors. This is similar to the examples in Hazard 1.1 (NIST, 1991). However, the SFPE Handbook of Fire Protection Engineering (SFPE, 1995) presents a more comprehensive method for evaluating the sound attenuation through barriers and spaces.

The above scenario was repeated with an elderly couple (80 years) substituted for the 41-year-old couple with a 3-year-old female sleeping in bedroom 2 with the door closed. The outcomes of the same trials were exactly the same; age alone makes no difference. However, if the requirement for assistance in escaping is included for all occupants, meaning they remain in their initial positions (in bed) and are exposed to the prevailing conditions, and they are not rescued by external assistance, then deaths are expected. This scenario is particularly relevant to rest home and care situations where smoke alarms may be installed but the majority of residents may not be able to take the necessary survival action themselves.

For further reading, a similar Hazard 1.1 (NIST, 1991) analysis of an actual rest home fire, with six fatalities, by Byrne (1994) is recommended.

6. SUMMARY AND CONCLUSIONS

6.1 Literature Survey

Significant findings in the literature are as follows:

1. The different smoke-detecting mechanisms in smoke alarms are more sensitive to different types of smoke. Therefore smoke type and fire type will affect response times. Ionisation alarms, the type in almost universal domestic use respond to

products of combustion rather than smoke particles. Often the combustion products are invisible at alarm time because they originate from fast-developing flaming fires. Photoelectric-type smoke alarms are less common and, while available for domestic use, are more expensive than ionisation type alarms. They depend on visible smoke to operate, and most often they respond better to smoke associated with smouldering fires.

2. Photoelectric alarms are less likely to react to the results of cooking and this makes them far more suitable for installation near kitchens or in confined spaces, such as bedsits, where false alarms with ionisation types of smoke alarm could be a problem.

3. Fires occurring when the household is asleep may start anywhere, but locating the smoke alarm where it is most likely to waken a heavy sleeper behind a closed bedroom door offers a far greater chance of escape than if the alarm was out of earshot downstairs. It also follows that it is safer to sleep with the bedroom door open.

4. For minimum protection an ionisation smoke alarm should be installed either just outside a bedroom (in a hallway) or at the top of the stairs in multi-storey dwellings. An additional smoke alarm (preferably an optical type) fitted downstairs in or near a kitchen will improve this minimum level of protection.

5. A comprehensive level of protection can only be achieved by strategically located smoke alarms of the appropriate type (ionisation or photoelectric) with the important requirement that they all be interconnected so that if one alarm activates the whole network sounds the alarm. This scenario reduces the dual problems of hearing distant alarms and the necessity for smoke to travel significant distances to activate individual alarms. Maximising the interval between alarm, and development of hazardous conditions dramatically improves the chances of successful escape.

6. Hazardous conditions in escape routes may occur before smoke reaches a detector to activate it. Therefore location is important to ensure the earliest practical warning, particularly if egress options are limited as they are in multi-storey buildings.

7. To counter the incidence of unsuccessful alarm operation, education in the testing and maintenance of alarms as well as general fire safety should be actively promoted. This assumes that alarms have been installed correctly in the first instance, which is best achieved in the initial stages of a promotional campaign to educate occupiers on correct installation and maintenance procedures.

6.2 Experimental Trials and Modelling Prediction

The experimental trials confirmed the operating properties of ionisation and photoelectric alarms found in the literature review, and also demonstrated their sensitivity and early warning potential.

Prediction of alarm times using CFAST and EXITT is reliable enough for modelling occupant arousal and actions, although no distinction can be made between ionisation and photoelectric alarms.

1. In single-level dwellings where escape would be possible through windows, single point alarms without interconnection provide a minimum level of protection. In the same situation where additional security measures such as lockable window catches are fitted to prevent intruders, then the level of fire protection needs to be increased to provide additional escape time through doors before such routes are blocked by smoke accumulation.

2. For multi-level dwellings where the escape option through windows is limited, the only practical and safe solution is for strategically placed interconnected alarms on each level. Otherwise remote alarms may not be heard and escape opportunities will be limited.

3. Apart from life safety issues the early detection of fire by an interconnected system may not only give the occupants additional time to escape safely, but may also provide some opportunity for investigation and extinguishment of a fire before it develops into a conflagration.

4. Assuming the successful operation of an alarm system, the actual occupant behaviour is very dependent on there being at least one occupant who can and does respond to an alarm. Various factors which have a significant impact on survival include an occupant's state, such as: deep sleep, influence of drugs or alcohol and whether assistance is required. Very young and very old people or people with disabilities, are in the category of those likely to require assistance and whether that assistance is rendered ultimately determines an occupant's fate.

6.3 General Comments

The most important advice that can be given regarding smoke alarms is that the manufacturer's recommendations regarding installation and maintenance must be followed. To improve the chances of escape then the earliest possible warning of a developing fire hazard is required.

The results of the modelling of fire development and occupant response confirm the significant benefits of a comprehensive and interconnected smoke alarm system compared with the level of safety achieved with just a single, even if ideally located, smoke alarm.

7. REFERENCES

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APPENDIX A.

Specification of materials used in construction of experimental dwelling, all dimensions in mm.

Floor joists:	150 x 50 at 450 centres Radiata pine
Wall framing, external:	100 x 50 Radiata pine
Wall framing, internal:	75 x 50 Radiata pine
Wall lining:	9.5 mm Standard Gibraltar board
Ceiling lining:	9.5 mm Standard Gibraltar board
Floor lining:	20 mm Pynefloor particleboard
Wall cladding:	6 mm, 240 smooth exterior fibre-cement cladding by James Hardie & Co Pty Ltd.
Roof:	15 deg pitch, Galvanised corrugated steel roofing, with plastic spouting and downpipes
Trusses:	R41 at maximum 1050 centres Radiata pine
Ceiling battens:	70 x 40 at 400 centres Radiata pine
Insulation:	Fibreglass Batts / Polyester Batts by INZCO
Doors, internal:	paint grade interior doors with cardboard honeycomb cores and slimline jambs, by Plyco
Doors, exterior:	Aluminium and glass, by Vantage Aluminium Joinery
Windows:	Aluminium, with condensation channels and double tongue catches, by Vantage Aluminium Joinery
Wall finishing:	None
Ceiling finishing:	None
Plumbing:	None
Electrical wiring:	None
Sprinkler system:	Quick response sprinkler heads (68°C) GEM 990 by Grinell with steel pipework, installed by Wormalds Ltd.
Smoke alarms:	Ionisation alarms by BRK Electronics. Model 86RACBAUS Photoelectric alarms by System Sensor. Model 2012 Carbon monoxide alarms by BRK Brands, Inc. Model NICO M05-0921-000

Note: Results obtained in this study relate only to the samples tested, and not to any other item of the same or similar description. BRANZ does not necessarily test all brands or types available within the class of items tested and exclusion of any brand or type is not to be taken as any reflection on it.

This work was carried out for specific research purposes, and BRANZ may not have assessed all aspects of the products named which would be relevant in any specific use. For this reason, BRANZ disclaims all liability for any loss or deficit, following use of the named products, which is claimed to be reliant on the results published here.

Further, the listing of any trade or brand names above does not represent endorsement of any named product nor imply that it is better or worse than any other available product of its type. A laboratory test may not be exactly representative of the performance of the item in general use.

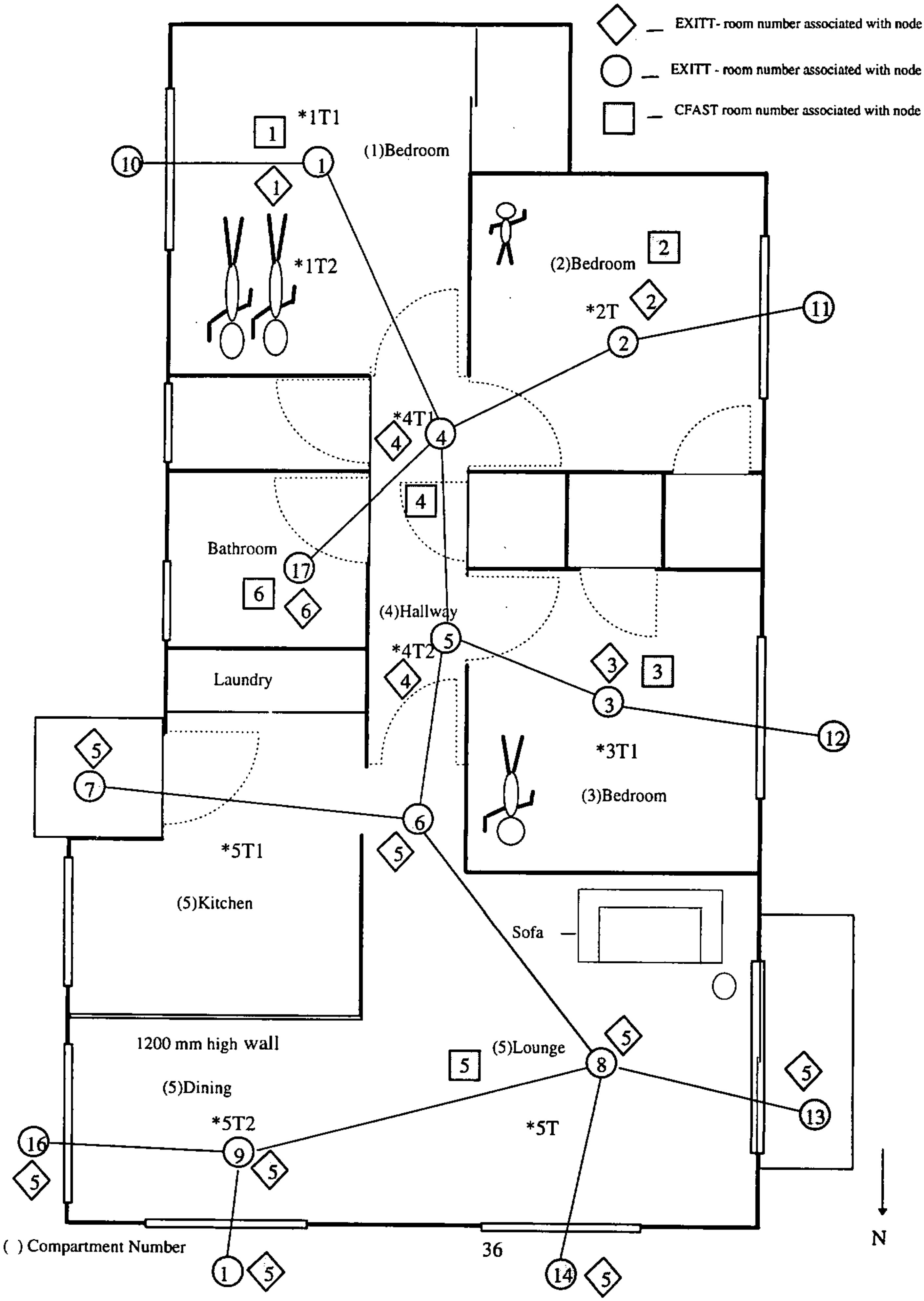
APPENDIX B: CFAST input file

```
VERSN     2                                              BTL Smoke Alarms
TIMES    5000      0    100    100      0
TAMB    293.   101300.        0.
EAMB    293.   101300.        0.
HI/F      0.00     0.00     0.00     0.00     0.00     0.00
WIDTH     2.80     2.46     2.46     0.85     6.00     1.75
DEPTH     3.20     2.86     2.99     3.50     5.00     1.60
HEIGH     2.40     2.40     2.40     2.40     2.40     2.40
HVENT    1  4  1    0.760    2.000    0.000
HVENT    1  7  2    1.420    2.000    0.600    0.000
HVENT    2  4  1    0.760    2.000    0.000
HVENT    2  7  2    1.420    2.000    0.600    0.000
HVENT    3  4  1    0.760    2.000    0.000
HVENT    3  7  2    1.420    2.000    0.600    0.000
HVENT    4  5  1    0.760    2.000    0.000
HVENT    4  6  1    0.760    2.000    0.000
HVENT    5  7  1    1.800    2.000    0.000    0.000
HVENT    5  7  2    4.250    2.000    0.600    0.000
HVENT    5  7  3    1.720    2.000    0.800    0.000
HVENT    5  7  4    0.800    2.000    0.000    0.000
HVENT    6  7  1    0.600    2.000    1.000    0.000
CVENT    1  4  1    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00
CVENT    1  7  2    0.50    0.50    0.50    0.50    0.50    0.50
0.50     0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
0.50     0.50
CVENT    2  4  1    0.01    0.01    0.01    0.01    0.01    0.01
0.01     0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
0.01     0.01
CVENT    2  7  2    0.10    0.10    0.10    0.10    0.10    0.10
0.10     0.10    0.10    0.10    0.10    0.10    0.10    0.10    0.10
0.10     0.10
CVENT    3  4  1    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00
CVENT    3  7  2    0.01    0.01    0.01    0.01    0.01    0.01
0.01     0.01    0.01    0.01    0.01    0.01    0.01    0.01    0.01
0.01     0.01
CVENT    4  5  1    0.01    0.01    0.01    0.01    0.01    0.01
0.01     0.01    0.01    0.01    0.01    0.01    0.02    0.10    0.20
0.70     0.80
CVENT    4  6  1    0.00    0.00    0.00    0.00    0.00    0.00
0.00     0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
0.00     0.00
CVENT    5  7  1    0.10    0.10    0.10    0.10    0.30    0.50
0.60     0.70    1.00    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00
CVENT    5  7  2    0.10    0.10    0.10    0.20    0.40    0.60
0.70     1.00    1.00    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00
CVENT    5  7  3    0.10    0.10    0.10    0.20    0.40    0.40
0.50     0.50    0.60    1.00    1.00    1.00    1.00    1.00    1.00
1.00     1.00
```

```
CVENT   5  7  4   0.10   0.10   0.10   0.20   0.30   0.50
0.60   0.70   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1.00   1.00
CVENT   6  7  1   0.00   0.00   0.00   0.00   0.00   0.00
0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00
0.00   0.00
CEILI GYP1/2    GYP1/2    GYP1/2    GYP1/2    GYP1/2    GYP1/2
WALLS GYP1/2    GYP1/2    GYP1/2    GYP1/2    GYP1/2    GYP1/2
FLOOR PARTBDHD  PARTBDHD  PARTBDHD  PARTBDHD  PARTBDHD
PARTBDHD
CHEMI    16.   50.  12.0    10000000.  288. 388. 0.000
LFBO    5
LFBT    2
FPOS     0.00    0.00    0.00
FTIME    1800.   2220.   2360.   2400.   2445.   2460.   2470.   2510.
2560.   2570.   2580.   2590.   2635.   2670.   4000.   5000.
FMASS   0.0000 0.0001 0.0001 0.0115 0.0202 0.0299 0.0385 0.0364
0.0412 0.0612 0.1865 0.1998 0.1998 0.1998 0.1998 0.1998 0.1998
FHIGH     0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
0.50    0.50    0.50    0.50    0.75    0.75    0.75    0.75    0.75
FAREA     0.50    0.50    0.50    0.50    0.50    0.50    0.50    0.50
0.50    0.50    0.50    0.60    0.60    1.00    1.00    1.00    1.00
FQDOT   0.00       1.00E+03 1.00E+03 1.15E+05 2.02E+05 2.99E+05
3.85E+05 3.64E+05 4.12E+05 6.12E+05 1.86E+06 2.00E+06 2.00E+06
2.00E+06 2.00E+06 2.00E+06 2.00E+06
CJET OFF
CT      1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000
HCR     0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080
CO      0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019
OD      0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013
STPMAX  5.00
DUMPR SMOK3.HI
DEVICE 1
WINDOW  0     0. -100. 1280. 1024. 1100.
GRAPH   1  100.    50.    0.  600.  475.   10.   3 TIME HEIGHT
GRAPH   2  100.   550.    0.  600.  940.   10.   3 TIME CELSIUS
GRAPH   3  720.    50.    0. 1250.  475.   10.   3 TIME
FIRE_SIZE(kW)
GRAPH    4  720.   550.    0. 1250.  940.   10.   3 TIME O|D2|O(%)
HEAT  0 0 0 0 3  1 U
HEAT  0 0 0 0 3  2 U
HEAT  0 0 0 0 3  3 U
HEAT  0 0 0 0 3  4 U
HEAT  0 0 0 0 3  5 U
HEAT  0 0 0 0 3  6 U
TEMPE 0 0 0 0 2  1 U
TEMPE 0 0 0 0 2  2 U
TEMPE 0 0 0 0 2  3 U
TEMPE 0 0 0 0 2  4 U
TEMPE 0 0 0 0 2  5 U
TEMPE 0 0 0 0 2  6 U
INTER 0 0 0 0 1  1 U
INTER 0 0 0 0 1  2 U
INTER 0 0 0 0 1  3 U
```

INTER	0	0	0	0	1	4	U
INTER	0	0	0	0	1	5	U
INTER	0	0	0	0	1	6	U
O2	0	0	0	0	4	1	U
O2	0	0	0	0	4	2	U
O2	0	0	0	0	4	3	U
O2	0	0	0	0	4	4	U
O2	0	0	0	0	4	5	U
O2	0	0	0	0	4	6	U

APPENDIX C: Figure 21: Plan of house showing EXITT nodes



APPENDIX D: Typical EXITT file (*.BLD) for building and occupants

```
ROOMS 6 17
NODESTOFAST  1 2 3 4 4 5 7 5 5 7 8 8 7 8 8 8 6
NODESTOEXITT 1 2 3 4 4 5 5 5 5 1 2 3 5 5 5 5 6
NODEHGT 2.4 2.4 2.4 2.4 2.4
 2.4 2.4 2.4 2.4 2.4
 2.4 2.4 2.4 2.4 2.4
 2.4 2.4
FLRHGT 0.  0.  0.  0.  0.
 0.  0.  0.  0.  0.
 0.  0.  0.  0.  0.
 0.  0.
AMBNOISE 35 35 35 35 35
 35 35 35 35 35
 35 35 35 35 35
 35 35
DETECTORS 3
-1 -1 -1.
8 5 1
79 79 80 80 81 85 81 88 85 78 78 79 82 82 82 82 80
82 82 82 85 88 82 79 79 79 79 79 79 79 79 79 79 82
88 82 82 82 82 81 80 81 81 82 80 80 80 80 80 80 82
NODETONODE 16
  1  4      2        1  10      1
  2  4      2        2  11      1
  3  5      2        3  12      1
  4  5      2        4  17      2
  5  6      1.5
  6  7      1.5      6   8      3
  8  9      2        8  13      1.5      8   14      1.5
  9  15     1.5      9  16      1.5
OCCUPANTS 4
41 41 12 3
1  0  1  0
0  0  0  0
1  1  2  3
0  0  0  1
50 0 50 50
-1 -1 -1 -1.
```

APPENDIX E: Typical EXITT result file showing alarm response, action of occupants and survival, file type (*.SRV).

```
SURVIVAL Version:  20.0 - Creation Date: 10/10/90 - Run Date: 06/25/96
CFAST HISTORY FILE:  SMOK3.HI
BUILDING/OCCUPANT FILE:  SMOK3.BLD
PRINTED OUTPUT FILE:  SMOK3.SRV
PLOTTING OUTPUT FILE:  SMOK3.PLT


NO. OF ROOMS (RUN WITH FAST)       6
NO. OF DOORS                       2
NO. OF WINDOWS                     6
TOTAL NUMBER OF NODES             17


EXITT NODE    EXITT ROOM    FAST ROOM    ROOM      FLOOR
  NUMBER        NUMBER        NUMBER     HEIGHT    HEIGHT
                                          (M)       (M)
     1             1             1        2.4       0.0
     2             2             2        2.4       0.0
     3             3             3        2.4       0.0
     4             4             4        2.4       0.0
     5             4             4        2.4       0.0
     6*            5             5        2.4       0.0
     7             5             7        2.4       0.0
     8*            5             5        2.4       0.0
     9*            5             5        2.4       0.0
    10             1             8        2.4       0.0
    11             2             8        2.4       0.0
    12             3             8        2.4       0.0
    13             5             7        2.4       0.0
    14             5             8        2.4       0.0
    15             5             8        2.4       0.0
    16             5             8        2.4       0.0
    17             6             6        2.4       0.0
* INDICATES NODE IS IN BURN ROOM


NODE NUMBER       NOISE LEVEL (DECIBELS)
     1                    35
     2                    35
     3                    35
     4                    35
     5                    35
     6                    35
     7                    35
     8                    35
     9                    35
    10                    35
    11                    35
    12                    35
    13                    35
    14                    35
    15                    35
    16                    35
    17                    35


NUMBER OF SMOKE DETECTORS:        3


SMOKE DET NO.         NODE       ACTIVATION TIME (SEC)
      1                4         DETERMINED BY EXITT TO BE   2182.0 SECONDS
      2                4         DETERMINED BY EXITT TO BE   2182.0 SECONDS
      3                4         DETERMINED BY EXITT TO BE   2182.0 SECONDS
EXITT NODE NUMBER      ALARM LEVEL (DECIBELS)
                              1    2    3
     1                       79   79   79
     2                       79   79   79
     3                       80   80   80
     4                       80   80   80
     5                       81   81   81
     6                       85   85   85
     7                       81   81   81
     8                       88   88   88
     9                       85   85   85
    10                       78   78   78
    11                       78   78   78
    12                       79   79   79
    13                       82   82   82
    14                       82   82   82
    15                       82   82   82
    16                       82   82   82
```

17		80	80	80

EDGE LIST

FROM NODE	TO NODE	DISTANCE (M)
1 -	4	2.00
-	10	1.00
2 -	4	2.00
-	11	1.00
3 -	5	2.00
-	12	1.00
4 -	1	2.00
-	2	2.00
-	5	2.00
-	17	2.00
5 -	3	2.00
-	4	2.00
-	6	1.50
6 -	5	1.50
-	7	1.50
-	8	3.00
7 -	6	1.50
8 -	6	3.00
-	9	2.00
-	13	1.50
-	14	1.50
9 -	8	2.00
-	15	1.50
-	16	1.50
10 -	1	1.00
11 -	2	1.00
12 -	3	1.00
13 -	8	1.50
14 -	8	1.50
15 -	9	1.50
16 -	9	1.50
17 -	4	2.00

TOTAL NUMBER OF DIRECTED EDGES 32

NUMBER OF PEOPLE 4

PERSON	LOCATION	AGE	SEX	STATE	SLEEP PENALTY	REQUIRE ASSISTANCE	TRAVEL SPEED
1	1	41	MALE	ASLEEP	50.0	NO	1.30
2	1	41	FEMALE	ASLEEP	0.0	NO	1.30
3	2	12	MALE	ASLEEP	50.0	NO	1.30
4	3	3	FEMALE	ASLEEP	50.0	YES	1.30

ACTIONS TAKEN BY PERSON 1

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
1	1	0.0	--	--	--	INITIAL POSITION
1	1	2192.0	--	2	--	BEING AWAKENED
1	1	2202.0	--	--	6	INVESTIGATE FIRE
4	4	2203.5	--	--	6	ARRIVE AT NEW NODE
5	4	2205.1	--	--	6	ARRIVE AT NEW NODE
5	4	2205.1	--	--	6	BAD SMOKE - CURRENT ACTION STOPPED
5	4	2208.1	3	--	2	GO TO AWAKEN OTHER
4	4	2209.3	3	--	2	ARRIVE AT NEW NODE
2	2	2210.4	3	--	2	ARRIVE AT NEW NODE
2	2	2210.4	3	--	--	AWAKEN OCCUPANT
2	2	2212.9	--	--	--	LEAVE BUILDING
11	8	2213.5	--	--	11	ARRIVE AT WINDOW

ACTIONS TAKEN BY PERSON 2

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
1	1	0.0	--	--	--	INITIAL POSITION
1	1	2192.0	1	--	--	AWAKEN OCCUPANT
1	1	2197.0	4	--	3	GO TO RESCUE OTHER
4	4	2198.5	4	--	3	ARRIVE AT NEW NODE
5	4	2200.1	4	--	3	ARRIVE AT NEW NODE
3	3	2201.6	4	--	3	ARRIVE AT NEW NODE
3	3	2201.6	4	--	--	PREPARE ANOTHER TO LEAVE BUILDING
3	3	2208.6	--	--	--	ASSIST OTHER(S) OUT OF BUILDING
12	8	2209.4	4	--	12	ARRIVE AT WINDOW

ACTIONS TAKEN BY PERSON 3

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
2	2	0.0	--	--	--	INITIAL POSITION
2	2	2210.4	--	1	--	BEING AWAKENED
2	2	2215.4	--	--	--	LEAVE BUILDING
11	8	2216.0	--	--	11	ARRIVE AT WINDOW

ACTIONS TAKEN BY PERSON 4

NODE	ROOM	TIME	SAV-ING	SAVED BY	DESTI-NATION	ACTION
3	3	0.0	--	--	--	INITIAL POSITION
3	3	2201.6	--	2	--	RECEIVING ASSISTANCE
3	3	2208.6	--	2	--	LEAVE BUILDING WITH ASSISTANCE
12	8	2209.4	--	2	12	ARRIVE AT WINDOW WITH ASSISTANCE

PERSON 1

TIME (SEC)	NODE	CONDITION	CAUSE	FED1 FED2 FED3	TEMP1 TEMP2	CT (G-MIN/M3)	FLUX (KW-SEC/M2)
2220.	11	WINDOW*		0.000E+00 0.158E-01 0.778E-01	0.200E+02 0.000E+00	0.219E-01	0.197E-02
5000.	11	FINAL TIME		0.000E+00 0.558E+00 0.264E+00	0.238E+02 0.000E+00	0.732E+02	0.296E+02

PERSON 2

TIME (SEC)	NODE	CONDITION	CAUSE	FED1 FED2 FED3	TEMP1 TEMP2	CT (G-MIN/M3)	FLUX (KW-SEC/M2)
2210.	12	WINDOW*		0.000E+00 0.158E-01 0.776E-01	0.200E+02 0.000E+00	0.196E-01	0.526E-04
3050.	12	INCAPACITATED	FED2	0.000E+00 0.100E+01 0.358E+00	0.450E+02 0.178E-01	0.422E+02	0.475E+02
3180.	12	INCAPACITATED	FED3	0.776E-02 0.268E+01 0.100E+01	0.489E+02 0.605E-01	0.701E+02	0.698E+02
3640.	12	INCAPACITATED	FED1	0.503E+00 0.354E+02 0.276E+02	0.618E+02 0.260E+00	0.213E+03	0.183E+03
3750.	12	DEAD	FED1	0.100E+01 0.542E+02 0.475E+02	0.641E+02 0.314E+00	0.251E+03	0.214E+03
3800.	12	INCAPACITATED	TEMP1	0.127E+01 0.643E+02 0.587E+02	0.650E+02 0.339E+00	0.269E+03	0.229E+03
4240.	12	INCAPACITATED	CT	0.494E+01 0.218E+03 0.230E+03	0.712E+02 0.611E+00	0.450E+03	0.387E+03
4500.	12	INCAPACITATED	FLUX	0.760E+01 0.344E+03 0.360E+03	0.731E+02 0.787E+00	0.563E+03	0.488E+03
4810.	12	INCAPACITATED	TEMP2	0.109E+02 0.509E+03 0.520E+03	0.749E+02 0.100E+01	0.696E+03	0.609E+03
5000.	12	FINAL TIME		0.131E+02 0.621E+03 0.624E+03	0.758E+02 0.114E+01	0.784E+03	0.691E+03

PERSON 3

TIME (SEC)	NODE	CONDITION	CAUSE	FED1 FED2 FED3	TEMP1 TEMP2	CT (G-MIN/M3)	FLUX (KW-SEC/M2)
2220.	11	WINDOW*		0.000E+00 0.158E-01 0.778E-01	0.200E+02 0.000E+00	0.786E-03	0.000E+00
5000.	11	FINAL TIME		0.000E+00 0.558E+00 0.264E+00	0.238E+02 0.000E+00	0.731E+02	0.296E+02

PERSON 4

TIME (SEC)	NODE	CONDITION	CAUSE	FED1 / FED2 / FED3	TEMP1 / TEMP2	CT (G-MIN/M3)	FLUX (KW-SEC/M2)
2210.	12	WINDOW*		0.000E+00 0.158E-01 0.776E-01	0.200E+02 0.000E+00	0.187E-01	0.000E+00
3050.	12	INCAPACITATED	FED2	0.000E+00 0.100E+01 0.358E+00	0.450E+02 0.178E-01	0.422E+02	0.475E+02
3180.	12	INCAPACITATED	FED3	0.776E-02 0.268E+01 0.100E+01	0.489E+02 0.605E-01	0.701E+02	0.698E+02
3640.	12	INCAPACITATED	FED1	0.503E+00 0.354E+02 0.276E+02	0.618E+02 0.260E+00	0.213E+03	0.183E+03
3750.	12	DEAD	FED1	0.100E+01 0.542E+02 0.475E+02	0.641E+02 0.314E+00	0.251E+03	0.214E+03
3800.	12	INCAPACITATED	TEMP1	0.127E+01 0.643E+02 0.587E+02	0.650E+02 0.339E+00	0.269E+03	0.229E+03
4240.	12	INCAPACITATED	CT	0.494E+01 0.218E+03 0.230E+03	0.712E+02 0.611E+00	0.450E+03	0.387E+03
4500.	12	INCAPACITATED	FLUX	0.760E+01 0.344E+03 0.360E+03	0.731E+02 0.787E+00	0.563E+03	0.488E+03
4810.	12	INCAPACITATED	TEMP2	0.109E+02 0.509E+03 0.520E+03	0.749E+02 0.100E+01	0.696E+03	0.609E+03
5000.	12	FINAL TIME		0.131E+02 0.621E+03 0.624E+03	0.758E+02 0.114E+01	0.784E+03	0.691E+03

FED1 - THE FRACTIONAL EFFECTIVE DOSE DUE TO CO,CO2,HCN AND O2 BASED ON THE HAZARD I TENAB FED PLUS AN OXYGEN TERM

FED2 - THE FRACTIONAL EFFECTIVE DOSE DUE TO CO,CO2,HCN AND O2 BASED ON PURSER'S EQUATIONS

FED3 - THE FRACTIONAL EFFECTIVE DOSE DUE TO CO2 BASED ON PURSER'S EQUATIONS

TEMP1 - THE AVERAGE TEMPERATURE OF THE LAYER OF THE ROOM TO WHICH THE PERSON IS EXPOSED - IT IS THE SAME AS TEMP USED IN THE HAZARD I TENAB

TEMP2 - THE FRACTIONAL EFFECTIVE DOSE DUE TO CONVECTIVE HEAT BASED ON PURSER'S EQUATIONS

* IF PERSON IS WAITING AT A WINDOW, HE IS CONSIDERED TO BE AT THE NODE (ROOM) FROM WHICH HE CAME PRIOR TO REACHING THE WINDOW THIS ALLOWS HIM TO CONTINUE TO BE EXPOSED TO THE ROOM FIRE CONDITIONS

THE RESOURCE CENTRE FOR BUILDING EXCELLENCE

MISSION

To be the leading resource
for the development of the
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