HSE
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Evaluation of carbon monoxide detectors in domestic premises

Summary report

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Summary report

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The Building Research Establishment (BRE) was commissioned by the Health and Safety Executive (HSE) and the Department of the Environment, Transport and the Regions (DETR) to recommend where electrical carbon monoxide (CO) detectors should be sited within the home to achieve the best possible protection of the occupants. This report summarises the research programme and presents the siting recommendations.

BRE performed a research programme to investigate both the build-up and movement of CO in a home, as a result of emissions from a faulty combustion appliance. This comprised both experimental work in a full-size test house and computational modelling using both CFD and multi-zonal codes. Additional research was undertaken on the audibility of the detectors and necessary details were collected of CO poisoning incidents.

The main recommendation is that a CO detector should be placed on the ceiling, or high up on a wall, in any room where there is a combustion appliance. Advice is given on prioritising rooms if the number of detectors is limited by budget. Further suggestions are given for locating a detector in rooms without a combustion appliance, particularly bedrooms and 'remote' rooms from which the occupant(s) may not hear a detector sounding elsewhere in the home.

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HSE BOOKS

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1. INTRODUCTION

The use of combustion appliances in the home can generate levels of carbon monoxide (CO) that may affect the health of the occupants. Each year, about 60 accidental deaths occur in the UK from the use of these appliances and there are many more non-fatal incidents. As a result of this problem, a number of electrical CO detectors have come onto the UK market for occupant protection.

Prior to the start of this project, both British and European Standards were being developed for these CO detectors (the British Standard has since been completed [1]). One of the main areas of concern in the preparation of these standards was the correct siting of the detectors in the home.

HSE and DETR commissioned the Building Research Establishment Ltd (BRE) to recommend where within the home the CO detectors should be sited to achieve the best possible protection of the occupants. The results were to be fed into both standards.

This report is a summary of the programme of work undertaken by BRE. More detailed reports of the research work are available (see Section 10 for details). The research programme was structured to determine both the distribution of CO in the home, from a domestic combustion appliance emitting CO directly into the home, and the sound transmission and audibility of CO detectors. This provided the necessary information to make recommendations for the siting of CO detectors based on early detection, audibility and also cost.

The programme comprised seven tasks and they are described separately in Sections 2 to 8. They are listed below in the order that they occur within this report.

(a) A review of CO poisoning incidents.

(b) A literature review on the movement of CO, released from a faulty-operating combustion appliance, within a home.

(c) An experimental and computational investigation into the distribution of CO within a room which contains a faulty-operating combustion appliance and which is emitting combustion products directly into that room.

(d) An experimental and computational investigation into the movement of CO from a faulty-operating combustion appliance to other rooms in the home.

(e) Research into the requirements of audibility of a CO detection system.

(f) Provide recommendations on the siting of a CO detection system in a home.

(g) An experimental investigation to verify previous results and recommendations by testing CO detectors in situ.

Section 9 highlights several areas in which it would be useful to obtain more information to enhance the siting recommendations. Finally, Section 10 describes how to obtain more detailed reports on this research programme.

2. DETAILS OF INCIDENCES OF CO POISONINGS

2.1 Introduction

To perform this project, information was required on incidences of CO poisoning. In particular, details were required on both the types of combustion appliances and the fuels associated with CO poisoning and the routes of CO exposure from the source to the victim.

2.2 Combustion appliances and fuel use associated with CO poisonings

Metra Martech Ltd. produced a report for the Consumer Safety Unit (CSU), Department of Trade and Industry (DTI), which analysed data on the fatal and non-fatal accidental poisonings from CO generated by domestic heating appliances during the period 1985-1992 [2]. It shows that most of these accidents were caused by fires/heaters or central heating boilers and a significant number were also caused by water heaters and cookers. Furthermore the majority of accidents are caused by flue-less or open-flued appliances rather than room-sealed appliances [3].

The 1991 English House Condition Survey (EHCS) provided some information on appliance use in households [4]. Taking account of the relative numbers of each type of appliance in homes, it is estimated that fires/heaters, central heating boilers and water heaters provide a similar risk of CO poisoning.

Data from the Metra Martech report also shows that approximately two-thirds of accidents occurred with gas-fuelled appliances whilst only a quarter were caused by solid-fuelled appliances (with relatively few cases caused by oil, paraffin or LPG). However the EHCS data shows that gas is much more commonly used than solid-fuel; taking this into account, it is estimated there is a factor of four greater risk from using a solid-fuelled appliance than a gas-fuelled one. This conclusion is based on the appliances as currently fitted in homes; it does not imply that, for example, there is a difference in risk between fuels for well-maintained or new appliances.

2.3 Routes of CO exposure

HSE evidence on fatal accidental CO poisonings from faulty-operating combustion appliances suggests that, in most of these cases, CO is emitted into the same room as the appliance is located [5].

Little information could be found on the HSE databases as to the rooms in which fatalities occurred, in relation to the room in which the faulty-operating appliance was located. However HSE suggested [6] that when CO is emitted from a gas fire/heater, the fatality or near miss usually occurs in the same room. However when the CO is emitted from a central heating boiler, the fatality or near miss usually occurs in another room, usually the room above. It is often thought that in the latter case, the CO passes directly upstairs through gaps where the water pipes pass rather than migrating through the home. There have also been a

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number of fatalities in living rooms from boilers and instantaneous water heaters located in adjacent kitchens.

HSE also provided data on rooms in which fatalities occurred [7]. Approximately 40% died in the lounge, 20% in the kitchen and 20% in a bedroom. Assuming that, in most cases, the fatality occurred in the room in which exposure occurred, these data suggest that most people are awake at the commencement of exposure. However it does suggest that a significant minority are asleep in bed.

3. LITERATURE REVIEW OF CO MOVEMENT IN THE HOME

3.1 Scope of the review

The amount of information available in the literature on the movement of CO in the home is limited. However as shown in the Section 2, CO is emitted typically into the room in which the faulty-operating combustion appliance is located. In these cases the emitted CO will be hot and therefore buoyant. Thus the review was extended to include relevant information on other buoyant gases in the indoor environment, particularly smoke from fires.

The following areas were covered in the review.

(a) Current requirements in standards for the siting of domestic detectors for buoyant gases; this includes carbon monoxide detectors, natural gas (methane) detectors and smoke detectors.

(b) Research work (if any) on which the siting instructions in the standards are based.

(c) Experimental research work on the flow of buoyant gases.

(d) Computational modelling of the flow of buoyant gases.

3.2 Factors that may affect the distribution of CO in the home

3.2.1 Introduction

The review highlighted a number of factors that may affect the distribution of CO both within a room and between rooms in a home. These have implications for the siting of CO detectors in a home. The list of factors included in this Section is not meant to be exhaustive, it simply provided a good foundation for the research programme.

3.2.2 Factors that may affect the distribution of CO within a room

There were many factors highlighted by the review that may affect the distribution of CO in a room. These are as follows:

(a) The flow will be dependent on source conditions, e.g. temperature, position, velocity, volume flow, angle of emission, particularly within the room in which the CO is emitted.

(b) If the gas is initially buoyant, there may be a vertical concentration gradient of CO in the room.

(c) If the gas is initially buoyant and emitted into the room where the appliance is located, the flow pattern in that room may result in 'pockets' of air at intermediate and floor heights where less CO is present.

(d) Close to the source, there are likely to be significant horizontal concentration gradients of CO. Depending on the flow pattern, there may also be significant horizontal concentration gradients close to vertical surfaces.

(e) There may be boundary effects close to surfaces (including walls, floor and ceiling). This could lead to either reduced or elevated CO levels close to these surfaces.

(f) There may be a difficulty in CO penetrating into corners where the ceiling and walls meet.

(g) CO levels may be lower in regions of draughts of fresh air, for example caused by open doors or windows.

(h) Objects (curtains, furniture etc.) may impede CO flow and result in regions of low CO levels.

(i) At ceiling height, CO levels may be reduced close to walls or light fittings.

(j) Additional heat sources, e.g. a radiator, may inhibit the rise of buoyant CO to the ceiling.

(k) CO distribution may be affected by surfaces that are much warmer or cooler than the rest of the room, e.g. uninsulated exterior walls, windows and ceilings.

(l) Partitions etc. may affect the flow of CO.

(m) CO levels may be significantly different at varying points on a sloped ceiling.

3.2.3 Factors that may affect the distribution of CO between rooms

The movement, and consequently the distribution, of CO through the rooms in a home will depend on source conditions, ventilation driving forces and ventilation pathways both between rooms and between the internal and external air. The review also indicated that buoyant gases would be readily transported and mixed with the air in accessible areas on the same floor of the home and on upper floors but there would generally be less penetration to floors below.

4. DISTRIBUTION OF CO WITHIN A ROOM THAT CONTAINS A COMBUSTION APPLIANCE THAT IS EMITTING CO INTO THE ROOM

4.1 Introduction

A study was performed to investigate the distribution of CO in the room in which a faulty-operating appliance is located. This comprised both experimental and computational simulations. To verify these results, additional experiments were performed with actual domestic combustion appliances.

4.2 Description of experimental studies

The experimental work was carried out within one room of a two-storey house at BRE's experimental facilities in Garston, Watford. Apparatus was constructed for this work, which generated heated CO. This provided a safe and controlled method of simulating CO emissions from a domestic combustion appliance. The emission rates were chosen such that the levels of CO generated in the house would comply with HSE regulations, whilst still adequately representing the flow of CO. Thirty-six CO electro-chemical sensors were used to measure the distribution of CO with time both in the internal room space and on the internal surfaces of the room. The sensor layout depended on the region of space that was of interest. Early experiments showed that the results were fairly repeatable for a given sensor layout. Therefore an experiment could be repeated with a different sensor layout and the results from the two sensor layouts combined, providing greater information on the CO distribution. Approximately 50 thermocouples were used to measure temperature, principally for the development of the computer model.

To simulate the CO emissions from a domestic combustion appliance, a basic experimental set-up was chosen similar to conditions that may occur in practice. The set-up was as follows:

- a 125 mm diameter circular outlet directed towards the ceiling.
- an outlet height of 860 mm.
- a source temperature of 100°C.
- a flow-rate of 2500 cm^3/s.
- all doors, windows and vents in the room closed.

As there is a wide range of conditions under which CO emissions may occur, a series of sensitivity experiments was performed to determine the effects of varying each of these parameters, both on their own and in combination with others.

Further experiments were also performed to investigate the effect of:

(a) objects in the path of the CO flow,

(b) light fittings,

(c) having the lights switched on,

(d) introducing an additional heat source in the room, and,

(e) having cooler external walls and windows.

In order to provide further verification of this work, a small number of experiments were performed with actual combustion appliances. Two flue-less combustion appliances were used; a natural gas-fired boiler and a portable LPG heater.

4.3 Description of computational studies

As a complementary approach, simulations were also performed using Computational Fluid Dynamics (CFD). The computer models provided a much more detailed description of the CO flow and distribution within a room and allowed investigation of conditions that could not be set up in a controllable manner within the experimental test facility.

The literature review suggested that a buoyant plume could be modelled with standard CFD techniques. A computer program called FLOVENT was selected, which has a k-ε turbulence model that has been optimised for building flows.

The CFD model was initialled validated by comparison with results from the basic experimental case. The CFD model was then used to investigate the effects of:

(a) altering the geometry of the room,

(b) introducing an additional heat source to the room,

(c) having cooler external walls and windows,

(d) introducing a partition within the room, and,

(e) changing from a horizontal to a sloping ceiling.

4.4 Results

The results showed that without an additional heat source in the room, the buoyant plume initially accelerates upwards, before subsequently slowing down as cooler air from the room becomes entrained into the plume, spreading and cooling the flow. Once the plume reaches the ceiling it spreads out in all directions and travels across the ceiling to the surrounding walls. Once there, the flow starts to descend down the walls. At this point the flow becomes more complex. Part of the flow is entrained back into the plume increasing the concentration in the upper part of the room. There is also a flow of elevated CO levels down the walls. Overall this flow pattern results in a significant vertical CO concentration gradient in the room with the highest levels occurring at ceiling height.

Varying the source parameters within the ranges considered resulted in a similar CO flow pattern and distribution. The vertical CO concentration gradient was observed to be reduced at relatively low heat inputs.

Increased ventilation resulted in a reduction of the overall levels of CO in the room. With an internal door open, ventilation of air through the doorway resulted in a significant drop in CO concentration below the height of the door. Whilst not tested, the same effect would also be expected for windows. The room had two air vents on an external wall, each 0.21 m wide and 0.13 m high and with a free openable area of 6654 mm^2. With air vents open, depending on the direction of the grill, there were reductions in CO concentration close to the vents due to airflow between the room and outside.

The CO concentration was reduced in the areas where the ceiling meets the walls and where two walls meet each other. The use of obstacles, e.g. furniture against a wall, was also observed to impede flow and reduce the CO level downstream of the object.

The CO concentrations at ceiling level showed no significant variation with proximity to light fittings, whether the lights were switched off or on. However, it seems prudent not to place a CO detector too close to a light fitting to avoid overheating etc.

Both the experimental and computational studies showed that an additional heat source could inhibit the CO plume rising directly to the ceiling. In these cases, much of the CO becomes entrained into the plume of hot air generated by the additional heat source, resulting in the CO concentration still rising to the ceiling. The overall result is that the CO concentration is still greater towards the upper part of the room.

As described at the start of this sub-section, there is a flow of CO down the walls of the room. The study showed that reducing the surface temperature (e.g. by having a cooler external wall and/or a cooler window) leads to an acceleration of the downward flow over the cooler surface as heat is transported from the air stream to the surface, reducing the temperature of the air stream. The overall result is a reduction in the vertical CO concentration gradient at these surfaces.

Computational studies showed that the general CO distribution was the same when the height or length of the room was doubled. In the latter case, there was a larger reduction in overall CO concentration at ceiling level from the ceiling above the source to the furthest wall.

A partition was introduced into the double length room computer model designed to be typical of the situation where two small rooms have been knocked together into one room. Thus what may be left is part of the wall and a beam across the ceiling. The partition was placed centrally in the room. The simulations showed that the plume first rises to the ceiling and then extends across the ceiling until it meets the partition. The horizontal movement is then halted briefly. But this layer cools and is continually added to by the continuing air stream across the ceiling so that the depth of the layer at the partition increases. So after a short period of time, this layer extends down far enough for it to start pouring underneath the ceiling beam. The layer is still buoyant, so once it has passed the ceiling beam it rises to the ceiling again on the other side. There is a marked reduction in CO concentration at the ceiling after passing the partition.

Finally, a computational study was carried out to investigate the effect of a sloped ceiling on CO flow. To be sure of observing any effect, we used a fairly large gradient of 1m rise per 4m. In this case when the plume meets the ceiling, a greater proportion of the flow rises up towards the top of the sloped ceiling than flows down towards the bottom of the ceiling. The overall effect is to produce a layer of higher CO below the higher side of the ceiling.

For verification, experimental studies were performed with two flue-less combustion appliances; a natural gas-fired boiler and a LPG heater. The results were similar to those observed in the simulation experiments.

5. MIGRATION OF CO FROM A COMBUSTION APPLIANCE THROUGH THE HOME

5.1 Introduction

A study was performed to investigate the migration of CO from a faulty-operating combustion appliance into rooms other than the one in which the combustion appliance is sited. This comprised both experimental and computational simulations.

5.2 Experimental study of the migration of CO through open doorways and stairway

A series of experiments was performed to monitor the movement of the CO, which is emitted into the room containing the combustion appliance, to other rooms in the test house through open doorways and stairways. The source conditions were similar to those used for the basic experiments described in Section 4.

First, experiments were performed with the source in either of two ground floor rooms and similar results were obtained for both rooms. In summary, there was a large vertical CO concentration gradient established in the source room, due to the buoyancy of the gas. This gradient diminished as the CO spread through the house and mixed with surrounding air. Varying the source velocity and temperature had little effect on the results. Closing internal doors effectively reduced the volume of the home that was easily accessible to CO and consequently increased levels of CO in those parts of the home that were easily accessible. Opening windows reduced the CO levels in the home especially in the rooms where the windows were open.

In the next set of experiments, the source was located in either of two first floor bedrooms. There were significant differences from the results with the source on the ground floor. With all the windows shut little, if any, CO was observed to be transported to the ground floor. Again there was a large vertical CO concentration gradient established in the source room which diminished as the CO spread throughout the upper floor. Varying the source velocity and temperature and closing internal doors had similar effects as before. With windows open, elevated levels of CO were observed on the ground floor, especially with a window open on the windward side of the house on the first floor and the opposite side of the house on the ground floor. This was due to cross ventilation through the home, forcing CO to flow from the first floor and down through the house.

5.3 Computational study of the migration of CO through open doorways and stairway

A computational study was also performed to investigate the movement of CO, which is emitted into the room containing the combustion appliance, to other rooms in the test house through open doorways and stairways. It provided a means to investigate the effect of ventilation conditions, which could not be investigated in a controlled manner with the experimental test facility. In particular, the study examined the effects of wind, temperature and house leakage.

BRE's BREEZE multi-zonal computer code was used for this task. Initially a computer model was constructed of the experimental test house and this was then validated by comparison with experimental data. Then a large number of simulations was performed to examine the migration of CO for a large range of ventilation conditions. The results from these simulations were used to calculate values of personal exposure to CO in each of the rooms.

In summary, the results showed that wind speed and direction were typically the most important factors affecting the flow of CO through the house. They led to a wide distribution of possible exposure values in each of the rooms. Indeed in extreme cases, no CO was actually transported from the source room to the rest of the house.

5.4 Experimental study into other routes of transport of CO between rooms

A further series of experiments was performed to investigate situations in which CO may enter a room not containing the source, other than through an open doorway to that room. For example, CO could enter through a broken flue that passes through the room or enter from a lower floor room containing a water-heating appliance via gaps surrounding water pipes that pass between the two rooms.

The results showed that if the CO is sufficiently buoyant on entering the room, it rises directly to the ceiling and then flows across the ceiling before flowing around and through the rest of the room. This results in a vertical CO concentration gradient within the room. It is more complex if the CO is non-buoyant. The experiments show that the CO distribution through the room is very dependent on source location, velocity and direction and it is not possible to generalise where CO will build up fastest for all scenarios.

6. AUDIBILITY OF CO DETECTORS

The problem of audibility is of most concern if the build-up of CO occurs whilst the occupants are asleep. The sound level an occupant with normal hearing is exposed to has to be sufficiently high for the occupant to be woken. Previous research has stated that a sound pressure level of at least 75 dBA (at the ear) is required to awaken people [8,9].

A brief experimental study was performed to study the audibility of CO detectors. Firstly, the sound power levels of two CO detectors were measured. These results were then used along with sound insulation measurements to predict sound pressure levels in rooms as a result of sound transmission from a 'sounding' CO detector located in another room. As an example, when all the internal doors in the house were closed and the two detectors, with sound pressure levels of approximately 82 dBA at 3 m from the detectors, were placed in the living room, the average sound pressure level in the neighbouring room was approximately 58 dBA.

The results from this study and a similar study of the audibility of smoke alarms were combined [9]. They suggest that the sound level from a CO detector, which meets the British standard for domestic CO detectors [1], may be insufficient to wake an occupant unless it is located within the bedroom itself.

7. RECOMMENDATIONS FOR THE SITING OF CO DETECTORS IN THE HOME

7.1 Introduction

Recommendations are made on the siting of CO detectors in the home based on the results of the research programme. The recommendations are based on the needs to:

(a) detect early the build-up of CO in the home, and,

(b) provide an audible warning that is loud enough for the occupants to hear so that appropriate action can be taken.

The cost of the detection system must also be considered. For example, one possible option would be to have an alarm in each room in the house and inter-connect them such that if one alarm detects CO then all the alarms sound. However it is unlikely that most people would be willing to pay this cost.

7.2 Recommendations

7.2.1 Room containing combustion appliance

The review in Section 2 suggests that, in most cases, CO is initially emitted into the room where the faulty-operating combustion appliance is located. Thus, to provide early detection of CO in most cases, an alarm should be placed in any room where there is a combustion appliance.

If there is an appliance in more than one room and the number of alarms is limited, the following should be considered:

(a) locate a detector in rooms containing a flue-less or open-flued appliance, and,

(b) locate a detector in rooms where the occupant(s) spend most time.

For best protection, all the detectors should be interconnected so that if one detector senses CO then all the detectors sound and the occupants are alerted.

Within these rooms, the detector should be located as follows.

1. The detector should preferably be located on the ceiling and at least 300 mm from any wall.

2. If the detector is located on a wall:

   (a) it should be located as high as possible but not within 150 mm of the ceiling;

   (b) it should be located higher than doors or windows.

3. The detector should located between 1 m and 3 m horizontally from the appliance.

4. If there is a partition or ceiling beam in a room, the detector should be located on the same side of the partition or beam as the appliance.

5. In rooms with sloped ceilings, the CO detector should be located towards the high part of the ceiling.

7.2.2 Remote rooms without a combustion appliance

A home may have 'remote' rooms in which the occupants spend considerable time whilst awake and in which they may not be able to hear the CO detection system. It may be desirable to have additional detectors, either in these rooms or within audible range of them. It is important to connect such detectors to those detectors in rooms containing combustion appliances.

The studies show that it is not possible to predict in general how the CO build-up will proceed in these rooms, without knowing details of the transport of CO from the source. Therefore, in contrast to rooms with a combustion appliance, it is best to locate the detector close to the typical breathing zone of the occupants in these 'remote' rooms.

A cheaper alternative may be simply to use a sounding device instead of a detector in the 'remote' rooms as in this case its main role is to alert the occupants to the build-up of CO elsewhere in the home. Such a device must be interconnected to those detectors in rooms containing combustion appliances.

7.2.3 Bedrooms without a combustion appliance

An alternative enhancement of the detection system is to have additional alarms to alert the occupants whilst they are asleep. This option will be of greater potential benefit if heating appliances are used over-night.

If additional alarms are used then, ideally, an alarm should be placed in every bedroom (used as sleeping quarters). The work in Section 6 suggests that an alarm located outside of the bedrooms may not be sufficient to wake up the occupant. It is important to connect such detectors to those detectors in rooms containing combustion appliances.

The studies show that it is not possible to predict in general how the CO will build-up in the bedrooms, thus each detector should be placed close to the typical breathing zone of the occupants of that bedroom.

Again a cheaper alternative may be to simply use a sounding device instead of a detector in the bedrooms, as its main role is to alert the occupants to the build-up of CO elsewhere in the home. Such a device must be interconnected to those detectors in rooms containing combustion appliances.

In particular situations, detectors or sirens may be needed in fewer bedrooms. For instance a detector may be less necessary in young children's bedrooms, as an adult should always be present in the home who will hear a detector sounding in the home whilst awake or be alerted by a detector sounding in their bedroom whilst asleep.

Alternatively, a detector could be placed instead in hallways outside bedrooms, though as discussed in Section 6 the detector may not be loud enough to wake the occupants. Depending on the layout of the floor, it may be necessary to have more than one detector in a hallway to ensure a direct line between a detector and each bedroom and hence minimise sound attenuation. The research suggests that the CO build-up in a hallway will be either greatest close to the ceiling or fairly well mixed, so fit the detector on the ceiling or high up on the wall, using the recommendations given in section 7.2.1.

7.2.4 All rooms in which detectors are sited

The following are general recommendations for any room in which a detector is sited. Do not put a detector in the following locations.

- Where it can be obstructed, e.g. by curtains or furniture.
- Where it is in a draught of cleaner air, e.g. near a door, window, or ventilation opening such as an air vent or extract fan.
- In an enclosed space not containing an appliance, e.g. in a cupboard.
- Directly above a source of moisture, e.g. a sink.
- Directly above or adjacent to a source of heat, e.g. a cooker, heater or light fitting.
- In an area where the temperature would drop below −10°C or rise above 40°C.
- Where dirt or dust could block the sensor and stop it working.
- Where it could be knocked easily or damaged, or where it could be accidentally turned off or removed.
- In a damp or humid area.

8. TESTING CARBON MONOXIDE ALARMS IN SITU

The purpose of this task was to verify a number of the results from the experimental monitoring and computational modelling stages, by testing actual CO alarms in situ. In particular this work focussed on investigating the effect of the buoyancy of the emitted gas on the siting of alarms. The reason for this was that the research programme had shown that the buoyancy of the gas was typically the most important factor affecting the CO distribution within the home and consequently was very influential in developing the recommendations for the siting of CO alarms.

The approach chosen was to perform a series of experiments in a BRE test house to simulate the CO build-up that may occur during the initial stages of spillage from a faulty combustion appliance. The CO alarms were arranged in two rows. Each row contained four alarms from different manufacturers with the same combination of alarms used in each row. This allowed alarms of the same make to be 'paired' between rows. The first row was located near the top of a room, either on the ceiling itself or high up on a wall. The second row of alarms was located on the wall just above floor level, where electric sockets would normally be positioned. Then the time taken for the alarms within each pair to 'sound' was compared. The experiments investigated the response of the alarms to the build-up of CO both in the room where the source was located and in other rooms within the house.

The work was problematic, in particular owing to the unreliability of the CO alarms especially those from two of the four manufacturers. The alarms from the other two manufacturers were more reliable, but still had differences in sensitivities that meant that care had to be taken in interpreting results. This work emphasised the importance of performing the experimental and computational work described in previous stages of the project, where more trust could be placed in the results.

The experimental results from this study agreed with those from the previous stages. The 'paired' alarms responded in the order expected from the previous work. This study confirms that:

(a) within the source room itself, the CO concentration is higher towards the top of the room,

(b) in the hallway outside of the source room, the CO concentration is still higher towards the top of the room,

(c) at other locations within the home, the CO stratification is less evident, if present at all.

9. IMPROVEMENTS TO THE RECOMMENDATIONS

The recommendations for the siting of CO detectors draw heavily on the details of CO poisoning incidents that were described in Section 2. It would be useful to obtain more information in some of these areas, which could enhance the siting recommendations, as follows.

(a) Whilst the data strongly suggests that, in most cases, CO initially builds up in the room with the faulty combustion appliance it would be useful to have further data to quantify this. It would be useful to determine the probability of CO being directly emitted into other rooms in the home.

(b) Obtain information on the relative location of the source and victim(s) and, if in different rooms, the route of transport of CO between the rooms.

(c) Whilst the data strongly suggests that, in most cases, the occupants are exposed whilst awake it would be useful to have further data to quantify this.

10. BACKGROUND REPORTS

There is a series of background reports containing full details of the research programme. These reports are published by HSE in the contract research report (CRR) series. The titles of the reports are given below.

1. Evaluation of carbon monoxide detectors in domestic premises:
   Literature review.

2. Evaluation of carbon monoxide detectors in domestic premises:
   Experimental and computational investigation of the movement of carbon monoxide within a single room.

3. Evaluation of carbon monoxide detectors in domestic premises:
   Investigation of the movement of carbon monoxide within a home.

4. Evaluation of carbon monoxide detectors in domestic premises:
   Recommendations for the siting of carbon monoxide detectors.

5. Evaluation of carbon monoxide detectors in domestic premises:
   Testing carbon monoxide detectors in situ.

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