

The image features a dark blue background on the left side, transitioning to white on the right. The background is decorated with a complex pattern of thin, light green lines that form a series of overlapping, curved shapes, resembling a stylized fan or a series of overlapping arcs. The 'bre' logo is positioned on the left side of the blue area.

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**ODPM Final Research Report:**

BD2538

Determining the best option for the provision of additional smoke alarms in dwellings and houses

226779

CI 71/5/29

**Prepared for :**

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24 March 2006

## Fire Safety

### BD2538

**Determining the best option for the provision of additional smoke alarms in dwellings and houses.**

### Final Research Report

Prepared for Anthony Burd

Prepared by Jeremy Fraser-Mitchell, Richard Chitty and Stephen Howard

BRE output ref. 226-779

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## Executive Summary

This project was commissioned by the ODPM Buildings Division against their specification for a project titled "Determining the best option for the provision of an additional smoke alarms in dwelling houses and apartments".

British Standard BS 5839-6:2004 recommends the provision of LD2 standard of fire detection. This involves the provision of smoke alarms in the circulation areas of the dwelling and an additional heat alarm in the principal habitable room. The current edition of Approved Document B (AD B) typically recommends fire detection in the circulation areas only. It is proposed to supplement this in the revised Approved Document with an additional smoke alarm in the principal bedroom.

The project consisted of a study of the fire statistics covering the years 1994 to 2002, computer modelling and a cost benefit analysis considering the three fire detection and alarm proposals, namely:

- The current recommendation of Approved Document B,
- Supplementing the current recommendations of Approved Document B with a smoke alarm in the principal bedroom, or
- Following the recommendations of BS5839-6:2004.

### ***Fire Statistics***

In the period 1994 to 2002, there were 3709 fatalities and 104268 injuries as a result of fires in domestic properties. 1238 fatalities occurred in dwellings in which provision was made for the detection of fire. Of these, 389 deaths occurred in dwellings in which the smoke alarms were not operational. The biggest cause of non operational fire detection equipment was missing or discharged batteries.

There were 397 deaths that occurred in dwellings in which the fire detection and alarm system was recorded as operational and functioned correctly. Based on the circumstances of the fire, it is estimated that changes to the number or position of fire detectors would not have changed the outcome in 45% of the fatalities.

### ***CRISP computer simulations***

The largest benefit is gained from installing any sort of detection system compared with no detectors at all. This reduces the risk of death to about 30% ~ 50% of the risks where there are no alarms.

The relative risks predicted by CRISP suggest that the benefits of additional alarms would be marginal. This is the same conclusion as given by an examination of the fire statistics.

### ***Cost-Benefit Analysis***

CBA including uncertainty analysis suggests that including alarms, where none were present before, has a good chance of being cost-effective (probability = 84%), but that further upgrades involving additional alarms are not cost-effective (probability < 4%).

### ***Conclusions***

The following recommendations are made based on the findings in this report:

1. The reasons why 25% of homes in the UK are not fitted with any form of fire detection and the possible improvements in fire safety for these homes should be examined further.
2. The installation of smoke and heat alarms, in addition to those currently recommended by AD B, did not lead to any discernable further reductions in risk.

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## Introduction

This project is in response to a request from ODPM Buildings Division against their specification for a project titled "Determining the best option for the provision of an additional smoke alarm in dwelling houses and apartments". ODPM Contract reference CI 71/5/29, BD2538. This project was commissioned under the ODPM Building Fire Safety Framework Agreement with the BRE led consortium.

The overall aim of this project was to produce a short research report for ODPM (and the Part B Working Party) which will eventually be published on the AD B page of the BRE Web site.

The project consisted of:

- A technical review of the three fire detection and alarm proposals,
- A study of the fire statistic covering the years 1994 to 2002,
- Computer modelling to assess time to 'fire awareness' and estimate the risks to life,
- A cost benefit analysis and
- Comment on the acceptability of the of the fire alarm options under review.

## Technical review

This section of the report consists of a technical review of the three alternative proposals for fire detection and alarm systems in domestic dwellings, namely:

- The existing requirements of Approved Document B (Fire safety) 2000 (ADB) in which smoke alarms are fitted to each level of the house with a linked heat alarm being used in the kitchen should the kitchen area not be separated from the stairway or circulation space by a door.
- The recommendations made in BS 5839-6:2004 - Fire detection and fire alarm systems for buildings – Part 6 Code of practice for the design, installation and maintenance of fire detection and fire alarm systems in dwellings- that supplements smoke alarms in the escape and circulation areas with heat alarms in the kitchen and smoke or heat alarms in principal habitable rooms.
- The proposed revision to the ADB in that the existing recommendations are supplemented with an additional smoke alarm in the principal bedroom of the dwelling.

The technical review considers in detail the installation of fire alarms in the various configurations of domestic premises by following the recommendations in BS 5839 Part 6 and Approved Document B (including proposed revision). The review covers the configurations of domestic premises modelled in this report. In addition the single floor dwelling has been increased to demonstrate the effect of increasing specific distances, how these should be interpreted and the material change to the installation.

The installations are compared for such factors as detection coverage, audibility and ease of installation.

The technical advantages and/or limitations of the various technologies used to detect fires available to the construction industry for the domestic market that meet the recommendations of BS 5839 Part 6 and/or Approved Document B. In particular the use of carbon monoxide (fire) and heat alarms, if available, in domestic applications is commented upon.

With the exception of single storey properties, this review has not considered in detail the fire alarm installations in large dwellings (a property with a single floor in excess of 200m<sup>2</sup>). With the exception of single storey properties, both the ADB and BS5839 Part 6 recommend the use of fire detection and alarm system consisting of fire detectors and sounders communicating with and powered by central control and indicating equipment.

## Comparisons of different installation standards

### Fire Alarm Installation in a two storey, 3 bedroom house to BS5839 Part 6.

Figures 1 and 2 are diagrammatical representations of a fire alarm installation in accordance with the recommendations of BS5839 Part 6.

The plans show a three bedroom detached property with the principal habitable room on the ground floor separated from the kitchen and the stairs.

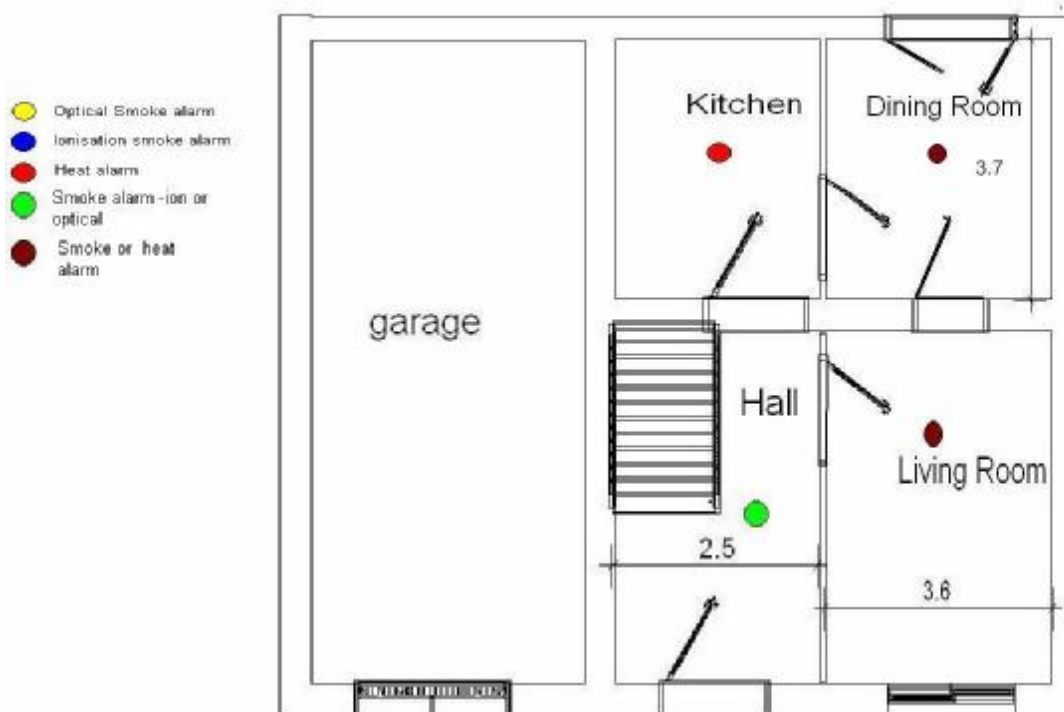


Figure 1 – Ground floor BS 5839 Part 6 installation (dimensions in metres)

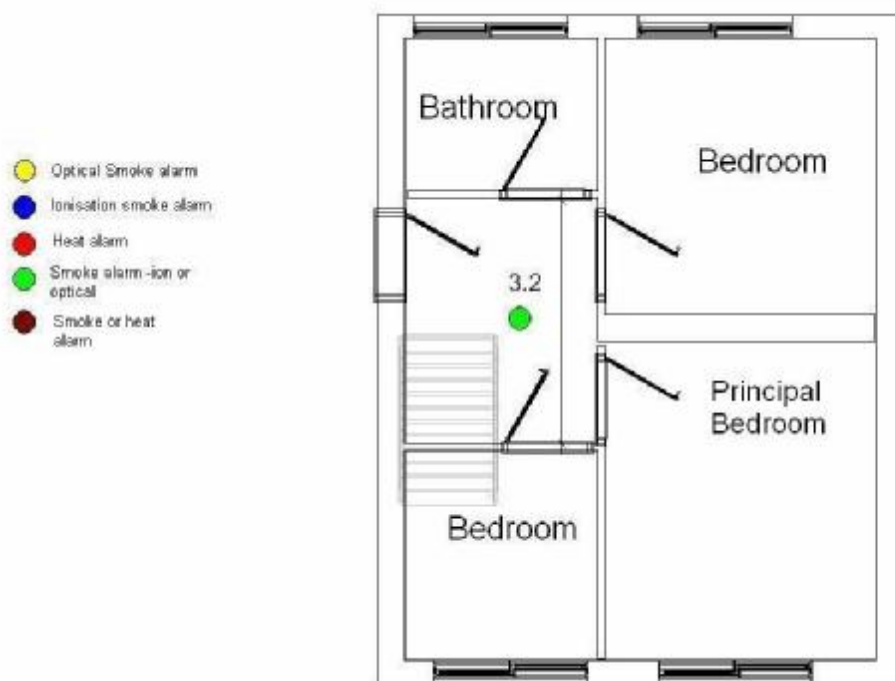


Figure 2 – First floor BS 5839 Part 6 Installation (dimensions in metres)

In following the recommendations of BS 5839 Part 6, the fire detection and alarm system should be a grade D system, category LD2.

This translates into a fire detection and alarm system consisting of mains powered interlinked smoke alarms fitted to in all circulation spaces that form part of the escape routes from the dwelling, and in all rooms or areas that present a high fire risk to occupants. Interlinked heat alarms are recommended for all kitchens.

The principal habitable room(s) should be fitted with either a smoke alarm, or if the risk of false alarm is not sufficiently low, a heat alarm. However, we would consider there is significant risk that if there is an option given between installing heat or smoke alarms, that the former will be fitted in preference as there is a reduced risk of false alarm and hence potential ongoing costs for the builder.

The BS Code of Practice also has requirements in terms of the maximum area a single alarm should cover. The number of alarms increases in proportion to the size of the protected area. It is recommended in BS 5839 Part 6 that no point in the protected area should be greater than 7.5 metres from a smoke alarm or 5.3 metres from a heat alarm.

However, the spacing requirements in BS5839 Part 6 may result in no change in the majority of domestic fire detection installations. In following the recommendations in BS 5839 Part 6, a smoke alarm could provide detection coverage to an area of 176 m<sup>2</sup>. Less than one percent of properties are 'large' as defined by Approved Document B and BS 5839 Part 6.



BS 5839 Part 6 also recommends that no bedroom door should be greater than approximately three metres from the nearest smoke alarm. It is not clear why this recommendation is made as the area covered by a single detector is defined in the standard and performance based criteria are included for the audibility of alarms throughout the property.

**Fire detection and alarms system meeting the requirements of the ADB including the proposed revision**

A fire detection and alarm system meeting the minimum requirements specified in revision of ADB is shown in figures 3 and 4.

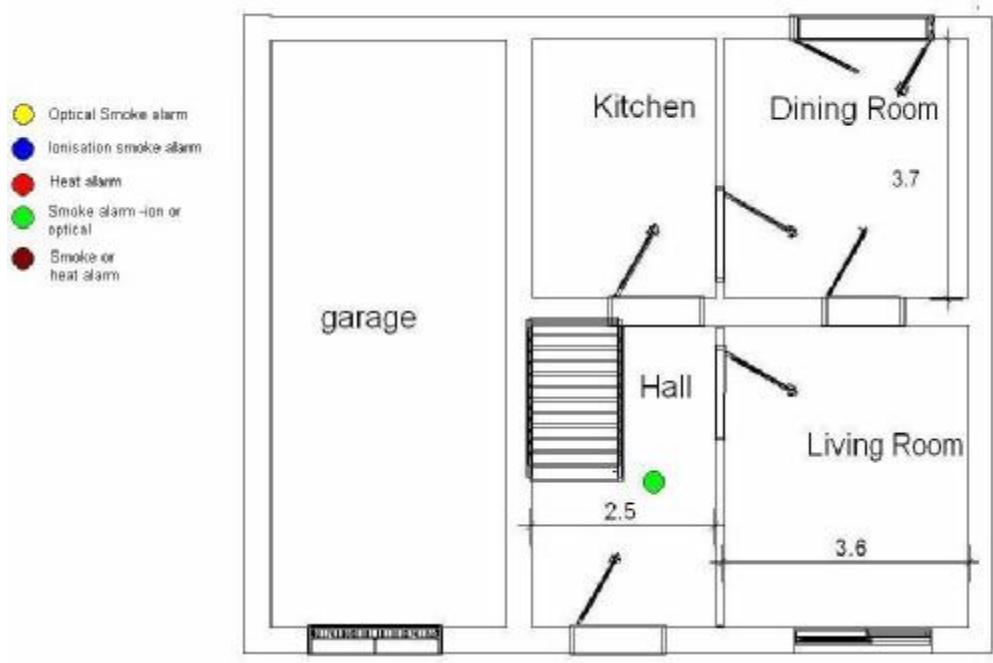


Figure 3. Ground floor to Approved Document B (including proposed revision, dimensions in metres)

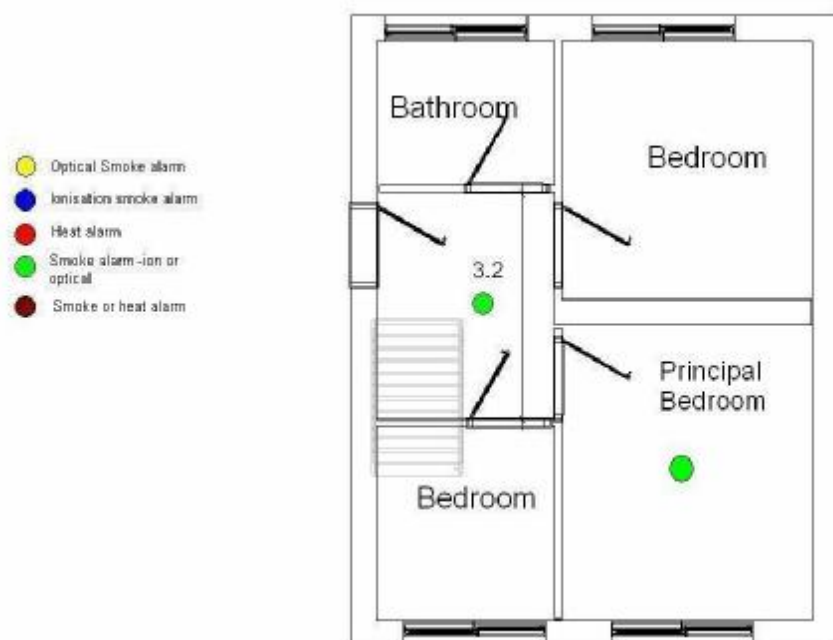


Figure 4 – First floor to Approved Document B, (including proposed revision, dimensions in metres)

The installation would consist of mains powered smoke alarms, not necessarily with a secondary supply.

The smoke alarms are required to be located in the main circulation areas, principal bedroom and if not separated from the circulation space or stairway by a door, an interlinked heat alarm should be located in the kitchen.

In relation to detection coverage, ADB requires that a smoke alarm is located within 7.5 metres of the door to each habitable room in the circulation area. There are no recommendations contained with ADB in terms of coverage area that would impact on the number of alarms in adjoining rooms. However, as noted above, recommendations in terms of coverage areas may not increase the number of alarms fitted in the vast majority of properties.

## Comparison of systems

### *Detection coverage*

The BS5839 Part 6 installation requires at least 2 smoke alarms for the circulation areas, two fire alarms using smoke or heat detection technologies for the principal habitable rooms and one heat alarm located in the kitchen giving a total of five fire alarms. The number of smoke alarms could also be increased if bedroom doors are greater than 6 metres apart, or rooms require greater number of alarms to meet the coverage guidelines. If the method of detection chosen for the principal habitable room is heat detection, then the likelihood of additional detectors increases as a result of reduced coverage areas i.e. reduced spacing recommended for heat alarms.

This compares with the proposed guidance in ADB in which compliance with this document can be achieved with three mains powered smoke alarms, one each in the circulation areas on the ground and first floor and one in the principal bedroom. If the kitchen area is not separated from the circulation space, an additional heat alarm is required in the kitchen area.

The technical advantages and disadvantages of the BS 5839 Part 6 installed system are:

- Better detection coverage on the lower floors of the building including the use of heat detectors in an area in which the greatest number of domestic fires start.
- Recommendations for increased detection coverage where the size of the room or the length of the corridor could compromise the performance of the fire detection system.

The technical advantages of a system installed to the proposed Approved document B are:

- The smoke alarm fitted in the principal bedroom will provide increased audibility and hence better chance of the correct response to a fire situation.
- The addition of an extra interlinked smoke alarm in the principal bedroom will reduce the time to alarm in some fires by the detection of a fire in this area.

The addition of a smoke alarm in the principal bedroom may also address a potential issue not directly addressed in either BS5839 Part 6 or ADB. Some properties are fitted with en- suite bathrooms or shower rooms off of the principal bedroom. The combination of two doors between a smoke alarm, that could be as much as 7.5 m from the bedroom door combined with noise levels that may occur within a bathroom, could prevent an occupant of the bathroom being adequately alerted to a fire developing in the rest of the property.

Smoke alarms need not necessarily have a secondary power supply.

The smoke alarms will be interlinked to ensure that the activation of one unit will result in all units sounding.

In relation to detection coverage, ADB requires that a smoke alarm is located within 7.5 metres of the door to each habitable room. This is consistent with spacing arrangements recommended in BS53839 Parts 1 and 6.

### *Power Supplies*

To comply with the recommendation in BS5839 Part 6, each fire alarm should be supplied with:

An independent circuit from the consumer unit in the premises supplying the alarms. This circuit should be reserved for the fire detection equipment in the premises. The code of practice also requires that the fire alarms are fitted with a secondary independent power supply.

Alternatively, the mains supply can be provided via a regularly used lighting circuit.

The provision of the secondary power supply ensures that the smoke alarms continue to operate in the event of a failure of power within the dwelling (short term power cut). Under such circumstances the householder may be using candles to provide lighting and therefore at increased risk of fire.

The recommendations made in terms of standby power supply are not sufficient to ensure continued operation of the fire detection and alarm should the isolation of the public supply from the fire detection system be for extended periods.

A fire detection and alarm system meeting the minimum requirements specified in ADB would consist of mains powered smoke alarms supplied with power in the same manner as a BS 5839 part 6 installation.

The smoke alarms meeting the requirements of the ADB and BS 5839 Part 6 will be interlinked to ensure that the activation of one unit will result in all units sounding.

### *Audibility*

The increased number of fire alarms in the BS 5839 Part 6 would lead to higher sound levels in the 'day time' accommodation areas of a domestic dwelling. The increased number of alarms is also likely to increase the sound level throughout the rest of the property; however this will depend on the construction of the property and the location of a smoke alarm on the ground floor in relation to bedrooms.

BS 5839 Part 6 also recommends that sound pressure measurements are made with the bedroom door open Clause 13.2 (e) and a recommended level for the smoke alarm audibility is provided. However, we question whether such measurements of the sound levels are undertaken in domestic installations.

The current revision of ADB requires very little in terms of audibility except for paragraph 1.11. That recommends that the alarms should be positioned so they are 'effective when the occupants are asleep'.

The proposed revision will increase the audibility in the principal bedroom, and is likely to increase audibility throughout the upper levels in a property, although again this will depend on the construction of the house.

### *Installation*

In terms of ease of installation, this can be subdivided into two factors namely the number of alarm units and the requirements for power and for communication between devices.

The costs of installation of fire alarms that are installed during the build process will be based on the number of smoke alarms fitted. The BS5839 Part 6 system will require additional smoke alarms and therefore addition mains wiring and interconnecting wiring.

Neither of the documents reviewed require fire resisting cable for the majority of domestic installations, i.e. those consisting of smoke alarms, and therefore the power supplies to the alarms and interlinking between the units can be domestic mains wiring. (Both documents recommend this type of cabling and both identify the need to use colour coding to differentiate the power supply to the alarms from the cores used to interconnect the alarms).

**Fire Alarm Installation in a two storey, 3 bedroom house open plan layout.**

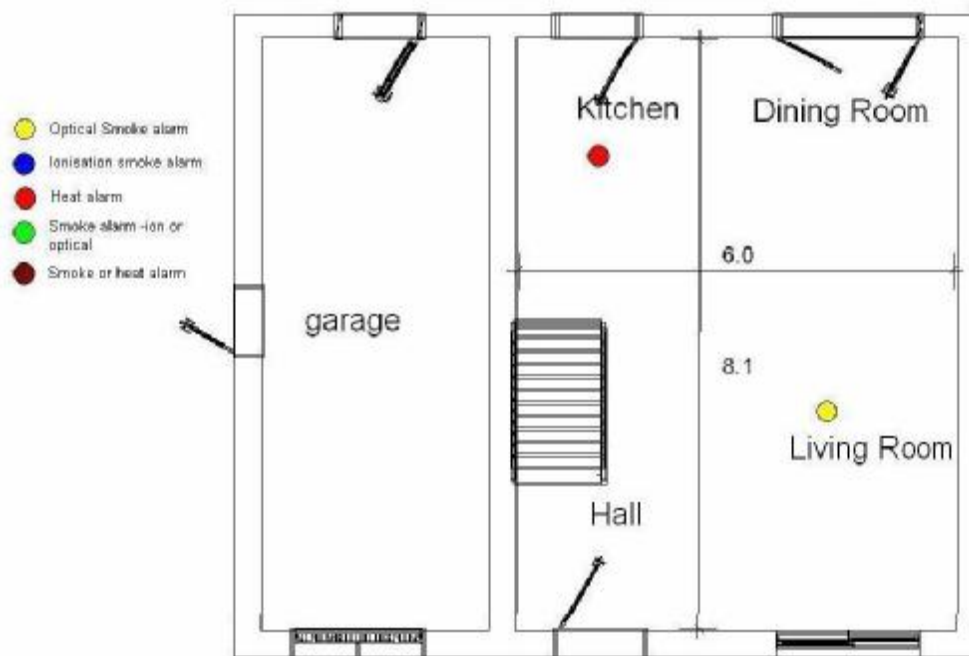


Figure 5 – Ground floor open plan layout meeting the requirements of BS 5839 Part 6 and Approved Document B.(Dimensions in metres).

Figure 5 shows the layout of the ground floor of the Cardington house in open plan layout. The installation above would meet the requirements of both the ADB and the BS code of practice. The first floor installation would be as Figure 2 for BS5839 Part 6, with the exception that it is recommended that the detection technology employed is 'optical' as opposed to ionisation to reduce the risk of false alarms.

The first floor of an ADB installation would be as figure 4.

The type of accommodation indicated above presents considerable technical challenges for the installation and correct operation of a fire detection and alarm system.

The main technical issues are-

- False alarms generated by cooking activities
- Increased spread of smoke and fire around the property and therefore a requirement to reduce the time to detection in order to give the best possible chance of escape.

Technologies currently available (optical and ionisation) are detailed in both documents in terms of sensitivity and false alarm performance. However, the ADB does not state the type of alarm that should be fitted if the circulation areas and/or stairs are open to the kitchen. Ionisation detectors will be more susceptible to false alarms if located near to a kitchen area

Both documents recommend the use of heat alarms in the kitchen in addition to smoke alarm(s) on the ground floor. In the above example, the smoke alarms are in the same compartment as the kitchen, and hence the heat alarms.

Under such circumstances, it is considered that the heat alarms would provide only a marginal reduction in time to alarm, and in many circumstances the smoke alarms, either on the ground floor or on the first floor landing, will react to a fire developing in the kitchen before the heat alarm. If the fire situation developing in the kitchen is as a result of unattended cooking activities, unless there is a very rapid transition to a flaming fire, the detection of the smoke generated will provide the earliest warning of the fire.

If ionisation type smoke alarms are used then the advantages of installing heat alarms are further reduced (ionisation smoke alarms are very sensitive to flaming fires). It is noted that, to reduce false alarms, that BS5839 Part 6 precludes the use of ionisation type alarms under such circumstances.

### **Fire Alarm Installation in a three storey, 4 bedroom house**

The provision of additional accommodation through the conversion of the loft space is covered in both documents. Unless the property is defined as 'large' (any storey exceeding 200 m<sup>2</sup> as defined by both documents), the addition of the extra accommodation only leads to the addition of an extra interlinked smoke alarm on the third level.

### Large Houses

Large houses are defined in Approved Document B as properties with any storey exceeding 200 m<sup>2</sup>.

The recommendations for provision of fire detectors and alarm systems changes at this limit (with one exception).

For single storey properties, Approved Document B recommends increases in the provision for the detection system. A fire detection and fire alarm system complying with the recommendations would consist of discrete smoke detectors and sounders, communicating with and deriving power from a central control panel. The wiring for the system is required to be fire resisting.

For the same size of single storey property, BS5839 Part 6 recommends the use of smoke and heat alarms.

This is a significant increase in the provision of the fire detection system and would be significantly more costly to install and maintain.

If the 'large house' has two or more storeys, then both BS 5839 Part 6 and ADB are consistent in their approach to the fire detection system.

### Fire alarm installation single storey property.

Figures 6 and 7 show a fire detection and alarm installation on a single storey property complying with the requirements of BS5839 Part 6 and Approved Document B (including proposed revision).

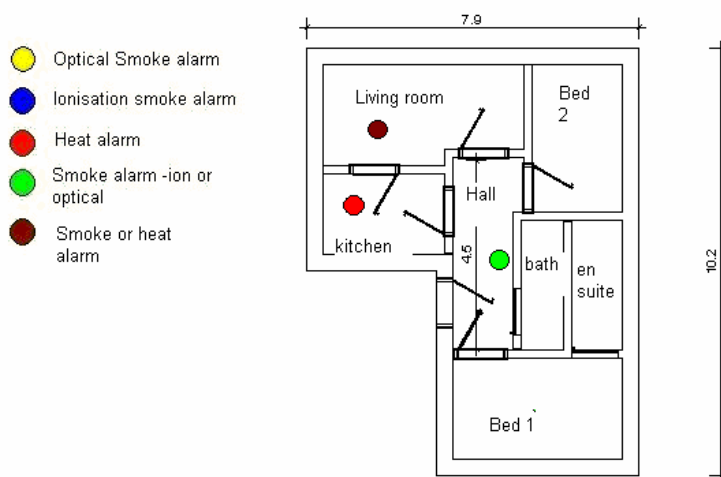


Figure 6. Fire detection and fire alarm installation single storey property of 65m<sup>2</sup> to BS 5839 Part 6 (dimensions in metres).

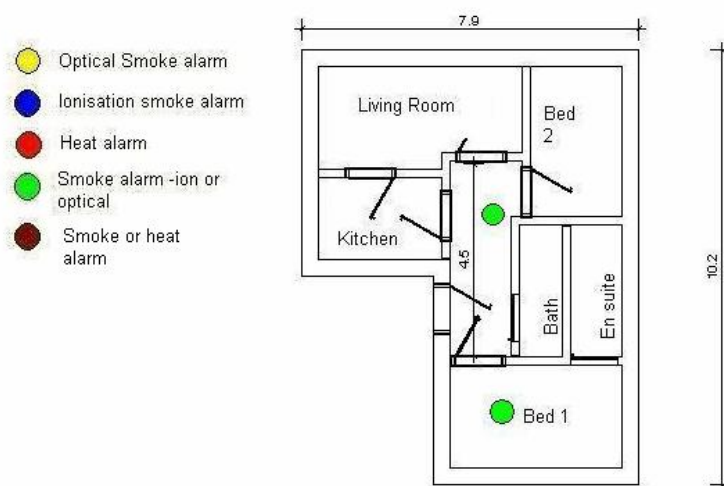


Figure 7. Fire detection and fire alarm installation single storey property of 65m<sup>2</sup> to Approved document B (including proposed revision, dimensions in metres).

The pattern of fire detection remains the same with the BS code recommending detection in the 'day time areas' of the property.

The above property is approximately 65m<sup>2</sup>, for review purposes the size of the above property has been increased to 180m<sup>2</sup>.

The increase in property size would lead to an additional smoke detector fitted to the corridor of the property if following the recommendations of BS5839 part 6 (clause 11.2b), otherwise the installations remain unchanged.

The installation of the detection equipment to Approved Document B remains unchanged.

The smoke and heat detectors would still be within the coverage recommendations of both ADB and the BS code of practice.



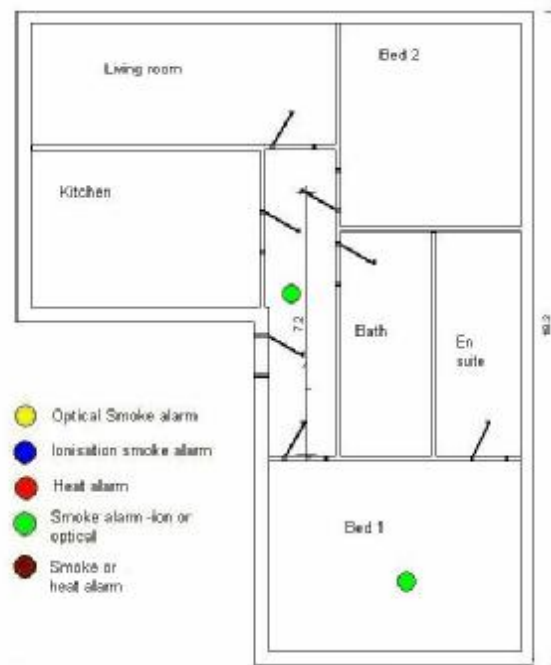


Figure 8. Fire detection and fire alarm installation single storey property of 180m<sup>2</sup> to Approved Document B. (Including proposed revision, dimensions in metres)

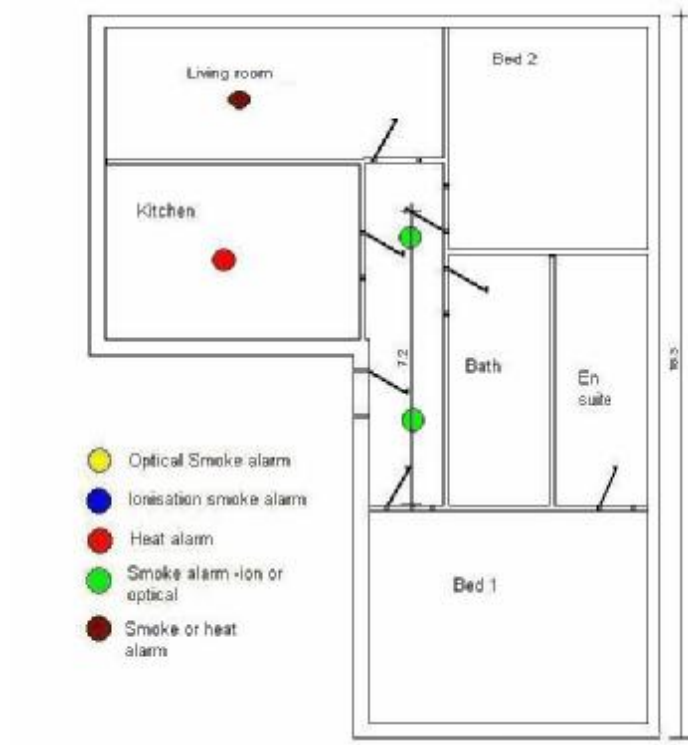


Figure 9. Fire detection and fire alarm installation single storey property of 180m<sup>2</sup> to BS 5839 Part 6.

### Equipment Available for Domestic Fire Detection and Fire Alarm Installations

The following devices are available to the construction industry in the form of self contained detection and alarm devices 'smoke and heat alarms'.

#### Smoke Alarms

Self contained smoke alarms form the majority of the fire detection in domestic premises in the UK. Smoke alarms using either optical or ionisation technologies are readily available to the construction industry. There are also an increasing number of heat alarms available for installation in domestic dwellings. All of the above units are available as mains powered, interlinkable with secondary power supplies.

Smoke detectors are in effect particle detectors, they may respond to aerosols, dust, fumes, talc etc. and false or unwanted alarms can be a major problem.

Smoke detectors are usually identified by their operating principle. The two main operating principles for smoke detectors are ionisation and optical (photoelectric). Smoke detectors operating on the optical principle may respond well to the smoke generated by smouldering fires, as these fires generally produce more of the larger smoke particles. Optical detectors also respond well to smoke which has aged and

where the smaller smoke particles have agglomerated. Detectors using the ionisation principle provide somewhat faster response to high-energy open flaming fires, since these fires produce large numbers of the smaller smoke particles. An ionisation smoke detector has a small amount of radioactive material which ionises the air in the sensing chamber, thus rendering it conductive and permitting a small current to flow through the air gap between two electrically charged electrodes. This gives the sensing chamber an effective electrical conductance.

When smoke particles enter the ionisation chamber, they decrease the conductance of the air by attaching themselves to the ions created by the ionisation process, causing a reduction in mobility of the charged particles. When the current flowing between the plates is less than a predetermined level, the detector responds.

In photo-electric detectors, the presence of suspended smoke particles generated during the combustion process affects the characteristics of a light beam passing through the air. The effect can be utilised to detect the presence of a fire in two ways:

- Scattering of the light beam or
- Attenuation of the light intensity over the beam path (optical beam detectors). Detectors using this method of detection would not normally be found in domestic premises.

Detectors utilising the photoelectric light scattering principle are usually referred to as optical 'point' detectors. When smoke particles enter a light path, the particles scatter the light beam. Point type optical detectors contain a light source and a photosensitive device so arranged that the light rays do not normally fall onto the photosensitive device. The light source and receiver are housed in a light-tight labyrinth. When smoke particles enter the light path, light strikes the particles and is scattered and 'seen' by the photosensitive device, causing the detector to respond. Optical smoke detectors are sensitive to optically dense smoke, but are less sensitive to the small particles found in clean-burning fires that produce little visible smoke. Detectors that operate on the principle of light scatter are more sensitive to light coloured smoke; very dark smoke, by definition, absorbs light rather than scatters it, but will be readily detected by a smoke detector that operates on the principle of obscuration (e.g. an optical beam type detector).

### **Heat (Thermal) Detectors**

Heat detectors are the least sensitive fire detectors and have the lowest false alarm rate of all automatic fire detectors; however, they are also the slowest in detecting fires. A heat detector is best suited for fire detection in either: a small confined space where rapidly building high heat output fires are expected; in compartments where ambient conditions would not allow the use of other fire detection devices; or where speed of detection is not the prime consideration. Heat detectors respond to the convected thermal energy of a fire and are generally located on or near the ceiling. They respond either when the detecting element reaches a predetermined fixed temperature or to a specified rate of temperature change or to a combination of the two phenomena. Heat detectors are typically referred to as 'fixed temperature' or 'rate of rise' heat detectors. Rate or rise heat detectors also contain a fixed temperature sensing element.

'Fixed temperature' detectors are designed to trigger when the temperature of the operating element reaches a specified point. The air temperature at the time of operation is usually higher than the rated temperature because it takes time for the air to raise the temperature of the operating element to its set point. This 'thermal lag' is related to the RTI or Response Time Index. Fixed temperature detectors are

available to cover a wide range of operating temperatures. High temperature detectors are necessary so that either detection can be provided in compartments that are normally subjected to high ambient (non-fire) temperatures, or when zoned, so that only detectors in the immediate fire area operate. 'Rate of rise' heat detectors respond to a predetermined temperature rise in a set period of time, usually 6 0C per minute.

The following technologies are also available for the detection of fire. We are not aware of any of the technologies below being packaged for domestic use.

### **Aspirating Smoke Detectors**

A type of smoke detector, which has become widely used in extremely sensitive applications, is the aspirating system. This device consists of two main components: a control unit that houses the detection chamber, an aspiration fan and operation circuitry; and a network of sampling tubes or pipes. Along the pipes are a series of predrilled holes that are designed to permit air to enter the tubes and be transported to the detector. Under normal conditions, the detector constantly draws an air sample into the detection chamber, via the pipe network. The sample is analyzed for the existence of smoke, and then returned to atmosphere. Various technologies are used to analyse for the presence of smoke, lasers, xenon flash tubes and Wilson Cloud Chambers are examples of the technologies which are utilised to detect smoke particles. The alarm is triggered if a pre-set threshold is exceeded. Aspirating detectors are extremely sensitive and are typically the fastest responding automatic detection method. However, long air transport times with the associated time delays and the large areas the device may be sampling from need to be taken into consideration.

The above method of detection has been applied in larger domestic premises and has the advantage that the sampling points can be hidden from view. This type of detector would be used in conjunction with control and indicating equipment and separate sounders.

### **Optical beam smoke detectors.**

Smoke detectors that operate on the principle of light obscuration or absorption consist of a light source, a light beam collimating system, and a photosensitive device. When smoke particles enter the light beam, the light reaching the photosensitive device is reduced, initiating the alarm. The light source is usually a light emitting diode (LED). This type of smoke detector is normally referred to a beam detector or optical beam detector and can work over path lengths of many tens of metres.

This type of detection would be used for fire detection in a large volume, and apart from specialist applications (very large dwellings) would not normally be found in domestic dwelling.

### **Carbon Monoxide Fire Detectors**

Carbon Monoxide is a toxic gas produced by fires and responsible for a high proportion of fatalities. For many years it has been known that the presence of Carbon Monoxide can be used as a means of providing early warning of fire and only recently has research associated with the automotive and micro-electronics industries lead to the development of a commercial Carbon Monoxide detector which is sufficiently sensitive for use as part of a fire detection system. Slowly developing/smouldering fires can produce large quantities of carbon monoxide, before traditional detectable smoke aerosols and particulates escape from the fire.

In these situations, when using carbon monoxide fire detectors, detection may occur before ion-chamber or photoelectric smoke detectors operate an alarm. Smoke movement is constrained by convection currents created by the fire, whereas Carbon Monoxide being a gas is much more mobile than smoke and also moves by diffusion. However, efficient combustion, such as that typified by fast flaming well ventilated fires produce very little carbon monoxide.

Carbon monoxide fire detectors are now available for use in commercial fire detection systems. Currently there are no carbon monoxide fire alarms for the domestic market.

### **Flame Detectors**

Flames from most fire sources emit electromagnetic radiation including ultra-violet and visible light, and infrared radiation in various intensities and characteristic wavelengths or frequencies. Sunlight and lighting and heating systems also generate radiation in the same parts of the spectrum and therefore flame detectors must be selected to discriminate flame from other radiation sources. Electromagnetic radiation travels at the speed of light. Flame detectors are line-of-sight devices and can have extremely fast response times. Flame detectors may respond to ultra-violet, infrared or a combination of the two radiation bands. Flame detectors should be chosen for applications where there is the likelihood of rapid flame development so that an alarm is required before products of combustion or heat would have reached smoke detectors or thermal detectors. The choice of infrared detectors or ultra-violet detectors or some combination will depend on the typical radiation from the expected fire hazard and the presence of false alarm sources in the vicinity.

Flame detectors are used in specific risk applications. It would be very unusual for the units to be considered suitable for domestic applications.

Two options for interlinking the devices are available. The interconnection between multiple smoke alarms can be hard wired or wireless links.

### **Householder interaction with fire protection equipment.**

To operate effectively smoke and heat alarms need to be sited on the ceiling (with some exceptions) and away from obstructions.

It is not therefore possible to conceal fire detection and alarm equipment, (with the exception of aspirating smoke detector) and for the equipment to continue to function correctly. Therefore, some consideration of householder interaction is required.

The vast majority of domestic fire detection installations in the UK are installed by the occupiers of the property. With the reliance on this method of installation for the majority of smoke alarms, there is a significant risk that the installations will not comply with the recommendations of either ADB or BS5839 Part 6 in full and hence, the performance of the units may be compromised, but the installation, in terms of alarm location will be accepted by the occupier(s) of the house.

If the recommendations of BS5839 Part 6 are followed the number of smoke alarms installed in the 'day time' areas of the building will be increased. There appears to be general acceptance of the fitting of fire

detection equipment in the escape routes in domestic dwellings (at least in 75% of properties), however we would question whether this acceptance would extend to fire detection equipment fitted in living and dining areas.

It is considered that there would be significant risk of the fire alarms being removed from living and dining areas because there are considered 'unsightly'. With this most likely to occur during the redecoration of the room in question. Any modifications to the wiring interlinking the smoke alarms may have a greater impact than just the removal of the smoke alarm in question, for example, interference with the cabling interlinking alarms may prevent all units sounding in response to a fire situation.

Although, the above could also apply to bedroom areas, it is considered less likely; although bedroom mounted units may be deemed unacceptable to the occupiers of the dwelling for other reasons. The increased sound levels on the upper floors may not be considered desirable for households with young children especially if the smoke alarms are prone to false activation.

## Review of fire statistics 1994-2002

This section of the test report considers fire deaths and injuries in the UK over the period 1994 to 2002 that occurred in domestic dwellings.

The data was reviewed for a number of factors including:

- The room in which the fire was deemed to have started.
- The time of day at which the fire started.
- The number of fatalities and injuries
- The time between the fire starting and discovery
- Whether smoke or heat alarms were fitted and how these impacted on the outcome of fires.

The review considered the above scenarios in terms of fire detection and whether changes to the number, type and possibly positioning of detectors would have an effect on the number of fire resulting in deaths and injuries.

The review considered the pattern of fires within properties with and without fire alarms and how the pattern of fires has changed as a result of the installation of smoke alarms

For the period 1994 – 2002 the number of fires, deaths and injuries are given in Table 1

Table 1 - Fire deaths

Estimate of total number of fires	500000
Total number of deaths (actual)	3709
Total number of injuries (actual)	104268
Estimate of the number of fires in homes with smoke alarms	170000
Estimate of the number of fires in homes without smoke alarms	330000

### Distribution of fires in properties with and without fire detection

Figures provide by the British Crime Survey indicate that in the region of 75% of domestic dwellings are fitted with one or more smoke alarms.

In properties fitted with smoke alarms there were 1238 deaths and 40347 injuries from an estimated 170000 reported fires.

In properties without fire alarms there were 2471 deaths, 63921 injuries and from an estimated 330000 reported fires

The 25% of properties that were not fitted with fire alarms accounted for 66% of reported domestic fires. These fires in turn are responsible for in excess of 60% of deaths and injuries across the UK.

Results from the British Crime Survey, reported in the summary of UK fire statistics 2002), suggest that approximately 75% of all dwellings have smoke alarms. The total number of dwellings is estimated to be 24.7 million (houses, individual dwellings within HMO's and blocks of flats, but not counting residential care homes) [Williams et al 2004]. Hence, the number of fires, deaths, and injuries per year per million dwellings can be estimated as in the following table.

Table 2. Fire Statistics per Million Dwellings per Year

	Deaths	Injuries	Fires (reported)
With alarm	7.4	243	1016
Without alarm	44.5	1151	5934

Table 3. Fire Statistics per Thousand Reported Fires

	Deaths	Injuries
With alarm	7.3	239
Without alarm	7.5	194

A simplistic interpretation of the above figures would suggest that dwellings where smoke alarms are fitted (voluntarily) are roughly six times less likely to have fires, but if a fire occurs, the alarm makes little difference. However this interpretation is almost certainly not correct. The key is the number of reported fires – if the fire brigade do not attend a fire, it will not be recorded in the fire statistics. It is probable that the early warning obtained, thanks to a working smoke alarm, enables many fires to be tackled by the occupants, without needing to involve the fire brigade. It is also likely that people who take the trouble to fit smoke alarms will also be more careful generally with respect to fire safety, and thus have fewer fires. However, the statistics do not enable us to determine the relative importance of these two effects.



Figures 10 and 11 compare the number, location and start time of fires in domestic dwellings.

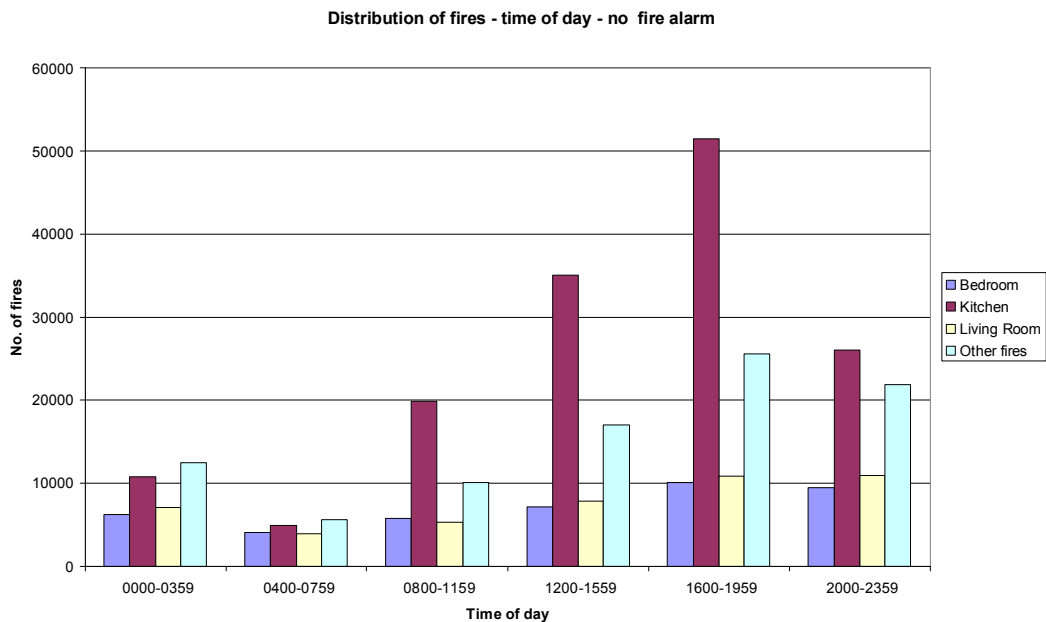


Figure 10 Distribution of fires, time of day, without fire alarms

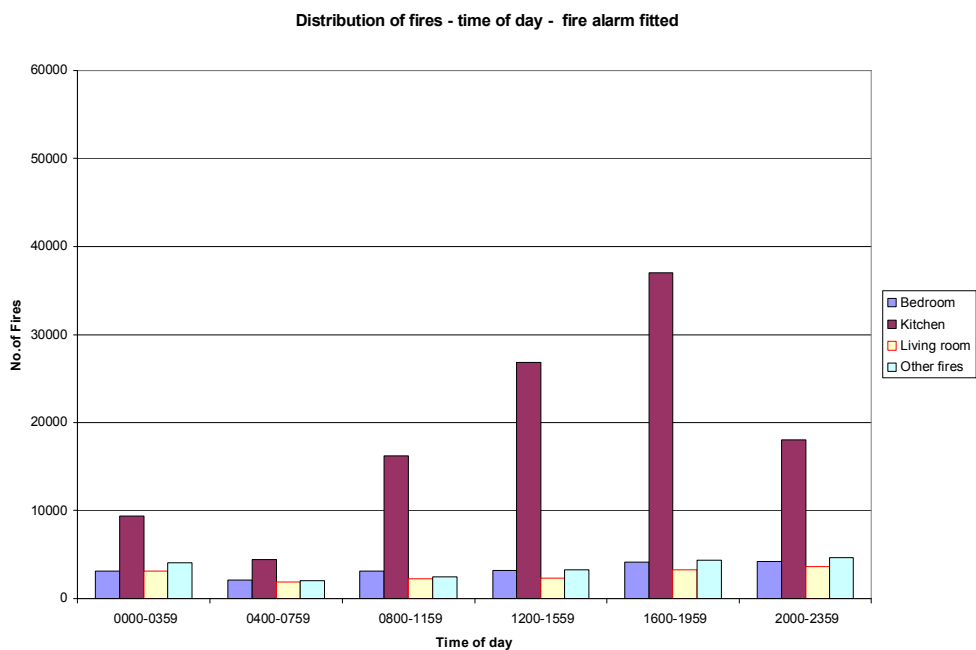


Figure 11 Distribution of fires, time of day, with fire alarms

### **Pattern of fires in properties without fire detection and alarm systems.**

In the 10 year period for 1994 to 2002, for properties without fire alarms, the greatest cause of death and injury is attributed to fires starting in the living room.

Fires starting in this area resulted in 1049 deaths and 12284 injuries with the majority of these deaths and injuries occurring between the hours of midnight and 8 am. It is considered that a large number of these deaths and injuries are occurring while the occupants are within bedrooms and are unaware of the fire starting. A significant number of deaths and injuries occur in the 08.00 to 12.00 time period, however it is not clear from the data and the way the data is reported what are the significant factors in these fires.

The second largest cause of death and injury are fire starting in bedrooms with 706 deaths, 12633 injuries from an estimated of 43000 fires. The majority of deaths and injuries are occurring when bedrooms are likely to be occupied.

### **Pattern of fires in properties with fire detection and alarm systems**

In properties fitted with fire alarms, the profile of fire type and location is different. It is also apparent that the number of fires resulting in death and injury is significantly lower in properties fitted with fire alarms.

In homes in which fire detection and alarm systems are fitted differ from those without alarms in that:

- The frequency of reported fires is greatly reduced from just under 6000 per million dwellings per year, to just over 1000 reported fires per million dwellings per year
- There were 451 deaths and 6173 injuries from fire starting in the living/ dining room.
- In percentage terms, of all fires leading to death and injury, living room fires drop from approximately 14% of domestic death and injury fires to just fewer than 10%.
- The frequency of fire starting in bedrooms is greater than those in the principal habitable rooms.
- Fires starting in the living room led to a greater number of fatalities than bedroom fires by a small margin
- Fires starting in a bedroom resulted in a greater number of injuries.

Figures 12 and 13 compare number of deaths for properties with and without fire detection.

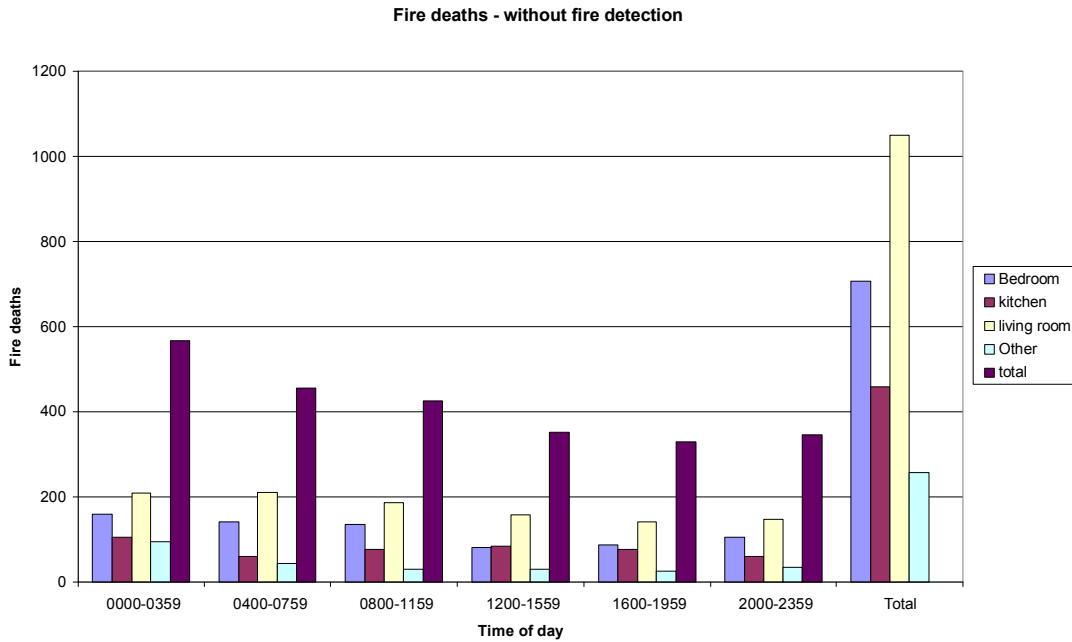


Figure 12 Fire deaths without fire alarms

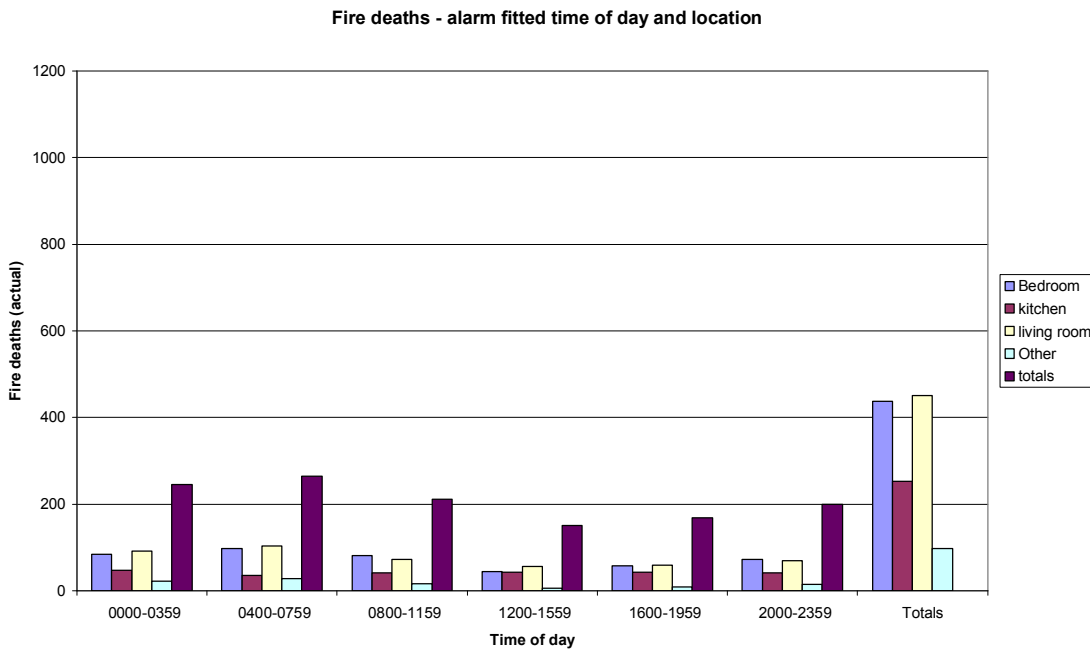


Figure 13 – Fire deaths with fire alarms fitted

Table 4. The number of deaths and injuries for properties with fire detection

Fire location	Deaths	Injuries	No. of fires (estimated)
Bedroom	437	7363	19851
Kitchen	253	22380	111978
Living room	451	6173	16480
Other	97	4431	20927

### **Fires in kitchens.**

Fires in kitchens have shown the least reduction in fires attributed to a single area. However, it is apparent that the death rate in terms of number of fatalities and deaths per 100 fires shows a 30% reduction between those properties fitted with alarms and those that are not.

The greatest number of fires starting in kitchen occurred during the midday to 8.00pm time window that coincides with cooking activities in the kitchen. Whilst these fires led to a significant number of deaths and injuries, fires starting in the kitchen during these times did not lead to the greatest number of deaths (although the greatest number of injuries). It is considered that the majority of these fires are starting in circumstances in which the occupiers are in close proximity, awake and are able to react to the fires.

The number of fires decreases outside of the above time window; however the total number of fatalities being caused by these fires increases. This is attributed to fire starting with the occupants being elsewhere in the building and unable to react in sufficient time to escape.

### **Review of fires in those properties fitted with a smoke alarm.**

Both the ADB and the BS Code of Practice agree in the benefits of protecting the escape routes in a dwelling, and the addition of fire alarms in properties has made a significant contribution to the reduction of deaths and injuries in domestic fires, however, from the data we have to date, we are unable to establish what contribution to the overall fire safety package fire alarms bring.

In properties that were fitted with automatic fire detection, there were 1232 deaths and in excess of 40000 injuries in the 9 year period of the statistics studied.

These deaths and injuries have been divided into three categories depending on the performance of the fire alarm system.

- Those fires in which the alarms failed to operate
- Fires in which the alarms were operational, but the occupants were alerted or the fire service called before the operation of the alarm.

- Fires in which the fire detection system was deemed to have functioned correctly and there were deaths and injuries.

Table 5. Statistics for all reported fires during 1994-2002, where alarms were present

	Alarm failed to operate	Alarm operated – but failed to alert occupants	Alarm operated as intended	Total
Fatalities	596	239	397	1232
Injuries	14784	4472	21070	40326
Fires	47176	18200	103890	329499
Deaths per '000 fires	12.6	13.1	3.8	7.3
Injuries per '000 fires	313	246	205	239

Once again, the fact that the fire statistics are based on reported fires leads to some apparent anomalies. For example, the risk of death where the alarm failed to operate, or alert occupants, is 12.6 ~ 13.1 deaths per thousand fires, significantly higher than the risk of death where no alarms are present (7.5 deaths per thousand fires). This effect is unlikely to be “real”.

#### **Fire alarms failing to operate.**

596 deaths were attributed to the failure of the fire alarms to operate at any time throughout the fire.

The greatest number of fatalities in this category, 318 are attributed to missing, discharged or failed batteries.

It is noted that the current revision of ADB recommends the use of mains powered devices and therefore this issue of alarms failing through battery faults is addressed

#### **Alarms operated, but failed to alert occupants.**

In reviewing the data in this category, a significant number of deaths and injuries occurred in properties fitted with operational fire detection.

In 835 deaths and 19256 injuries, the fire detection system either failed to operate at any time during the fire or operated late. The statistics include the complete failure of the fire detection and alarm system to operate or the alarm system was considered operational, but other factors for example, poor positioning of the detector, was a significant contributory factor to the deaths and injuries.

The fatalities in the above two categories were reviewed in detail.

In 389 (46%) deaths and 11358 injuries (59%) it is clearly identifiable that the fire detection and alarm system would not have detected the fire and alerted occupants under any circumstances. The above figure includes categories 'battery missing', 'zone isolated' and 'systems turned off' and 'faulty'.

Excluded from the above figures are failures attributed to poor positioning of detectors, fire products not reaching detector and ambiguous reasons within the fire statistics. Also excluded were detectors that were too severely damaged to tell if operational or not.

Of the 389 deaths in this category, 331 are attributed to a failure of the battery (missing, failed or discharge). However, we do note from the statistics that this category of failure is also applied when the smoke alarm fitted is designated as mains powered or mains/battery backed units

. The other categories from the fire statistics included were:

- Alarm did not operate: detector removed or isolated or set incorrectly.
- Alarm did not operate: fault in system
- Alarm did not operate: system turned off
- Alarm did not operate: zone isolated.

In 192 deaths and 1985 injuries data is unclear or ambiguous. These have been excluded from further examination.

### **Alarms operated as intended**

There were 397 deaths in which the fire detection equipment was reported as operational. These were examined in detail. .

The circumstances of the fire were recorded in the fire statistics, and this information was used to determine whether the performance of the fire detection was a significant contributory factor to the outcome of the fire.

Identified below are the recorded circumstances in which improvement in fire detection may have changed the outcome of the fire:

Trapped by the fire – unaware, trapped by fire for other reason, or trapped by smoke.

Changes in the number and or location of fire alarms was considered unlikely to change the outcome of the fire under the following recorded circumstances:

Suicide/self harm, rescue attempt, chair ridden, bed ridden, other immobility, injury (accidental at start of fire), injured by blast, fighting fire, fell onto fire, escaping, drunk or drugged, discovering fire, or returned to fire.

The cases of victims escaping, or discovering fire, are borderline, and could possibly have been improved with earlier detection.

Better detection and hence earlier warning may have led to fewer fatalities under the categories "trapped by smoke, fire, and other". The fatalities under "awaiting inquest" and "other" are tabulated separately.

The results of the data processing for the years of this study are shown in table 6.

Table 6. Circumstances of fatalities, in fires where detectors raised alarm

No of fatalities in trapped fires.	
Living room	68
Bedroom	70
Kitchen	19
Other	22
Total	180
Fire detection unlikely to change outcome	
205	
Awaiting inquest/other	
72	

It can be seen from the above data, that in 45% of cases, a fully operational fire alarm system was unlikely to have a significant effect on fire fatalities and injuries.

## VALIDATION OF CRISP FOR DOMESTIC APPLICATIONS.

### Introduction

CRISP is a Monte-Carlo model of entire fire scenarios. The sub-models representing physical 'objects' include rooms, doors, windows, detectors and alarms, items of furniture etc, hot smoke layers, and people. The randomised aspects include starting conditions such as various windows and doors open or closed, the number, type and location of people within the building, the location of the fire and type of burning item.

The basic structure of CRISP is a two-layer zone model of smoke flow for multiple rooms, coupled with a detailed model of human behaviour and movement. All the physical 'objects' are supervised by the Monte Carlo controller, making each one perform for each time step. The Monte Carlo controller also handles all the input and output, initialisation for each run, and starts each run automatically. Functions are included to generate random numbers from any distribution. The calculations for each run are carried out iteratively, with variable time intervals to ensure the program's efficiency, accuracy and stability.

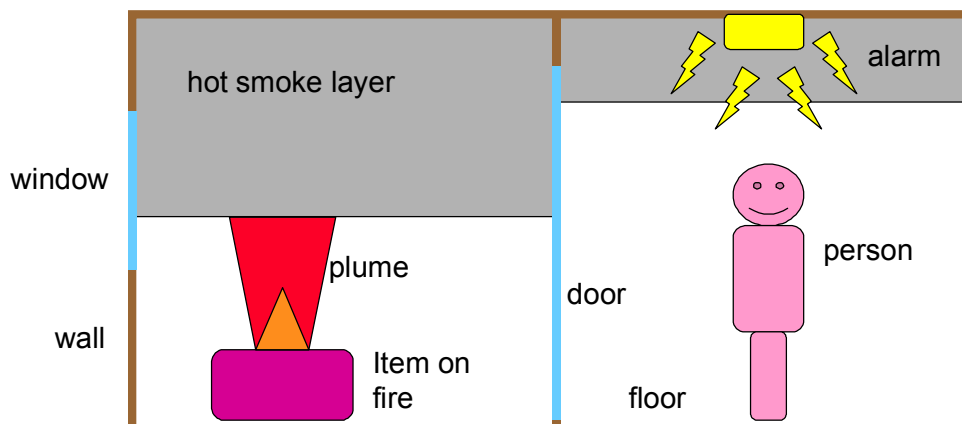


Figure 14. A graphical representation of some of the components of the CRISP model.

Smoke moves between rooms by means of vent flows, driven by pressures arising from buoyancy differences. These flows may form vent plumes, which may cause further mixing of the gas layers in the room they flow into. The geometry of the room determines how quickly a growing smoke layer will descend. Combustion products are transported between the various cold air and smoke layers by plumes and vent flows. Heat may also be lost by radiation and conduction through the walls of the compartment. The buoyancy of the hot and cold layers determines whether plumes and vent flows rise or sink.

Vents are defined as doors and windows, or any other opening which smoke may move through. They may open or close during the simulation as people move through them. However, doors can be specified as self-closing. The traversal difficulty (for people) includes physical and psychological aspects.

CRISP does not explicitly model fire resistance, all barriers are assumed to retain their integrity for the duration of the simulation. The great majority of scenarios are resolved in a few minutes, so this assumption is sufficiently accurate. It is also assumed there is no smoke spread through cavities.



People are assumed to adopt distinct behavioural roles, either naturally or due to training. Their behaviour can be described in terms of actions, which may be abandoned, and substituted by new ones, depending on the state of the environment. Rational decisions are made based on current knowledge (which may be limited and/or incorrect). People rarely 'panic' (in real life, 'panic' behaviour is actually extremely rare).

As the people move around, they are exposed to smoke and acquire a fractional effective dose (FED). When the FED reaches 100%, the person is assumed to be 'dead'. The risk is expressed simply in terms of the fraction of people originally present who end up 'dead', averaged over a sufficiently large Monte-Carlo sample.

### **Objective of the validation exercises**

As the brief description of the model in the previous section implies, CRISP is a rather complex model. This complexity is not to do with the individual algorithms, many of which are quite simple. Instead the complexity arises as a consequence of the interactions between the different components of the model. Validation of the model in its entirety is probably impossible. However, confidence in the model can be increased by validation of the behaviour of its components, independent from one-another.

The objective of the validation exercises reported here was to demonstrate the acceptable functioning of the zone model for smoke movement. This is one of the key aspects of the model, since the risk calculations are based on the exposure of people to smoke.

We have examined the archives of previous FRS experimental tests in the house built within the Cardington Laboratory. Some of the "control" fires performed as part of the project to examine the effectiveness of residential sprinklers [Williams et al 2004] seemed to fit our criteria of a reasonably repeatable fire scenario within a realistic domestic environment.

However, as the experiments had aspects that were beyond our control (for example, differences in fire growth rate); we also did a comparison between CRISP and another zone model, CFAST [Jones et al 2005]. CFAST has been developed by NIST in the United States over many years, and is in widespread use throughout the fire community.

The acceptance criteria for the zone model would be a reasonable agreement between smoke layer masses and temperatures, as functions of time, within different rooms of the building. We did not attempt to compare the concentrations of species such as carbon monoxide, carbon dioxide, etc. For any "real" fire (the experiments we were attempting to simulate had burning TV sets), the yields of different combustion products are usually specified as input parameters, rather than quantities which the model can calculate. If the input yields from the burning item are correct (this is a big "if"), and if the zone model is giving a reasonable approximation to the physics of the smoke transport, then the concentrations of different species at different locations should be reasonably accurate.

In addition to attempting to simulate the experiments, we also performed comparisons between CRISP and CFAST simulations of a fire in a single room. By modelling as simple a scenario as possible, any differences between the two models should be highlighted.

### Comparisons between models, for a fire in a single room.

The room in question was the lounge of the Cardington experimental house. The lounge has dimensions 4.2m x 3.55m x 2.4m high. There was one opening, a door to the hall (which is assumed to lead directly outside, for the purposes of this series of simulations). The door was 1.981m high and 0.762m wide.

For the first comparison, a steady fire with a total heat output of 100kW was used. Heat losses to the compartment walls were ignored. The results are shown in the appendix, figures A1 ~ A3. The interface height (Figure A1) predicted by CRISP is slightly less than predicted by CFAST. In this case it might be because the layer temperature (Figure A2) predicted by CRISP is slightly greater, although in other simulations the interface in CRISP is lower even when the hot layer temperature is lower than in CFAST. Note that the CRISP temperatures are shown as a rise above the starting temperature (290K), whereas in CFAST the temperatures are degrees Celsius (i.e. a rise above 273K).

One reason for the increased temperature in CRISP was that in CFAST, all of the fire's radiant heat is simply lost, whereas in CRISP some of the radiated fraction may be absorbed directly in the hot layer (assumed optically thick), or re-radiated via the walls into the hot layer. (Note that the cold layer is assumed optically thin, therefore does not absorb any of the radiated heat.)

The plume entrainment rate is shown in figure A3. CRISP normally uses the equations derived by Zukowski [Zukowski 1978], whereas CFAST can only use the equations derived by McCaffrey [Jones et al 2005]. However for the purposes of model comparison, CRISP was required to use the McCaffrey equations. There is a difference in the entrainment rates at the very early stages of the simulation, but when equilibrium is reached the entrainment rates are very similar, the slight difference arising due to the difference in rise height from the burning item to the hot/cold interface.

Note that neither model accounts for the leaning plume that is deflected by the inflow of fresh air coming through the doorway. This deflection can increase entrainment rates by up to 100%, with a corresponding reduction of hot layer temperature.

The next series of comparisons used the same compartment geometry, but different steady-state fire sizes. For a 30kW fire (figures A4 – A5), CRISP has constant interface height of 2.4m, i.e. a hot layer does not form. The criterion that CRISP uses to determine whether a stable hot layer forms is that the average absolute temperature (K) of the plume (the convective heat release rate, divided by the plume mass entrainment rate and the specific heat capacity) must be 5% higher than the absolute temperature of the cold layer. If this criterion is not satisfied, the fire's convective heat and combustion products are deposited in the cold layer instead. The "cold" layer heats up, and (in this case, since the fire size is constant) a hot layer never forms. Note that CRISP does not allow incoming fresh air to form a cold layer beneath the existing "cold" layer.

The CRISP layer temperature (a "fudge" in CRISP ensures the upper layer always has a temperature at least as great as the lower layer, even when the upper layer has no mass) is an average for the whole compartment. In CFAST, the upper layer only occupies about half the compartment volume. The CRISP temperature is therefore lower, because the fire's energy is heating up a greater mass of gas.

In the case of the 300kW steady fire (figures A6 – A7), the interface heights are less than for the 100kW fire, and the layer temperatures are greater, as expected. In the case of the 1000kW fire, not all of the data from CRISP could be plotted. This was because CRISP was using very short time steps to retain model stability – the number of data points was in excess of what the spreadsheet package could plot. Normally,

CRISP would transpose to a one-zone model for this compartment once the interface height falls below 0.5m (or full room involvement if flashover occurs). In one-zone mode, the model is more stable and does not require such short time steps. However, for model comparisons, the transition to one-zone model was prohibited for this series of simulations.

Note that, for the 1000kW fire, both CRISP and CFAST are predicting layer temperatures (figure A9) that would be sufficient to cause flashover to occur as a consequence of radiation from the hot smoke layers. Both models have the capability to ignite other fuel packages within the compartment when the radiant heat flux is sufficient; however for this series of simulations there were no other fuel sources, so no flashover.

Figures A10 – A13 show results for a growing fire. The heat release rate (figure A10) is that of a television set, as measured by a furniture calorimeter. Both CRISP and CFAST are treating this item as a “heat source” for these simulations, rather than a real fire. Figure A10 confirms that both models are in fact using the same fire (heat) source, although because the CFAST data is only plotted at 10s intervals, the sharp rise just after 800s is less noticeable.

As with previous simulations, the interface height (figure A11) in CRISP is slightly lower than in CFAST, and the layer temperature (figure A12) is a bit higher. Note that in CFAST, the interface height starts to fall as almost as soon as the fire starts to produce heat ( $t=50s$ ), whereas in CRISP it is not until  $t=200s$  until the fire produces sufficient heat for the hot layer to form.

In both CRISP and CFAST, plume entrainment (figure A13) starts at  $t=50s$ . Between this time and  $t=200s$ , the entrainment rate is much greater in CRISP than in CFAST. This is because in CRISP, the height of rise is to the compartment ceiling, whereas in CFAST the entrainment is based on a rise only to the hot/cold interface. Also, in CFAST, there is a modification to the McCaffrey equations, limiting the amount of mass entrained so that the average plume temperature is not less than the hot layer temperature. The justification for this constraint is to prevent the hot layer building up in mass too quickly, with temperature rising too slowly, in the initial stages of growing fires. CRISP deals with this issue by not transferring mass, etc into the hot layer until the average plume temperature is sufficient for a stable layer to form. Thus the large initial entrainment rate observed in CRISP is not really significant, since mass entrained from the cold layer is being deposited back where it came from.

Up to this stage, all the simulations have assumed no heat losses to the walls. The next set of graphs shows results for a single compartment where heat is lost to the walls. The compartment walls are assumed to be “Celcon” lightweight concrete blocks 0.15m thick, with density  $600 \text{ kg m}^{-3}$ , thermal conductivity  $0.00015 \text{ kW K}^{-1} \text{ m}^{-1}$ , and specific heat capacity  $1.05 \text{ kJ kg}^{-1} \text{ K}^{-1}$ . In CFAST the nearest equivalent material was used, this had a density of  $525 \text{ kg m}^{-3}$ , with the other properties similar to “Celcon”.

For a 100kW steady fire, the results are shown in figures A14 – A16. The interface heights and entrainment rates are similar for the two models, and also similar to the results for no heat losses to walls. The upper layer temperatures (figure A16) are, not surprisingly, lower than the 100kW fire with no heat losses to the walls. However, the temperature of the hot layer is slightly less in CRISP than in CFAST. At a time of  $t=100s$ , CFAST has a layer temperature of  $120^{\circ}\text{C}$ , whereas in CRISP the temperature is about  $100^{\circ}\text{C}$ . After 900s, both models have achieved similar temperatures of about  $135^{\circ}\text{C}$ . Compare these values with the steady-state temperatures achieved with no heat losses to the walls,  $150^{\circ}\text{C}$  in CFAST and about  $185^{\circ}\text{C}$  in CRISP. It is clear that, in the CRISP model, more heat is being lost to the walls than in the CFAST model, at least in the earlier stages of the fire. This is presumably because the wall surface temperature rises more slowly in CRISP than in CFAST (if the wall surface temperature was the same as the hot layer temperature, there would be no heat loss by the layer). There are a number of reasons why this might be so, e.g.

different convective heat transfer coefficient values, different values for the emissivity and absorptivity of the walls, and different numerical schemes (CRISP uses a uniform mesh for the 1-d conduction equation, CFAST uses a non-uniform mesh).

For a growing fire (figures A17 – A19), the interface heights and plume entrainment rates are again similar to the corresponding fire with no heat losses to the walls. As above, the temperature of the hot layer in CRISP is more strongly affected by heat losses to the walls than in CFAST. For example, at a time of 500s, the upper layer in the CFAST model has reached about 150°C (was 180°C with no heat loss to walls), and at t=800s the temperature is about 250°C (was 280°C with no heat loss). In CRISP the corresponding temperatures are 140°C (previously 215°C) at t=500s, and 240°C (was 365°C) at t=800s. The net effect of the greater heat losses to the walls in CRISP, coupled with greater radiative heat transfer from the fire to the hot layer, is to cancel out, thus both models predict similar temperature profiles.

### **Comparisons between models and experiments, for a fire in a multi-room house.**

A number of experimental fires were conducted in the Cardington experimental house, as part of the ODPM project looking at the effectiveness of sprinklers in residential premises. Some of the fires were “control” experiments, with sprinklers prevented from operating. The control fires using television sets as the item first ignited seemed to be the most “repeatable”, although of course each fire was different. The fires all originated in the lounge, which was fully furnished. At different points during the different tests, the fires spread beyond the item first ignited, to involve other room contents. When this happened, the heat release rate of the experimental fires would diverge significantly from the heat release rate of the television alone. Also, as mentioned before, even individual televisions, supposedly identical, did not give identical fires. The models were taking, as input, the heat release rate of a burning television measured by a calorimeter. However the actual heat release rate during the experiments in the house would not match this, and so good agreement between the experimental measurements of smoke temperatures, and the predictions by the models, would not necessarily be achieved. All the scenarios were therefore modelled using both CRISP and CFAST, in the hope that the two models would at least give consistent results.

Some parts of the house were sealed off, so that smoke could not enter them. As a result, it was not necessary for all of the rooms in the house to be included in the computer models. The rooms that were included are shown in figure 15, below.

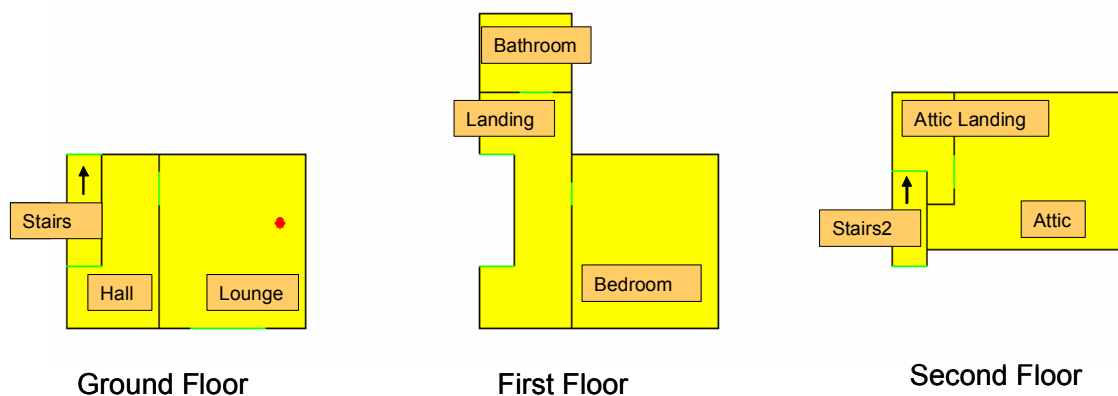


Figure 15. Geometry of the Cardington experimental house. The green lines show the positions of the openings (doors) between different rooms. Arrows on the stairs show the “up” direction. The fire location is indicated by a red spot.

There were three different fire scenarios:

- door between lounge and hall left open
- door between lounge and hall kept closed
- open-plan lounge: the entire wall between the lounge and hall was removed (creating a giant “door”)

Conditions in the lounge, hall and bedroom, predicted by the two models, were compared with one-another and also with experimental measurements of temperatures at different heights in these rooms.

### Lounge door open

The results for the scenario with the lounge door open are shown in figures A20 – A28. In the lounge, the predicted interface height (figure A20) is a little lower than for the growing fire in the single compartment. This is because the vent flow from the lounge no longer goes to the outside, but to the hall. As there is also a hot layer in the hall, the hot layer in the lounge must fall a little lower in order to get sufficient vent outflow to balance the vent inflow / plume entrainment. The two models are in reasonable agreement with one-another.

The CRISP temperature graphs, for this and subsequent simulations, are now given in terms of degrees Celsius, rather than a rise above the starting temperature of 290K. The CRISP graphs are therefore on the same scale as the CFAST temperature results. Due to the higher rate of heat loss to the walls, the lounge temperature (in Celsius) predicted by CRISP is about 75% of the value predicted by CFAST (figure A21). In absolute temperatures, the CRISP value is about 90% of the CFAST value.

In the experimental measurements (figure A22), there is very little temperature rise before  $t=600\sim 650$ s. This could be due to differences in the fire behaviour, as discussed in the introduction to this section, rather than errors in the model predictions of smoke mass and heat transport. Also note, it is hard to define a clear interface between a hot and a cold layer, each of fairly homogenous temperature. If the zone model approximation of two layers holds good, we would see a group of curves at a similar high temperature, and another group of curves at a similar low temperature. Instead (particularly at the peak temperature), there is a considerable temperature gradient over the height of the compartment.

Given the variability in heat release rate from fire to fire, for supposedly identical fuel packages, we should not expect perfect agreement between the models and the experiment. For this case, CRISP appears to give a better match than CFAST, but this is probably just coincidence.

CRISP predicts a slightly greater interface height in the hall than CFAST does (figure A23). This differs for the trend in the room of fire origin, where CRISP interface heights trend to be a bit less than CFAST. The hall temperature (figure A24) is consistently lower in CRISP than in CFAST. Here there is no radiation from the fire entering the hot layer to counterbalance the increased heat loss to the walls, in the CRISP model compared to CFAST.

The experimental measurements of temperature in the hall (figure A25) show a similar shape  $T(t)$  to the measurements in the lounge, as expected. At a time  $t=700$ s, the measured temperature in the hall is about 50%~67% of the temperature in the lounge. At  $t=1000$ s, this ratio is 63%. For CFAST, at  $t=500$ s the ratio of hall temperature to lounge temperature is 74%, and at  $t=800$ s the ratio is 68%. For CRISP, the ratios at the same points in time are 61% and 63% respectively. On the basis of ratio of temperatures in hall and lounge, CRISP appears to be a better match to the experiment.

In the bedroom, CFAST maintains an interface height (figure A26) of 2.4m, i.e. no distinct hot layer is formed. In CRISP, the hot layer does not become distinct until about  $t=350$ s, by which time the hot layer in the landing is below the soffit of the door to the bedroom. In CRISP the hot layer rapidly fills the room (the smoke has nowhere else to go), until at  $t=550$ s the interface is below 0.5m above the floor, and CRISP switches into one-zone mode for this room. Both models are therefore telling a similar story, that there is not a distinct stratification between hot and cold layers. In CFAST, the zone is "cold", whereas in CRISP it is "hot". The temperature of the CFAST layer (figure A27) reaches a peak value of about 55°C, nearly double the temperature rise predicted by CRISP.

In the CRISP model, there is a spike in the temperature graph at  $t=350$ s, when the smoke just starts to spill into the bedroom. The layer is initially at the same temperature as the landing hot layer, but it cools very rapidly (a large surface area in contact with a cold ceiling, and only a small volume with a small heat content). As the smoke layer in the landing descends, more smoke is able to flow into the bedroom, and eventually a stable temperature is reached. Similar spikes may occur in the CFAST model, although hot layers are always given a nominal mass to prevent spikes such as this; also, as CFAST outputs data only every 10s, rapid transients may be missed.

The experimental measurements show a temperature (figure A28) of 30°C at  $t=650$ s, peaking at about 70°C later when the lounge fire is producing its peak heat output. There is not much evidence of stratification. The temperature rise in the bedroom is about one-third of the rise in the hall. At  $t=500$ s, the ratio of bedroom to hall temperatures is closest in CRISP, whereas at  $t=800$ s the CFAST model gives a better match to the temperature ratio.

### Lounge door shut

The interface height in the lounge, predicted by the two models, is shown in figure A29. As before, CRISP initially does not form a hot layer, while the heat release rate from the fire is too low to give the hot layer sufficient buoyancy for stability. Once the layer does form, it quickly fills the room. CFAST predicts the interface falls below 0.5m at  $t=200s$ , CRISP a little later at  $t=250s$ . CRISP switches to one-zone mode at this point; CFAST continues with two layers even though the cold layer is almost non-existent.

As there is only a small leak past the shut lounge door, most of the fire's heat is contained within the compartment. As a result, both models predict that the temperature is greater when the door is closed (figure A30) than when the lounge door is open. The temperature predicted by CRISP (in Celsius) is only 57% of that predicted by CFAST at  $t=500s$ , although better consistency occurs at peak temperature, where CRISP's value is 78% of CFAST.

However, both models are treating the fire as a "heat source", which is not a good representation of reality in this scenario. The experimental measurements (figure A31) show a much lower temperature in the lounge with the door shut, compared to when the door is open. This is because the real fire is starved of oxygen, and cannot sustain the same heat release rate as when the door was open and fresh air was coming into the room.

Both CFAST and CRISP can take account of insufficient oxygen, by reducing the heat output from the fire according to the equivalence ratio of the oxygen available compared to the oxygen required for complete combustion of the pyrolysed fuel. Figure A32 shows the predicted lounge temperature in CRISP, for a vitiated fire. The temperature is about 60% of the "heat source" value (figure A30), although still higher than the experimental measurements.

In the hall, CRISP predicts a very shallow upper layer (figure A33), whereas CFAST predicts a deeper but cooler layer (figures A33 – A34). It is not clear why this difference in behaviour arises; it may be due to entrainment by the vent flow as it enters the cold air in the hall. CFAST has entrainment by "vent plumes" but CRISP does not. The experimental measurements show no temperature rises at any height within the hall (figure A35). Presumably the real door was less leaky than assumed by the CRISP and CFAST models.

In the bedroom, both CRISP and CFAST predict constant interface heights of 2.4m (figure A36). As CFAST predicts a temperature rise of about  $5^{\circ}C$  (figure A37), and CRISP a negligible rise, it is not surprising that no hot layer is formed. Experimental measurements show no temperature rise in the bedroom (figure A38).

### Open-plan lounge / hall

In the open-plan configuration, it is expected that more oxygen would be available to feed the fire, and there would be more rapid transport of smoke to other regions of the house, with less smoke in the lounge as a result. As both models are running with a "heat source" instead of a real fire, the greater probability of fire spread beyond the item first ignited does not feature.

However, the layer interface heights in the living room do behave as expected (figure A39). In CFAST the interface is about 0.2m lower than the scenario with the lounge door open. In CRISP the interface is also initially about 0.2m lower, but the height starts to oscillate with a short time period. Note that the hall interface height (figure A42) also oscillates. At  $t=800s$ , the oscillation trips CRISP into one-zone mode for

the hall and lounge. Fortunately this transition to one-zone mode occurs at the end of the simulation, so the temperature (figure A40) during the growth phase is unaffected. When CRISP undergoes a transition to one-zone mode, any remaining cold layer is instantly mixed with the hot layer, causing a step reduction in the hot layer temperature.

The experimental measurements (figure A41) show a rise in temperature occurring earlier for the open plan lounge, compared to the lounge with door open. This may be due to random differences between fires, or a consequence of greater oxygen availability. There is little evidence for temperature stratification. The peak temperature is about 250~300°C, but an average temperature for the upper half of the compartment (or the temperature at head height) could be lower by 50°C or more. This uncertainty is similar to the differences between CFAST and CRISP. In this case it seems that CFAST gives a closer match to the experiment.

The interface height in the hall (figure A42) is almost identical to the height in the lounge. This is as expected, since in the open-plan configuration, the hall and lounge are effectively one compartment. The oscillation in the interface height predicted by CRISP eventually just takes the value below 0.5m, at which point transition to one-zone mode occurs in the hall. The vent flows between the hall and lounge now draws some of the hall's hot layer (which extends to the floor) into the lounge, with the results that the interface in the lounge soon drops below 0.5m and one-zone mode applies there too.

The temperatures in the hall (figure A43) again show CRISP predicting lower temperatures than CFAST. The experimental measurements (figure A44) show very similar values to the experimental measurements in the lounge – not surprising, since the hall and lounge are effectively a single compartment. Both CFAST and CRISP predict lower temperatures in the hall compared to the landing. Of course, if the geometry had been defined differently, with the hall and lounge as a single room, rather than two rooms joined by a large “door”, then a single temperature would have applied for the whole region.

The predicted interface heights for the bedroom (figure A45) for CFAST and CRISP behave in very similar ways to the respective simulations for the lounge door open scenario. In CRISP, the formation of the hot layer, and the time by which it fills the room, both occur a little earlier than the “door open” scenario, because smoke can move more rapidly out of the open plan lounge. The temperature predictions (figure A46) are very similar to the “door open” scenario. The experimental measurements in the bedroom (figure A47) suggest CFAST has made a better prediction in this case. There is little evidence for stratification, which both models agree on.

## Conclusions

CRISP and CFAST predict similar interface heights in most circumstances. Where there are differences, in many cases these are due to the different strategies adopted by the models to deal with situations where two stratified layers do not exist. Such situations can arise at the start of a fire, when CFAST uses a constrained plume entrainment rate to stop the hot layer growing too quickly, whilst CRISP does not form a hot layer at all until it would have sufficient buoyancy to remain stable. Other circumstances can arise when vent flows have low buoyancy, in CFAST there is a greater tendency for vent flows to remain in the “cold” layer of their destination room (which heats up while the “hot layer” does not – this can be rather disconcerting to the first-time user of CFAST!). In CRISP, when the hot layer interface is less than 0.5m above the floor, a transition to a single, well-mixed, zone filling the entire room occurs. In a “dead end” such as the bedroom, the “hot” layer can quickly fill the room even though its temperature is not very high – it is equivalent to the “cold” layer in CFAST filling the room in analogous circumstances.



The temperature predictions of CRISP tend to be lower than those in CFAST, this seems to be caused by different treatment of heat losses to the compartment boundaries. Further work would be required to determine the precise differences responsible for the effect.

In terms of predicting the concentration of combustion products within the smoke layers, the interface height is probably more important than the temperature.

Given the amount of variation between experiments, it is hard to say whether CRISP or CFAST gives a “better” match to the experimental measurements. In some cases CRISP appears better, in other cases CFAST. There are also many other factors, unrelated to the heat and mass transport due to smoke movement within the building, that lead to errors and uncertainties in the absolute value of CRISP risk predictions. (Some of these are discussed in the section dealing with the Monte-Carlo simulation.)

The “bottom line” is that the smoke movement and heat transfer algorithms seem reasonably valid. There may however be scope for improvement in the heat transfer to the compartment walls, but this is likely to be less significant than other factors leading to errors / uncertainties in CRISP.

## Monte Carlo modelling for detector optimisation

### Introduction

BRE's CRISP model has been used to compare the performance of three different fire alarm systems in four building layouts. Simulations have also been performed without a detection system as a reference case.

The alternative detection systems considered were:

- No detection (reference case)
- Using existing requirements of ADB in that smoke alarms were fitted at each level of the house with a linked heat alarm being used in the kitchen if the kitchen was not separated from a stairway or circulation space by a door.
- Using the recommendations of BS 5839 part 6 in addition to the requirements of ADB, i.e. including additional heat or smoke alarms in the principal living room/s and/or kitchen
- Using an additional smoke alarm in the principal bedroom in addition to the requirements of ADB

The building layouts were:

- A two bed room flat (not including the risk to occupants outside the apartment of fire origin)
- A two storey, three bedroom house (based on Cardington experimental house)
- A two storey, three bedroom house with open plan kitchen and living area on the ground floor.
- A three storey, four bedroom house (extending geometry of the Cardington experimental house)

For each of the sixteen cases a sufficient number of Monte-Carlo runs were performed (typically 2000) using different fire locations with occupant numbers and initial locations. This was repeated for waking response time of 60s and 120s for sleeping occupants. The results were analysed statistically to identify trends so that the benefits, or otherwise of the different alarm configurations in the different building types could be identified.

Requirement B1 of the Building regulations 2000 states that a building should be designed and constructed so that there are appropriate provisions for the early warning of fire and appropriate means of escape from the building to a place of safety. The Approved Document B, Fire Safety, ADB, presents an approach to meet this requirement. This report is concerned with the specification given in ADB of an alarm system in dwellings to meet the "early warning of fire" requirement of the Building Regulations, which is in paragraphs 1.2 through to 1.22.

The existing requirement of ADB is that smoke alarms should be fitted to each level of the house with a linked heat alarm being used in the kitchen, if the kitchen area is not separated from the stairway or circulation space by a door.

The configurations considered here are the basic requirement from ADB, the use of additional detectors in the principal habitable rooms and additional detectors in the principal bedrooms.

### Building layouts

For each of the building layouts a schematic plan is shown indicating the function of each room together with a table showing the detectors used for each of the detection options. Detailed dimensions are not given here, however the overall dimensions of the plan and area of the building footprint are given.

#### Two bedroom flat

The flat is enclosed by a rectangle 7.7m by 10.1m and has a floor area of 65m<sup>2</sup>.

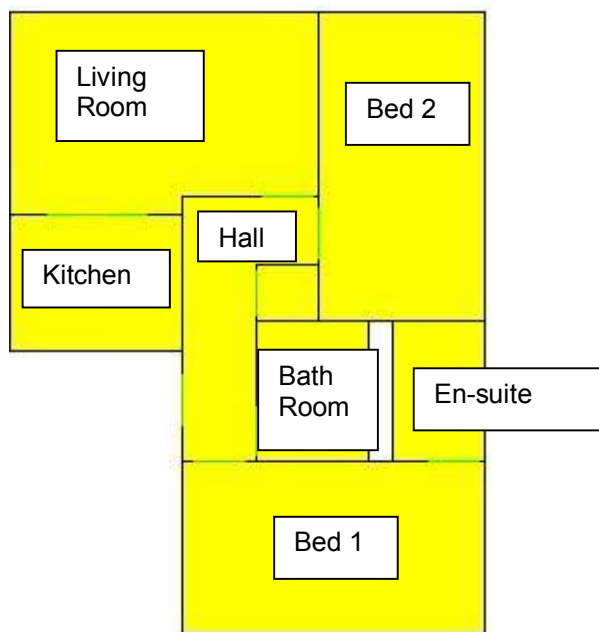


Figure 16. Schematic plan of two bedroom flat

Table 7. Detector locations in two bedroom flat

AD B ('Alarms ADB')		BS5839 Pt6 ('Alarms BS')		AD B with proposed revision ('Alarms Bed')	
Hall	Smoke alarm	Hall	Smoke alarm	Hall	Smoke alarm
		Kitchen	Heat alarm	Bed 1	Smoke alarm
		Living room	Smoke alarm		

**Three bedroom house**

The three bedroom house is based on the “Cardington Experimental House” with a plan 6m by 7m and a floor area of 42m<sup>2</sup> at each level.

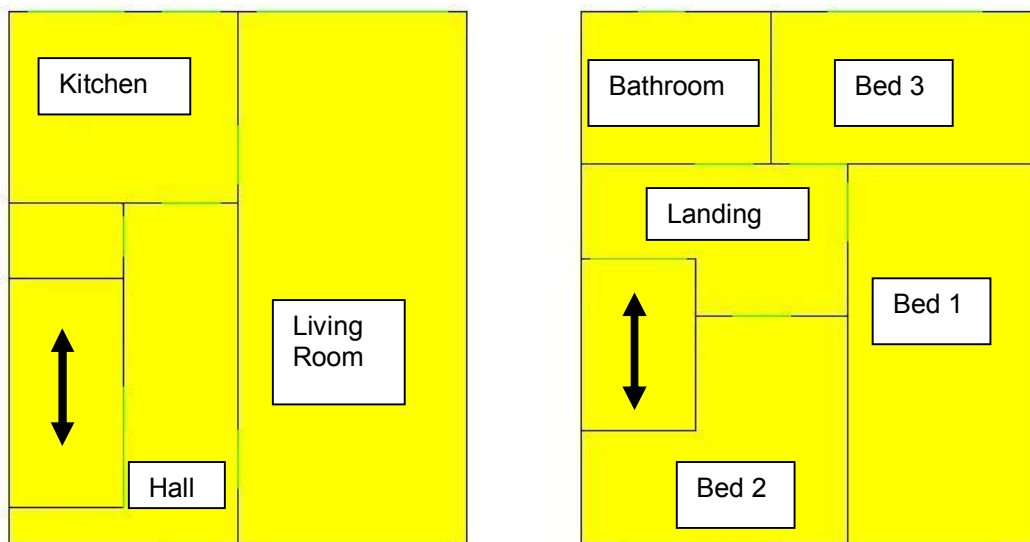


Figure 17. Plan of three bedroom house

Table 8. Detector locations in three bedroom house

AD B ('Alarms ADB')		BS5839 Pt6 ('Alarms BS')		AD B with proposed revision ('Alarms Bed')	
Hall	Smoke alarm	Kitchen	Heat alarm	Hall	Smoke alarm
Landing	Smoke alarm	Hall	Smoke alarm	Landing	Smoke alarm
		Living room	Smoke alarm	Bed 1	Smoke alarm
		Landing	Smoke alarm		

**Three bedroom house (open plan ground floor)**

The three bedroom house with an open plan ground level, is based on the “Cardington Experimental House” with a plan 6m by 7m and a floor area of 42m<sup>2</sup> at each level.

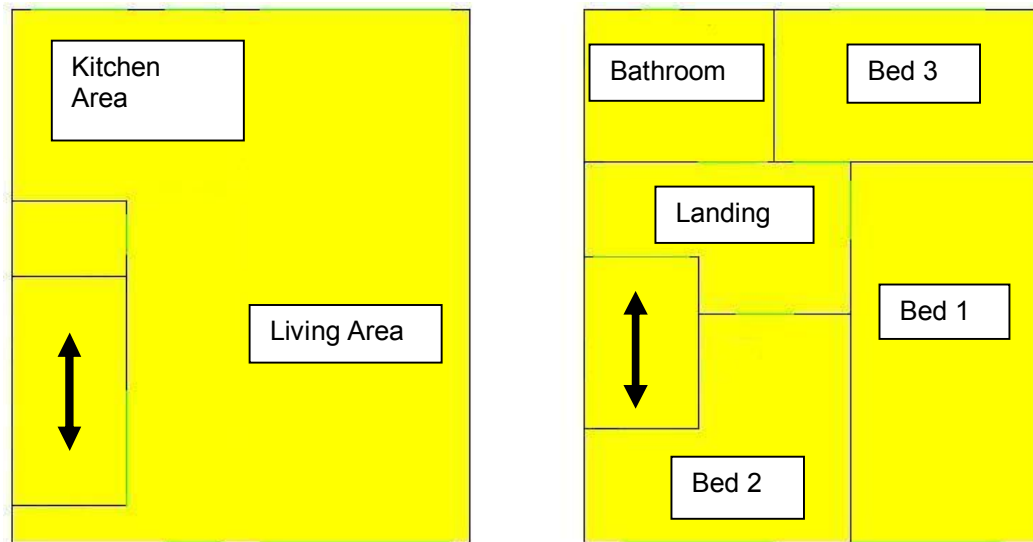


Figure 18. Plan on open plan three bedroom house

Table 9. Detector locations in open plan three bedroom house

AD B ('Alarms ADB')		BS5839 Pt6 ('Alarms BS')		AD B with proposed revision ('Alarms Bed')	
Living area	Smoke alarm	Kitchen	Heat alarm	Landing	Smoke alarm
Landing	Smoke alarm	Landing	Smoke alarm	Living area	Smoke alarm
Kitchen	Heat alarm	Living room	Smoke alarm	Bed 1	Smoke alarm
				Kitchen	Heat alarm

**Three floor, four bedroom house**

The four bedroom house is based on the “Cardington Experimental House” with a plan 6m by 7m. The bedroom on the second floor (Bed 4) measures 3m by 5m (area 15m<sup>2</sup>).

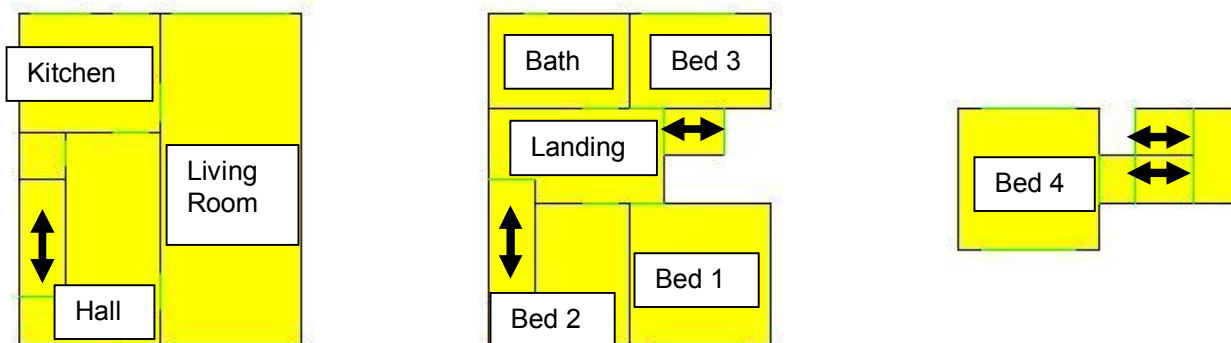


Figure 19. Plan of four bedroom house

Table 10. Detector locations in four bedroom house

AD B ('Alarms ADB')		BS5839 Pt6 ('Alarms BS')		AD B with proposed revision ('Alarms Bed')	
Landing	Smoke alarm	Kitchen	Heat alarm	Landing	Smoke alarm
Bed 4	Smoke alarm	Landing	Smoke alarm	Bed 1	Smoke alarm
Hall	Smoke alarm	Living room	Smoke alarm	Bed 4	Smoke alarm
		Bed 4	Smoke alarm	Hall	Smoke alarm
		Hall	Smoke alarm		

**CRISP simulations**

The BRE risk assessment model, CRISP, has been run for each of the sixteen combinations of building type and detector configuration. In addition the sensitivity to the reaction time of sleeping occupants has also been examined by repeating the runs with waking response times of 60s and 120s. Occupants who are asleep can only be alerted by an alarm or by another (awake) occupant of the building, they are not sensitive to the presence of smoke in the room they occupy

Initially we did up to 10,000 runs for each of 16 cases x 2 waking times, but with sleepers quite sensitive to the presence of smoke (smell/irritancy). This showed only a small benefit when alarms were fitted; this seemed counter intuitive, and also contradicted earlier CRISP work [Fraser-Mitchell 1997] which suggested

the risk of death was 3 x higher without alarms compared to alarms present. When we repeated the simulations with sleepers not responding to smoke, we obtained results that were more in line with the 1996 CRISP simulation.

For each combination typically 2000 simulations have been run where the program randomly selects:

- Time of day
- Fire location
- Numbers and initial location of occupants

The results for each run have been collated and are presented as:

- A table and plot of the mean number of occupants per fire which have accumulated a Fraction effective dose (FED) of greater than 1%, 3%, 10% (injured) , 30% and 100% (dead). The error values given in the tables are one standard deviation of the error on the mean value.
- A plot of the mean number of people per fire against their time to be alerted

We have only presented the results for the simulations where the sleeping occupants were not awakened by the smoke, as we suspect that this may be nearer the true situations – but further research on arousal of people by smoke is required to be clearer on this point.

A comparison of the risk of death for each of the building types is also presented, to clearly show the effects of different alarm options, and also the effect of waking response times of 60s and 120s. This comparison has also been presented for the simulations where sleepers were allowed to be aroused by the smoke. This enables the upper and lower bounds of the effect of the ease of arousal on the risk of death to be determined.

## Results

Table 11. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Two bedroom flat, waking response time 60s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	value	error	value	error	value	error
FED > 1	0.49	0.02	0.22	0.01	0.22	0.02	0.24	0.02
FED > 3	0.42	0.02	0.16	0.01	0.16	0.01	0.16	0.02
FED > 10	0.32	0.02	0.12	0.01	0.11	0.01	0.12	0.01
FED > 30	0.26	0.02	0.09	0.01	0.09	0.01	0.10	0.01
FED > 100	0.18	0.01	0.07	0.01	0.07	0.01	0.08	0.01

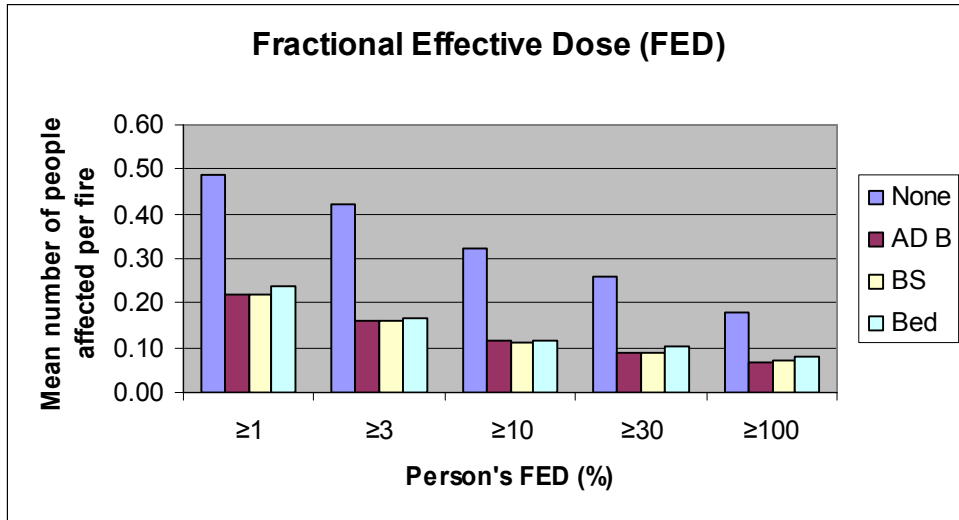


Figure 20. Two bedroom flat, waking response time 60s.

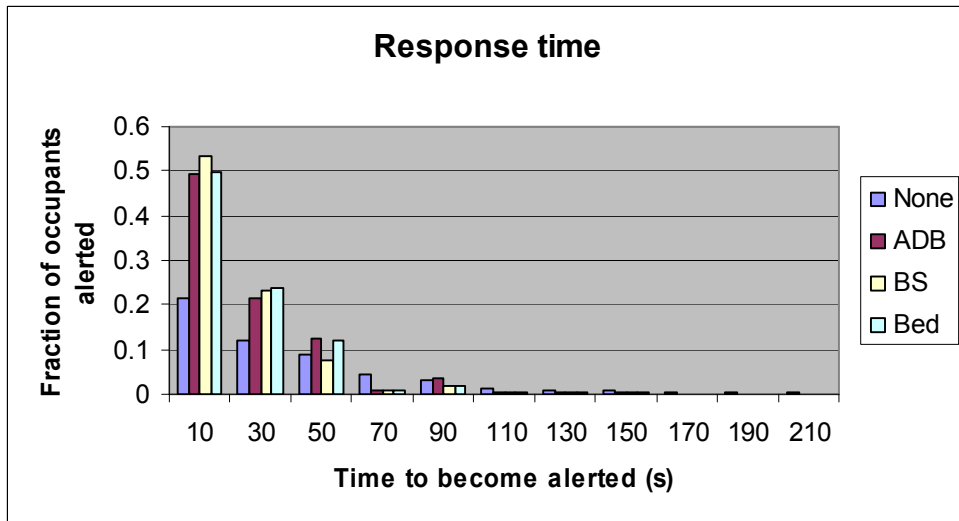


Figure 21. Two bedroom flat, waking response time 60s.



Table 12. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Three bedroom house, waking response time 60s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	value	error	value	error	value	error
FED > 1	0.39	0.03	0.19	0.01	0.17	0.02	0.14	0.02
FED > 3	0.33	0.03	0.13	0.01	0.12	0.01	0.10	0.02
FED > 10	0.24	0.03	0.09	0.01	0.08	0.01	0.07	0.02
FED > 30	0.17	0.02	0.07	0.01	0.06	0.01	0.05	0.01
FED > 100	0.12	0.02	0.05	0.00	0.04	0.01	0.03	0.01

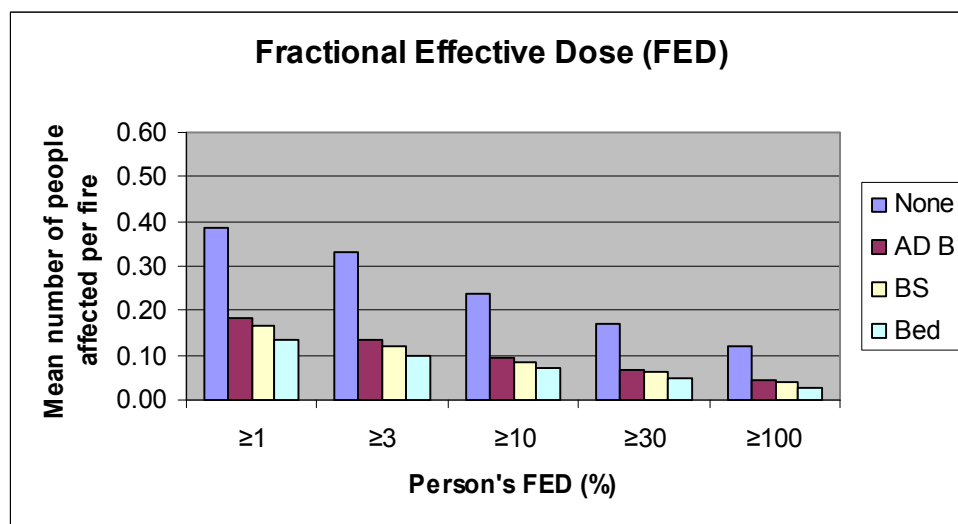


Figure 22. Three bedroom house, waking response time 60s.

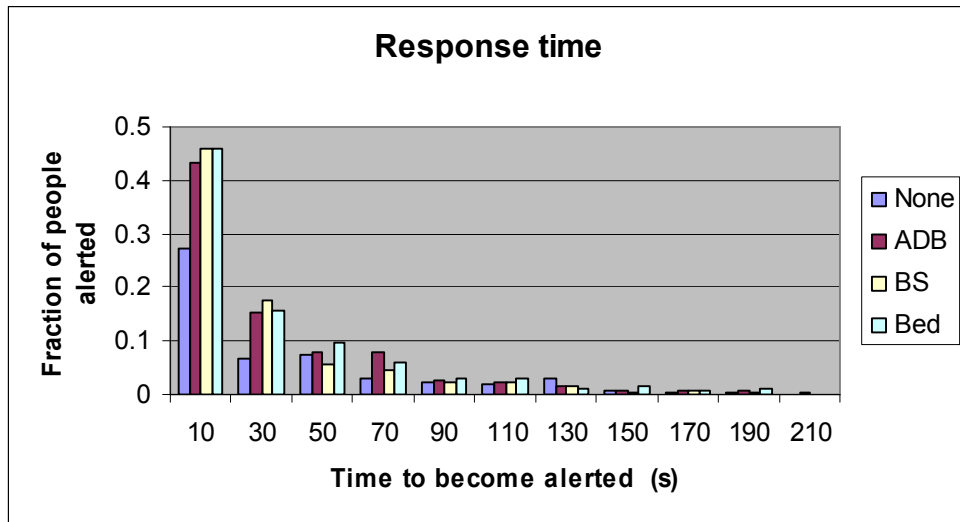


Figure 23. Three bedroom house, waking response time 60s.

Table 14. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Three bedroom open plan house, waking response time 60s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	Value	error	value	error	value	error
FED > 1	0.47	0.05	0.16	0.02	0.14	0.02	0.15	0.03
FED > 3	0.38	0.05	0.11	0.02	0.11	0.02	0.12	0.02
FED > 10	0.27	0.04	0.07	0.01	0.08	0.01	0.06	0.02
FED > 30	0.21	0.04	0.06	0.01	0.05	0.01	0.05	0.02
FED > 100	0.16	0.03	0.04	0.01	0.04	0.01	0.04	0.01

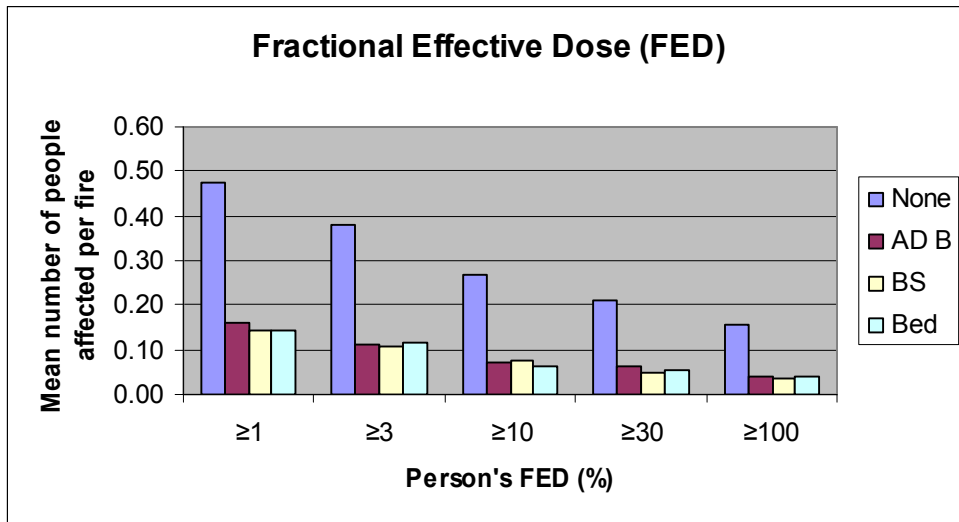


Figure 24. Three bedroom open plan house, waking response time 60s.

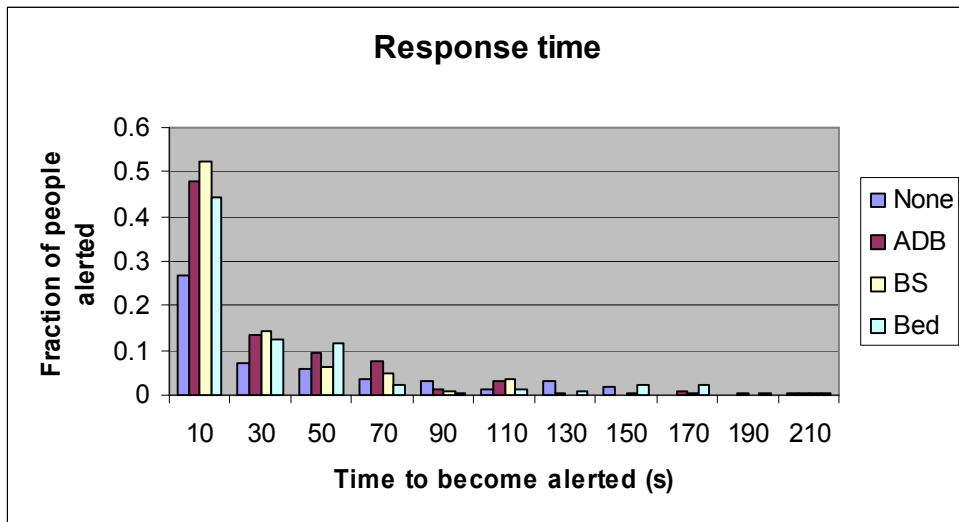


Figure 25. Three bedroom open plan house, waking response time 60s.

Table 15. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Four bedroom house, waking response time 60s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	Value	error	value	error	value	error
FED > 1	0.42	0.04	0.18	0.02	0.21	0.04	0.17	0.02
FED > 3	0.32	0.03	0.12	0.02	0.13	0.03	0.11	0.02
FED > 10	0.23	0.03	0.09	0.01	0.10	0.02	0.07	0.01
FED > 30	0.16	0.02	0.06	0.01	0.07	0.02	0.05	0.01
FED > 100	0.11	0.02	0.03	0.01	0.05	0.02	0.03	0.01

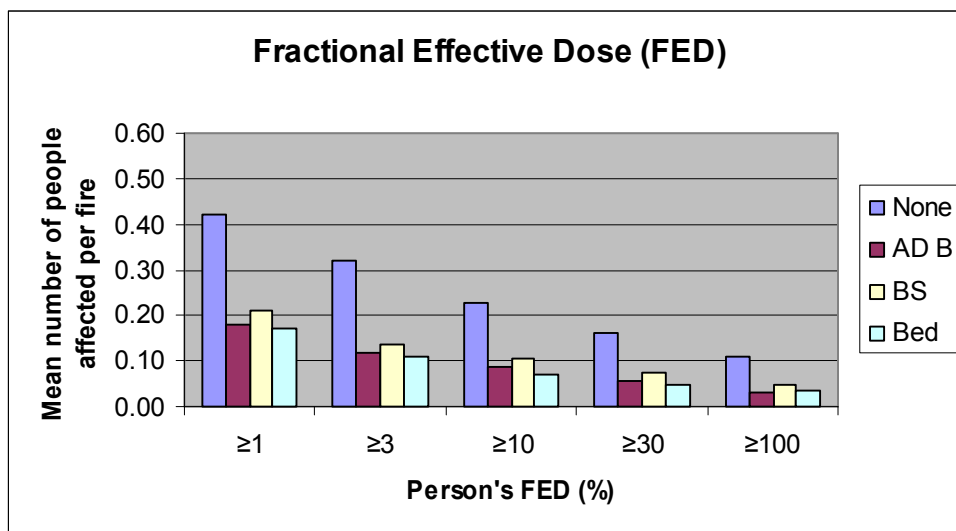


Figure 26. Four bedroom house, waking response time 60s.

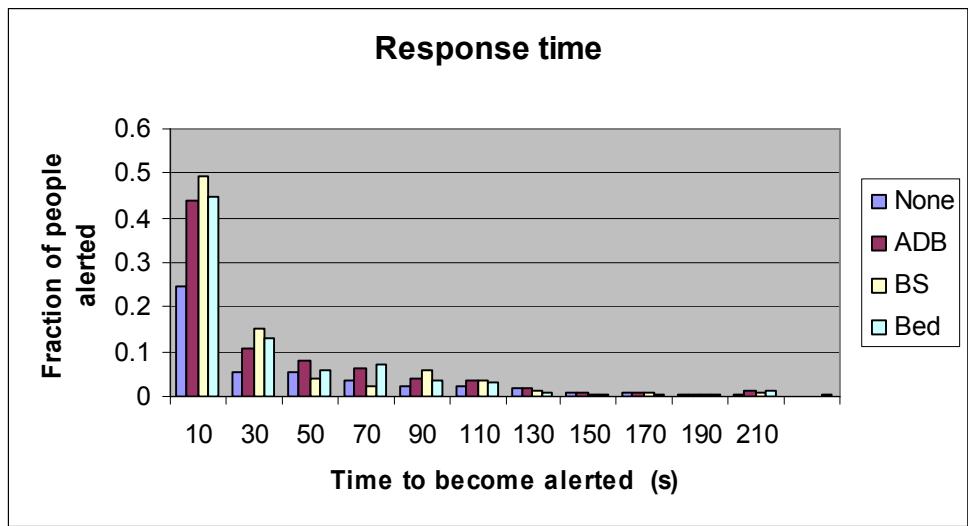


Figure 27. Four bedroom house, waking response time 60s.

Table 16. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Two bedroom flat, waking response time 120s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	Value	error	value	error	value	error
FED > 1	0.55	0.03	0.29	0.02	0.26	0.02	0.30	0.02
FED > 3	0.47	0.02	0.24	0.02	0.22	0.01	0.24	0.01
FED > 10	0.36	0.02	0.19	0.02	0.17	0.01	0.17	0.01
FED > 30	0.28	0.02	0.14	0.01	0.12	0.01	0.14	0.01
FED > 100	0.20	0.02	0.11	0.01	0.09	0.01	0.11	0.01

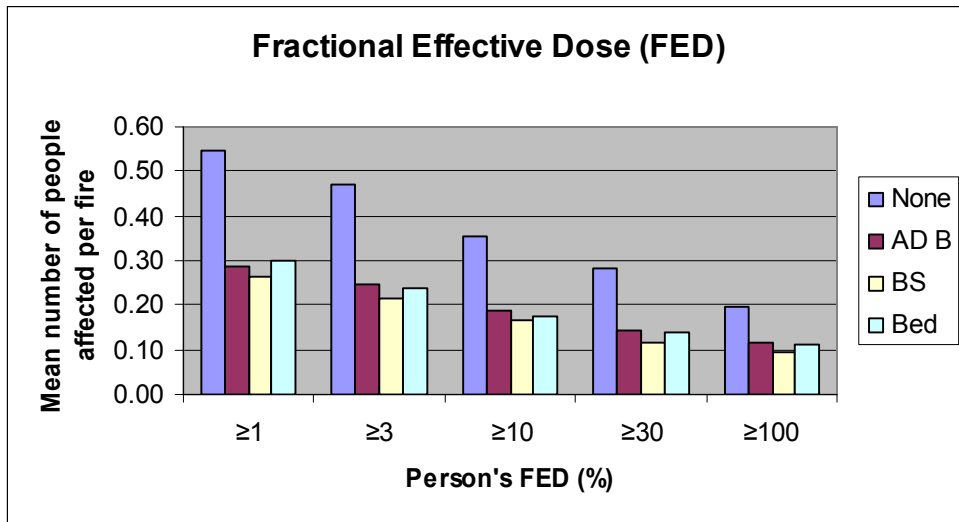


Figure 28. Two bedroom flat, waking response time 120s.

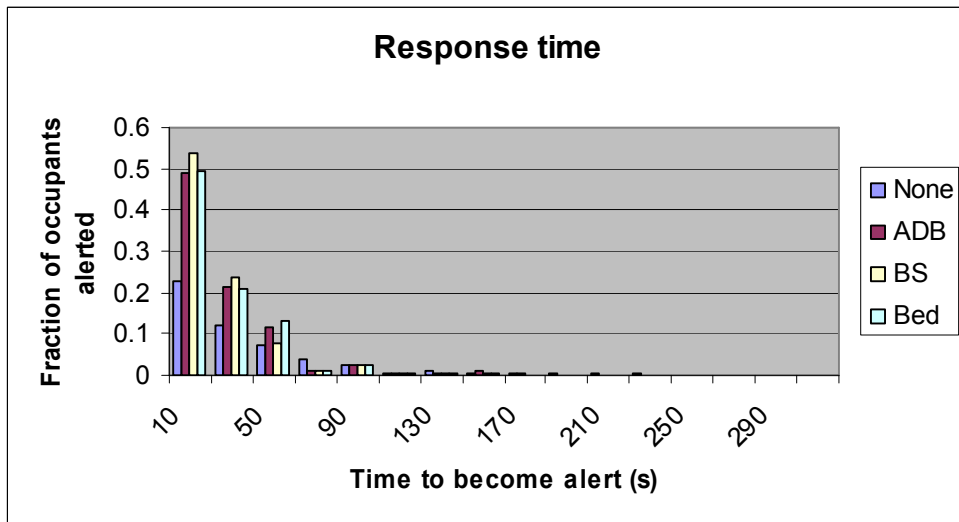


Figure 29. Two bedroom flat, waking response time 120s.

Table 17. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Three bedroom house, waking response time 120s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	Value	error	value	error	value	error
FED > 1	0.48	0.05	0.26	0.02	0.20	0.02	0.24	0.03
FED > 3	0.40	0.04	0.20	0.02	0.15	0.01	0.18	0.03
FED > 10	0.27	0.03	0.12	0.01	0.09	0.01	0.11	0.02
FED > 30	0.20	0.03	0.08	0.01	0.06	0.01	0.07	0.01
FED > 100	0.13	0.02	0.04	0.01	0.04	0.01	0.04	0.01

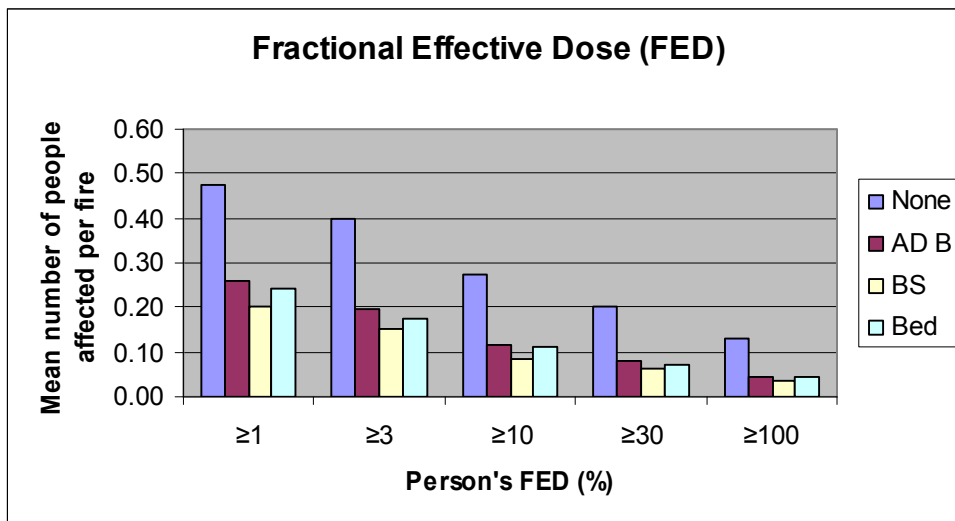


Figure 30. Three bedroom house, waking response time 120s.

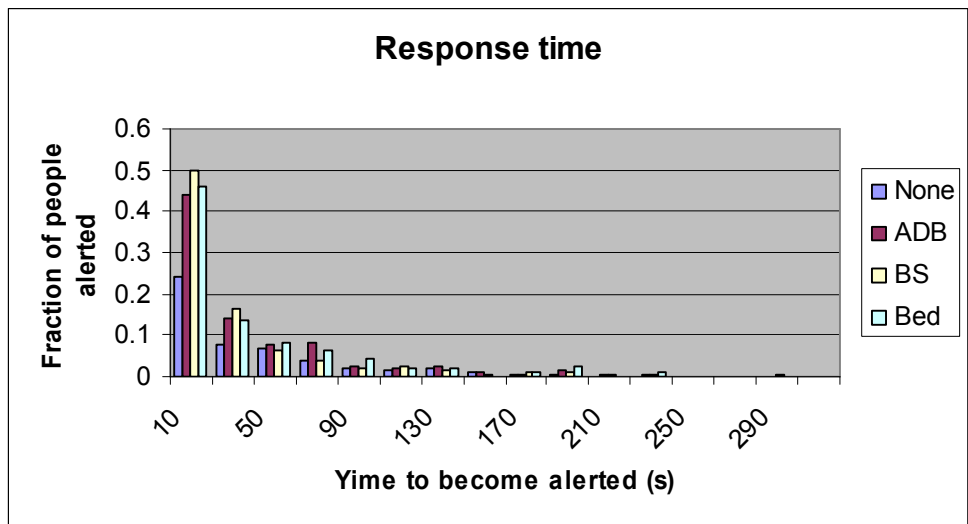


Figure 31. Three bedroom house, waking response time 120s.

Table 18. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Three bedroom open plan house, waking response time 120s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	Value	error	value	error	value	error
FED > 1	0.41	0.05	0.23	0.02	0.22	0.04	0.22	0.03
FED > 3	0.37	0.05	0.17	0.02	0.18	0.04	0.17	0.03
FED > 10	0.27	0.04	0.11	0.01	0.07	0.02	0.10	0.02
FED > 30	0.21	0.03	0.06	0.01	0.05	0.02	0.07	0.01
FED > 100	0.15	0.03	0.04	0.01	0.05	0.02	0.06	0.01



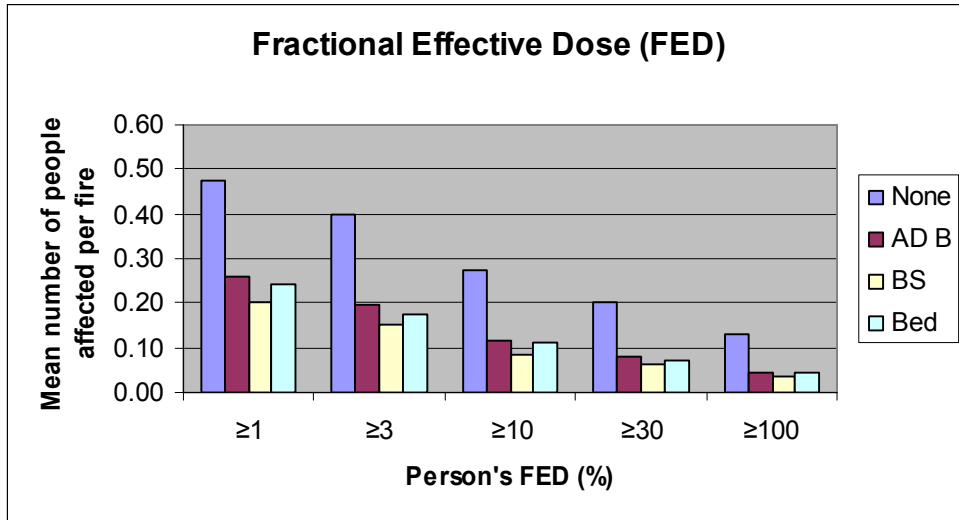


Figure 32. Three bedroom open plan house, waking response time 120s.

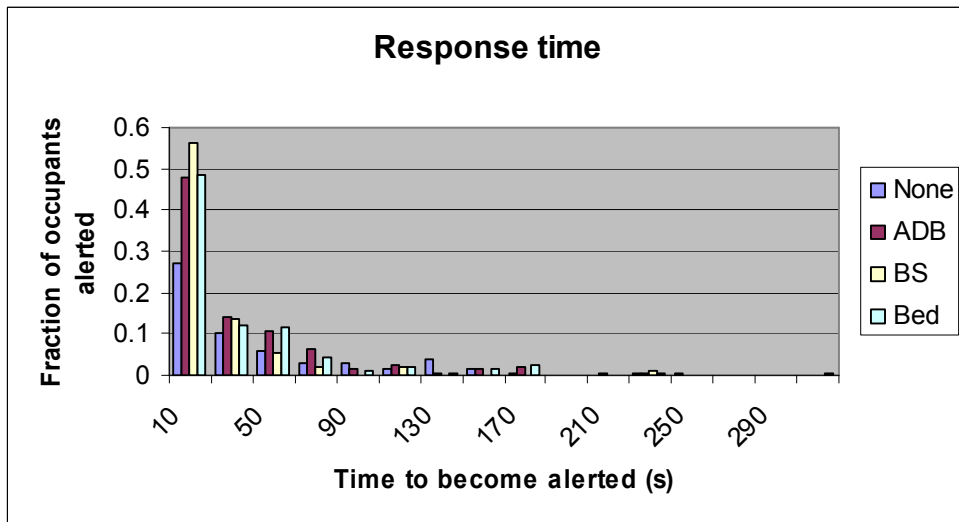


Figure 33. Three bedroom open plan house, waking response time 120s.

Table 19. Number of people, per fire, with varying levels of toxic dose from exposure to smoke. Four bedroom house, waking response time 120s.

	Alarms: None		Alarms: AD B		Alarms: BS		Alarms: Bed	
	value	error	value	error	value	error	value	error
FED > 1	0.39	0.04	0.27	0.03	0.20	0.03	0.27	0.03
FED > 3	0.29	0.03	0.20	0.03	0.13	0.02	0.18	0.03
FED > 10	0.22	0.03	0.15	0.02	0.08	0.02	0.11	0.02
FED > 30	0.17	0.02	0.11	0.02	0.05	0.01	0.07	0.02
FED > 100	0.10	0.02	0.06	0.01	0.04	0.01	0.03	0.01

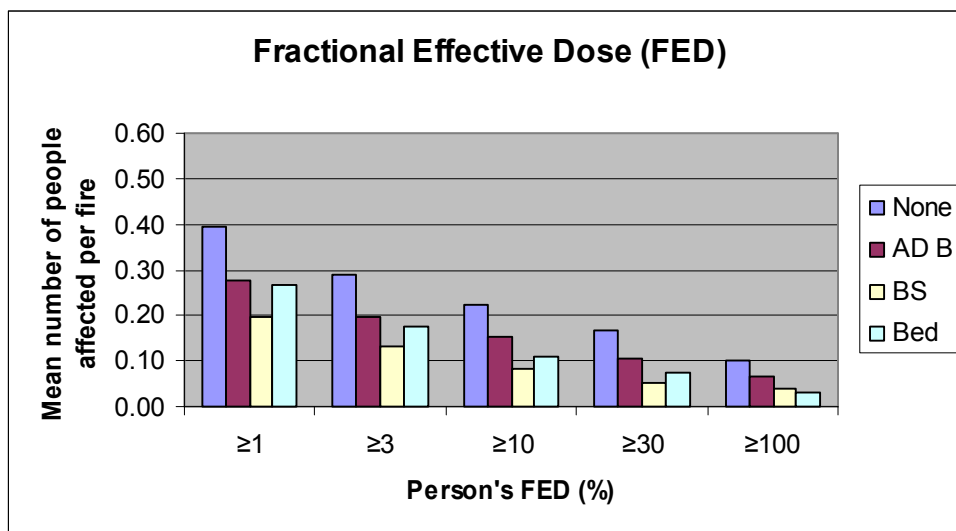


Figure 34. Four bedroom house, waking response time 120s.

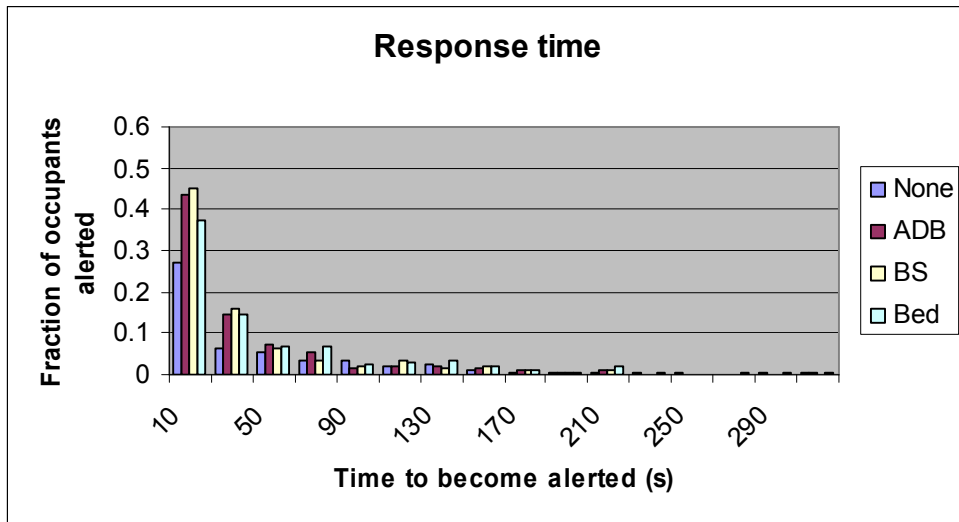


Figure 35. Four bedroom house, waking response time 120s.

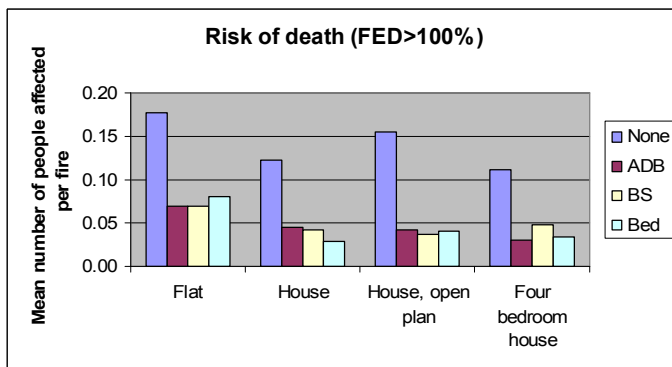


Figure 36. Risk of death, 60s waking response

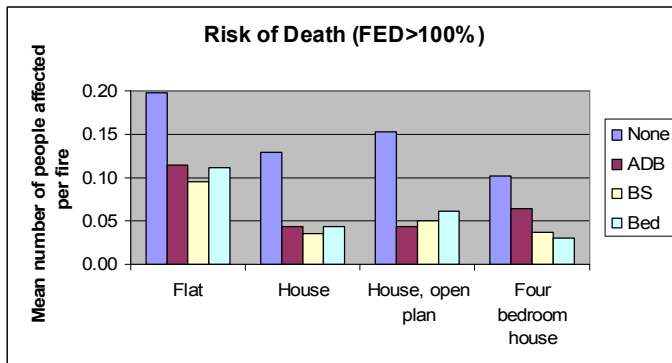


Figure 37. Risk of death, 120s waking response

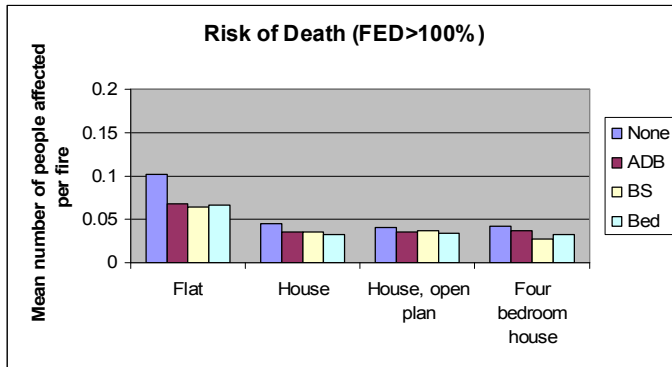


Figure 37. Risk of death, 60s waking (sensitive to smoke)

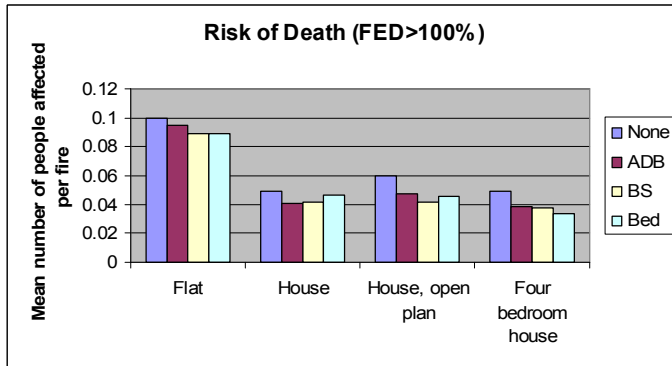


Figure 37. Risk of death, 120s waking (sensitive to smoke)

### Discussion

The largest benefit (assuming sleepers are not aroused by smoke) is gained from installing any sort of detection system compared with no detectors at all. This reduces the risk of death to about 30% ~ 50% of the risks where there are no alarms.

For the flat and three bedroom house the configuration from BS5839Pt 6 offers a small improvement to the requirements of Approved Document B, however the difference is within the error of the analysis. In the case of the four bedroom house the benefit of the additional detection specified in BS5839Pt 6 is most significant for the longer waking response time.

It was assumed that sleepers would be woken by the sound of an alarm, provided there was not more than one closed door between their location and that of the alarm.

Arousal noise thresholds have been measured [Pezolt & Van Cott 1978]; it was found that 75dB(A) at bed head gave a 50% chance to awaken a sleeping person. As this is the sound level required by BS5839 pt.1 for sleeping occupancies, it follows that there is a possibility that none of the sleeping occupants may be awakened. An interlinked alarm sited in the principal bedroom might therefore be more effective than CRISP predicts. In the CRISP model, the extra alarm in the bedroom is only beneficial in providing early

detection of fire in that room. An alarm on the hall or landing would be sufficiently loud to wake sleepers in the bedrooms, in the case of fire in other locations.

The graphs showing the percentage of people reacting at various times after ignition reveal that in most cases, detection is very rapid. Without alarms, about 25% of people respond almost instantly, rising to about 50% when alarms are present. The model assumes that an awake person in the room of fire origin will notice the fire almost immediately, whereas in reality the person might be engrossed in some activity that prevented this. Smoke alarms are assumed to respond as soon as the hot layer optical density exceeds a detection threshold ( $0.1\text{m}^{-1}$ ), without taking account of the hot layer depth below the ceiling, so detection may be very rapid. (Heat detection calculates the heat transfer and temperature rise of the detector element as a result of immersion in the hot smoke layer, so takes longer, typically 1-2 minutes.) Note that, in CRISP, "ignition" is actually the onset of flaming combustion; any prolonged smouldering prior to this is not modelled.

The initial runs assumed that sleeping occupants could be awakened by exposure to smoke, if the temperature, carbon dioxide concentration (affecting breathing rapidity) or smoke optical density exceeded certain threshold values. Whilst the sleeper obviously could not see the smoke, the irritancy was assumed to be proportional to the optical density. In these initial runs, it was found that there was almost no difference in risk between alarms present or not. This prompted further investigation, especially as earlier CRISP simulations [Fraser-Mitchell 1997] had predicted significantly greater risks, especially in cases where no alarm was present. The discrepancy between the 1996 results and the initial results of this work was demonstrated to lie in the ease or otherwise by which sleeping occupants could be alerted. Graphs have been plotted showing the risk of death for the initial runs (awakened by smoke) as well as the later runs (sleepers only wakened by alarms or other people). Sensitivity of people to smoke, not surprisingly, has the greatest impact when there are no alarms present, but also has a lesser impact when there are alarms.

Another uncertainty connected with sleeping occupants is the time required for them to wake up once aroused. We looked at delays of 60s and 120s; as expected, the longer delay gives higher risk, though not substantially.

It should be noted that there are many other factors that can lead to uncertainties or errors in the CRISP risk predictions. For example, in CRISP the risk depends solely on the exposure to smoke (FED), whereas in real life other causes (e.g. burns) may also contribute to the numbers of deaths. Even as far as exposure to smoke is concerned, there is mounting evidence for considerable variation between individuals in their susceptibility to given levels of exposure. Fire behaviour is another source of uncertainty, for example the production of toxic species is estimated from very limited experimental data, and an understanding of the variations between supposedly identical fire sources is lacking.

We believe that the relative risks assessed by CRISP are reasonable, but the absolute accuracy of the risk level is much more uncertain.

The relative risks predicted by CRISP suggest that the benefits of additional alarms would be marginal. This is the same conclusion as given by an examination of the fire statistics.

Note that, by concentrating on results where sleeping occupants were assumed not to be aroused by smoke, the benefits of detection and alarm would be maximised. Despite this, the benefits of the additional alarms are still marginal, so we can be confident that this would be so in reality.

## Cost-Benefit Calculations

Calculations of the costs and benefits of installing different types of alarms have been considered. The options include those modelled in the previous section, plus some additional combinations. The full list of calculations is as follows:

- Upgrading an “average dwelling” from no alarms, to alarms in hall and landing
- Upgrading an “average dwelling” with alarms in hall and landing, to include extra alarm(s) in:
  - Lounge
  - Bedroom
  - Kitchen
  - Lounge + Bedroom
  - Kitchen + Lounge
  - Kitchen + Bedroom
  - Kitchen + Lounge + Bedroom

The basic format of the calculations is similar to that employed for a previous project [Williams et al 2004]. In particular, we have retained a similar approach to the uncertainty analysis, in order to estimate the probability that a particular option will prove to be cost-effective.

## Costs

Costs have been split into the amount required to purchase the detectors, and the amount required for installation. Annual maintenance costs have been assumed to be negligible.

Cost estimates for various detectors have been obtained from a supplier's website. These are quoted below, together with the lifetime of the detector.

Detector type	Cost (inc. VAT)	Lifetime (warranty)
Ionisation, mains power	£17.99	6 years
Ionisation, mains power	£28.99	10 years
Ionisation, main power, radio interlinked	£64.99	5 years
Heat, mains power	£24.99	6 years
Heat, mains power	£38.99	10 years
Heat, mains power, radio interlinked	£82.99	5 years

Installation cost (during construction of new-build) was assumed to be minor. A nominal additional time of 15~30 minutes was assigned for wiring in each detector, costing an assumed £25 +/- £12.50 (2006 prices).

Both the detector and installation costs are one-off, and need to be discounted over an appropriate time period. For the detector cost, the time period was taken as the warranty lifetime +/- 1 year. For installation, a lifetime of 50 years +/- 5 years was assumed. In accordance with Treasury Guidelines [HM Treasury 2003], a discount rate of 3.5% per annum was applied.

The capital recovery factor (the fraction of the initial cost that is paid off each year) is given by

$$K = r \frac{(1+r)^y}{(1+r)^y - 1}$$

where  $r$  is the rate of interest expressed as a decimal fraction, e.g. 0.035 for 3.5%, and  $y$  is the length of the payback period in years. If the uncertainty in the payback period is  $\Delta y$ , then the uncertainty in the capital recovery factor is

$$\Delta K = \left( \frac{\partial K}{\partial y} \right) \Delta y$$

Using the relation

$$\frac{d(a^x)}{dx} = \ln(a).a^x$$

and the quotient rule for differentiation

$$\left( \frac{u}{v} \right)' = \frac{u'.v - v'.u}{v^2}$$

then with some further manipulation it can be shown that

$$\Delta K = K \cdot \ln(1+r) \cdot \left( 1 - \frac{(1+r)^y}{(1+r)^y - 1} \right) \Delta y$$

The discounted costs for a 6-year warranty or a 10-year warranty detector are very similar. For simplicity, the cost-benefit calculations have only considered the 10-year warranty detectors. Thus, an ionisation detector costs £29, and a heat detector costs £39.

## Benefits

As explained in the discussion of the previous section on Monte-Carlo modelling, the uncertainty in the absolute risk estimates from the CRISP model means that they should not be used directly for cost-benefit analyses. (The relative risks, though, provide a useful insight into whether one option will provide greater benefits than another.) We will therefore attempt to estimate the effectiveness of the various detector options, based on the review of the statistics.

For the first calculation, we examine the benefits of fitting two smoke alarms, in the hall and landing, of a dwelling home that has no other detection available. It was pointed out in the section on the statistics that an apparent 6-fold difference in the number of fires, between homes that do or do not have smoke alarms fitted, could partially be attributed to the alarms, and partially to the occupants being more careful about fire safety in general. However, if we assume the first calculation is for a new-build house, then the probability of a “more careful” occupier would be the same as the proportion in the whole country, namely about 75%. Hence, the baseline risk should be the average risk for the entire country, with and without smoke alarms.

This average risk can be derived from the figures of 3703 deaths, 104427 injuries, and 498765 reported fires over a nine-year period. There were an estimated 24.7 million dwellings in 2002 [Williams et al 2004], hence the numbers of deaths, injuries and fires per million dwellings per year are 16.7, 470 and 2245 respectively. The numbers of deaths and injuries per thousand fires are 7.4 and 209 respectively.

When smoke alarms operate, and alert the occupants, the numbers of deaths and injuries per thousand (reported) fires are 3.8 and 205 respectively. The most common reason for alarms not to operate is if the battery (most are battery-powered) is missing or run down. If detectors are mains powered, this failure mode would not apply, and so the risks per fire should be as above. Thus, the effectiveness of smoke detectors in reducing deaths and injuries would be about  $(7.4-3.8)/7.4 = 49\%$  for deaths, and  $(209-205)/209 = 2\%$  for injuries. The number of fires would not be affected. As the effect of reducing injuries was so small, it was neglected in the calculations.

In 2002, the value (benefit) of each death prevented was taken as £1.243 million. Assuming a 2% increase (in line with GDP) over 4 years, the value in 2006 is estimated as £1.345 million. (The results of the calculation do not depend that critically on this value – the conclusions are clear-cut)

Details of the cost-benefit calculation are given in Appendix B. The net benefit is £1.90 per dwelling per year, +/- £1.94 (2 standard deviations). The probability that fitting detectors would be cost effective is 84%..

For the subsequent calculations, we examined the effect of adding additional alarms to a home where there was already mains-powered smoke detection available in the hall and landing. In this case the baseline risk



would be what remained after the alarms were fitted to the first case, namely 51% of 16.7 (= 8.5) deaths per million dwellings per year.

We do not have statistics that enable us to directly estimate the effect of additional alarms. However, by examining the circumstances of each fatality in fires where an alarm operated and alerted the occupants, it was possible to calculate the proportion of these fatalities who were trapped by fires in different rooms of origin. These proportions are given in the table below.

Table 20. Proportion of residual fire deaths, trapped by fires with various rooms of origin

Room of origin	Proportion
Lounge	18%
Bedroom	17%
Kitchen	5%
Other	6%
Total	45%

If we assumed, optimistically, that a detector in the room of origin would save all of the victims trapped by such fires (but was of no additional benefit in the case of fires originating elsewhere), then the effectiveness of the additional detectors would be the percentages in the table above. Also note, a consequence of this assumption would be that for several additional detectors, the benefits would be additive. For example, a detector in the lounge plus a detector in the kitchen would be expected to save 23% of the residual deaths.

This marginal improvement in the risks is consistent with the CRISP results, which showed little improvement in the relative risks when additional detectors were provided.

The cost-benefit calculations are presented in Appendix B. None of the permutations for additional detector(s) had more than a very low probability (4%) to be cost-effective.

## Conclusion

The conclusion from the calculations is that including alarms, where none were present before, has a good chance of being cost-effective (probability = 84%), but that further upgrades involving additional alarms are not cost-effective (probability < 4%).

## Conclusions and Recommendations

Examination of the fire statistics suggested that the presence of working smoke alarms was beneficial, although it was not straightforward to distinguish the effect of detection from differences between groups of occupants, one group being those who would voluntarily install alarms, the other group being those who would not bother. Our best estimate was that for a newly-built property, with mains-powered detectors, the risk of death would be 50% of the current average risk for the whole country.

We also investigated the number of people who might be saved by additional alarms, extra to those recommended by AD "B". Of the residual deaths (50% of the current level), examination of each circumstances of each fatality (where alarms were working) suggested that about half of the deaths would not benefit from additional detection. Extra detection was assumed only to be of benefit in cases where the fire had started in the room where the detector was situated (thus enabling a more rapid detection than by a detector in a circulation space).

The majority of the fatalities in the period studied by this report occur in dwellings in which either fire alarms are not fitted or are not working at the time of the fire. It is recommended that a further study is undertaken of the 25% of homes not fitted with fire alarm equipment to determine whether the addition of fire alarm equipment would reduce the fatalities and injuries in this group. It is considered that there are factors in addition to the installation of fire alarms that has led to the reduction in the frequency of fires and the number of deaths and injuries in homes fitted with smoke alarms when compared to those without. The reduction in fires, deaths and injuries could be a consequence of the success of the 'fire safety message', of which fire detection is only one aspect.

The modelling work led to similar conclusions to the statistical study. The presence of any alarm could reduce the risk of death by up to a factor of three, compared to a dwelling where no alarm was present. However, additional alarms beyond those currently recommended by AD B did not lead to any discernable further reductions in risk.

The cost-benefit analysis showed that fitting mains-powered detectors would be cost-effective (84% confidence level), compared to a baseline case of no detection. However, further detectors beyond the recommendations of AD "B" would not be cost-effective (confidence level <4%).

The current revision of Approved Document B already addresses the main issue highlighted in this report by recommending the installation of fire alarms in all new homes. The biggest factor appears to be whether fire alarms are fitted or not, however as the housing stock changes and the number of homes without fire alarms reduces as a percentage, the impact on fire frequency, deaths and injuries may not be as marked as could be predicted from the statistics in this report. The majority of domestic fire alarm installations are installed by the occupier, and this suggests a level of fire safety awareness. As smoke alarms become 'standard fitment' the true impact of fire alarms on the number fire casualties should become clearer.

The factor having the biggest influence on fire survivability in domestic premises is whether fire alarms are fitted. It appears from the statistics and the modelling undertaken that any improvements gained by installing additional fire alarms in addition to those required by Approved document B will be marginal.

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## **Appendix A – CRISP Validation Results**

### **Graphs of smoke layer depth and temperature, arising from CRISP and CFAST calculations, and experimental measurements.**

The figures are all included in an appendix to make the discussion of the CRISP validation easier to read. The following list of figures is supplied for ease of reference.

#### **Single room, 100kW steady fire, no heat losses to walls.**

Figure A1. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A2. Comparison of upper layer temperature, calculated by CFAST and CRISP.

Figure A3. Comparison of plume entrainment rate, calculated by CFAST and CRISP

#### **Single room, 30kW steady fire, no heat losses to walls.**

Figure A4. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A5. Comparison of upper layer temperature, calculated by CFAST and CRISP.

#### **Single room, 300kW steady fire, no heat losses to walls.**

Figure A6. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A7. Comparison of upper layer temperature, calculated by CFAST and CRISP.

#### **Single room, 1000kW steady fire, no heat losses to walls.**

Figure A8. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A9. Comparison of upper layer temperature, calculated by CFAST and CRISP.

#### **Single room, growing fire, no heat losses to walls.**

Figure A10. Comparison of heat release rate, plotted by CFAST and CRISP.

Figure A11 Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A12. Comparison of upper layer temperature, calculated by CFAST and CRISP.

Figure A13. Comparison of plume entrainment rate, calculated by CFAST and CRISP.

**Single room, 100kW steady fire, with heat losses to walls.**

Figure A14. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A15. Comparison of plume entrainment rate, calculated by CFAST and CRISP.

Figure A16. Comparison of upper layer temperature, calculated by CFAST and CRISP.

**Single room, growing fire, with heat losses to walls.**

Figure A17. Comparison of layer interface height, calculated by CFAST and CRISP.

Figure A18. Comparison of plume entrainment rate, calculated by CFAST and CRISP.

Figure A19. Comparison of upper layer temperature, calculated by CFAST and CRISP.

**Experimental house, growing TV fire, lounge door open.**

Figure A20. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

Figure A21. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

Figure A22. Experimental temperature measurements in the lounge.

Figure A23. Comparison of hall layer interface height, calculated by CFAST and CRISP.

Figure A24. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.

Figure A25 Experimental temperature measurements in the hall.

Figure A26. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.

Figure A27. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP.

Figure A28. Experimental temperature measurements in the bedroom.

**Experimental house, growing TV fire, lounge door shut.**

Figure A29. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

Figure A30. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

Figure A31. Experimental temperature measurements in the lounge.

Figure A32. Calculation of lounge upper layer temperature by CRISP, with vitiated fire effects.

Figure A33. Comparison of hall layer interface height, calculated by CFAST and CRISP.

Figure A34. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.

Figure A35. Experimental temperature measurements in the hall.

Figure A36. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.

Figure A37. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP.

Figure A38. Experimental temperature measurements in the bedroom.

**Experimental house, growing TV fire, open-plan lounge/hall.**

Figure A39. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

Figure A40. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

Figure A41. Experimental temperature measurements in the lounge.

Figure A42. Comparison of hall layer interface height, calculated by CFAST and CRISP.

Figure A43. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.

Figure A44. Experimental temperature measurements in the hall.

Figure A45. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.

Figure A46. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP.

Figure A47. Experimental temperature measurements in the bedroom.

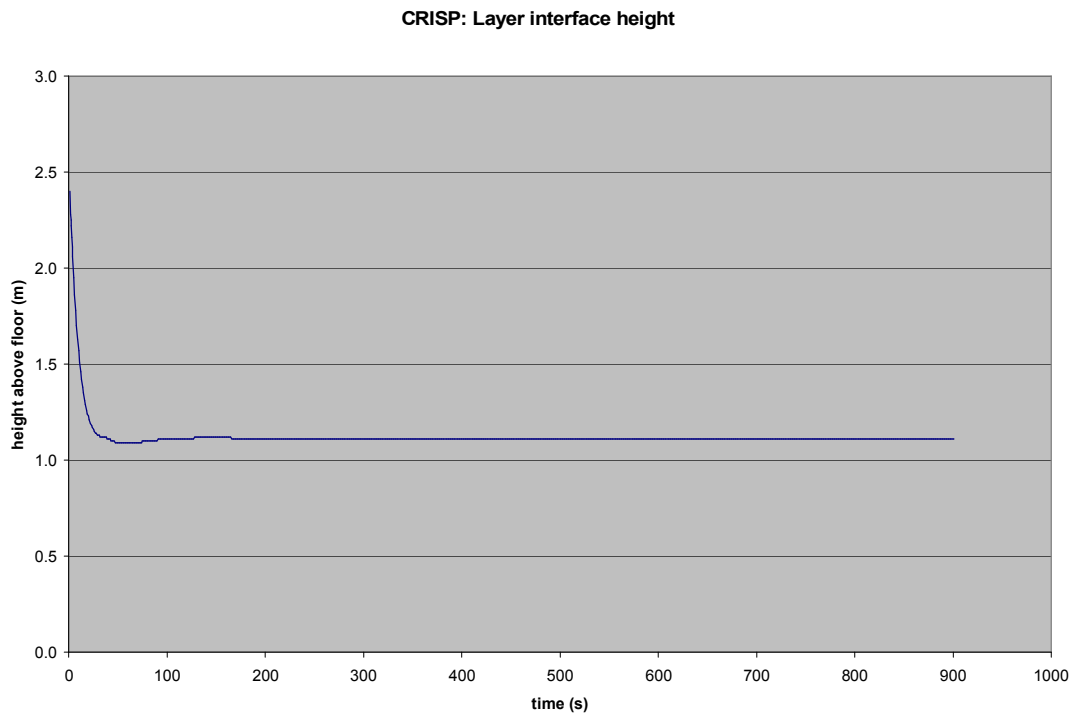
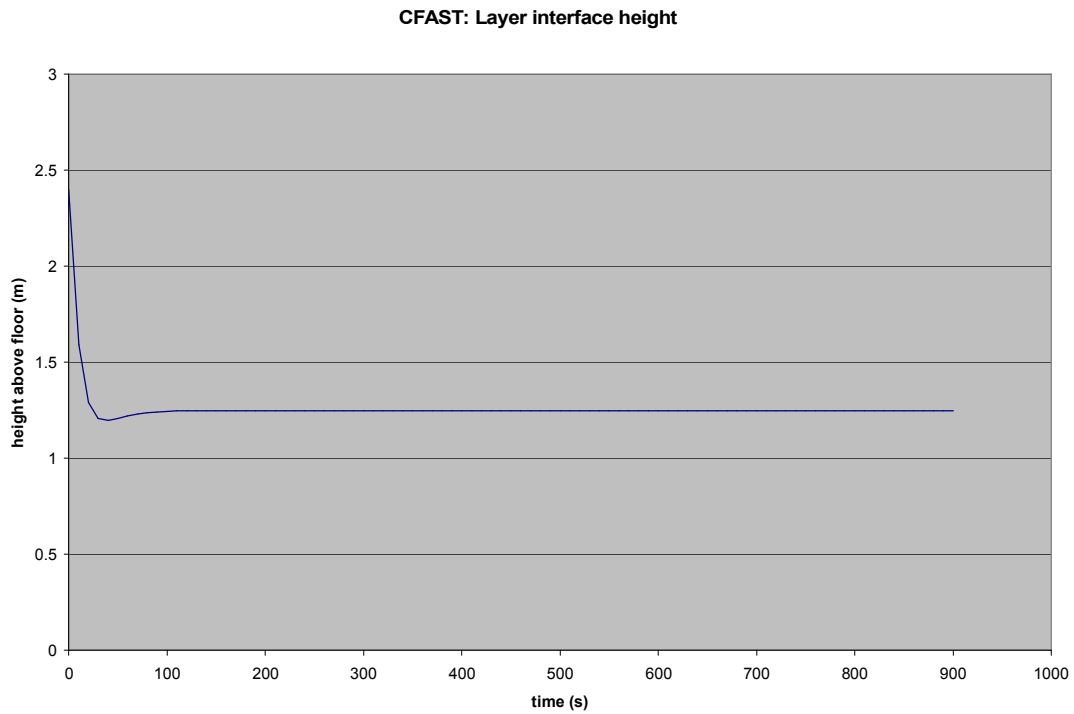


Figure A1. Single room, 100kW steady fire, no heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

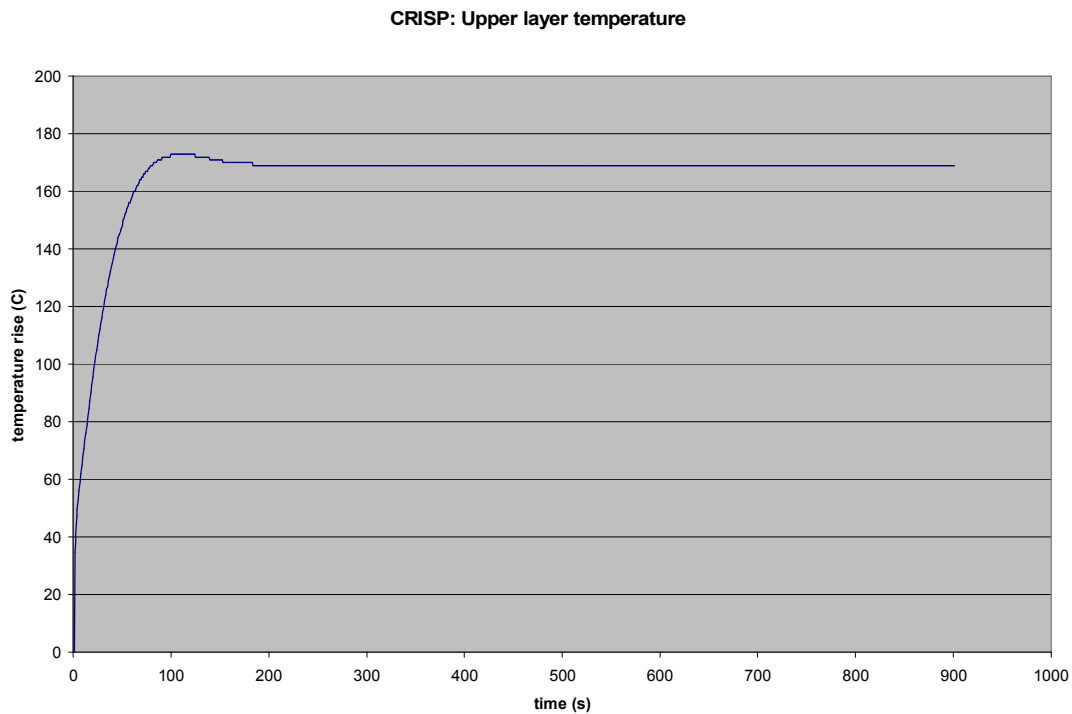
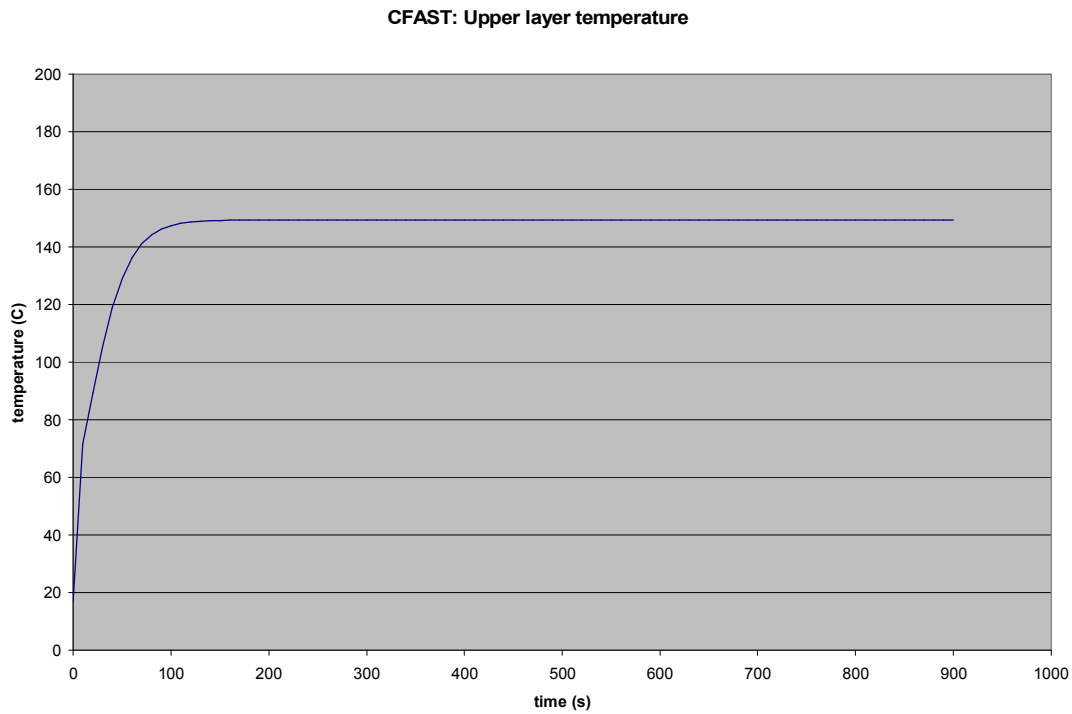


Figure A2. Single room, 100kW steady fire, no heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.



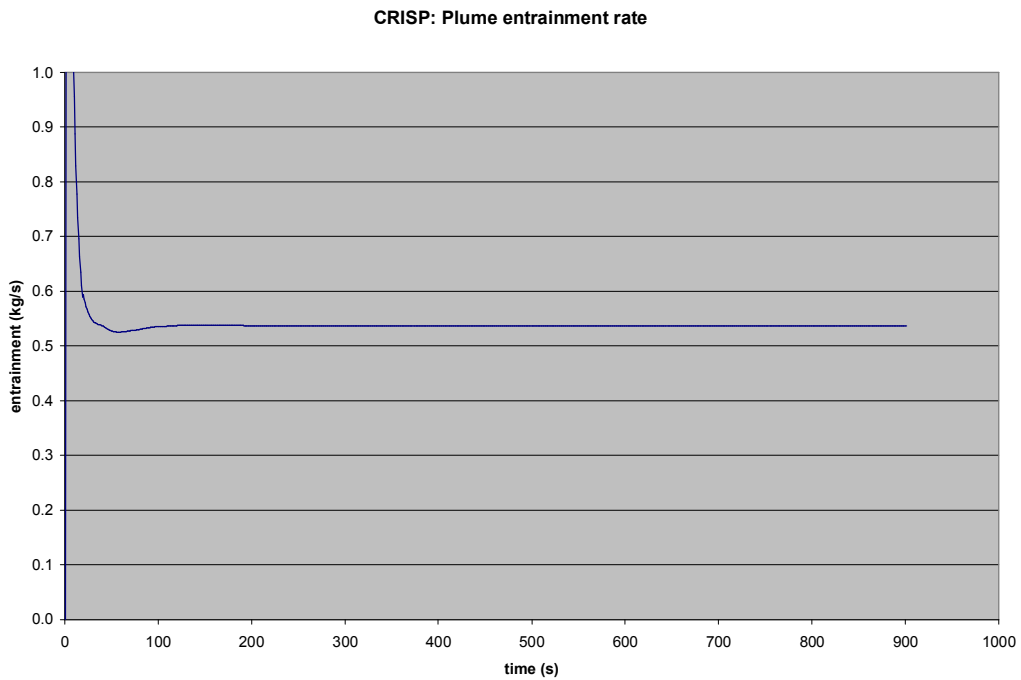
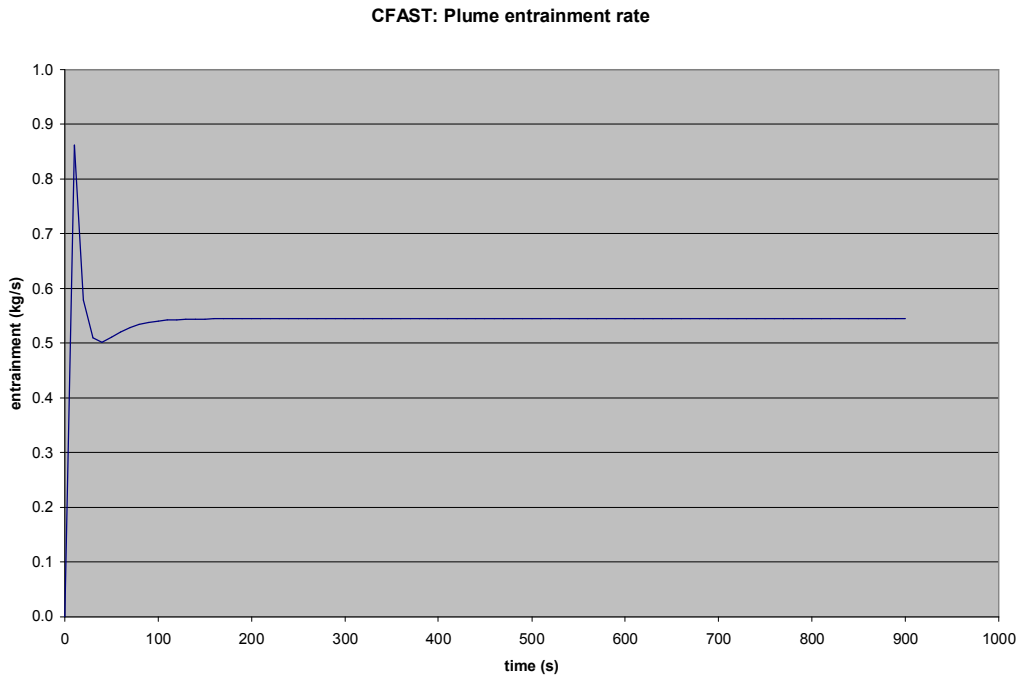


Figure A3. Single room, 100kW steady fire, no heat losses to walls. Comparison of plume entrainment rate, calculated by CFAST and CRISP. The rate calculated by CRISP is 0.0 kg/s at t=1, 2.0 kg/s at t=2, then falls rapidly until equilibrium is reached.

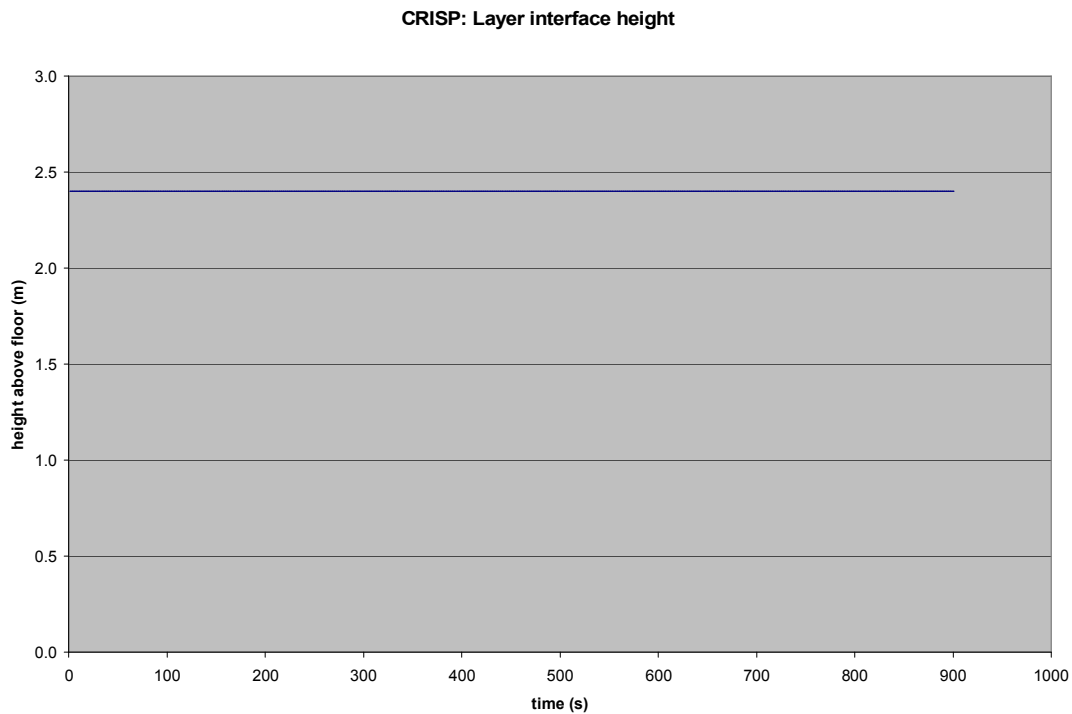
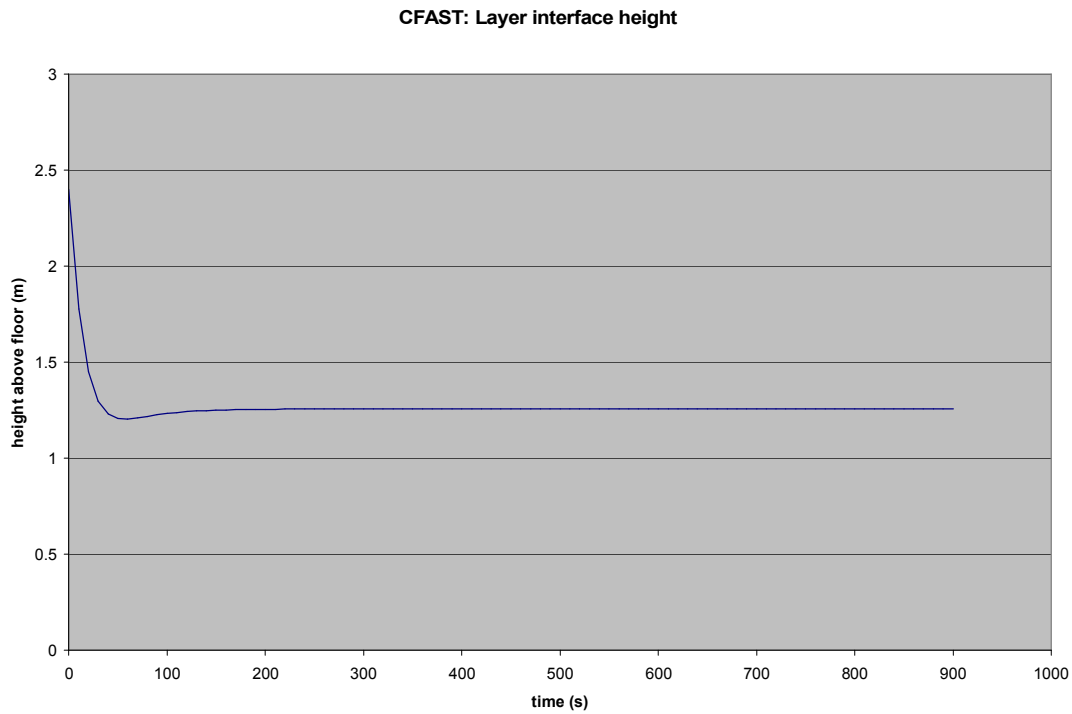


Figure A4. Single room, 30kW steady fire, no heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

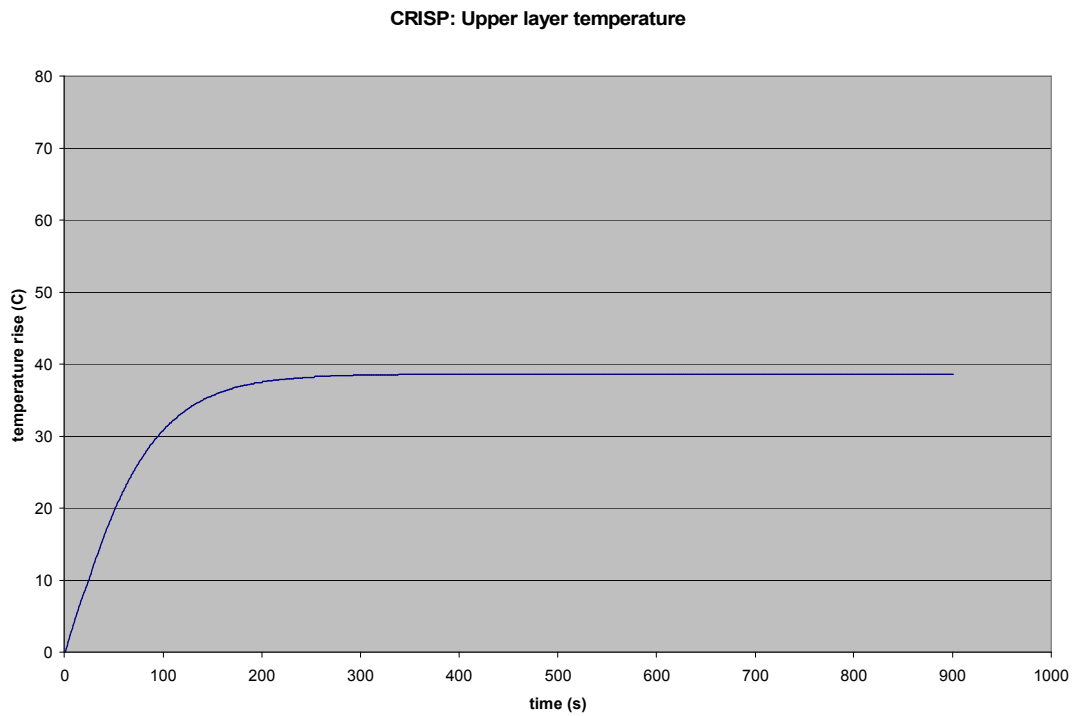
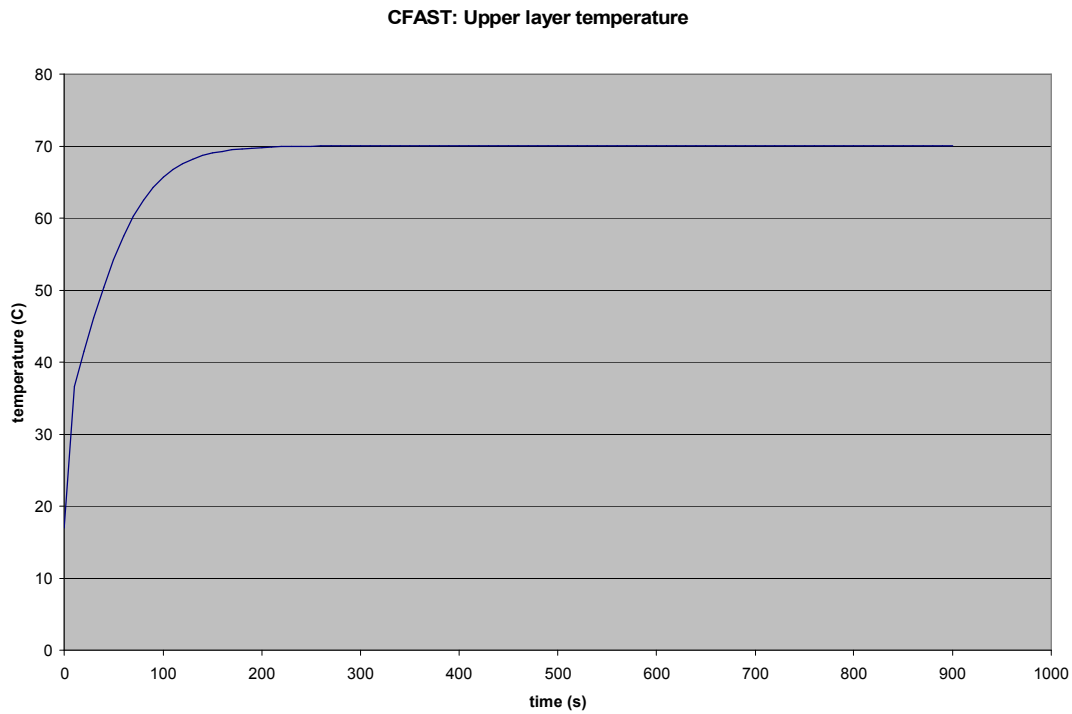


Figure A5. Single room, 30kW steady fire, no heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

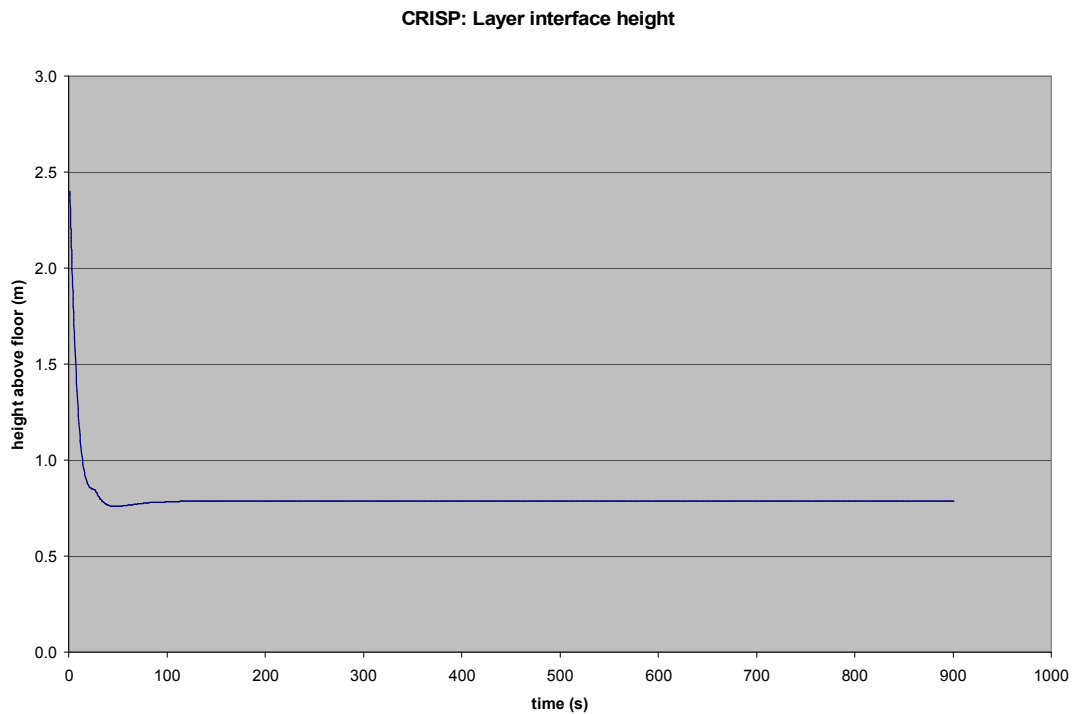
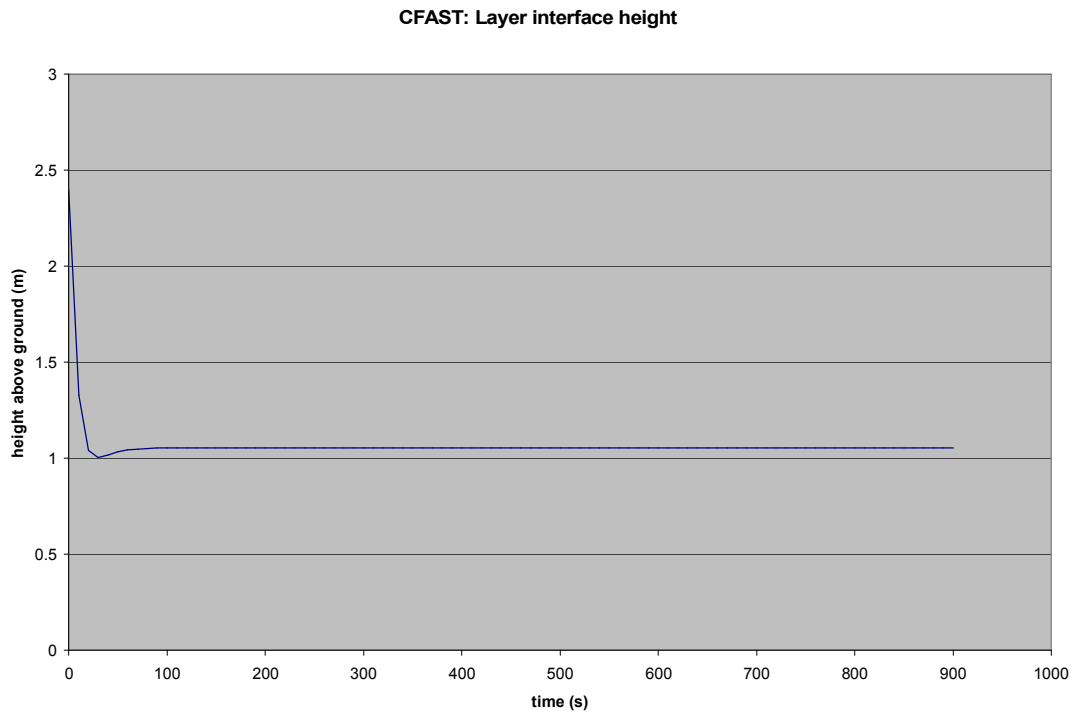


Figure A6. Single room, 300kW steady fire, no heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

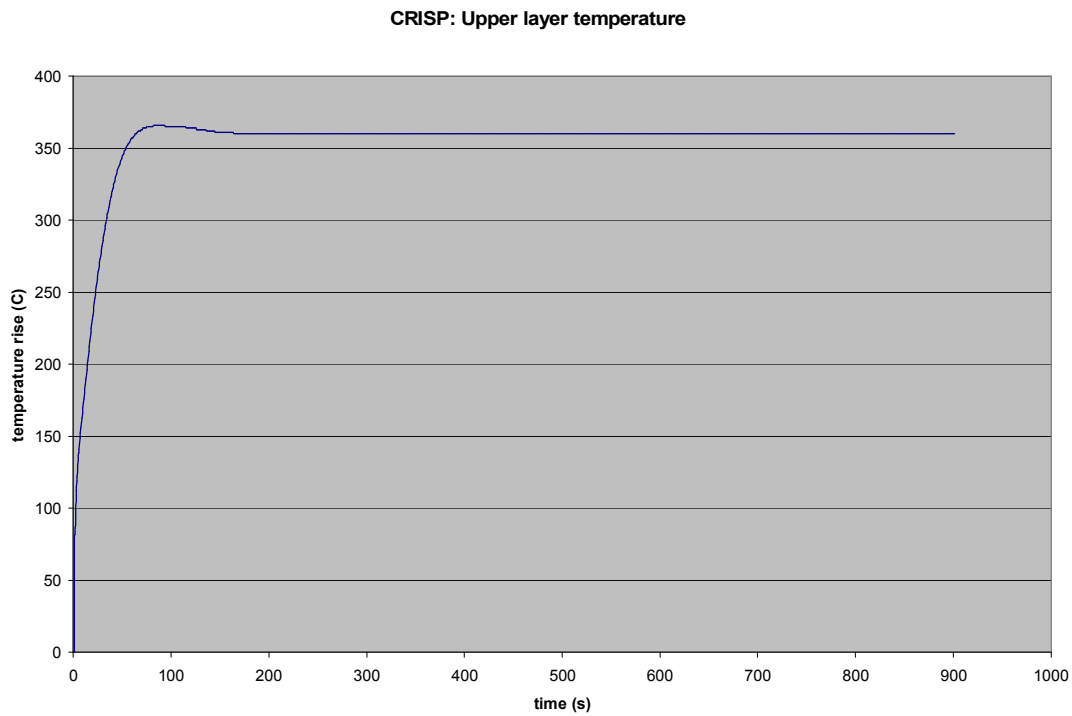
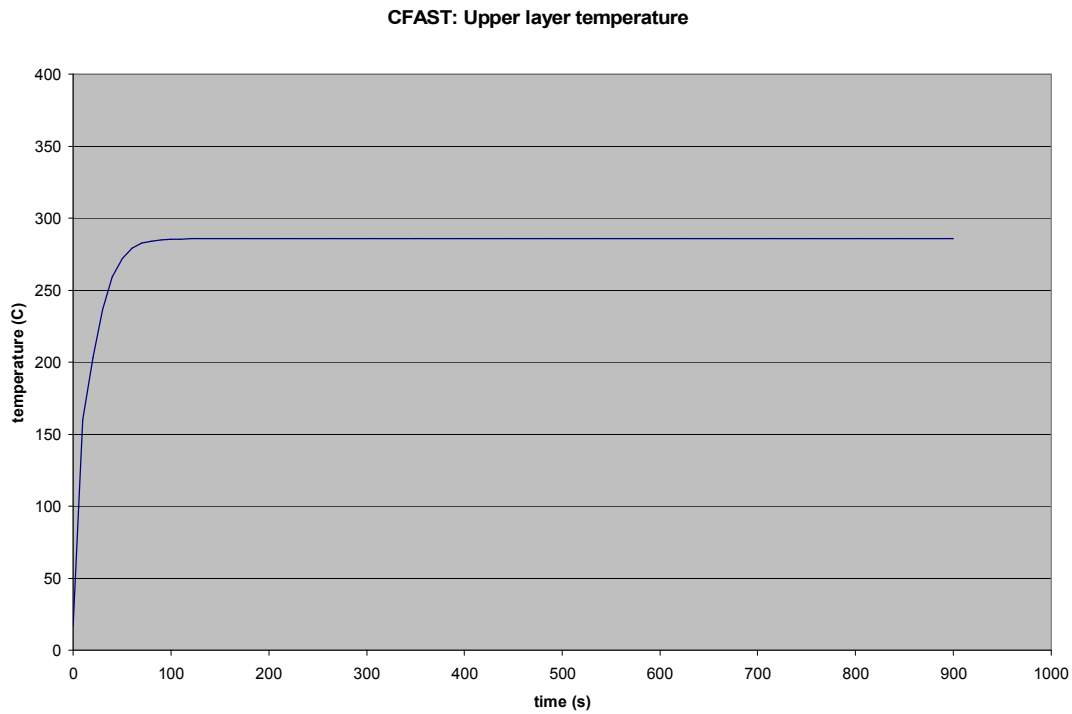


Figure A7. Single room, 300kW steady fire, no heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

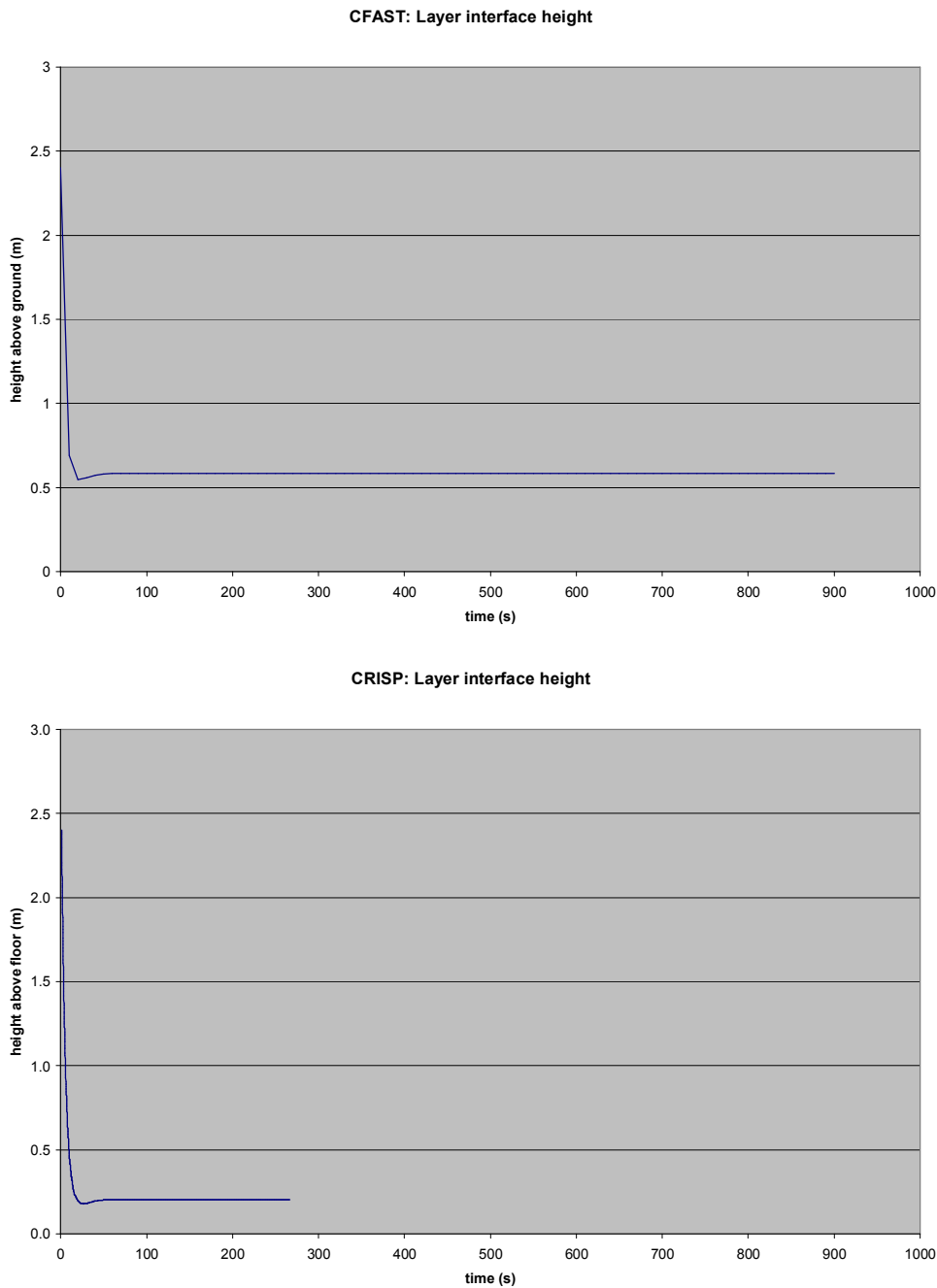


Figure A8. Single room, 1000kW steady fire, no heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP. For this simulation, CRISP was forced to retain a two-layer configuration in order to mimic CFAST more closely (the default behaviour would be to switch to a single layer once the clear depth is less than 0.5m). As a consequence of this constraint, CRISP was forced to use very short time steps to ensure model stability – this produced more data points than could be plotted in Excel

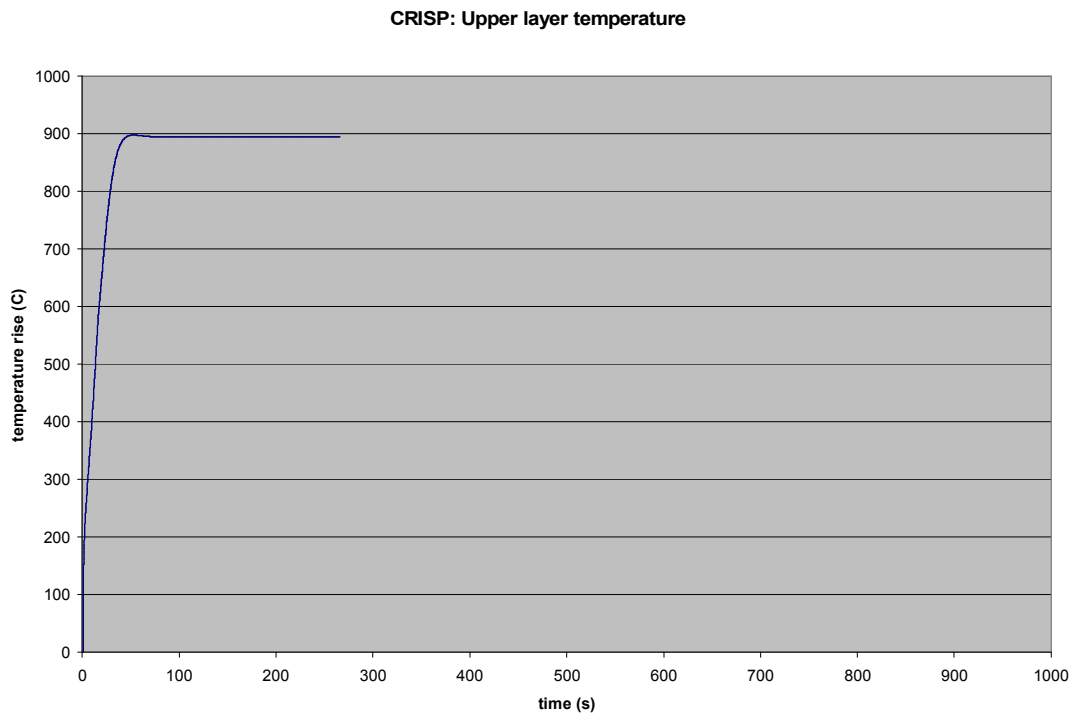
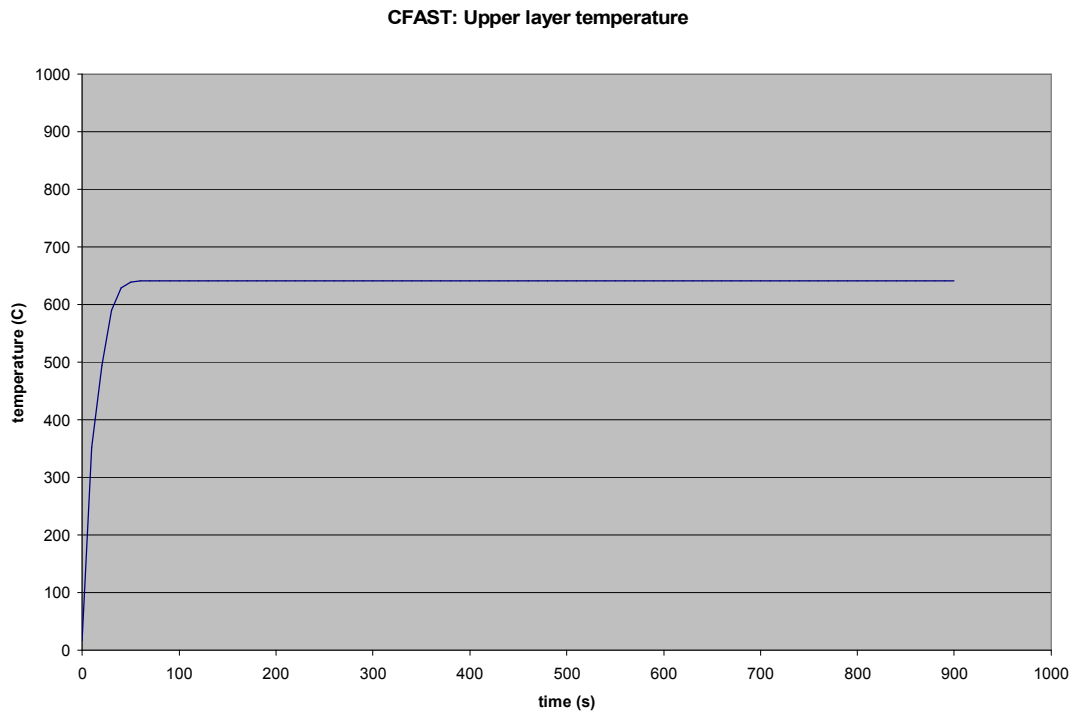


Figure A9. Single room, 1000kW steady fire, no heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

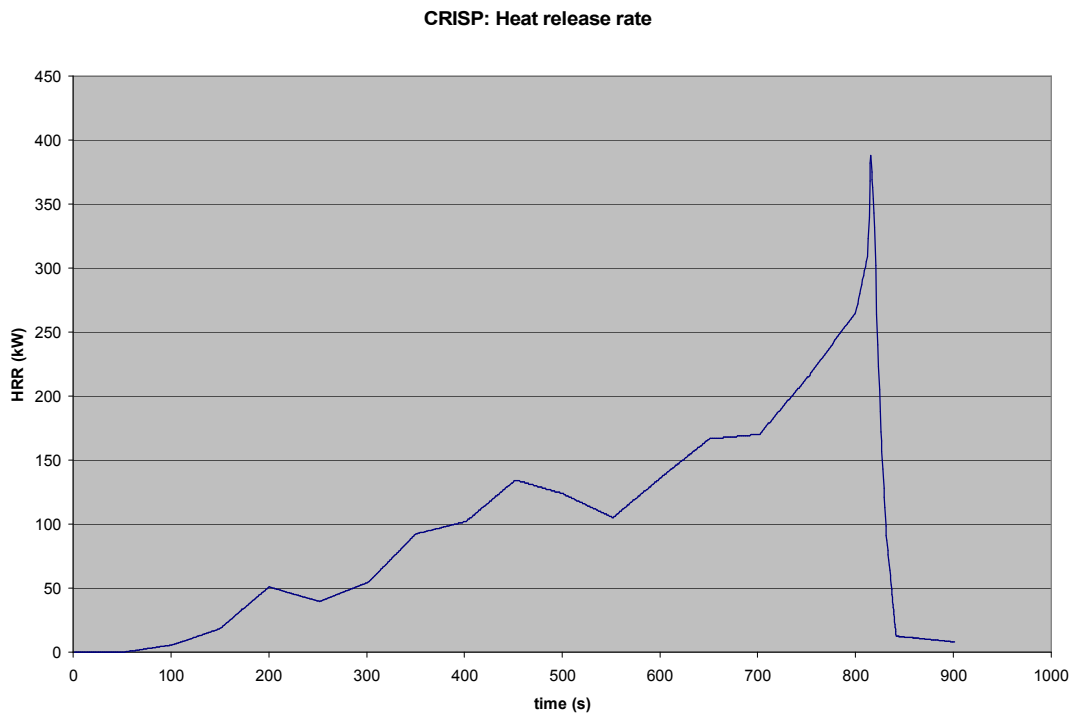
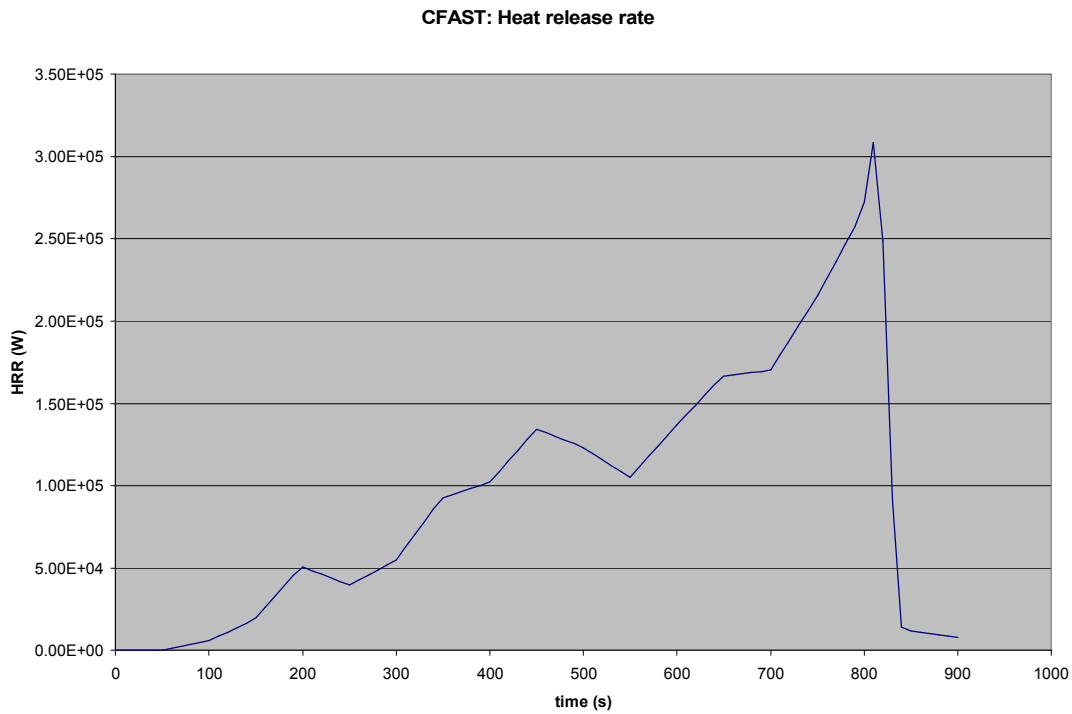


Figure A10. Single room, growing fire, no heat losses to walls. Comparison of heat release rate, plotted by CFAST and CRISP.



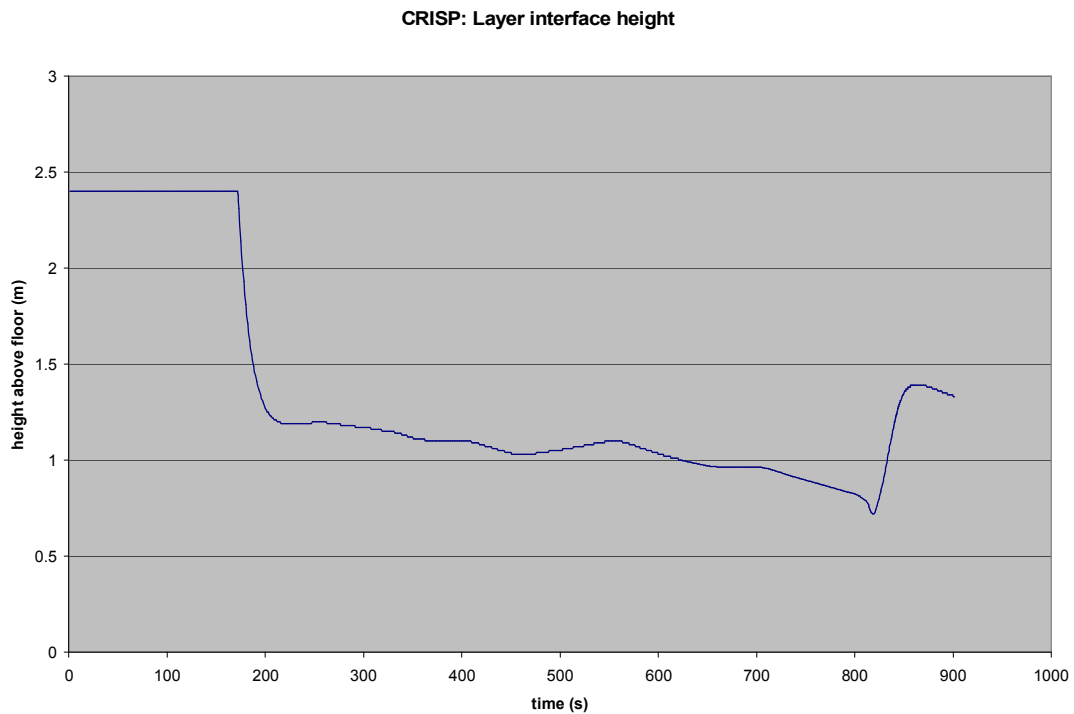
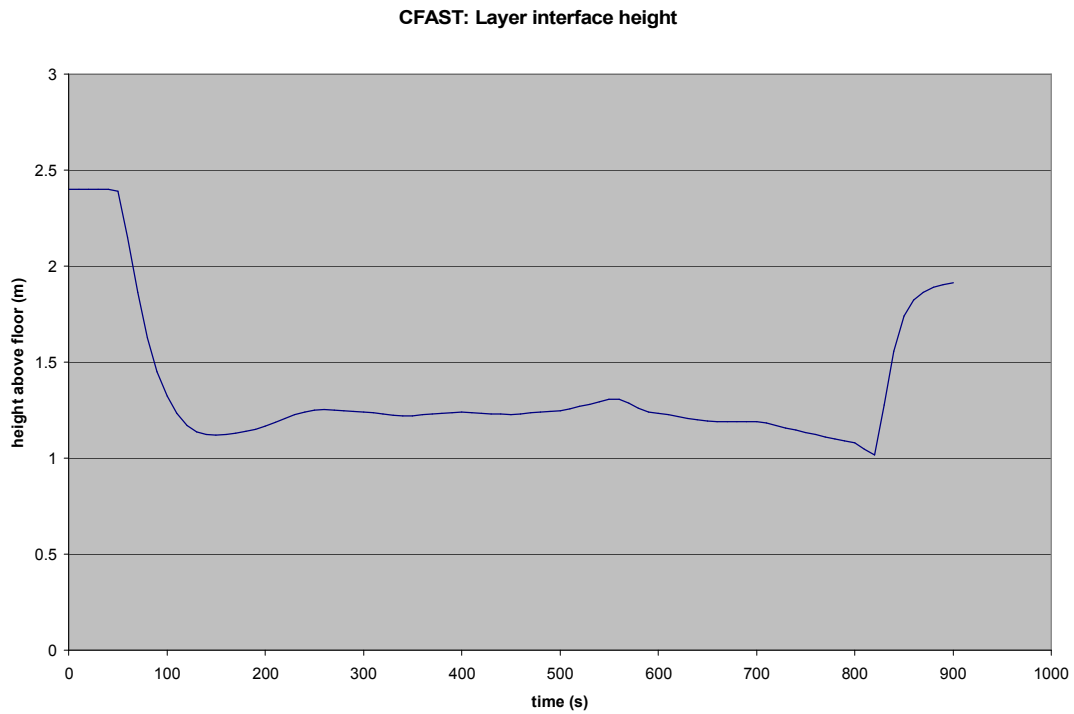


Figure A11. Single room, growing fire, no heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

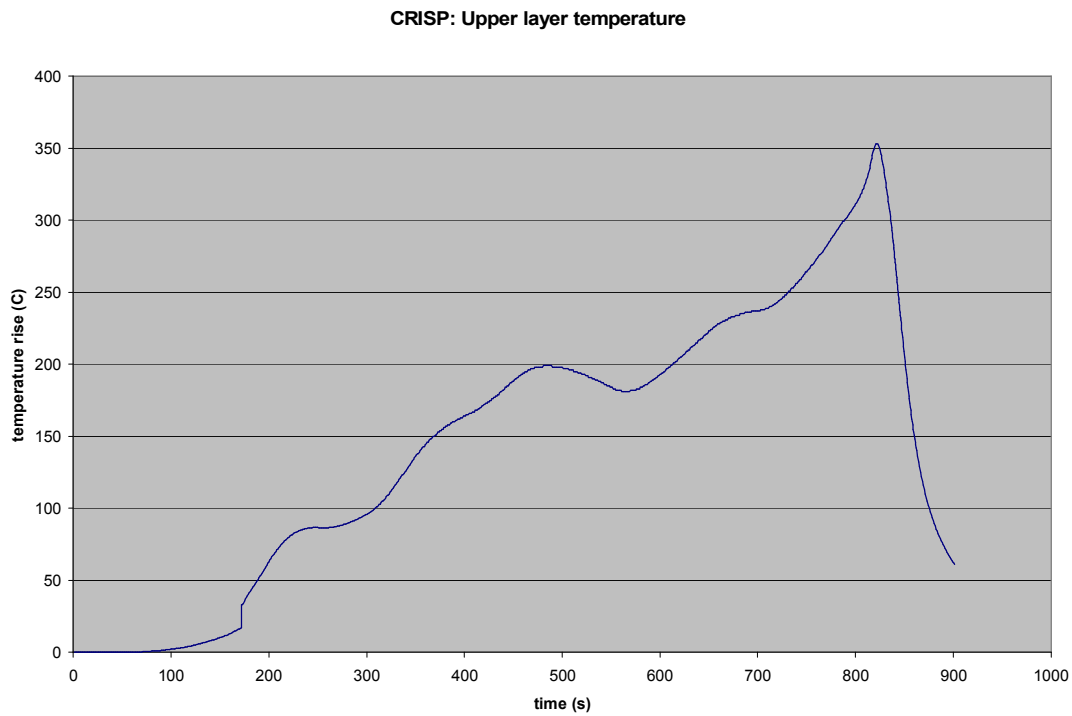
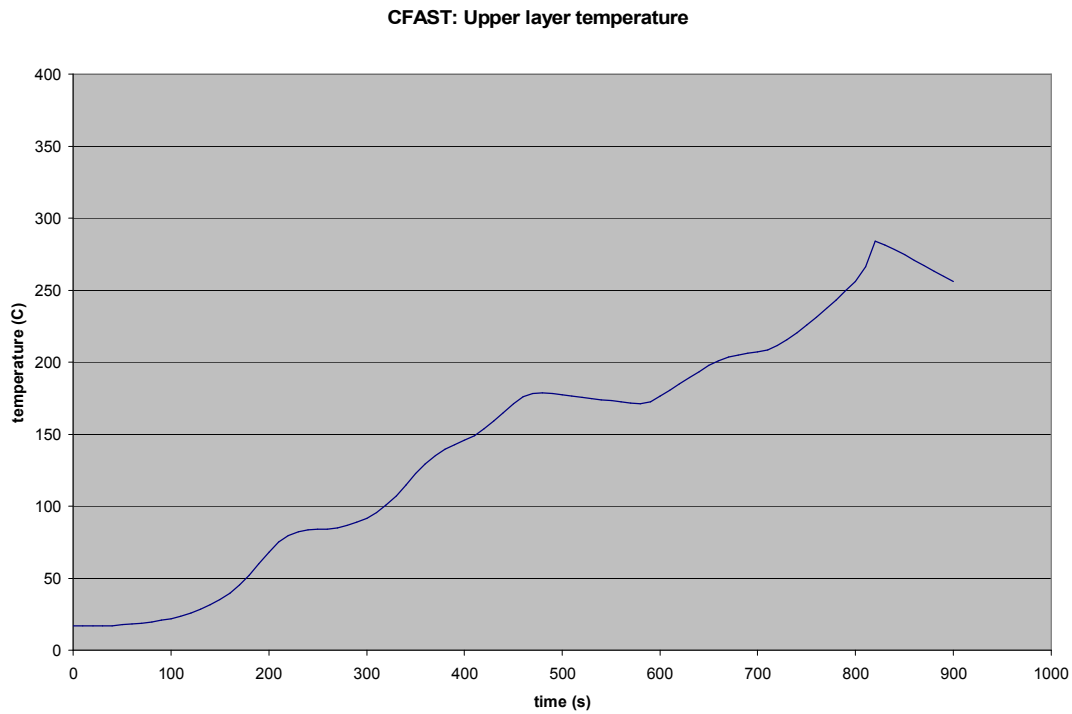


Figure A12. Single room, growing fire, no heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

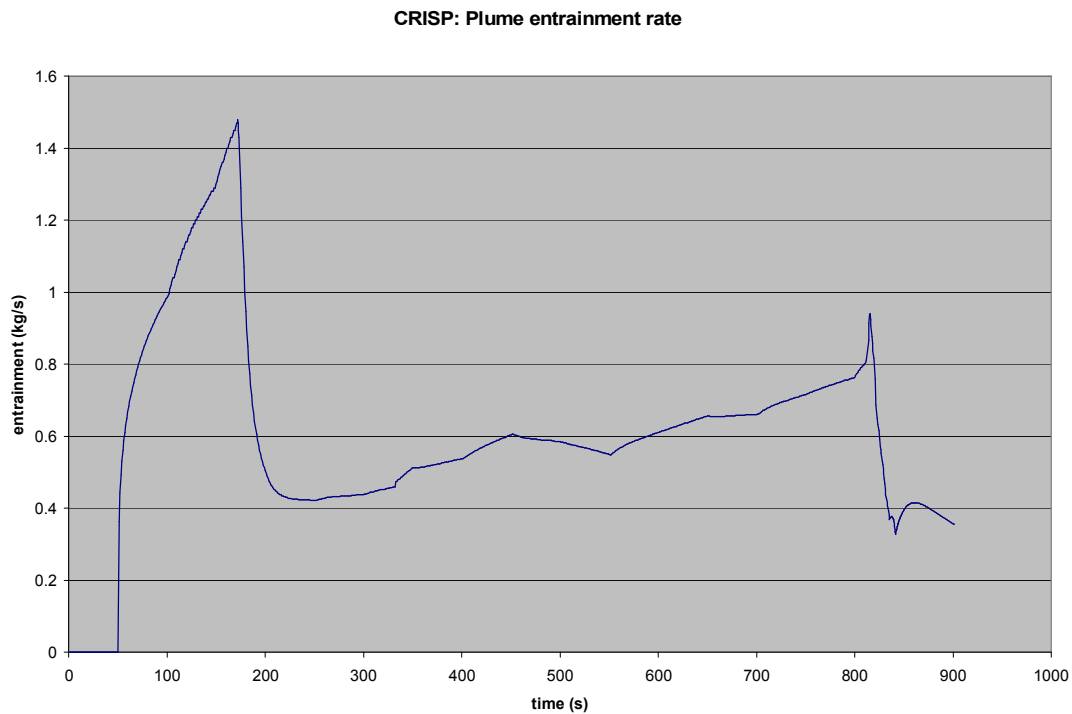
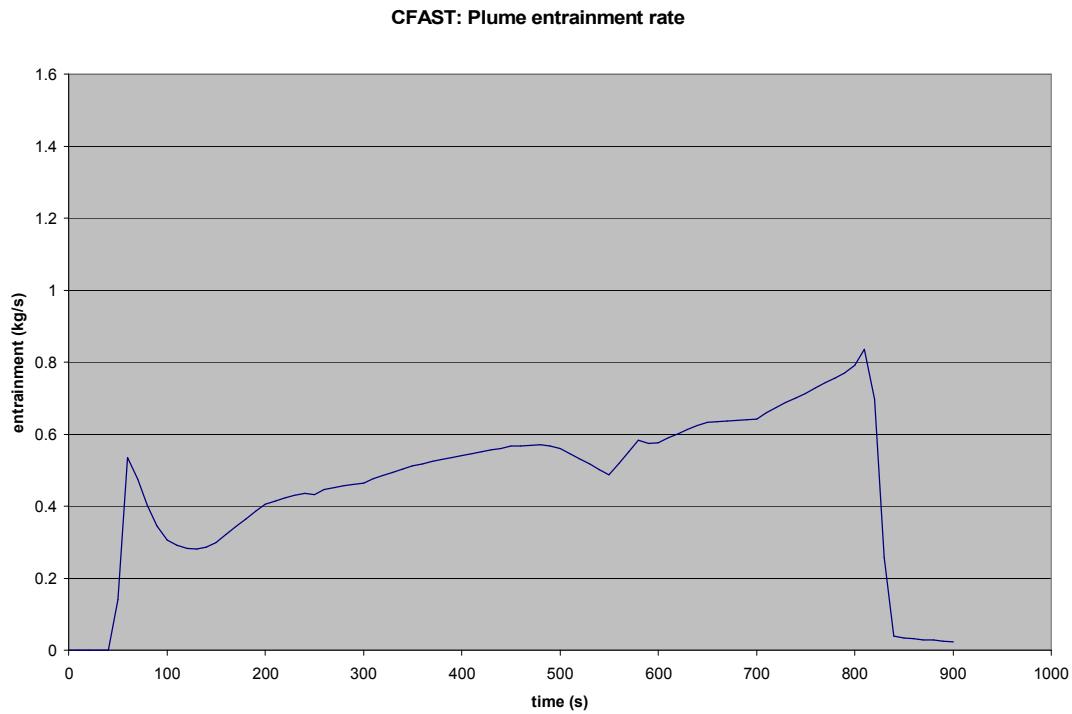


Figure A13. Single room, growing fire, no heat losses to walls. Comparison of plume entrainment rate, calculated by CFAST and CRISP.

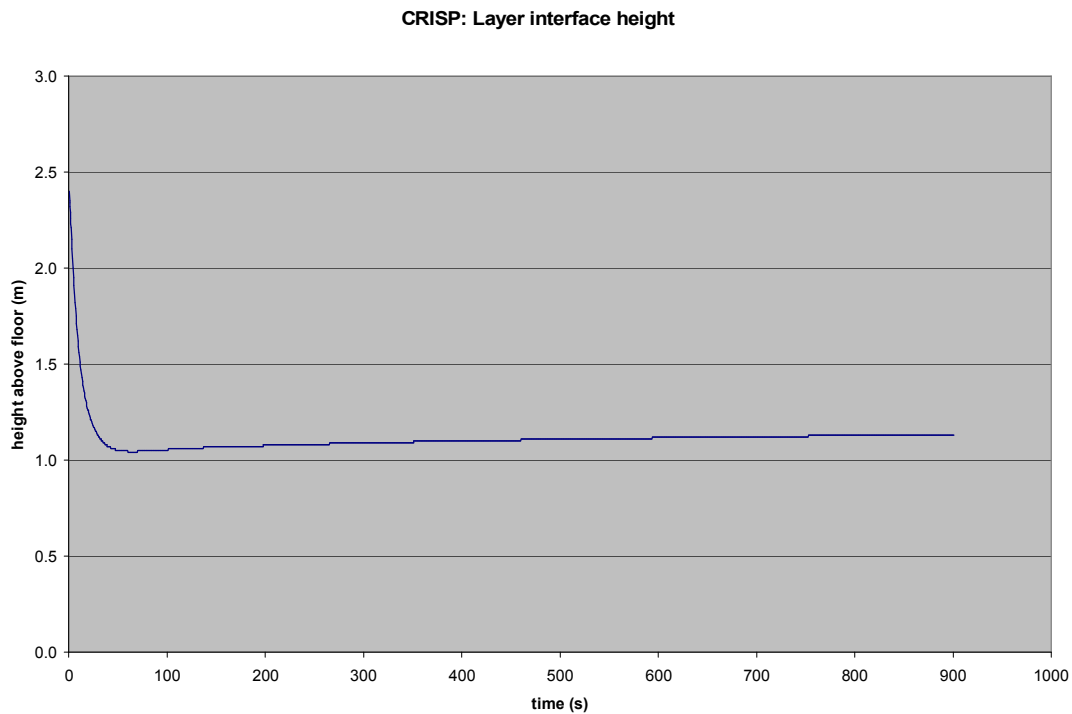
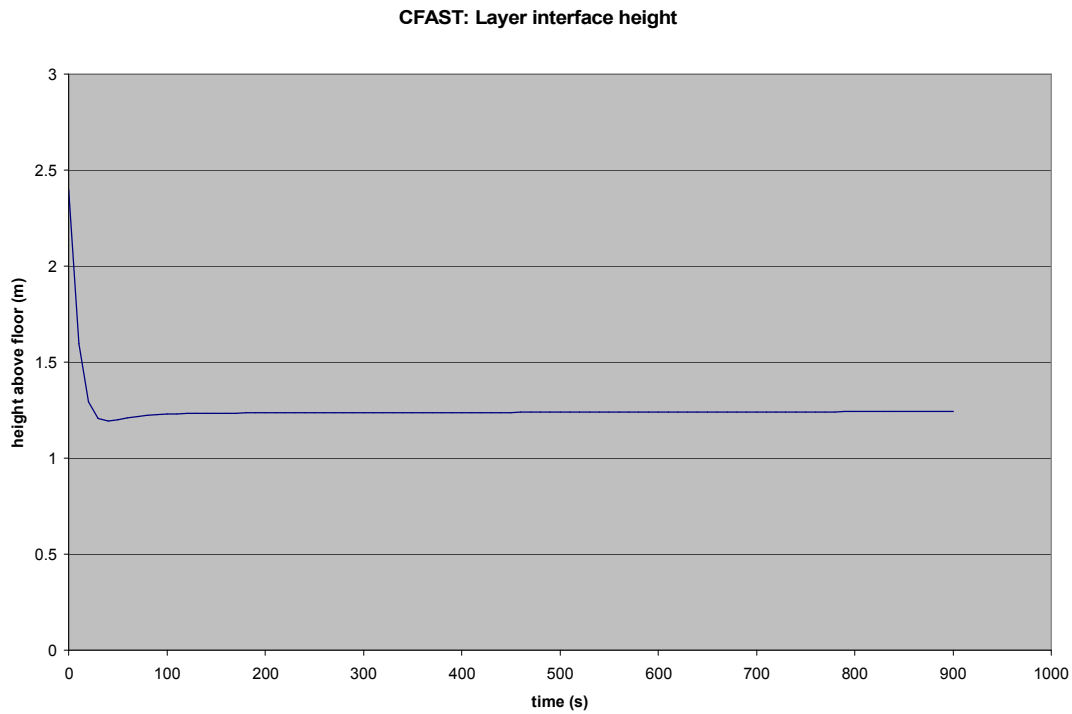


Figure A14. Single room, 100kW steady fire, with heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

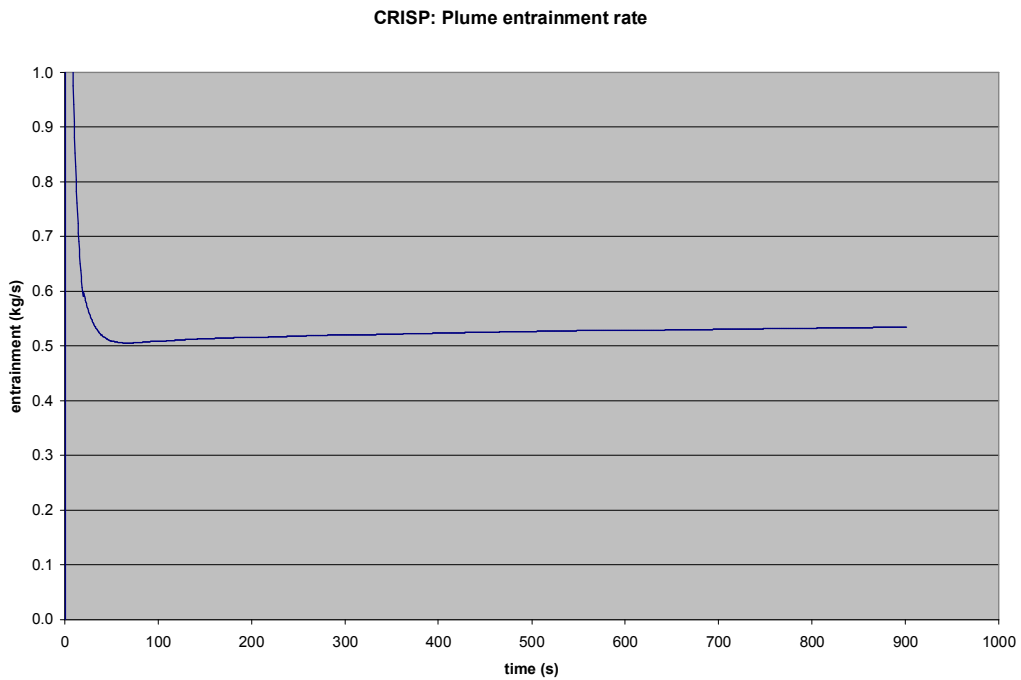
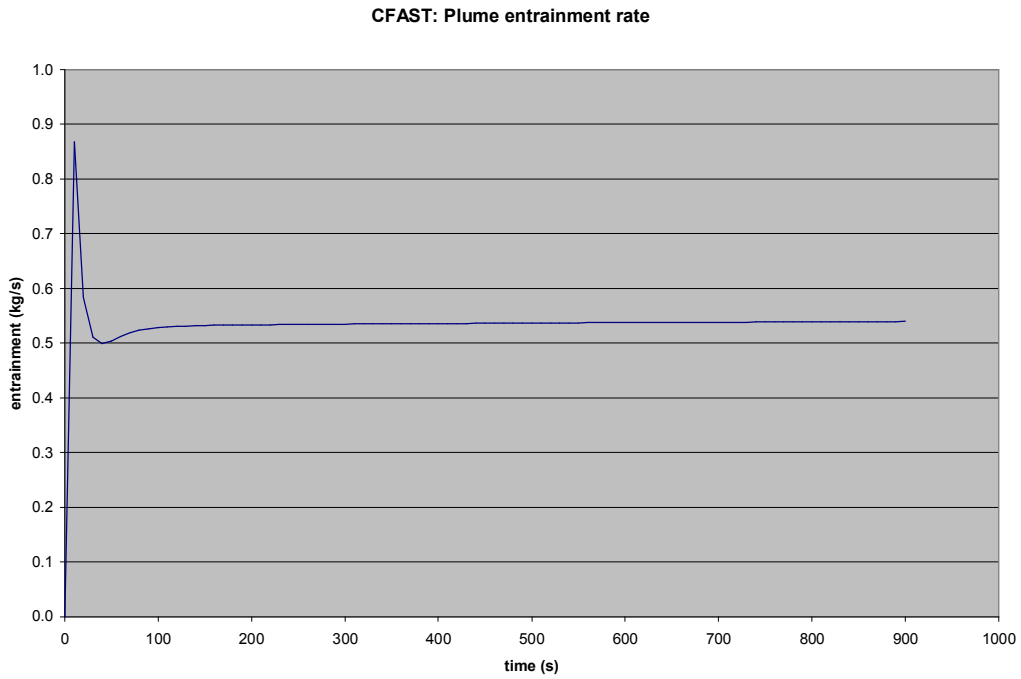


Figure A15. Single room, 100kW steady fire, with heat losses to walls. Comparison of plume entrainment rate, calculated by CFAST and CRISP. The rate calculated by CRISP is 0.0 kg/s at t=1, 2.0 kg/s at t=2, then falls rapidly until equilibrium is reached.

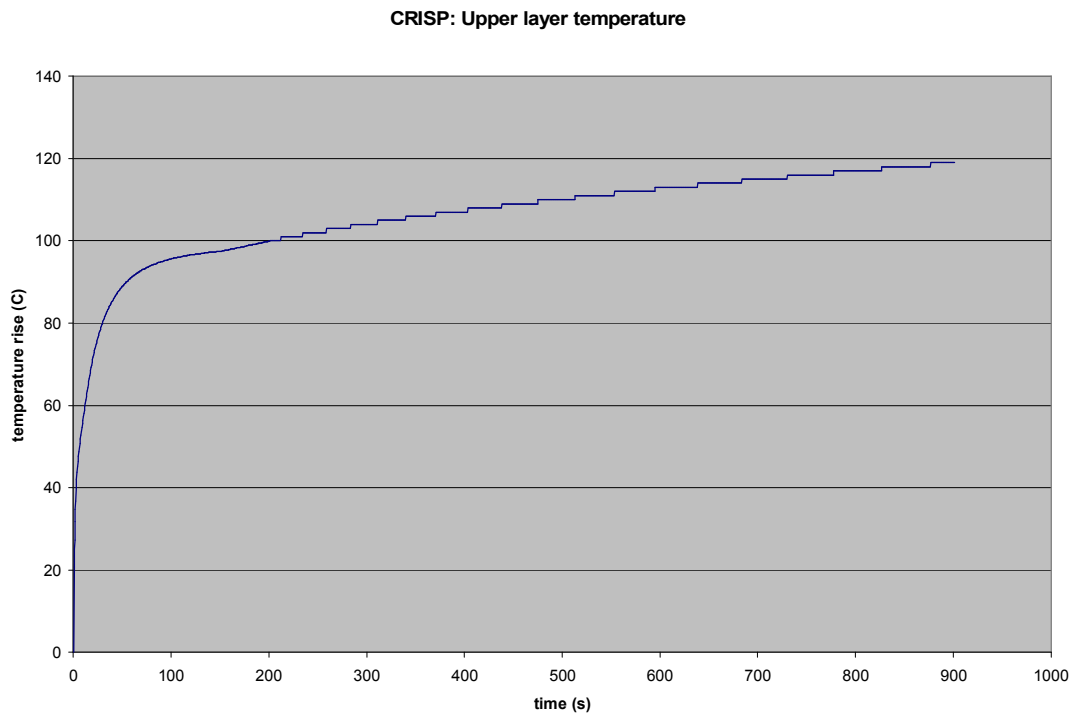
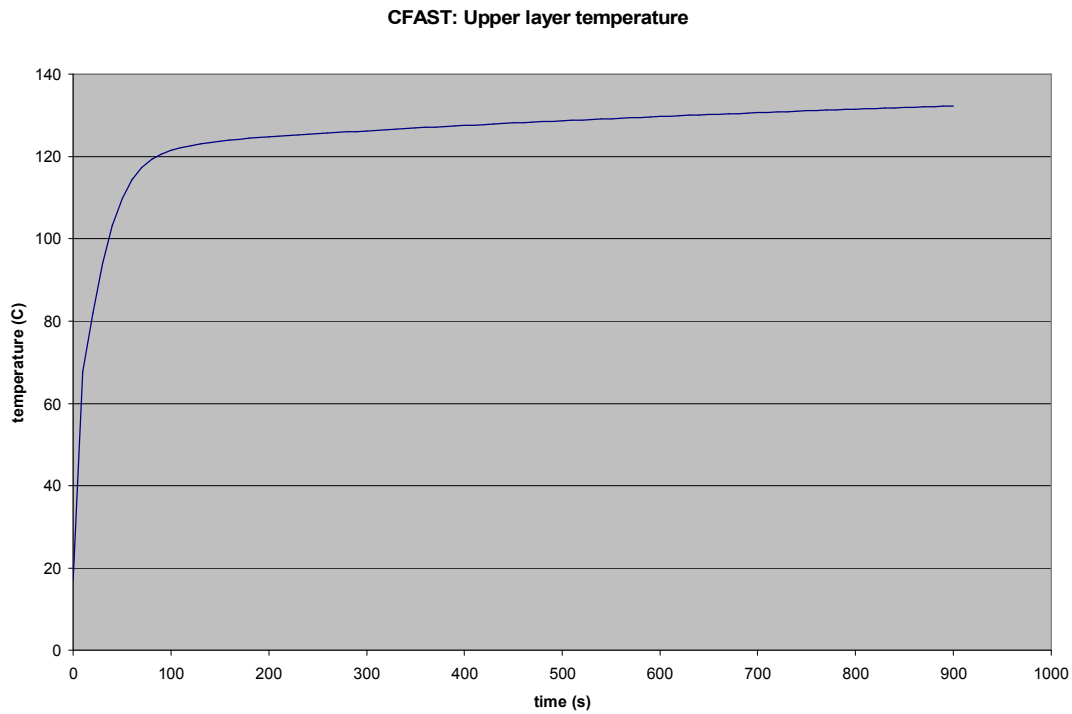


Figure A16. Single room, 100kW steady fire, with heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

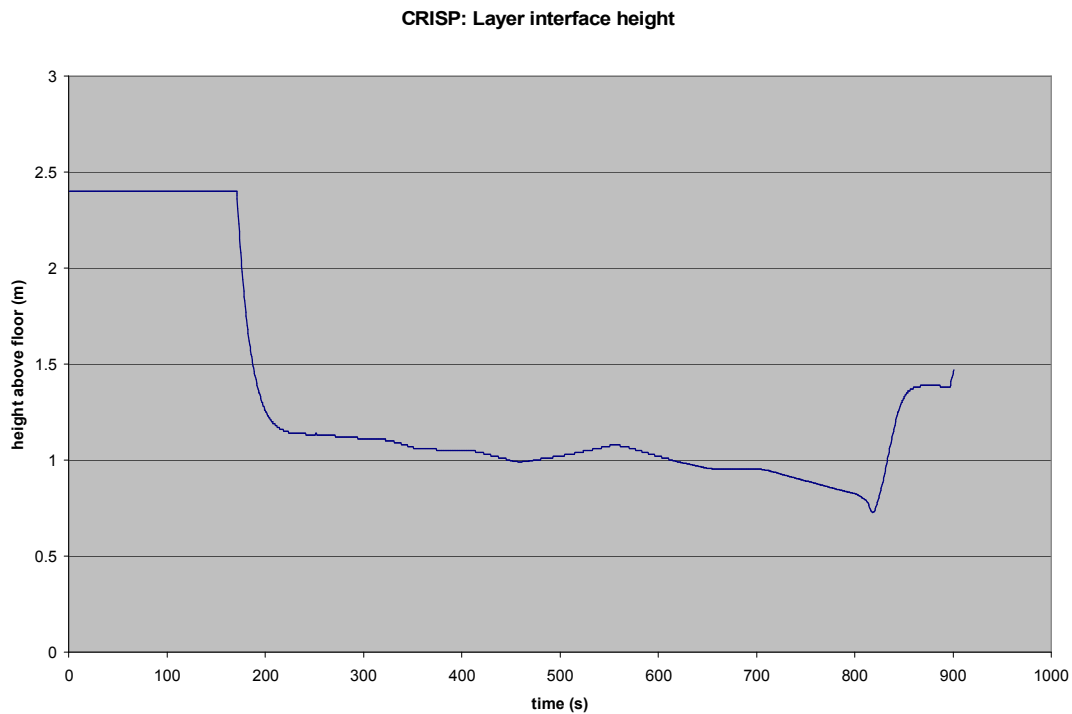
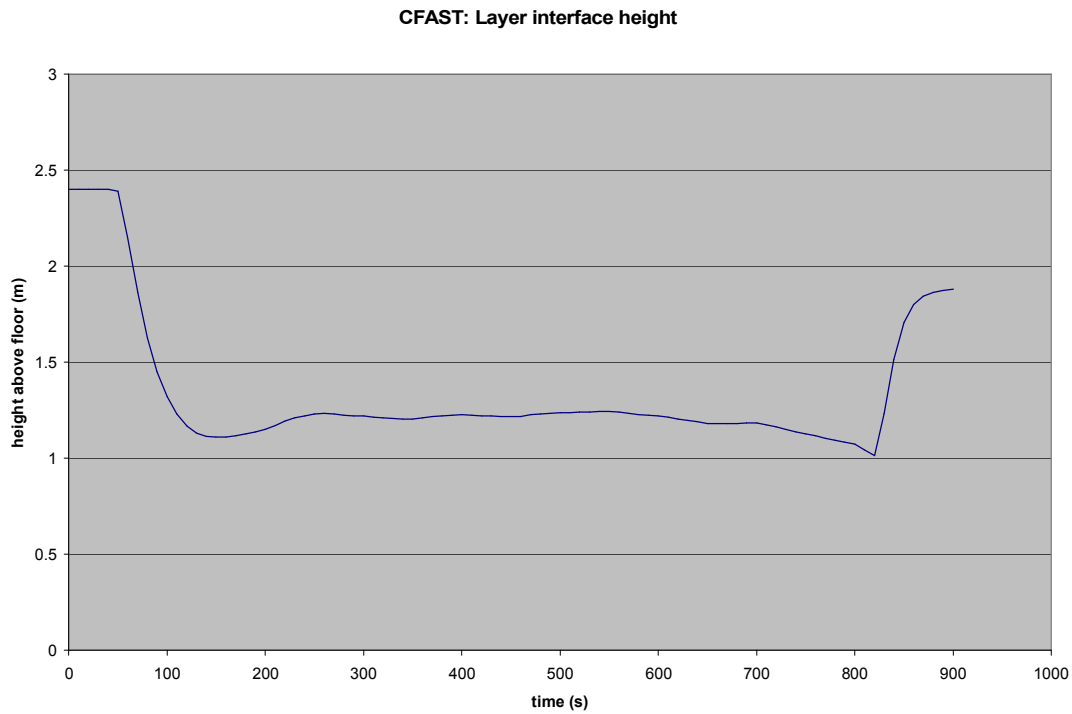


Figure A17. Single room, growing fire, with heat losses to walls. Comparison of layer interface height, calculated by CFAST and CRISP.

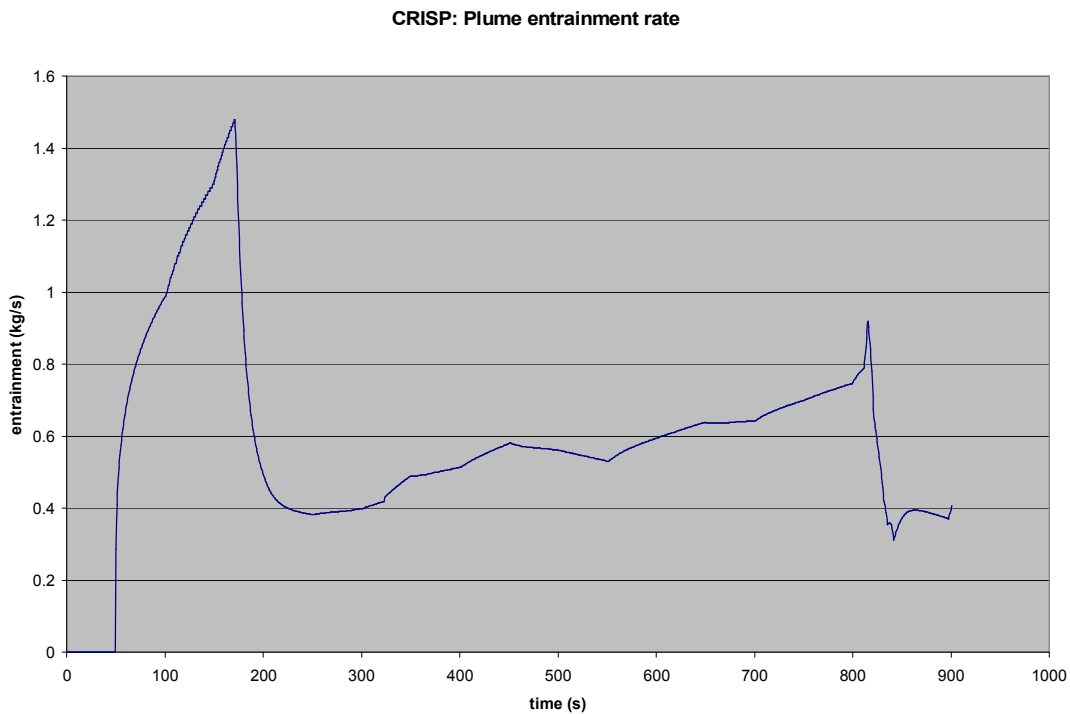
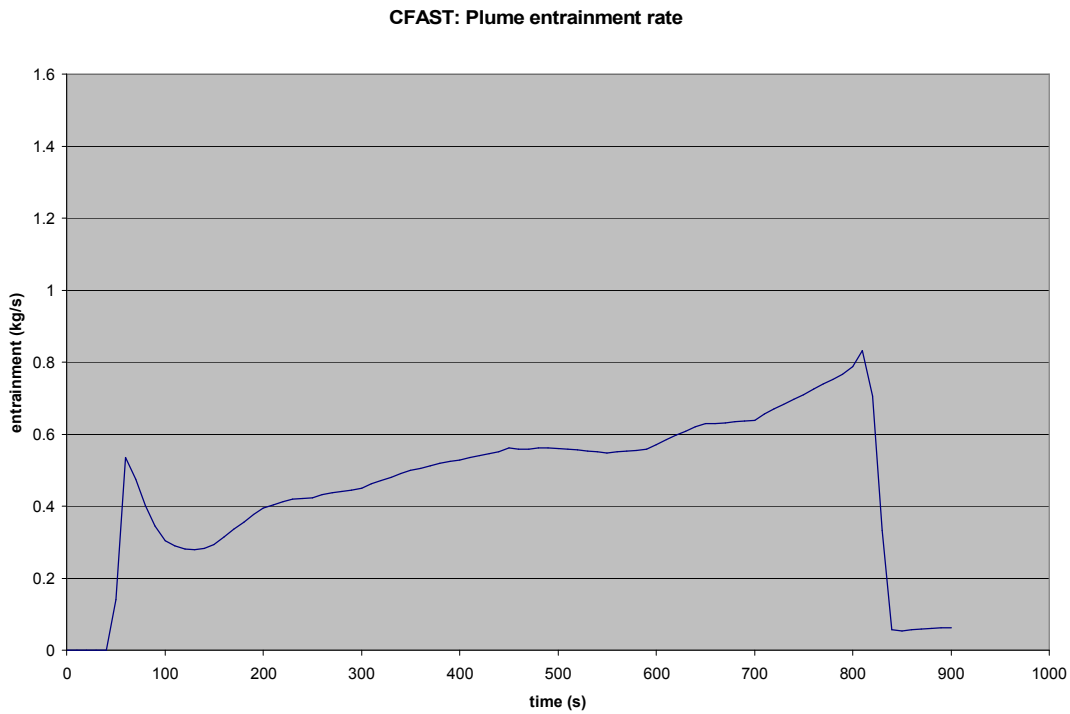


Figure A18. Single room, growing fire, with heat losses to walls. Comparison of plume entrainment rate, calculated by CFAST and CRISP.



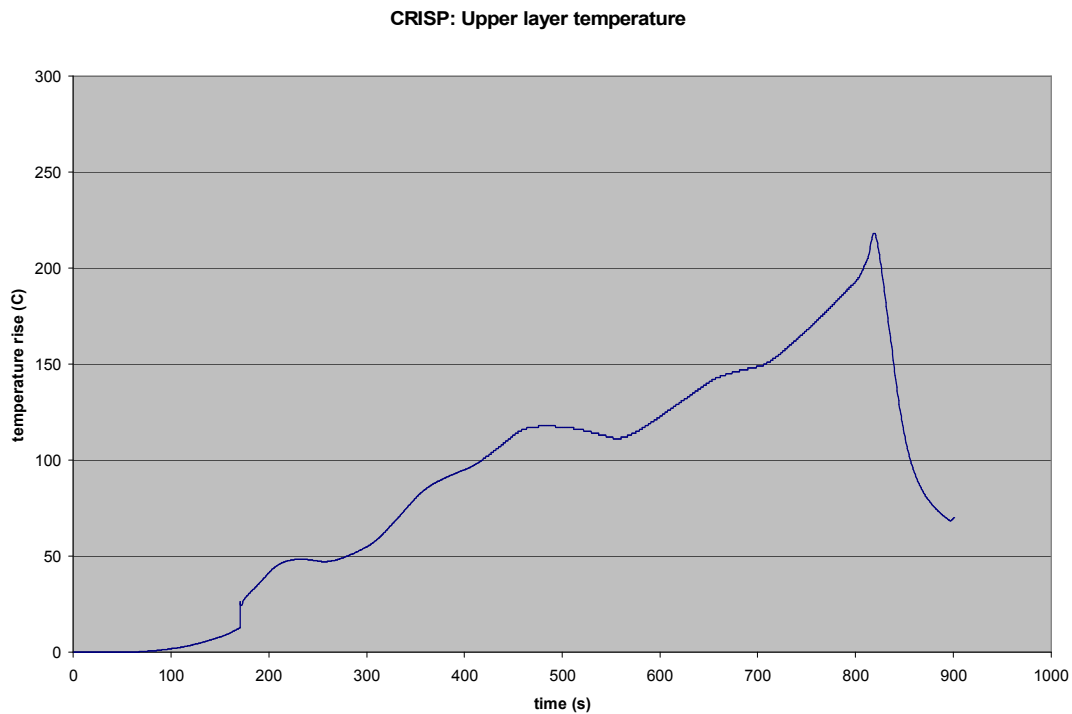
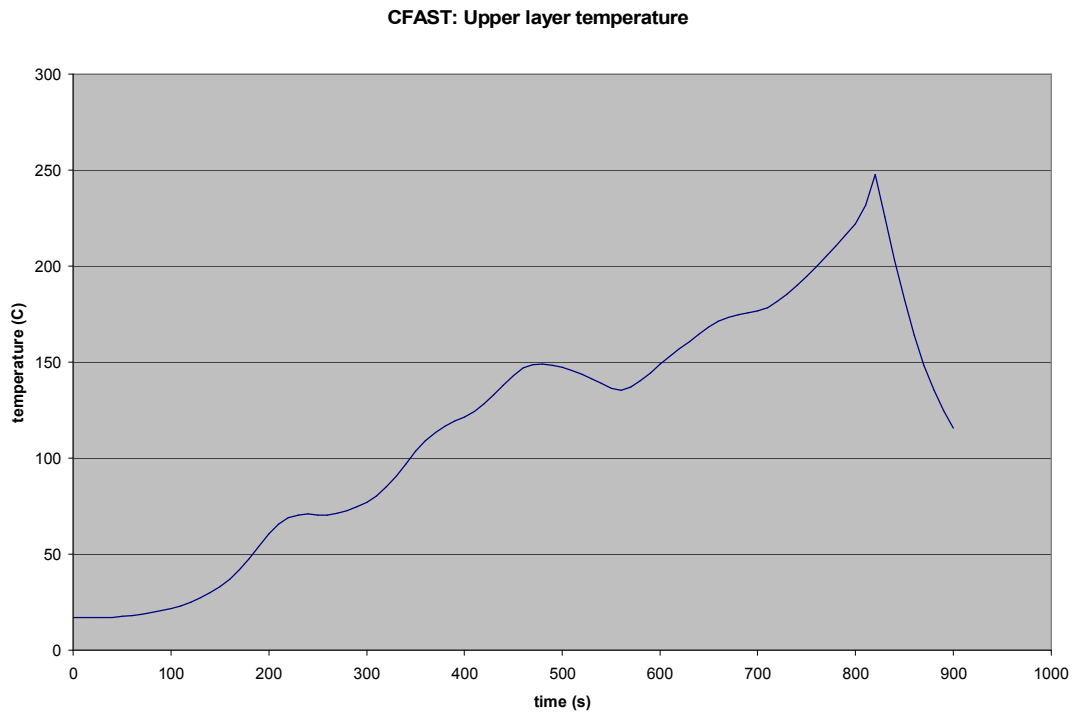


Figure A19. Single room, growing fire, with heat losses to walls. Comparison of upper layer temperature, calculated by CFAST and CRISP.

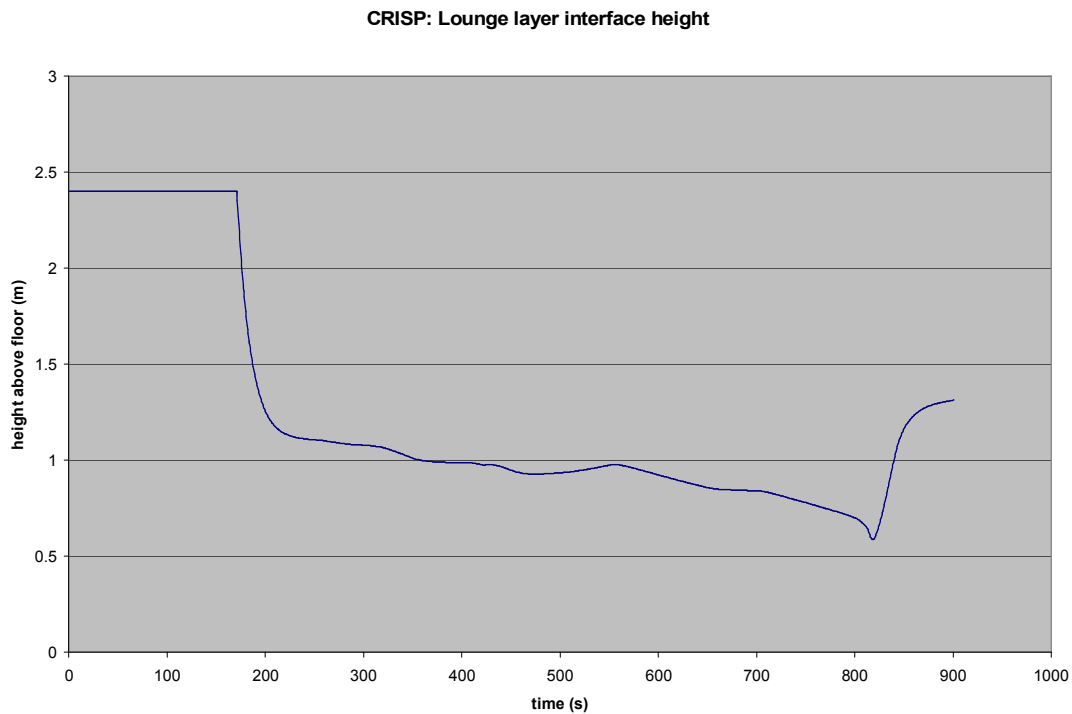
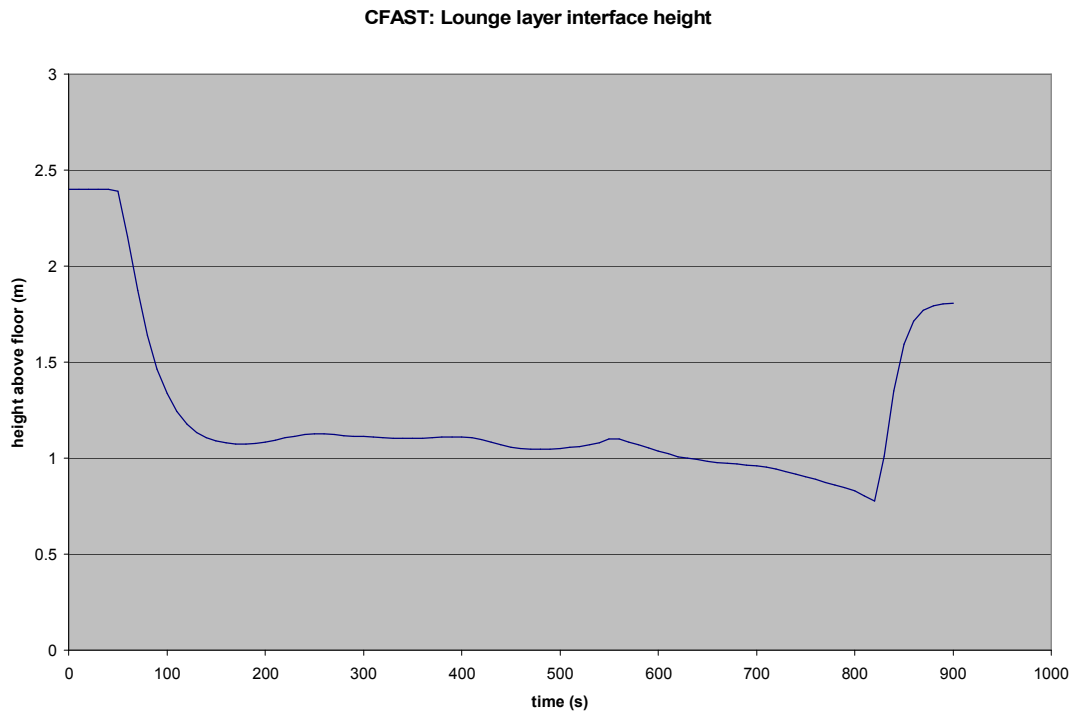


Figure A20. Experimental house, growing TV fire, lounge door open. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

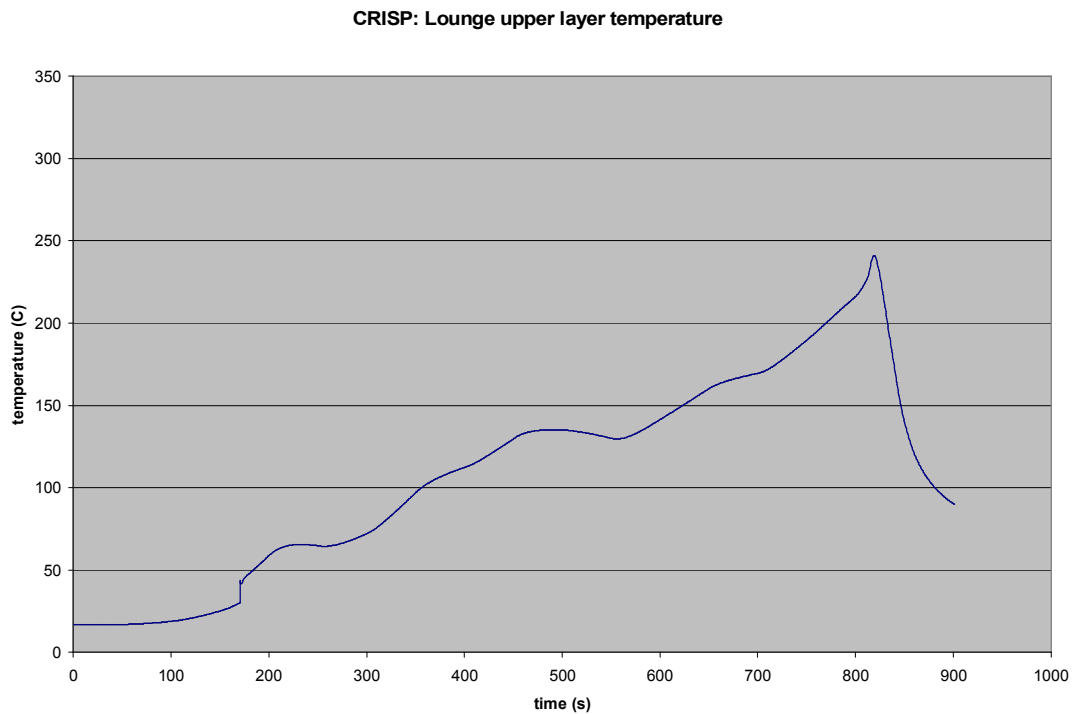
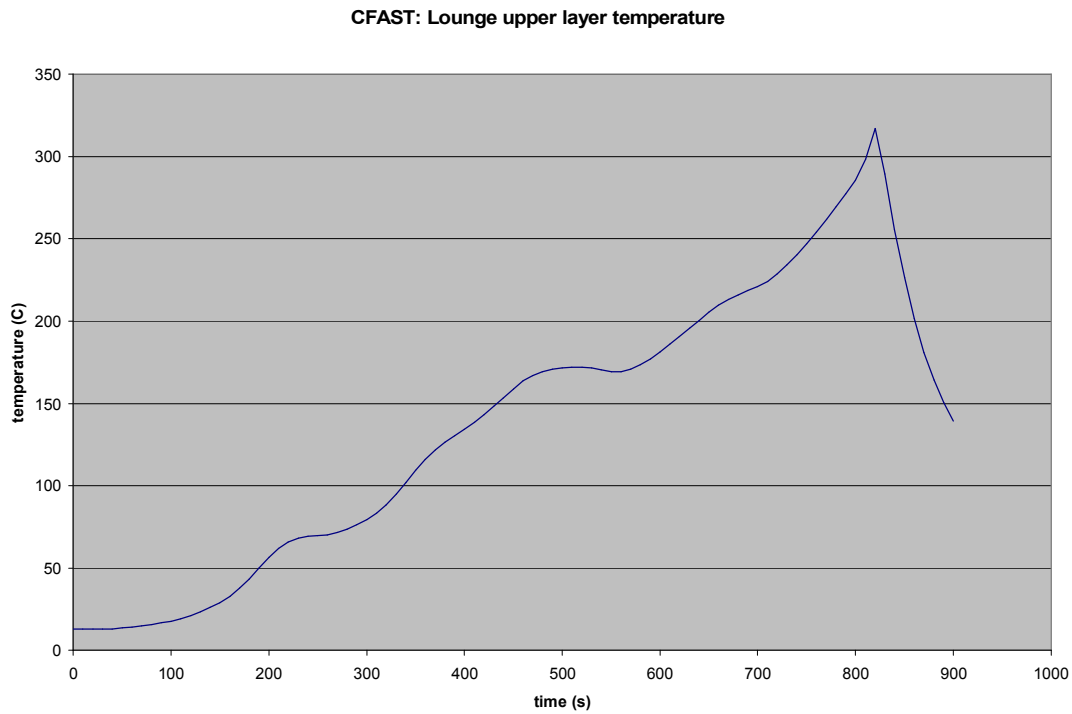


Figure A21. Experimental house, growing TV fire, lounge door open. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

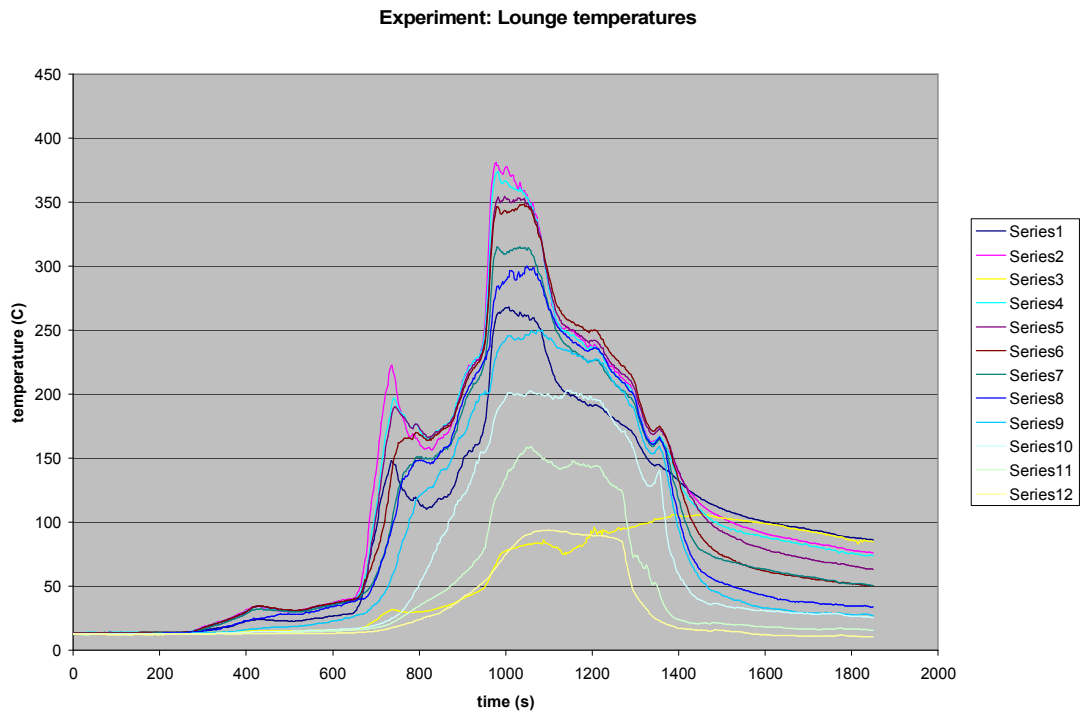


Figure A22. Experimental house, growing TV/room fire, lounge door open. Temperature measurements in the lounge (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

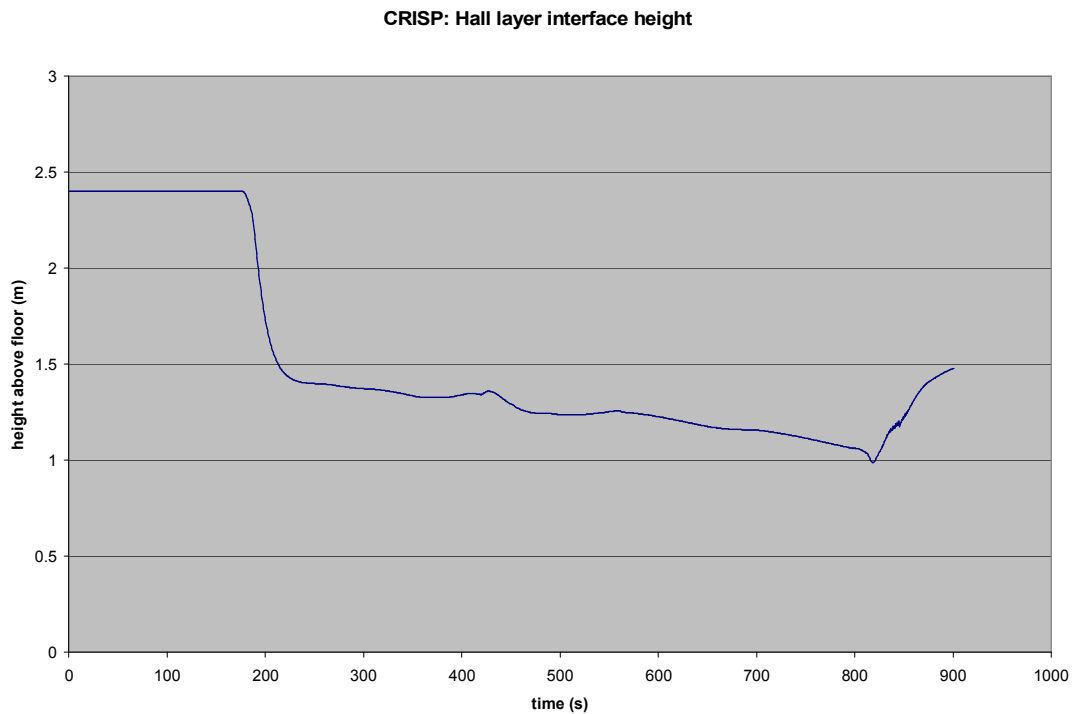
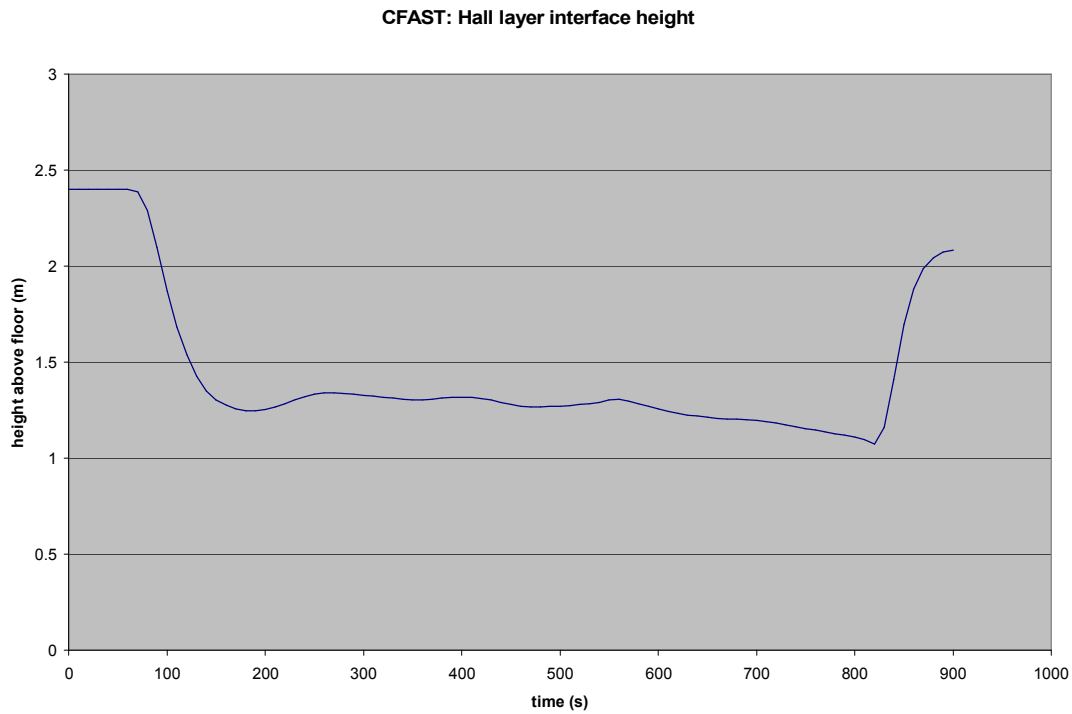


Figure A23. Experimental house, growing TV fire, lounge door open. Comparison of hall layer interface height, calculated by CFAST and CRISP.

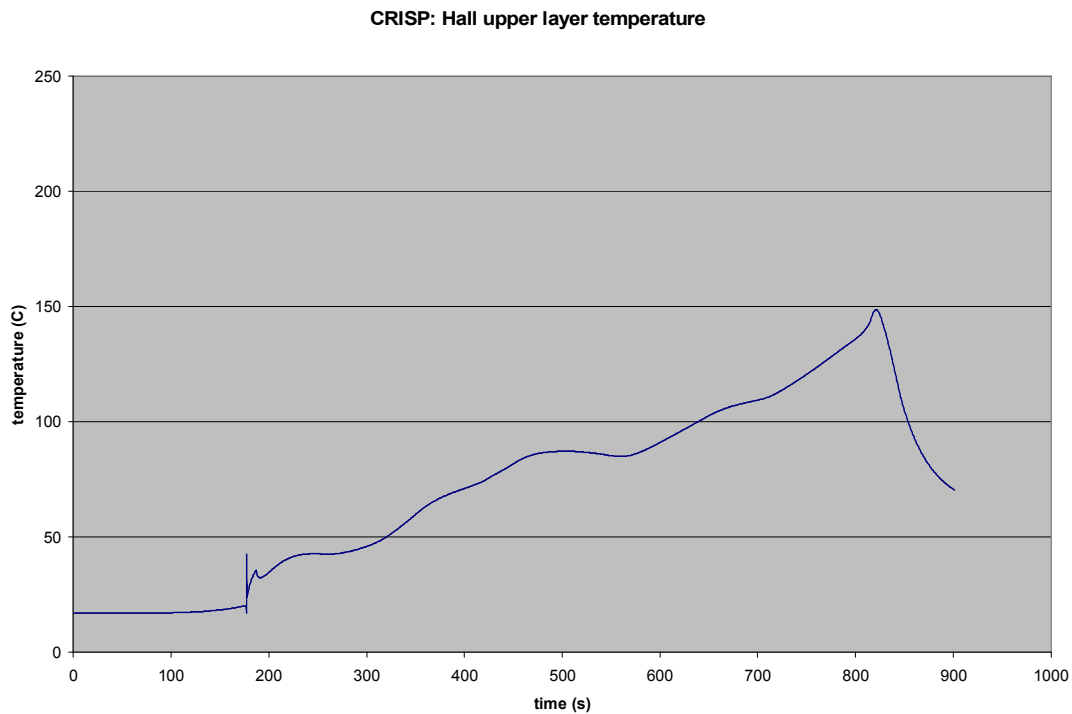
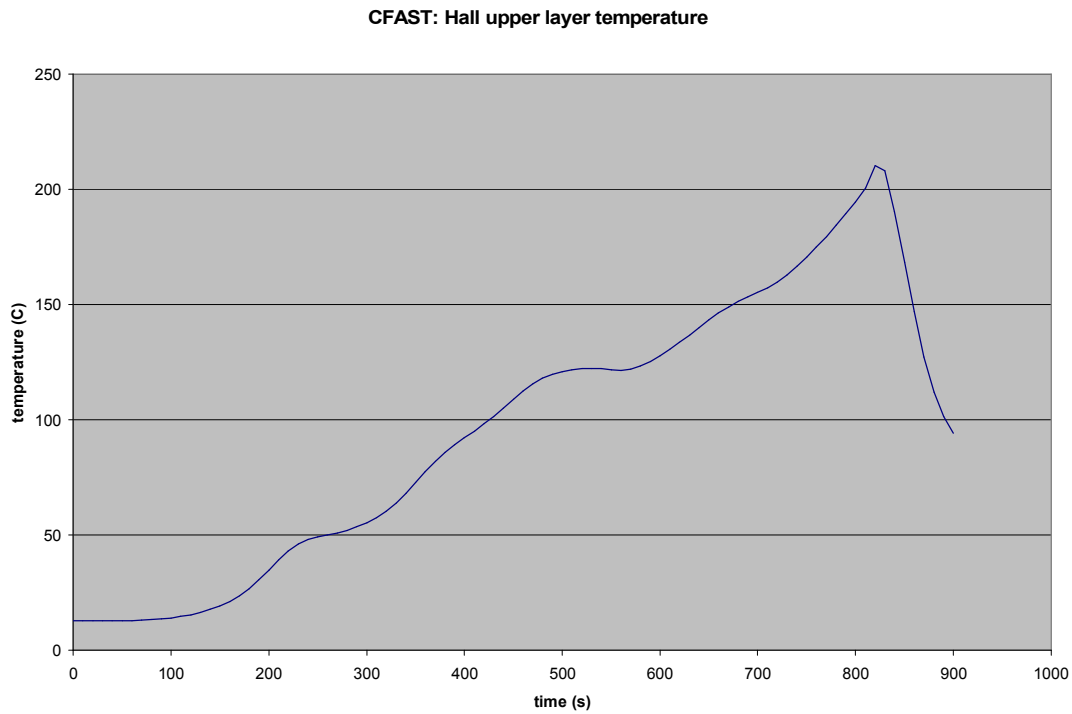


Figure A24. Experimental house, growing TV fire, lounge door open. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.

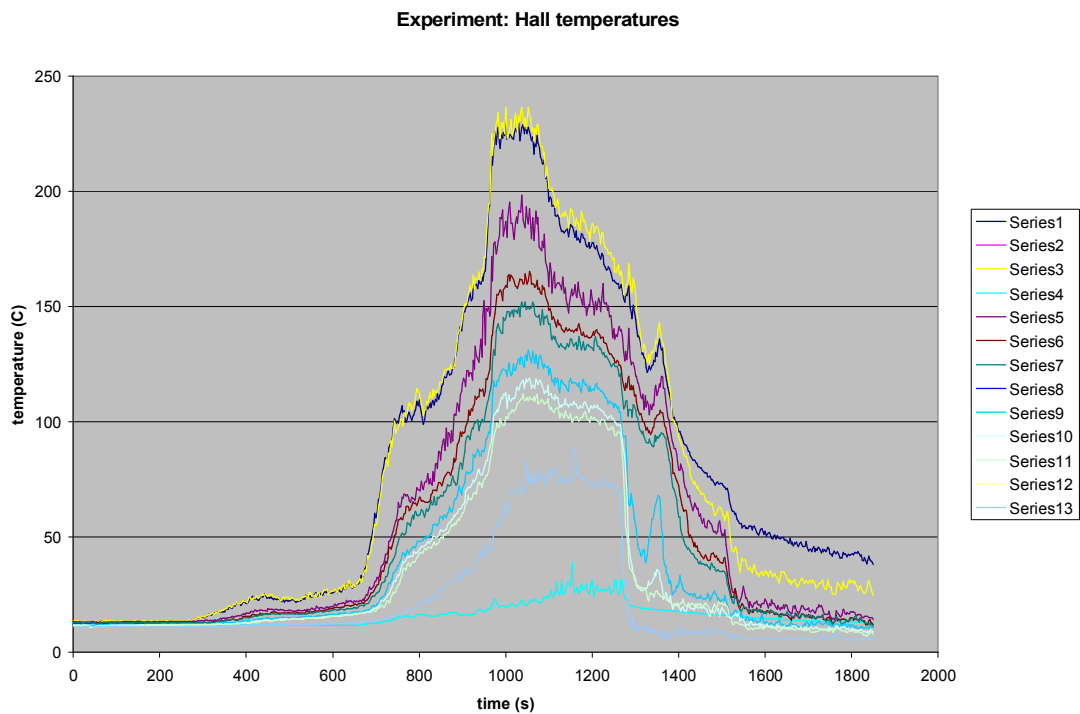


Figure A25. Experimental house, growing TV/room fire, lounge door open. Temperature measurements in the hall (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

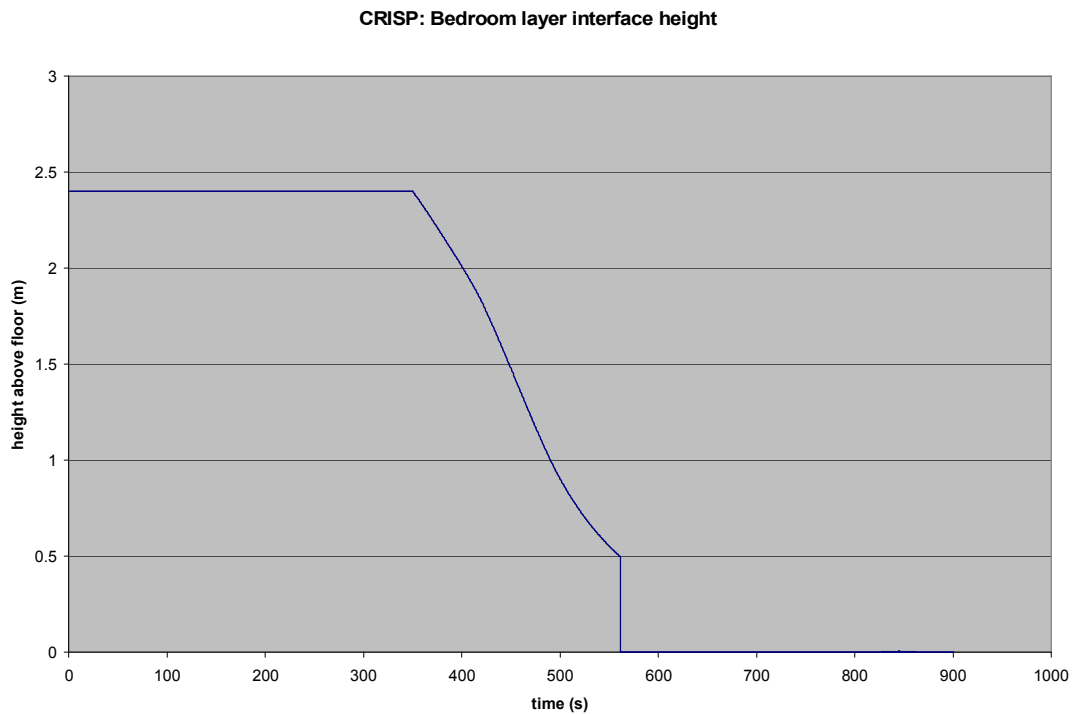
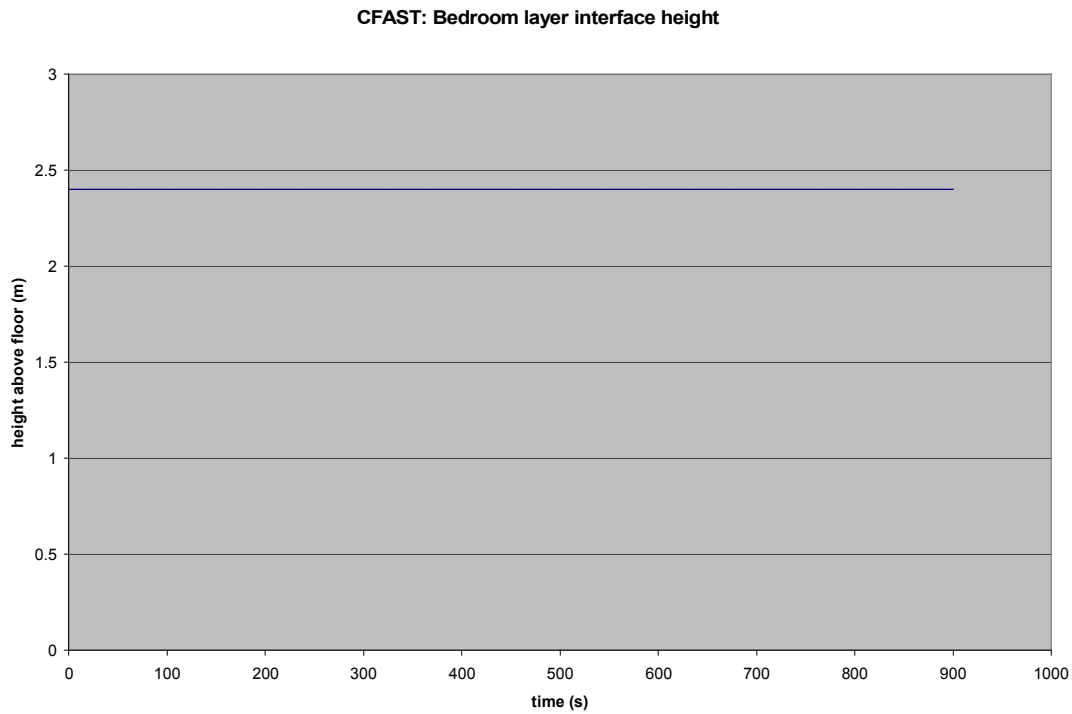


Figure A26. Experimental house, growing TV fire, lounge door open. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.



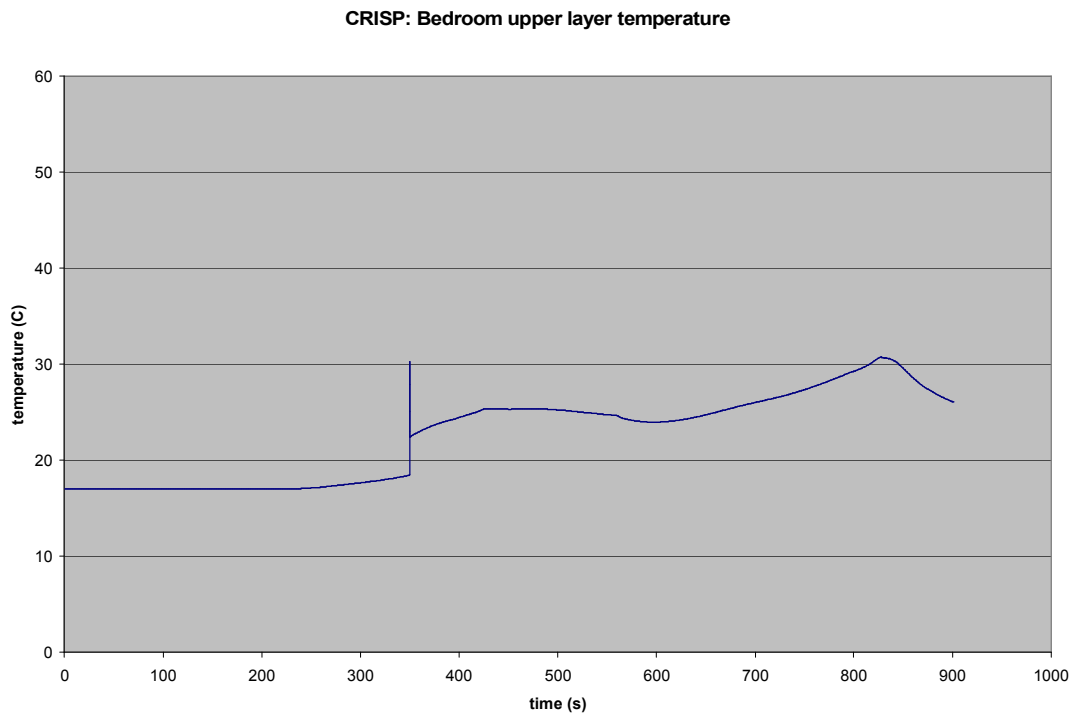
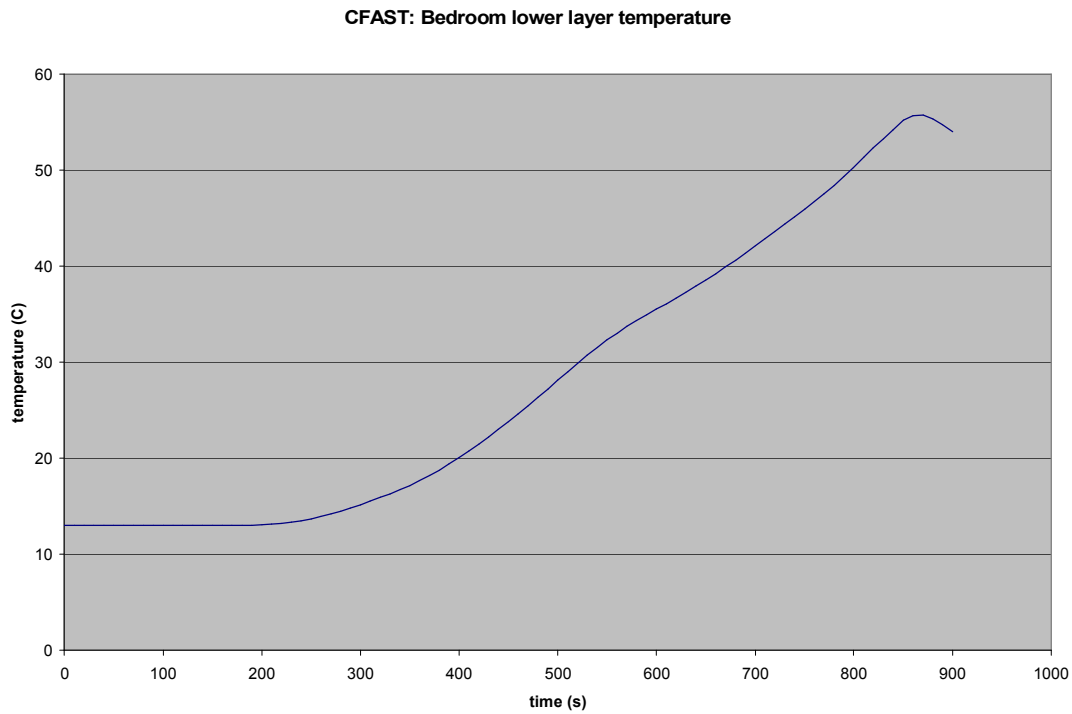


Figure A27. Experimental house, growing TV fire, lounge door open. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP.

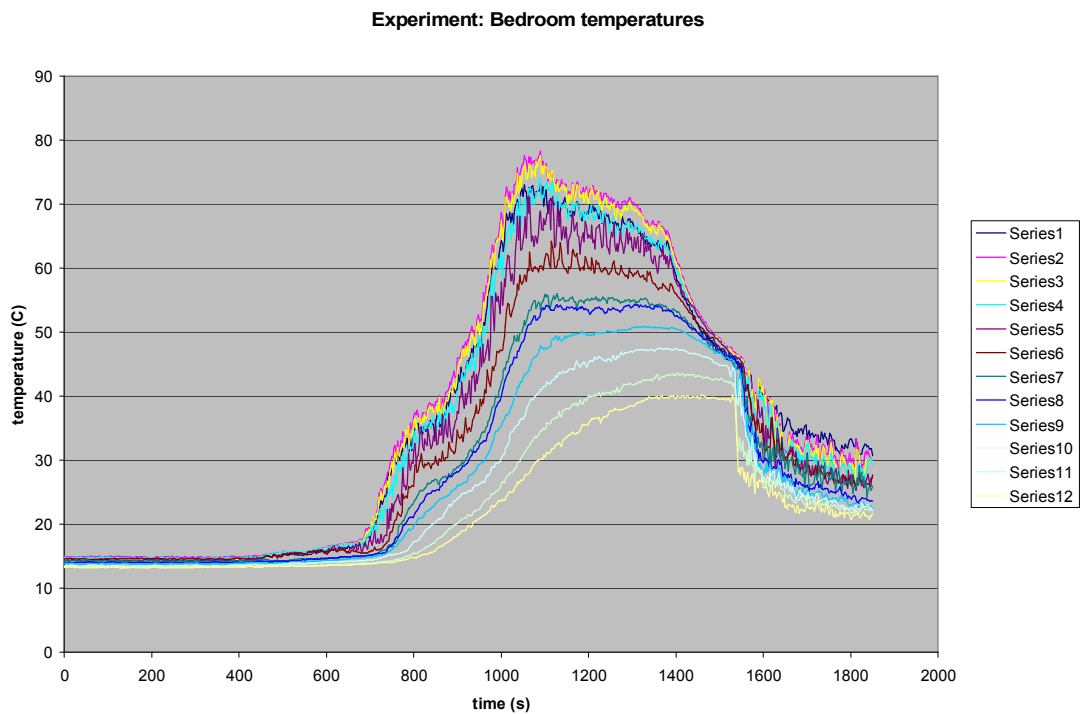


Figure A28. Experimental house, growing TV/room fire, lounge door open. Temperature measurements in the bedroom (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

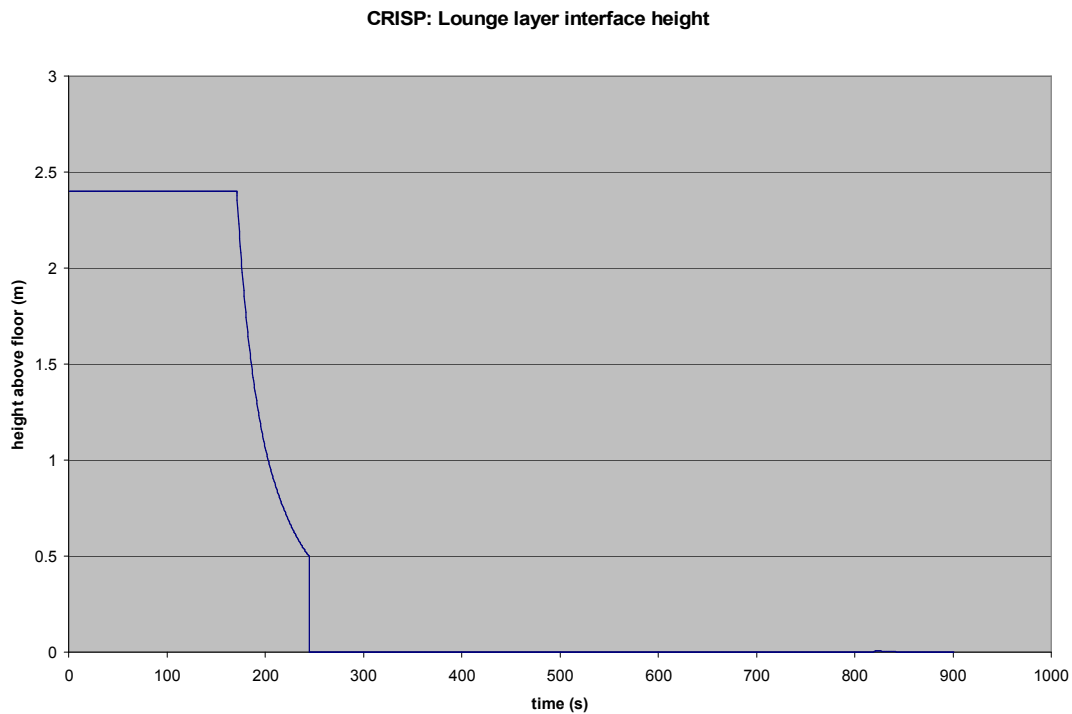
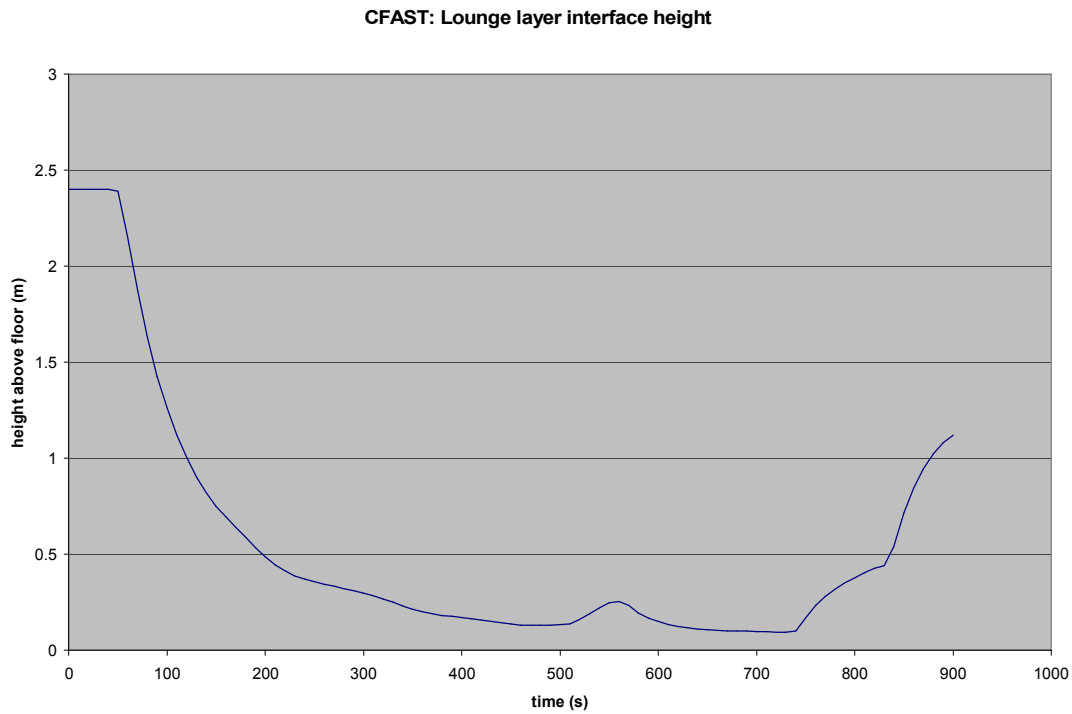


Figure A29. Experimental house, growing TV fire, lounge door shut. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

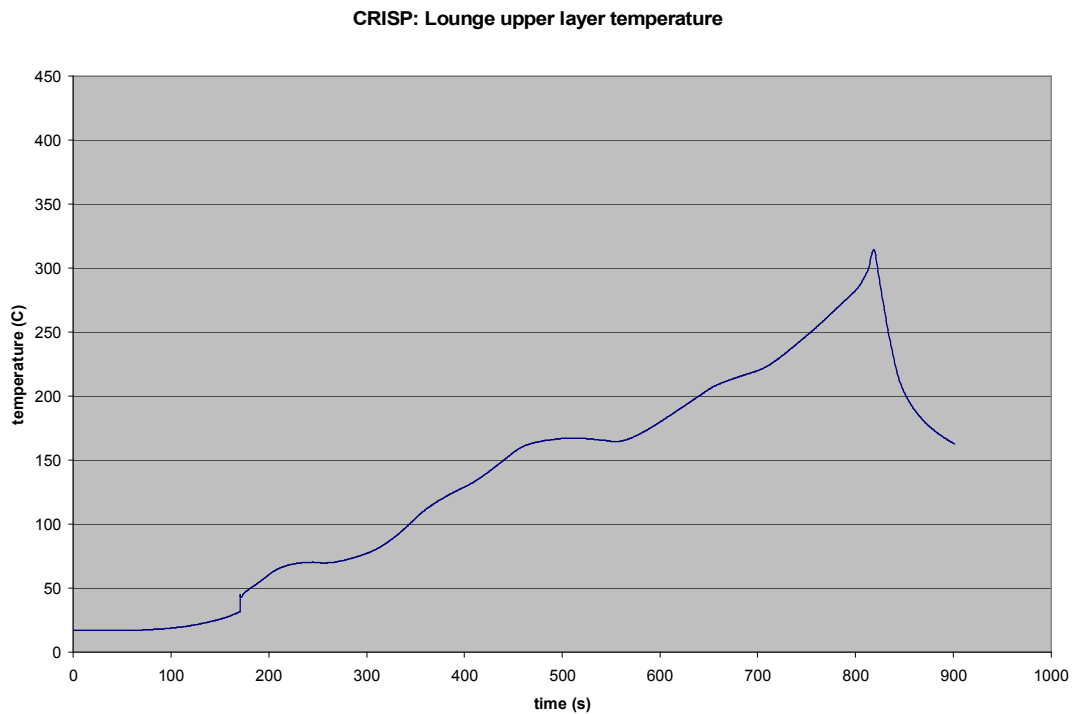
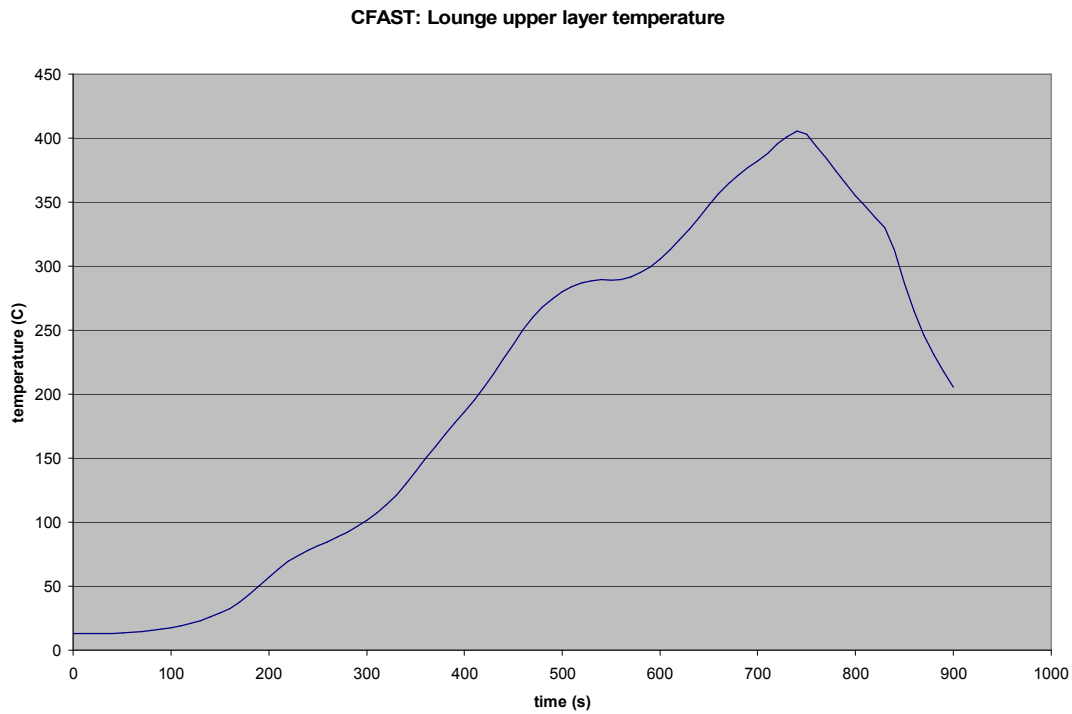


Figure A30. Experimental house, growing TV fire, lounge door shut. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

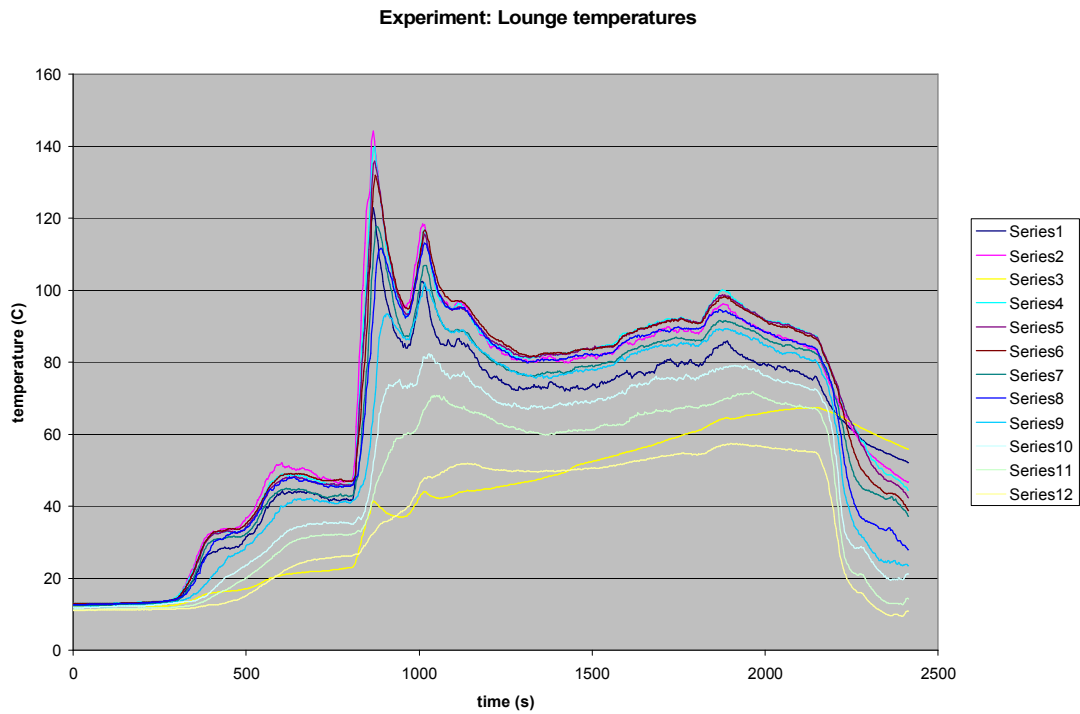


Figure A31. Experimental house, growing TV/room fire, lounge door shut. Temperature measurements in the lounge (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

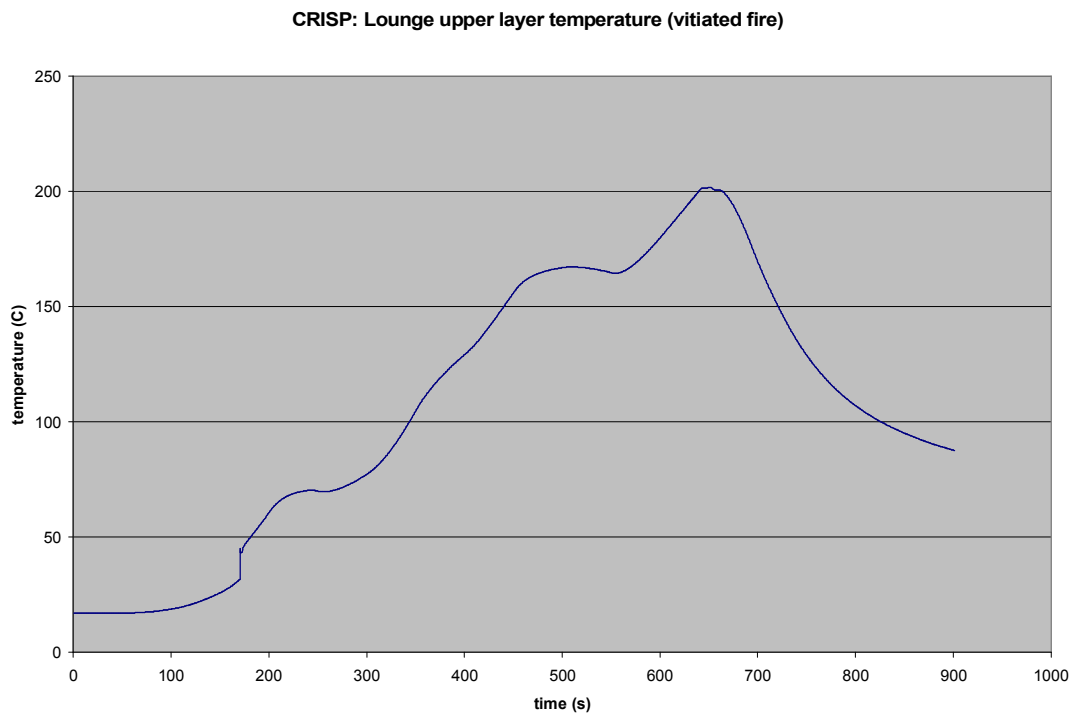


Figure A32. Experimental house, growing TV fire, lounge door shut. For this CRISP simulation, the heat release rate of the fire is not prescribed; rather, it is the pyrolysis rate that is the input data. The heat release rate then depends on the amount of oxygen available. As a consequence, the temperature is reduced, giving better agreement with the experimental fire.

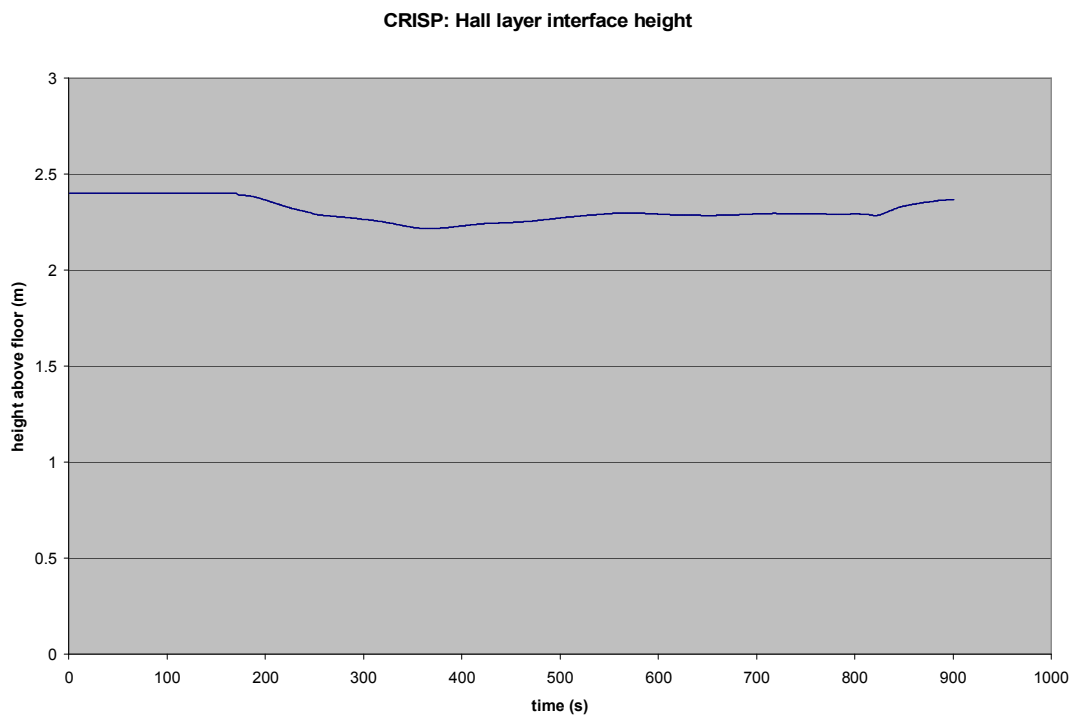
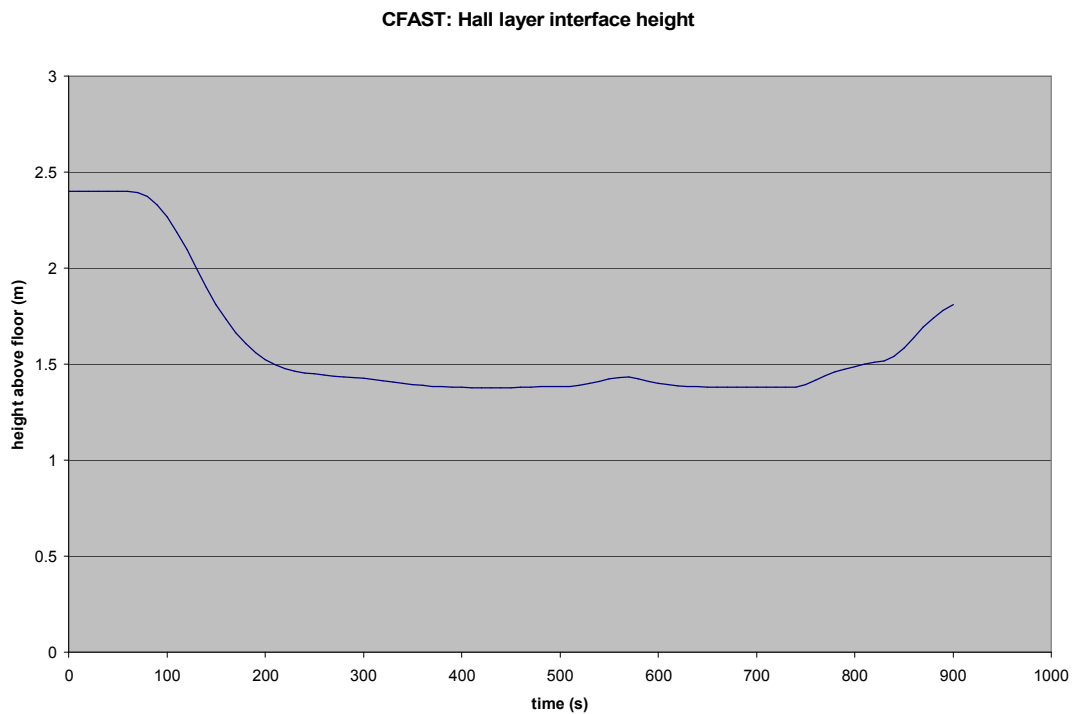


Figure A33. Experimental house, growing TV fire, lounge door shut. Comparison of hall layer interface height, calculated by CFAST and CRISP.

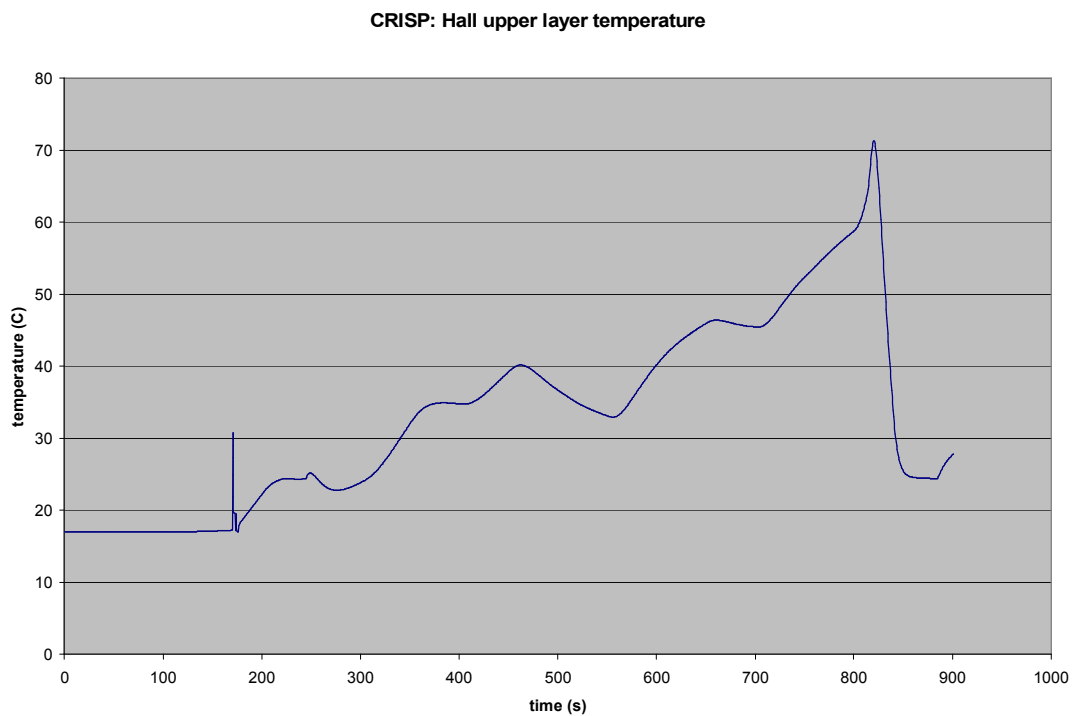
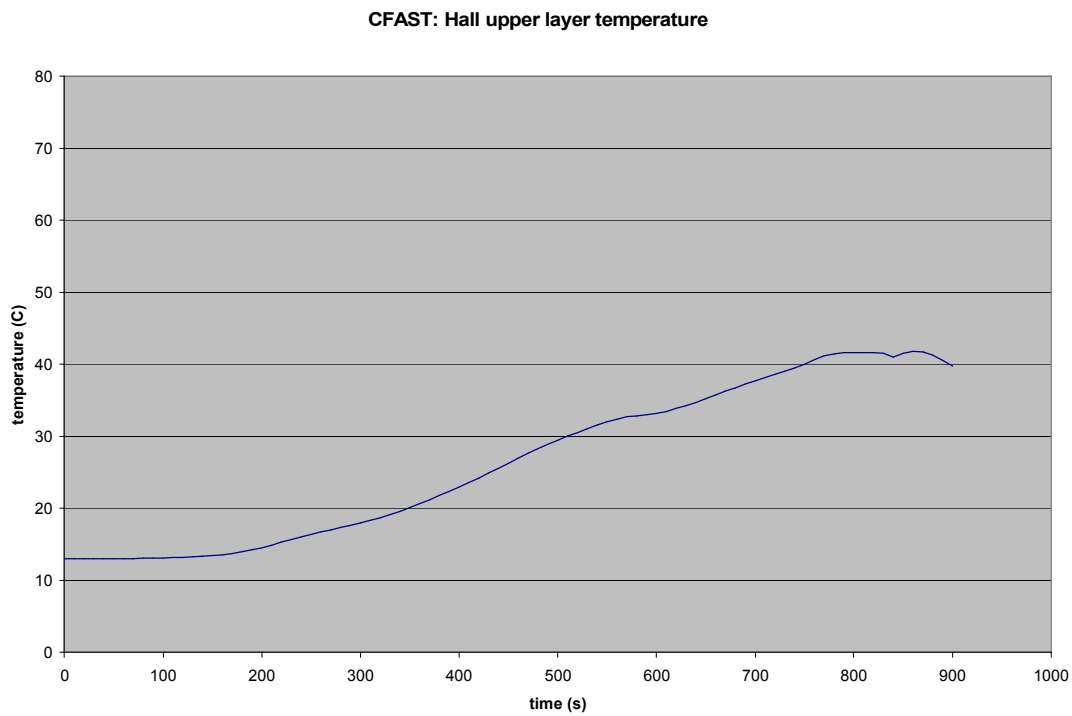


Figure A34. Experimental house, growing TV fire, lounge door shut. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.



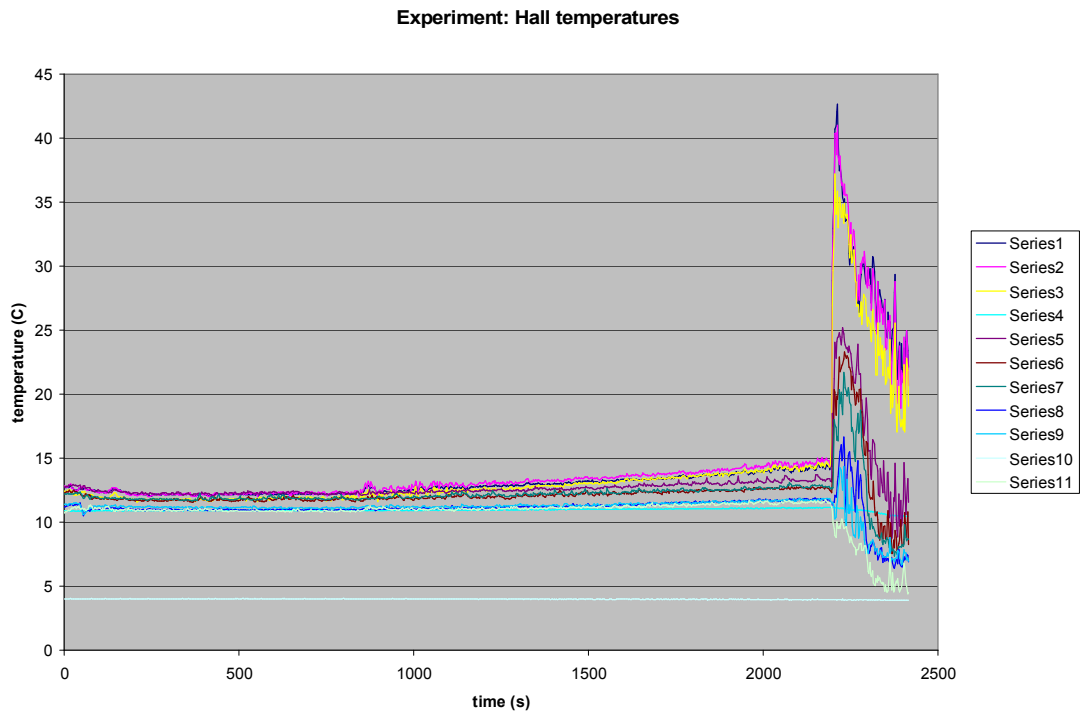


Figure A35. Experimental house, growing TV/room fire, lounge door shut. Temperature measurements in the hall (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

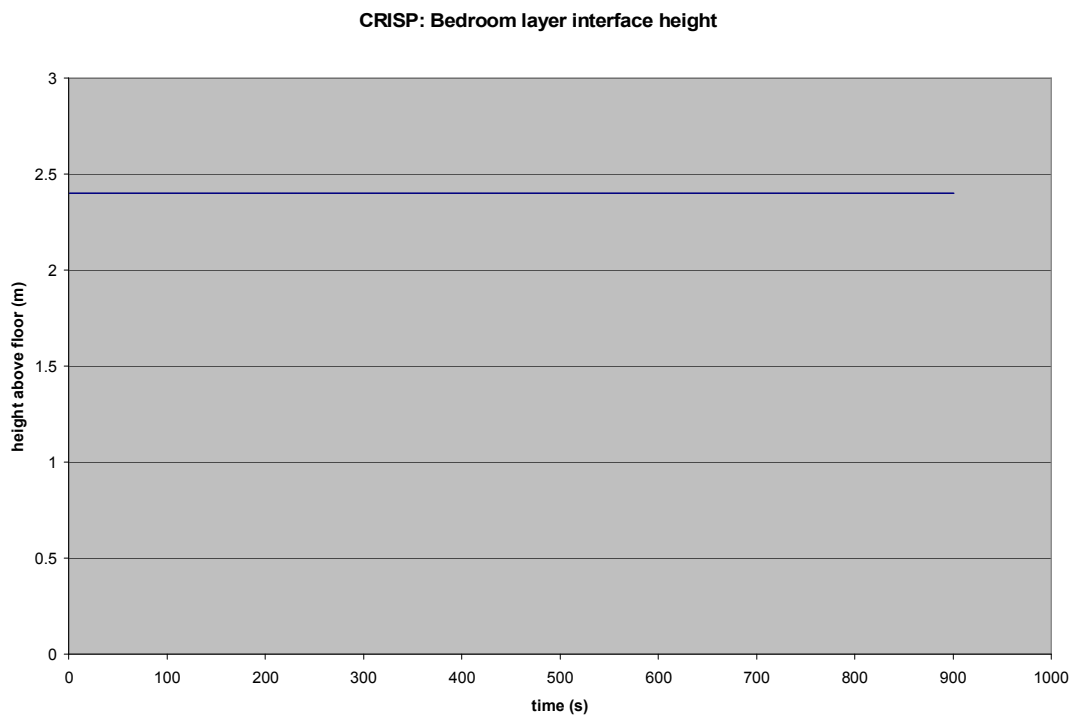
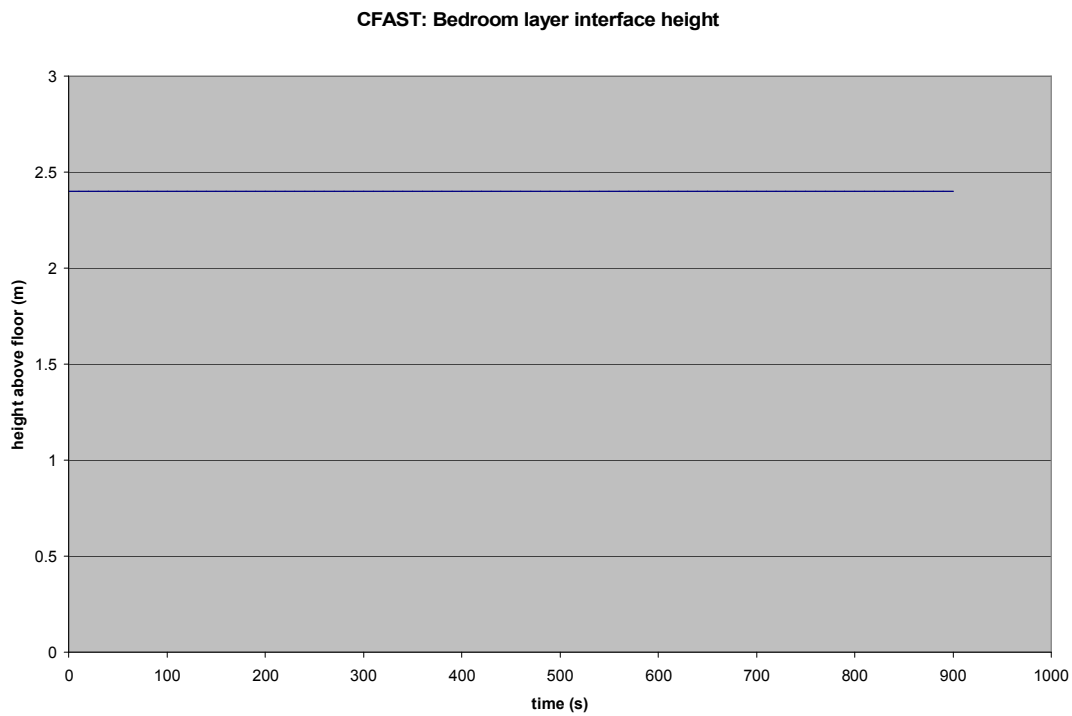


Figure A36. Experimental house, growing TV fire, lounge door shut. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.

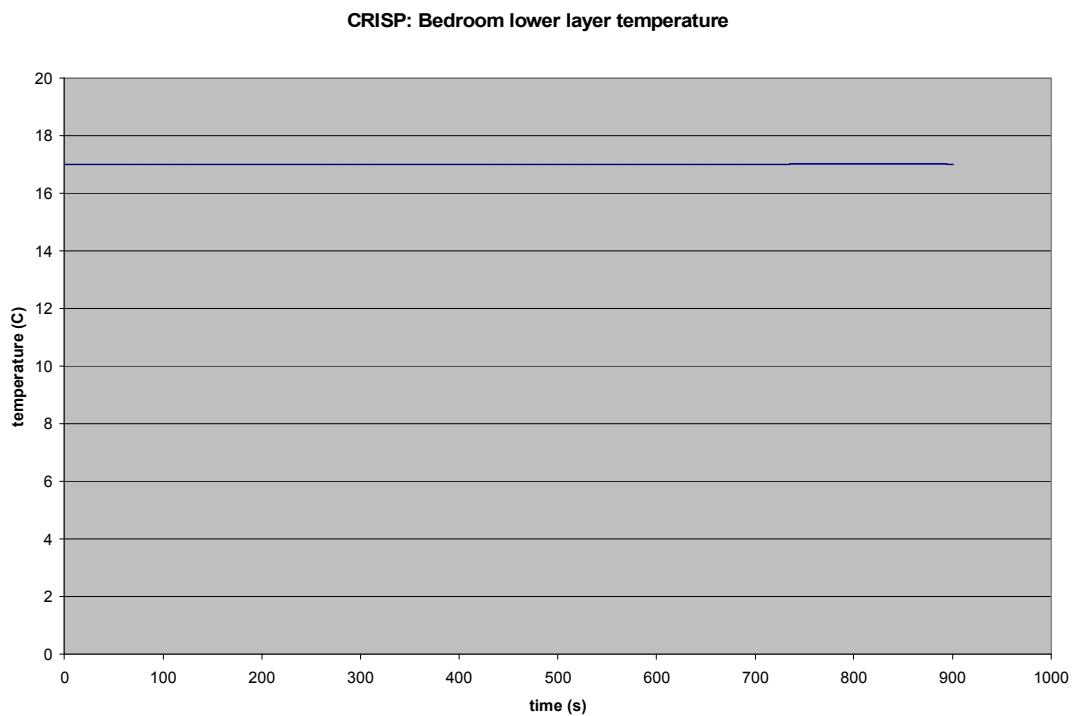
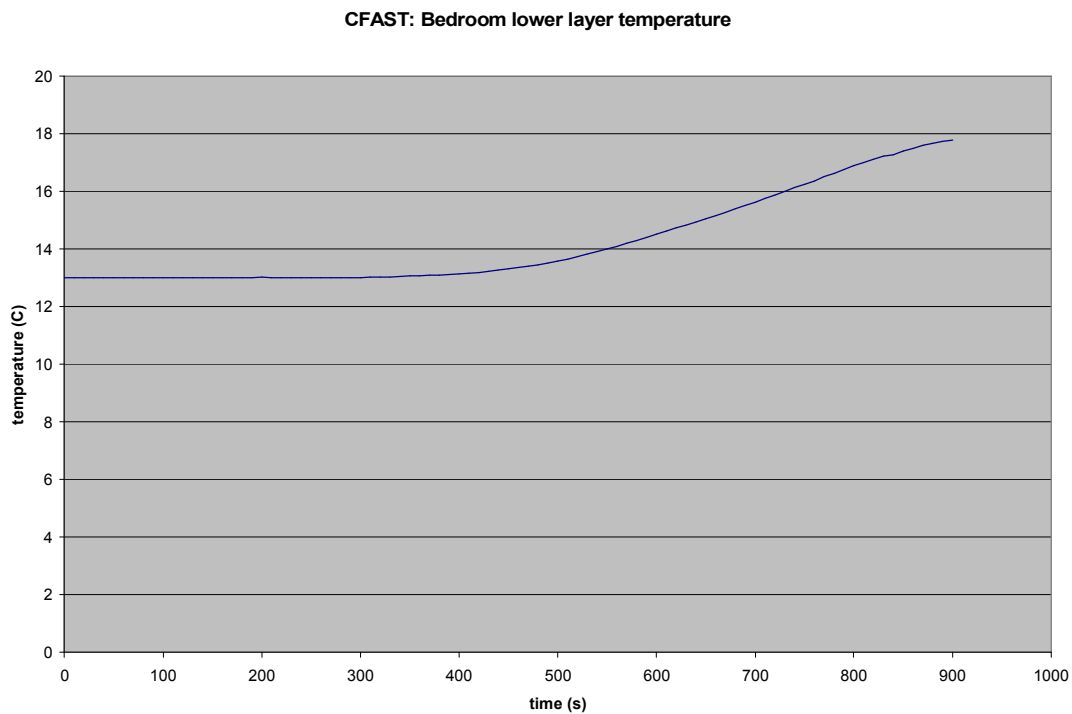


Figure A37. Experimental house, growing TV fire, lounge door shut. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP.

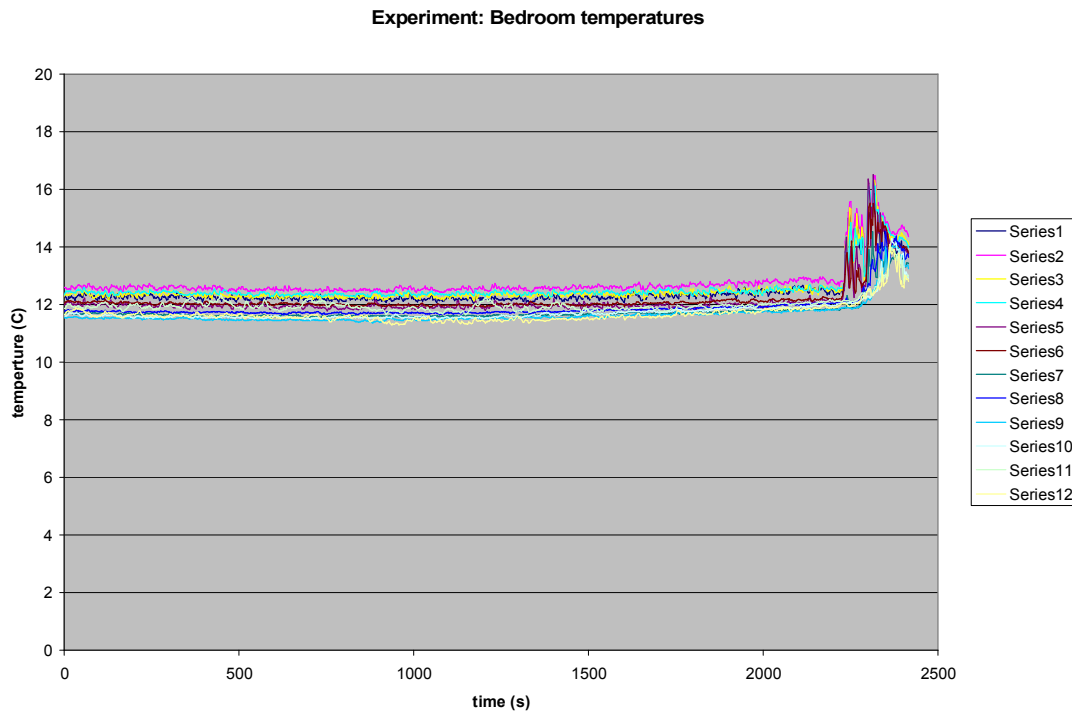


Figure A38. Experimental house, growing TV/room fire, lounge door shut. Temperature measurements in the bedroom (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

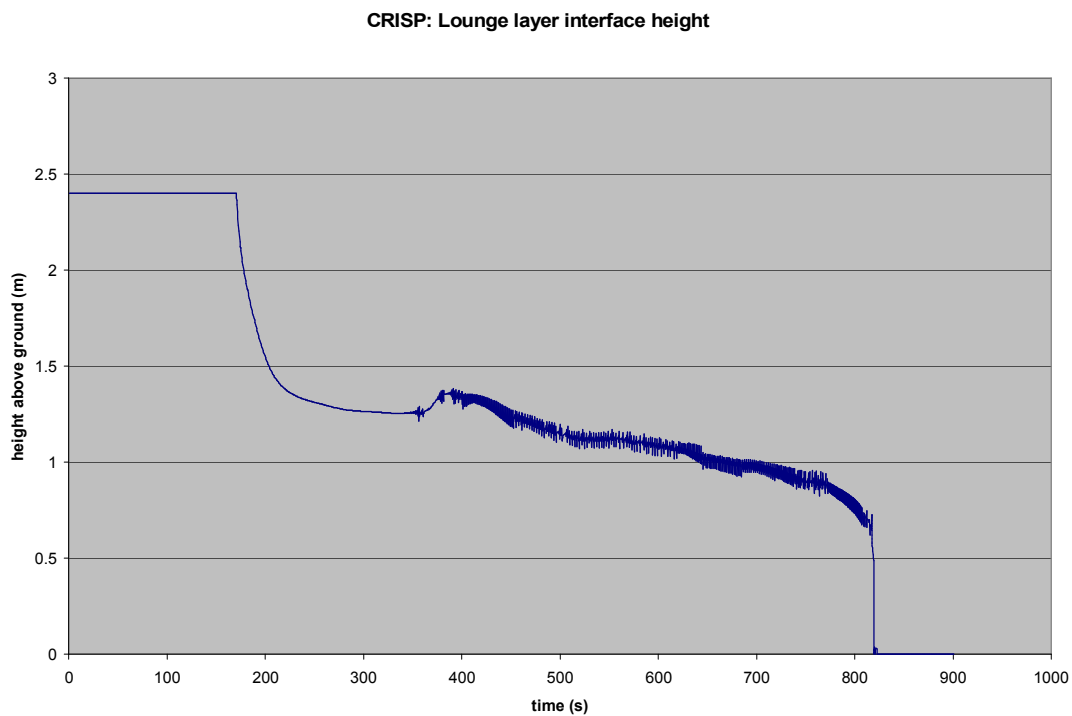
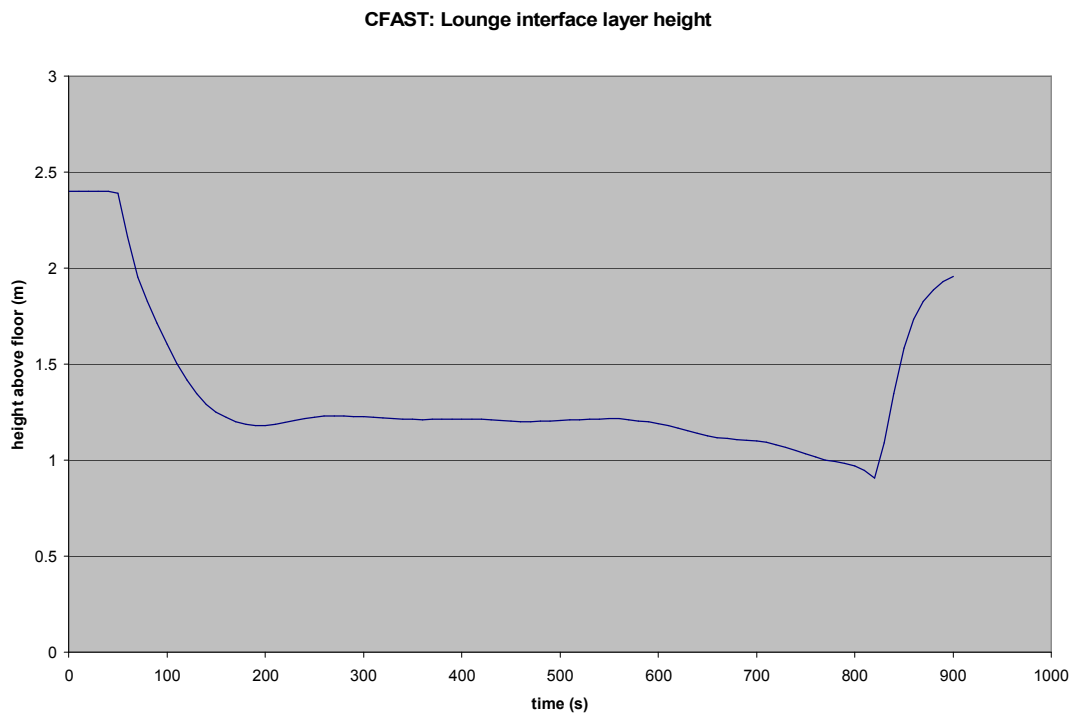


Figure A39. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of lounge layer interface height, calculated by CFAST and CRISP.

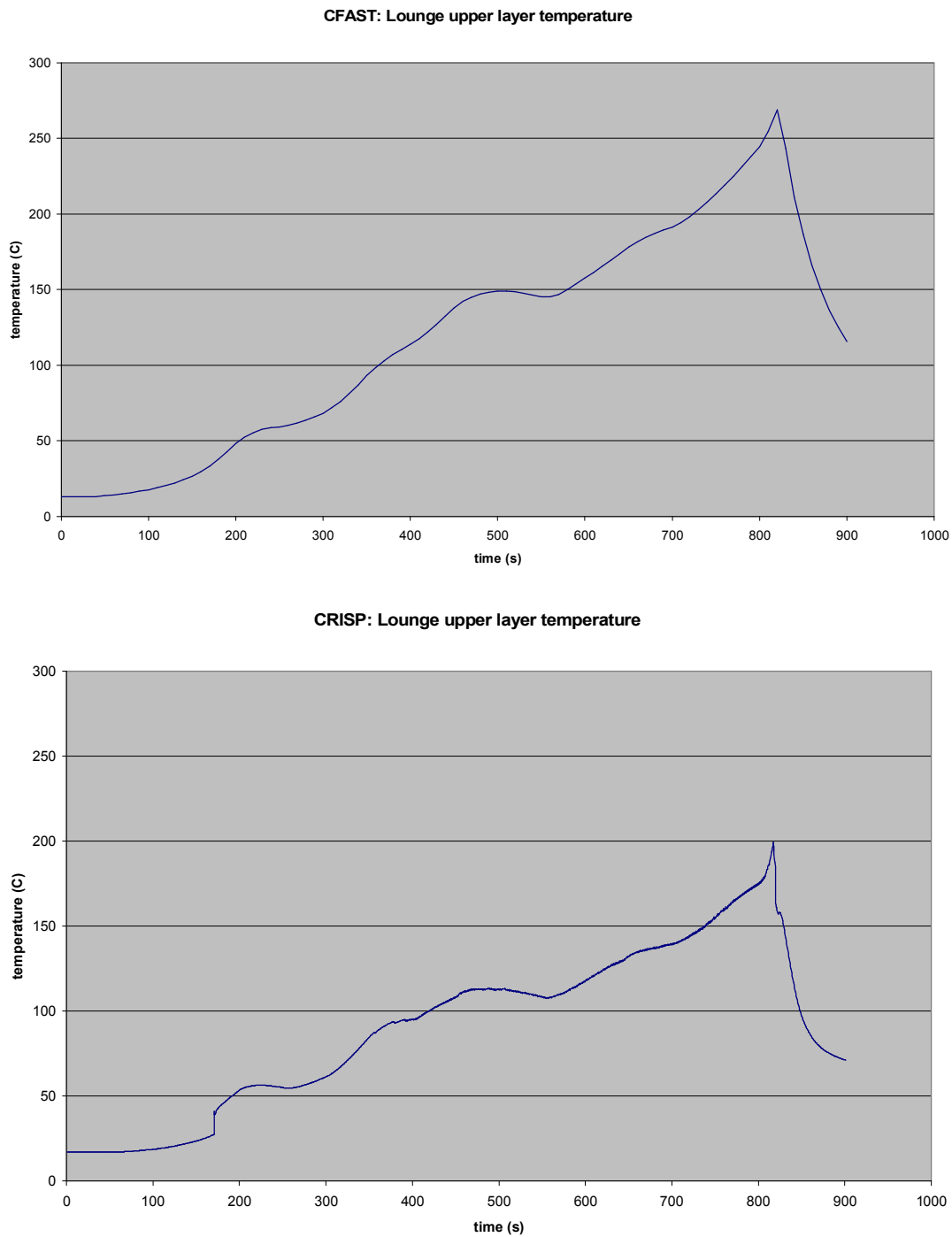


Figure A40. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of lounge upper layer temperature, calculated by CFAST and CRISP.

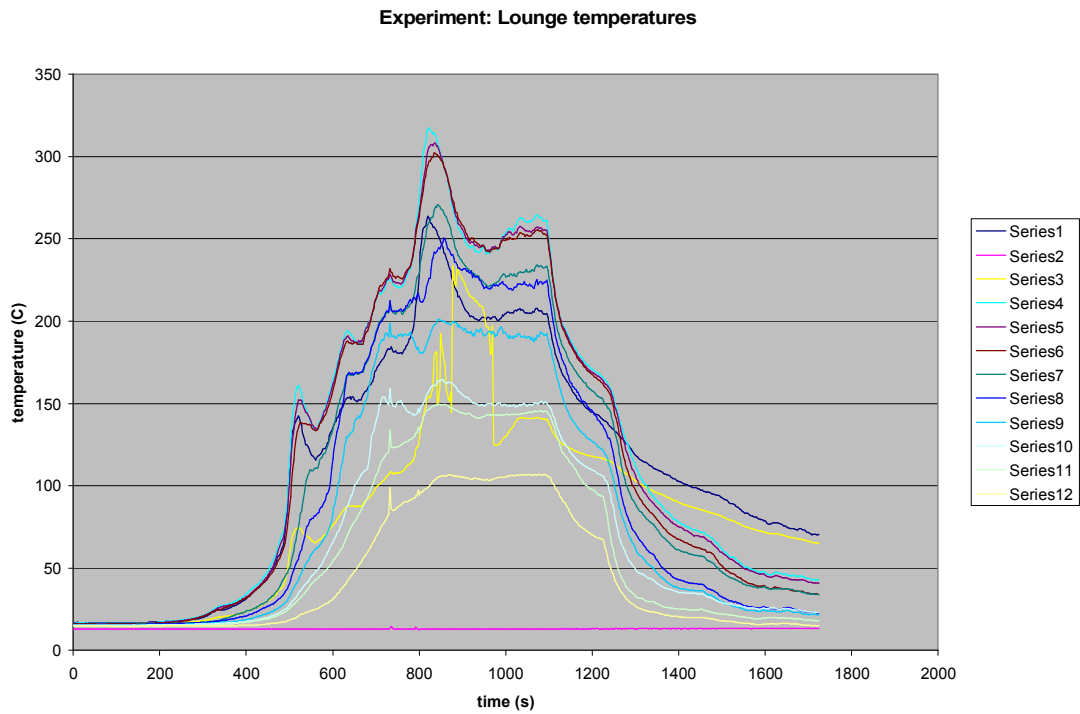


Figure A41. Experimental house, growing TV/room fire, open-plan lounge/hall. Temperature measurements in the lounge (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

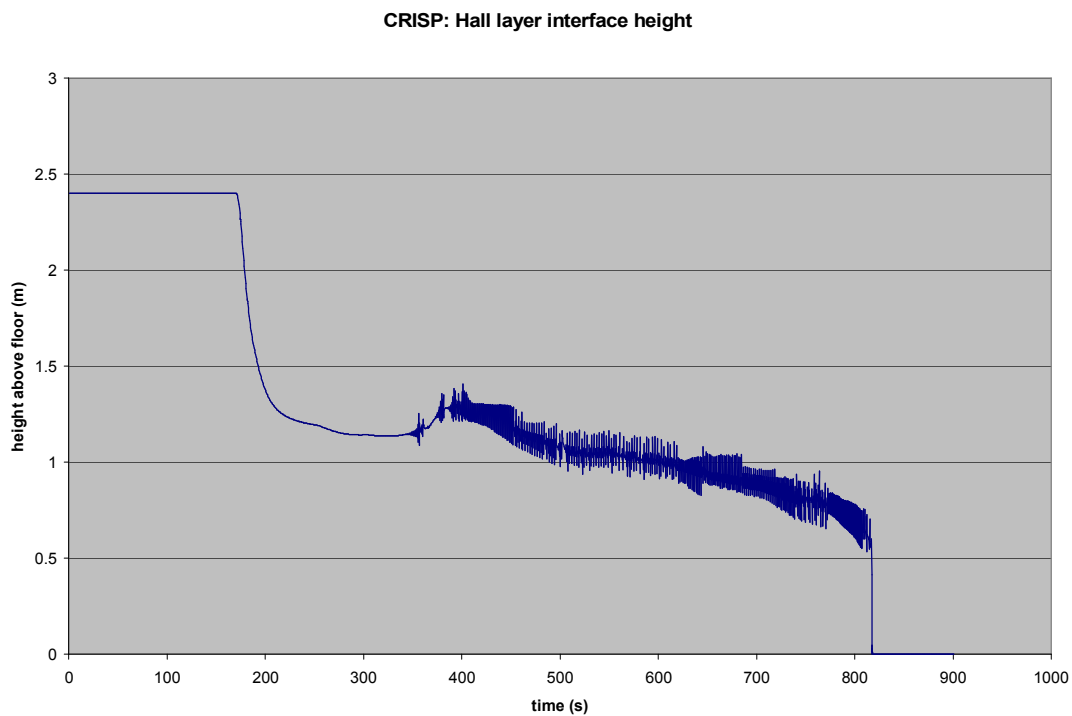
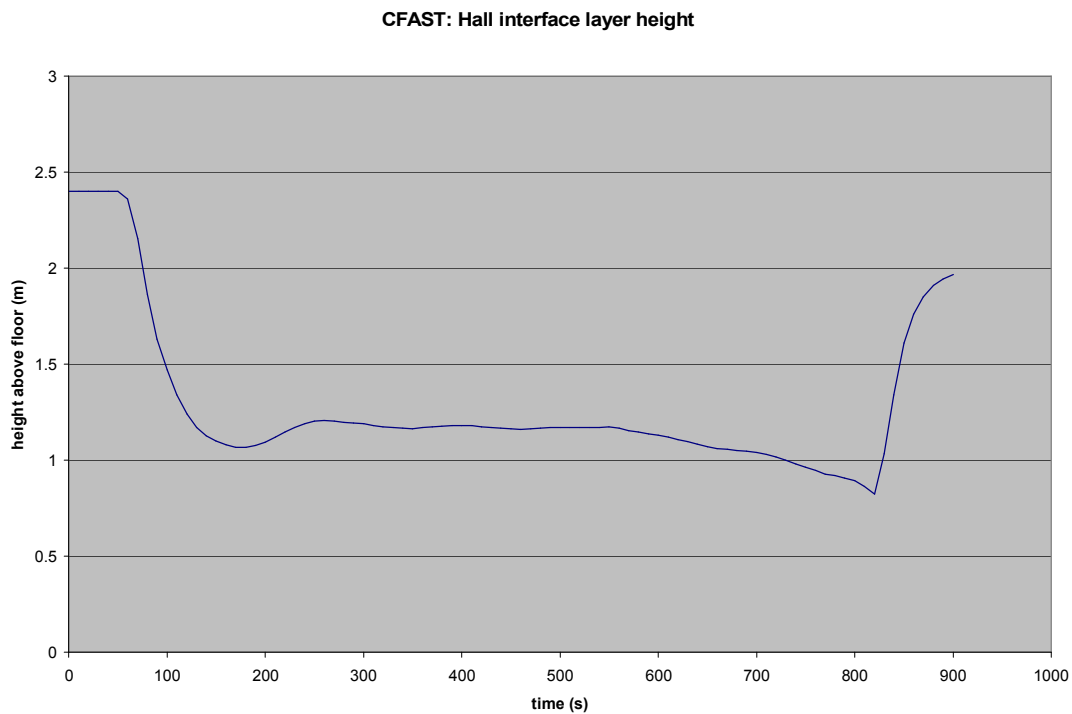


Figure A42. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of hall layer interface height, calculated by CFAST and CRISP.



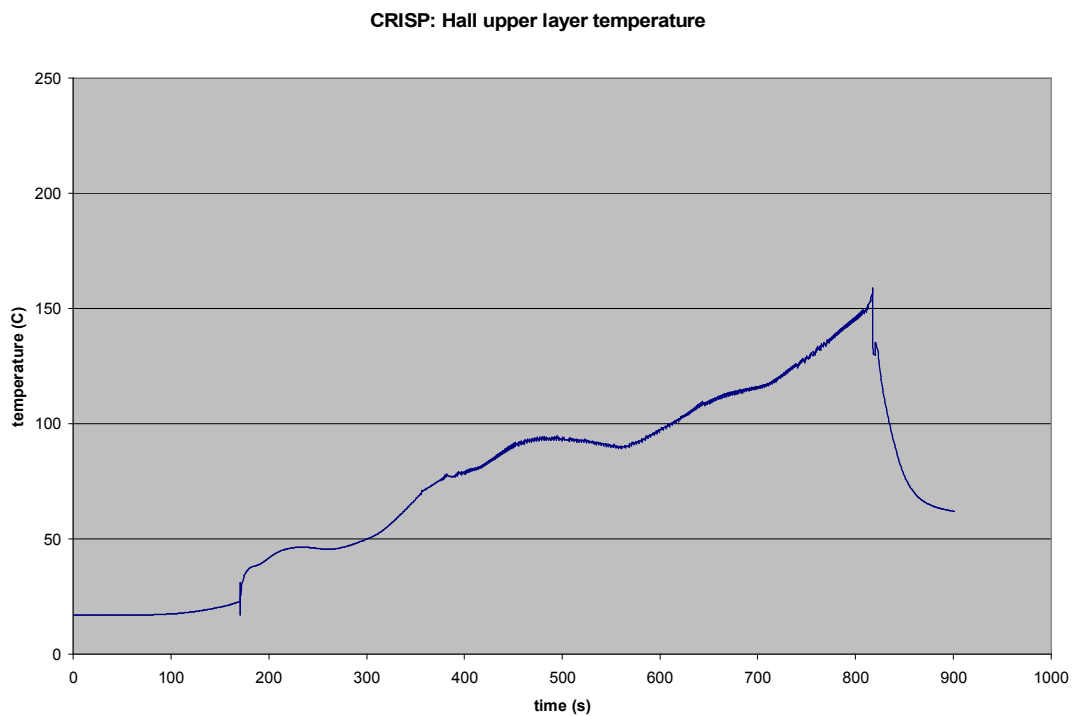
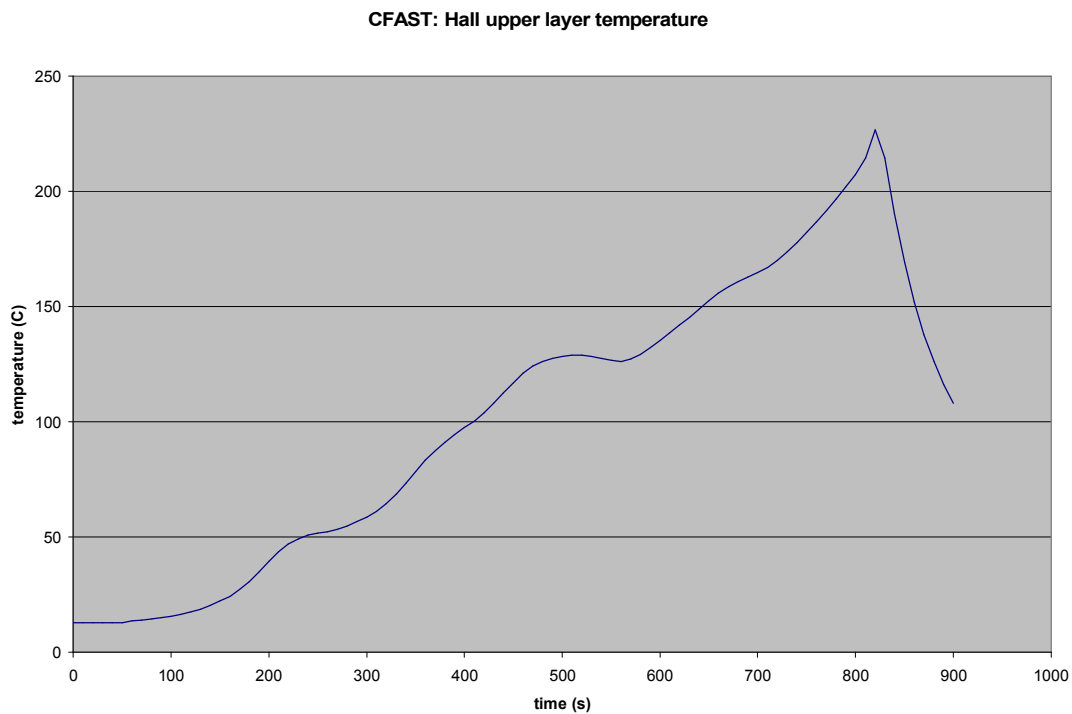


Figure A43. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of hall upper layer temperature, calculated by CFAST and CRISP.

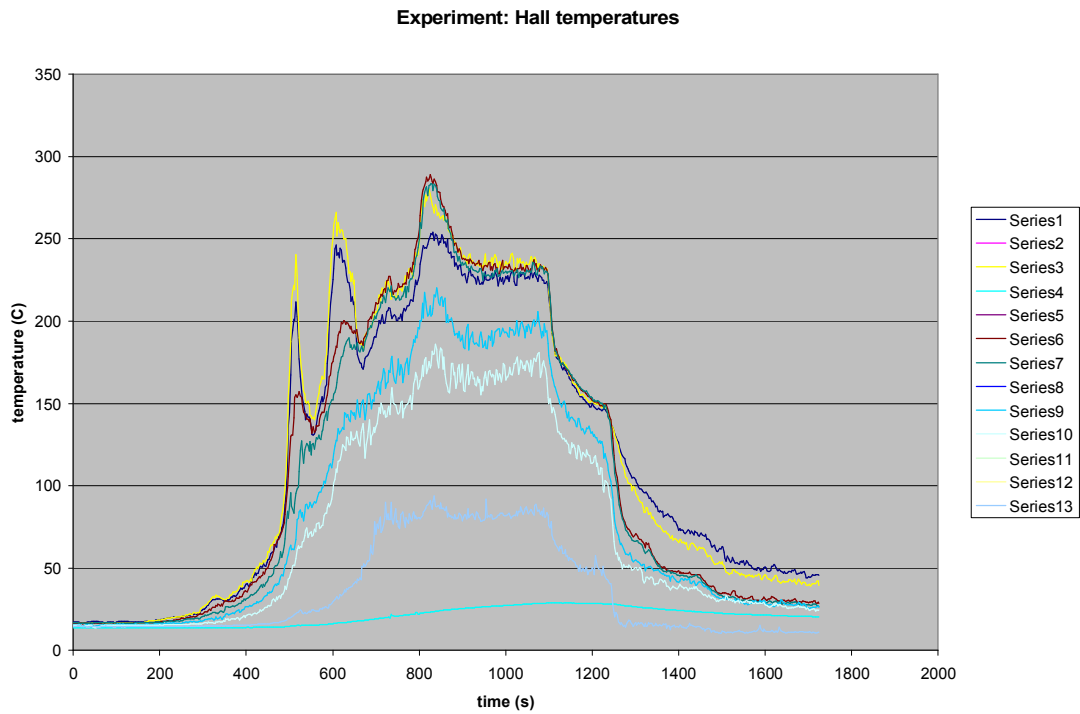


Figure A44. Experimental house, growing TV/room fire, open-plan lounge/hall. Temperature measurements in the hall (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

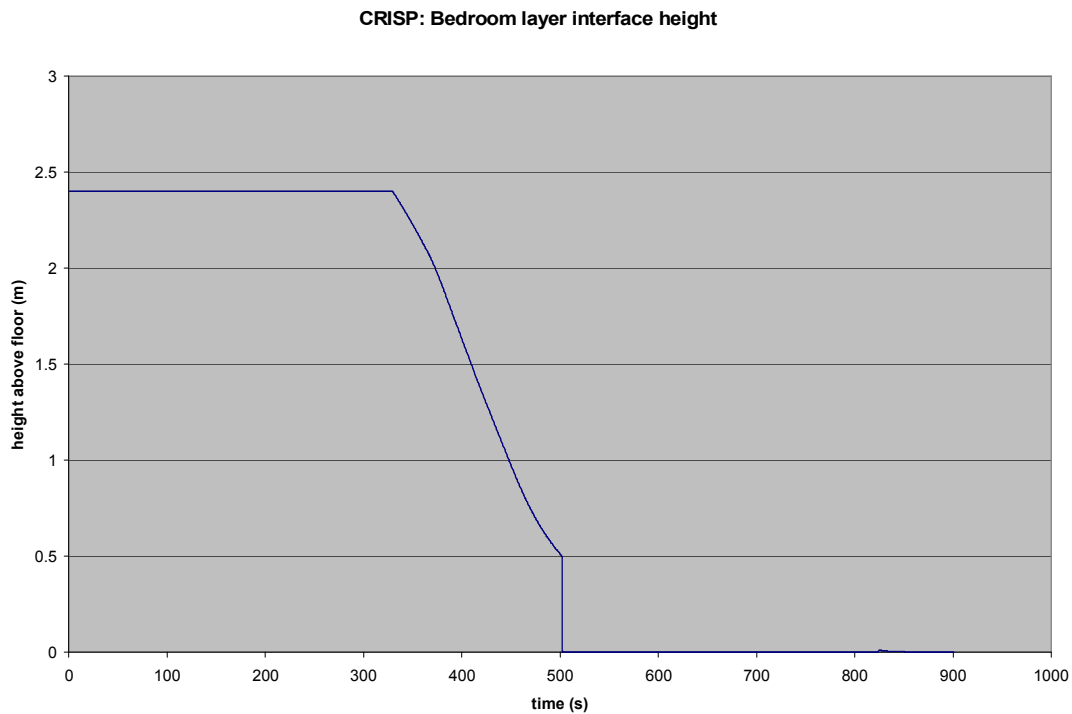
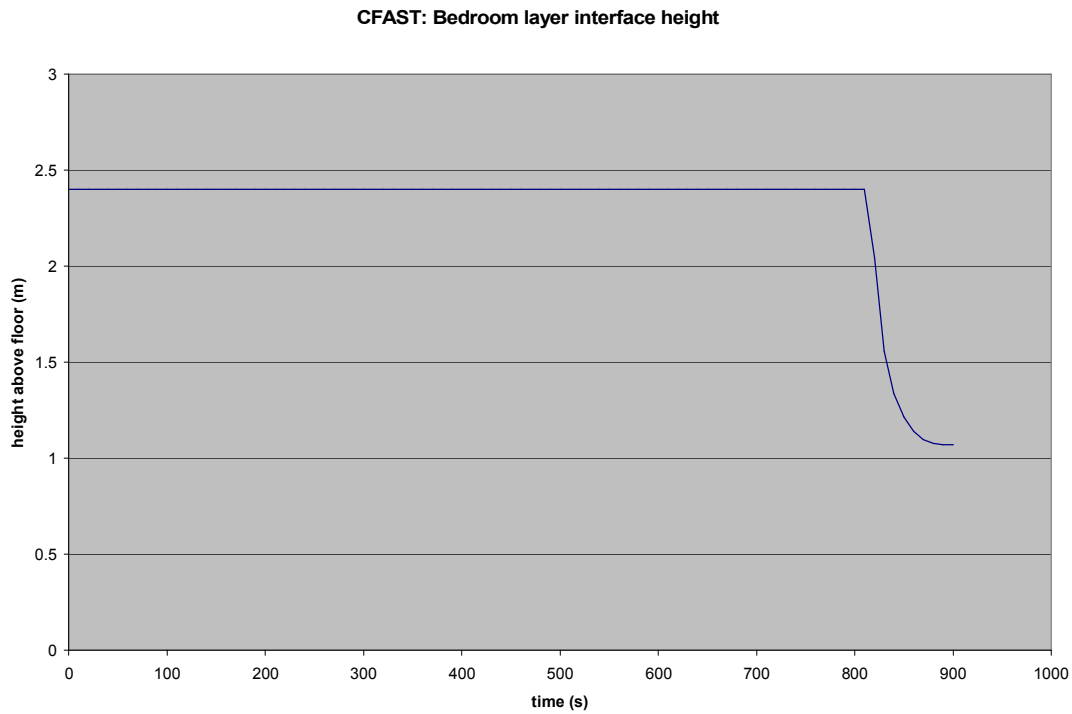


Figure A45. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of bedroom layer interface height, calculated by CFAST and CRISP.

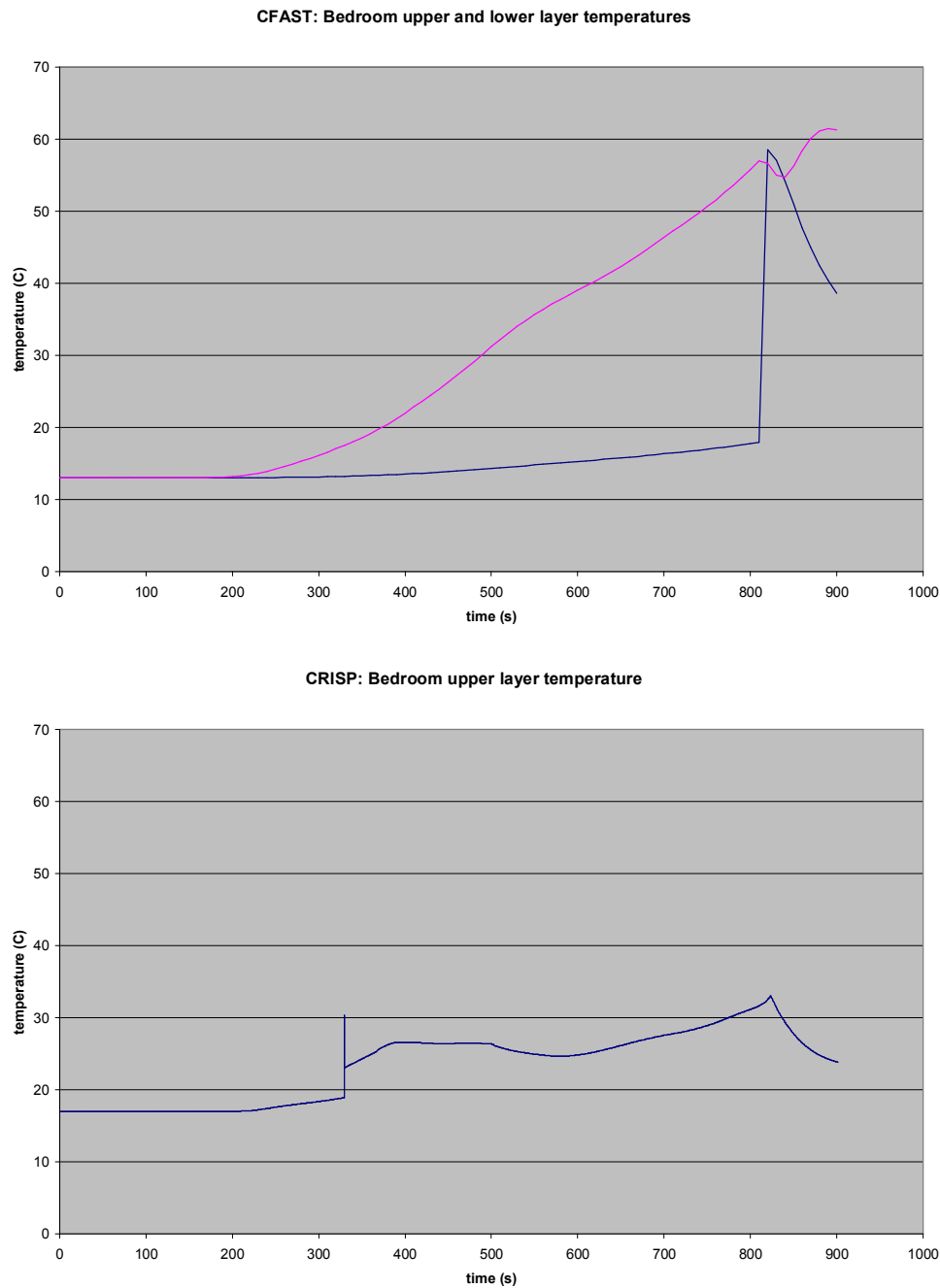


Figure A46. Experimental house, growing TV fire, open-plan lounge/hall. Comparison of bedroom upper layer temperature, calculated by CFAST and CRISP. The top graph also shows the lower layer temperature calculated by CFAST, which may be a more appropriate quantity, given that the upper layer does not really exist in CFAST until 800 seconds after ignition.

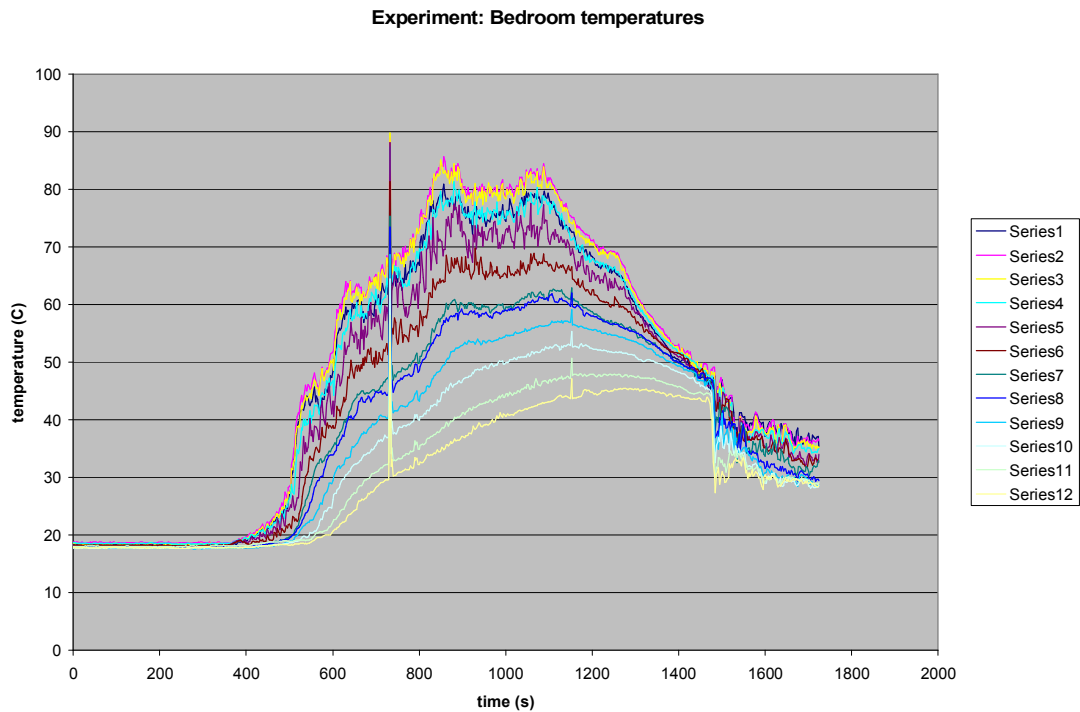


Figure A47. Experimental house, growing TV/room fire, open-plan lounge/hall. Temperature measurements in the bedroom (series 1 is at the top of the thermocouple tree, series 12 at the bottom)

## Appendix B – Cost-Benefit Calculations

Cost-Benefit calculations have been performed for the following strategies:

- Upgrading an “average dwelling” from no alarms, to alarms in hall and landing
- Upgrading an “average dwelling” with alarms in hall and landing, to include extra alarm(s) in:
  - Lounge
  - Bedroom
  - Kitchen
  - Lounge + Bedroom
  - Kitchen + Lounge
  - Kitchen + Bedroom
  - Kitchen + Lounge + Bedroom

The conclusion from the calculations is that including alarms, where none were present before, has a good chance of being cost-effective (probability = 84%), but that further upgrades involving additional alarms are not cost-effective (probability < 4%).

**PROPERTY TYPE: Dwelling, no alarms**  
(upgrading to AD "B" standard)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£58	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.58
Annual Cost of Loan	£6.97		
Installation charge (per dwelling)	£50	£25	£1.07
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.08
Annual Cost of Loan	£2.13		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£9.11</b>		
<b>Deaths</b> per Million Dwellings	17	1	£0.40
Alarm Effectiveness Factor	0.49	0.03	£0.67
Deaths saved per Million Dwellings	8		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.55
Monetary Benefit per Single Dwelling	£11.01		
<b>Total Monetary Benefit per Dwelling</b>	<b>£11.01</b>		
<b>Benefit - Cost difference</b>	<b>£1.90</b>	<b>+/-</b>	<b>£1.94</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>84%</b>		

**PROPERTY TYPE: Dwelling, with alarms**  
(adding alarm in lounge)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£29	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.29
Annual Cost of Loan	£3.49		
Installation charge (per dwelling)	£25	£13	£0.53
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.04
Annual Cost of Loan	£1.07		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£4.55</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.14
Alarm Effectiveness Factor	0.17	0.04	£0.46
Deaths saved per Million Dwellings	1		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.10
Monetary Benefit per Single Dwelling	£1.97		
<b>Total Monetary Benefit per Dwelling</b>	<b>£1.97</b>		
<b>Benefit - Cost difference</b>	<b>-£2.59</b>	<b>+/-</b>	<b>£1.41</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>3%</b>		



**PROPERTY TYPE: Dwelling, with alarms**  
(adding alarm in bedroom)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£29	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.29
Annual Cost of Loan	£3.49		
Installation charge (per dwelling)	£25	£13	£0.53
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.04
Annual Cost of Loan	£1.07		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£4.55</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.15
Alarm Effectiveness Factor	0.18	0.04	£0.46
Deaths saved per Million Dwellings	2		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.10
Monetary Benefit per Single Dwelling	£2.08		
<b>Total Monetary Benefit per Dwelling</b>	<b>£2.08</b>		
<b>Benefit - Cost difference</b>	<b>-£2.47</b>	<b>+/-</b>	<b>£1.41</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>4%</b>		

**PROPERTY TYPE: Dwelling, with alarms**  
(adding alarm in kitchen)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£39	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.39
Annual Cost of Loan	£4.69		
Installation charge (per dwelling)	£25	£13	£0.53
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.04
Annual Cost of Loan	£1.07		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£5.76</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.04
Alarm Effectiveness Factor	0.05	0.02	£0.23
Deaths saved per Million Dwellings	0		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.03
Monetary Benefit per Single Dwelling	£0.58		
<b>Total Monetary Benefit per Dwelling</b>	<b>£0.58</b>		
<b>Benefit - Cost difference</b>	<b>-£5.18</b>	<b>+/-</b>	<b>£1.37</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>0%</b>		

**PROPERTY TYPE: Dwelling, with alarms**

(adding alarms in lounge &amp; bedroom)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£58	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.58
Annual Cost of Loan	£6.97		
Installation charge (per dwelling)	£50	£25	£1.07
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.08
Annual Cost of Loan	£2.13		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£9.11</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.27
Alarm Effectiveness Factor	0.34	0.06	£0.65
Deaths saved per Million Dwellings	3		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.20
Monetary Benefit per Single Dwelling	£3.93		
<b>Total Monetary Benefit per Dwelling</b>	<b>£3.93</b>		
<b>Benefit - Cost difference</b>	<b>-£5.17</b>	<b>+/-</b>	<b>£1.84</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>0%</b>		

**PROPERTY TYPE: Dwelling, with alarms**

(adding alarms in kitchen &amp; lounge)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£68	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.69
Annual Cost of Loan	£8.18		
Installation charge (per dwelling)	£50	£25	£1.07
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.08
Annual Cost of Loan	£2.13		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£10.31</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.19
Alarm Effectiveness Factor	0.23	0.05	£0.58
Deaths saved per Million Dwellings	2		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.13
Monetary Benefit per Single Dwelling	£2.66		
<b>Total Monetary Benefit per Dwelling</b>	<b>£2.66</b>		
<b>Benefit - Cost difference</b>	<b>-£7.65</b>	<b>+/-</b>	<b>£1.84</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>0%</b>		

**PROPERTY TYPE: Dwelling, with alarms**

(adding alarms in kitchen &amp; bedroom)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£68	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.69
Annual Cost of Loan	£8.18		
Installation charge (per dwelling)	£50	£25	£1.07
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.08
Annual Cost of Loan	£2.13		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£10.31</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.19
Alarm Effectiveness Factor	0.24	0.05	£0.58
Deaths saved per Million Dwellings	2		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.14
Monetary Benefit per Single Dwelling	£2.78		
<b>Total Monetary Benefit per Dwelling</b>	<b>£2.78</b>		
<b>Benefit - Cost difference</b>	<b>-£7.53</b>	<b>+/-</b>	<b>£1.84</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>0%</b>		

**PROPERTY TYPE: Dwelling, with alarms**

(adding alarms in kitchen, lounge &amp; bedroom)

	average	uncertainty	net effect
Purchase Cost of Alarms (per dwelling)	£97	£2	£0.24
System lifetime (years)	10	1	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.120	0.010	£0.98
Annual Cost of Loan	£11.66		
Installation charge (per dwelling)	£75	£38	£1.60
System lifetime (years)	50	5	
Discount rate	3.5%	0%	
Capital Recovery Factor	0.043	0.002	£0.12
Annual Cost of Loan	£3.20		
Annual Maintenance Cost	£0	£0	£0.00
<b>Total Annual Cost</b>	<b>£14.86</b>		
<b>Deaths</b> per Million Dwellings	9	1	£0.32
Alarm Effectiveness Factor	0.40	0.06	£0.69
Deaths saved per Million Dwellings	3		
Monetary Value per Death Saved	£1,345,463	£67,273	£0.23
Monetary Benefit per Single Dwelling	£4.63		
<b>Total Monetary Benefit per Dwelling</b>	<b>£4.63</b>		
<b>Benefit - Cost difference</b>	<b>-£10.23</b>	<b>+/-</b>	<b>£2.35</b>
<b>Confidence Level: pr(net benefit +ve)</b>	<b>0%</b>		