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Fire Hazards in Residential Buildings

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Preface

This work was carried out to quantify fire hazards in a domestic building, and to compare modelling with fire and smoke movement in a real building situation. Data was gathered and analysed to determine hot layer levels and average temperatures within the various rooms. These results were then compared with the predictions of a proprietary computer model. Response times of smoke alarms, heat detectors and sprinklers were also compared with computer model predictions.

Intended Audience

This report is intended for code writers, researchers, designers and fire safety consultants.

FIRE HAZARDS IN RESIDENTIAL BUILDINGS

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REFERENCE

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KEYWORDS

Fire; Flashover; Hazards; Hot Layer; Modelling; Residential Buildings; Sprinklers; Smoke Alarms; Smoke Transport.

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ABSTRACT

Fire hazards in residential buildings were investigated by conducting a range of fire experiments on a purpose-built typical low-cost New Zealand dwelling. Hazards evaluated ranged from limited liquid fuel fires to larger-scale burns using items of furniture. The effectiveness of a range of detection and suppression devices was also tested.

A selection of experimental results was analysed to determine smoke and toxic gas movement, along with temperature rises in the various rooms of the house; these results were compared with the predictions of fire growth computer models.

It was concluded that reliable predictions of smoke alarm, heat detector and sprinkler activation may be based on an initial temperature rise in the upper layer in combination with the first indications of descent of the upper layer. The effect of open vents can be reliably modelled, provided account is taken of the equivalent open area. For closed doors the gaps around the perimeter are measured and a leakage allowance is included in the model input. Reconstruction of fire scenarios is where computer models appear to be more useful, rather than predicting possible outcomes beforehand, due to the benefit of being able to use clues as to the progress of a fire.

Contents

Page No.

Tables

Figures

Appendices

1. INTRODUCTION AND BACKGROUND

The aim of this project was to quantify the fire hazards associated with a typical New Zealand dwelling, by comparing both limited and full-scale burning of a domestic dwelling with that predicted by a fire-growth computer model. It also helped to develop valuable understanding of fire development and behaviour in a fully instrumented building under controlled conditions.

Statistics (Cropp, 1991) show that, of an annual average of 30 deaths by fire in buildings, 90% occur in residences and of these a disproportionately high number occur in rented accommodation. Also contributing significantly to the statistics are fire deaths occurring in rest homes. The greatest cause of death in residential fires is smoke inhalation. This project shows the way relative hazards to life develop; the effectiveness of computer modelling in predicting those hazards and the value of detection and suppression devices.

The data gained from the hundreds of fires in residential buildings that occur annually in New Zealand dwellings lacks scientific recording of the fire's development and detailed measurement of temperatures reached and smoke developed.

It has been some years since an instrumented experimental fire has been conducted on an actual building in New Zealand, and since then considerable advances have occurred internationally in fire growth modelling techniques. These techniques are increasingly being used to justify fire engineering assessments of fire performance in buildings, and continued validation and verification of their usefulness is essential both in New Zealand and overseas. This has been done in this project using construction methods, materials, and furnishings common to the New Zealand housing stock. Instrumentation and monitoring included records of: gas and room surface temperatures, smoke spread, gas species concentrations (oxygen, carbon monoxide) and heat radiation.

This report covers progress in the first two years of the project. For further reading on fire safety in dwellings, BRANZ Bulletin 309 (BRANZ, 1993) outlines many of the safety measures highlighted by this study.

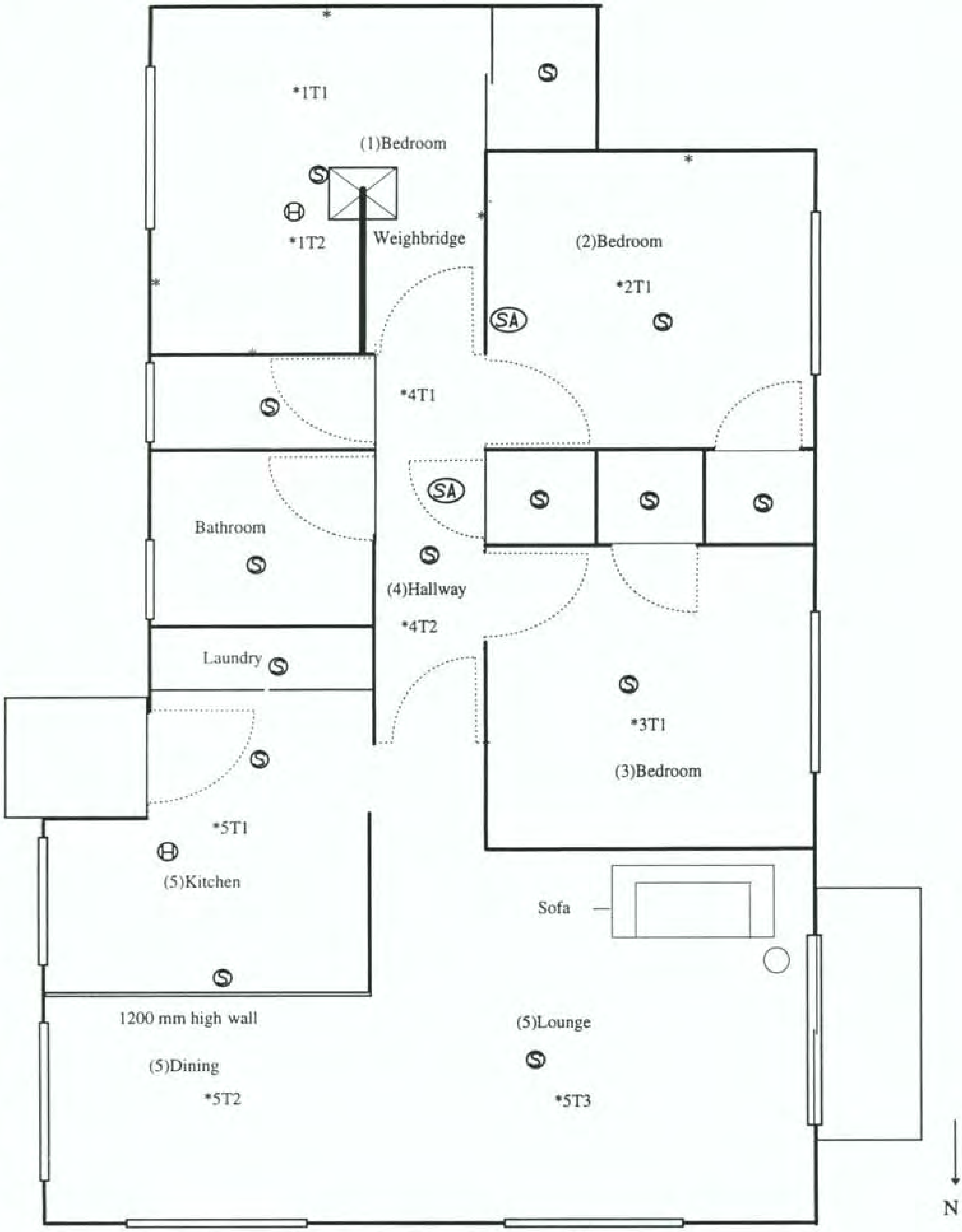
2. EXPERIMENTAL

2.1 Construction of Building

The building chosen for the experimental work was a modern, low-cost, three bedroom, single storey New Zealand dwelling, with a floor area of 69.3 m^2. The construction is light timber framing, clad with unpainted fibre cement board and roofed with corrugated galvanised steel. Internally the floor is particleboard and the walls are lined with paper-faced gypsum board. External walls and ceiling are insulated with a mixture of fibreglass and polyester batts. A domestic sprinkler system has been installed throughout the house. The building is located at the Building Research Association of New Zealand, at Judgeford.

A photograph and a floor plan of the building are attached as Figures 1 and 2, and a detailed specification of the materials used is given in Appendix A.

Figure 1: Experimental house.



( ) Compartment Number   Sprinklers   Heat detectors   SA Smoke alarms   * ?T? Thermocouple trees

* Disc thermocouples in wall cavity

Figure 2: Floor plan of house.

2.2 Instrumentation

A schedule of the instrumentation installed in the house is given in Appendix B. A more complete description of the instrumentation follows.

2.2.1 Temperatures

Three bedrooms, the hallway and the lounge/dining/kitchen area were instrumented with thermocouples. A total of 98 thermocouples were installed; 72 of them were in nine thermocouple trees spanning from floor to ceiling, in the five compartments involved in the experimental trials. Type K thermocouples were used throughout the house.

The thermocouple trees had eight thermocouples each (to measure the hot layer stratification and depth of the smoke layers using the method of Cooper et al [1982]. The remaining 26 thermocouples, disc type, were installed in the wall cavities (at locations shown in Figure 1) and on the upper side of the ceiling linings (above the thermocouple trees) to measure heat loss through the walls and ceilings of the compartments involved in the fires. The location of the thermocouple trees are shown in Figure 1 and the configuration of the trees is illustrated in Figure 3.

2.2.2 Fuel mass loss

For the measurement of the rate of fuel consumption a weighbridge based on a cantilever beam was designed and built. The fuel load being burnt was suspended in a pan from the beam and the deflection of the beam was measured by strain gauges feeding directly to the data logger. Fuels burnt were methylated spirits and a wooden crib. The rate of mass loss and rate of heat input to the compartment were determined from the weight loss.

2.2.3 Heat flux

Heat flux measurements of the fire sources were taken using Gardon-type heat flux meters or calorimeters. The heat flux measured, a combination of radiation and convection, was compared with the mass loss rate determination of heat input and offered an improved input to the software modelling package used to predict fire outcomes. This instrumentation and the weighbridge was used in experimental run 10 onwards.

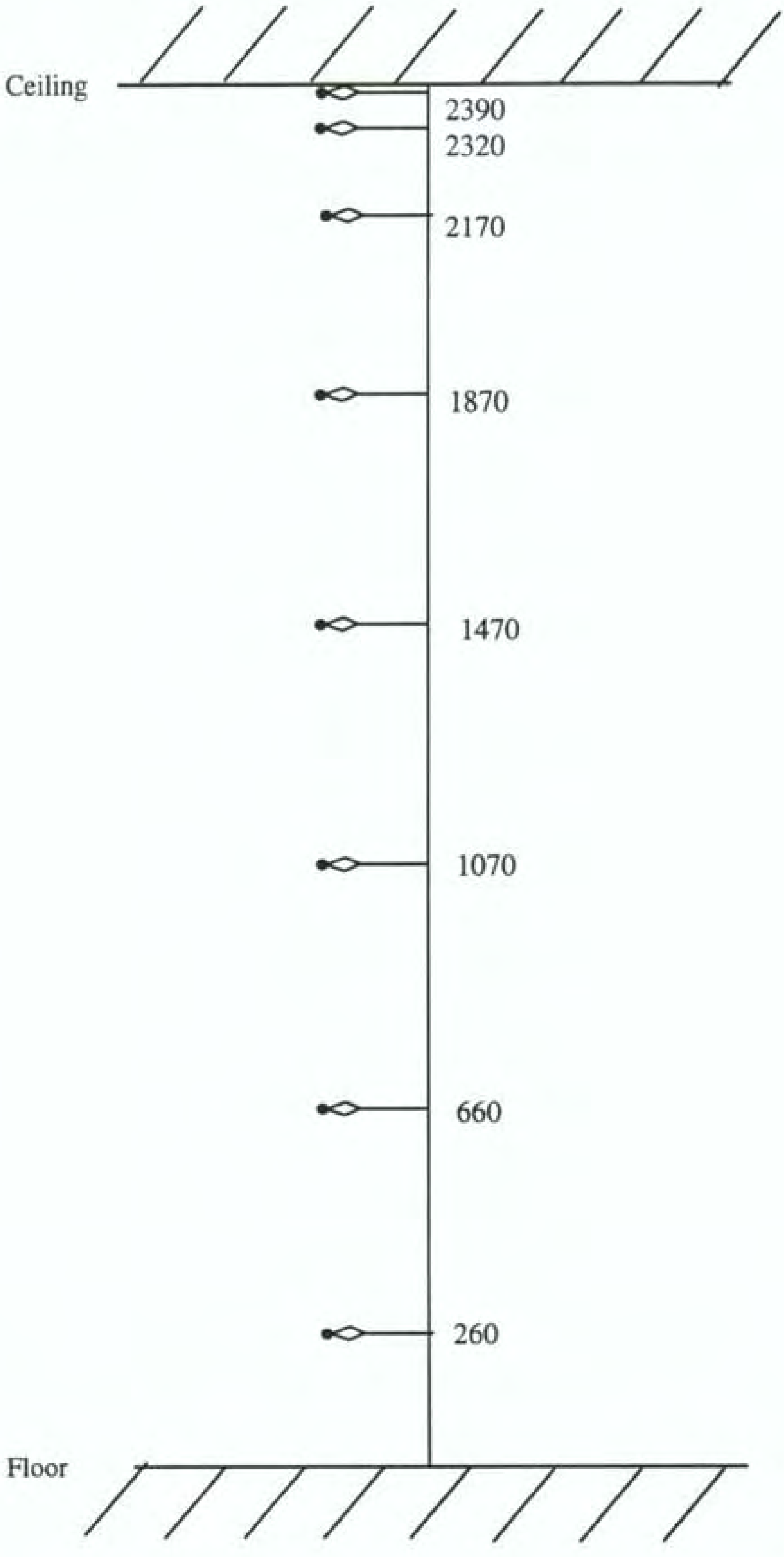


Figure 3: Thermocouple tree, elevations in mm above floor.

2.2.4 Gas analysis

Oxygen and carbon monoxide were recorded, in the room of fire origin at various heights ranging from 500 mm to 1500 mm above the floor, using a portable gas meter. The results were later down-loaded into the datalogging PC for subsequent analysis.

2.3 Recording of Data

All data, with the exception of the gas analysis, was recorded on an IBM-compatible PC with a 128 channel data logging system. This allowed the data to be written to ASCII files for later retrieval and analysis. Comparisons of the recorded data with those predicted by a fire engineering software package were made. A schedule of the data logging points is presented in Appendix B.

2.4 Modelling of Fire Scenarios

Three fire scenarios were modelled using a computer fire and smoke transport model called CFAST (NIST,1992). CFAST is a zone model based on the assumption that in a fire situation the volume in each compartment is divided into two zones, an upper (hot) layer and a lower (cool) layer, as shown in Figure 4. As a fire develops the upper layer increases in volume and temperature as the fire plume "pumps" hot gases into it. When the depth of the hot layer increases (downward) to the soffit level of an opening, such as open doors or windows, the hot gases then begin to flow through these openings, displacing cooler gases in the lower layer, which may flow in the reverse direction. The zone model can predict the magnitude of a wide range of parameters including temperatures, layer interface, oxygen consumption, toxic species generated, heat fluxes and vent flow, etc. The division of a compartment's volume into two zones is a simplification which enables the complex calculations involved to be performed on a PC, and reliable outputs are possible as the user gains experience. Figure 4 illustrates the principle of a zone model.

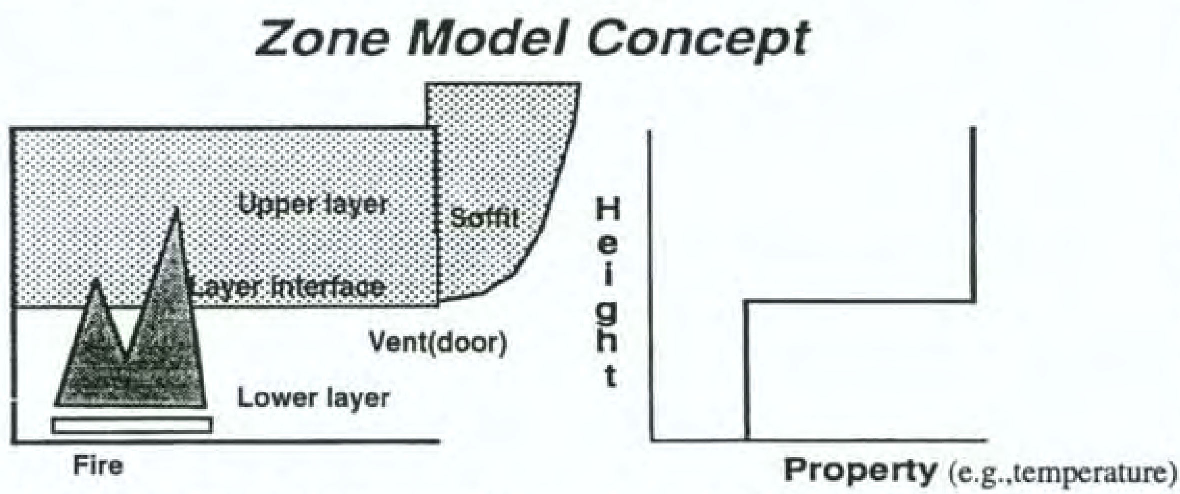


Figure 4: Principle of a zone model concept, showing layers, vent and fire.

Typical input required for the model CFAST is shown in Appendix C, and includes ambient conditions, building geometry (including openings), material specification of walls, floor and ceiling, specification of the type, size, and location of the fire, as well as the graphical display required.

The operation of the sprinkler system was analysed by Firecalc (CSIRO, 1992).

3. PART ONE: PRELIMINARY TRIALS

The preliminary experiments were conducted to check the adequacy of the instrumentation, the operation of the data logging system and to compare smoke spread between the rooms with computer models. Three bedrooms and the hallway were used for this first series of trials. The door between the hallway and the lounge/kitchen/dining areas was closed for the initial trials and the data logging equipment was set up in the kitchen area.

3.1 The Fire Sources

Four fire sizes of 9, 24, 48 and 80 kW were used. From these trial runs it was established that the temperature rises and smoke movement generated were realistic and suitable for modelling purposes. The location of the fire source in each experimental run was in bedroom 1 (compartment 1), see Figure 1. The fire source used in each trial was a tray(s) of methylated spirits to generate the heat input, and smoke was introduced artificially into the plume via a smoke generator as a visual tracer permitting observation of hot gas flow. These fires, of a relatively constant heat output and duration, and with the addition of smoke, produced realistic effects. Although not representative of building fires, the fire and smoke sources were quite suitable in demonstrating the CFAST model's ability to predict temperature rises and layer heights. A total of six trials were conducted as listed in Table 1.

Table 1: Experimental Trials Conducted In Part 1 Of Programme

Trial no.	Fire Size kW	Duration minutes *
1	24	4
2	48	4
3	48	8
4	79	4
5	9	20
6	48	6

* Durations are only approximate and are based on the volume of methylated spirits in the tray(s) and a constant recession rate.

The heat outputs were calculated as follows (SFPE, 1988):

$$\dot{Q} = \dot{m}Ah_c$$

where:

$\dot{Q}$ = heat output, kW

$\dot{m}$ = burning rate of fuel, 0.015 kg / m^2 sec

A = surface area of fuel, m^2

h_c = heat of combustion, 26,200 kJ / kg

<u>Note</u>: The burning rate and the heat of combustion for methylated spirits has been approximated from the values of its constituents. The heat outputs calculated are based on the assumption that the burn rate and heat evolved are proportional to the surface area of the burning pool and assumes 100% combustion. This is questionable, given

that the burn rate would be expected to increase as the pool temperature rises, and oxygen starvation and unburnt fuel closer to the centre would be expected with large pools. Consequently the fire size figures have been rounded downwards to the next whole number.

For trials 1 to 5 the door to bedroom 2 (compartment 2) was closed while the doors from bedrooms 1 and 3 to the hallway were open. For trial 6 the door from the hallway to bedroom 2 was wedged open to form a gap of 100 mm. All windows to the outside and the doors to the bathroom and toilet were closed during the trials.

3.2 Smoke Alarms

Two domestic ionisation-type smoke alarms were installed for the trials, and these were located in the following positions:

1. In the hallway, wall mounted above the door soffit into the kitchen, at an elevation 125 mm below the ceiling.

2. In bedroom 2, wall mounted above the door soffit at an elevation 125 mm below the ceiling.

4. RESULTS AND ANALYSIS OF EXPERIMENTAL TRIALS

Of the six trials conducted, trials 3, 4 and 6 were selected for analysis, because they had more realistic heat outputs producing greater temperature rises and were more applicable to the computer model (CFAST).

4.1 Summary of Trial No. 3

Two trays measuring 250 mm x 250 mm x 100 mm deep, each containing 0.6 litres of methylated spirits, were used as the fire source. The theoretical heat output was 48 kW with a duration of 8 minutes. The two trays were located in bedroom number 1 and smoke, as a tracer, was artificially introduced by a smoke generator. Visual observations of the smoke layer (hot layer interface) descending from the ceiling in all four compartments were recorded manually, for later correlation with the hot layer as measured by the thermocouple trees. The smoke alarm situated at the kitchen end of the hallway was activated at 35 seconds after ignition, while the smoke alarm in the closed bedroom (no. 2) activated at 357 seconds.

It was observed that flames from one of the trays of burning methylated spirits were impinging on one of the thermocouple trees in bedroom 1. Excessive temperatures recorded at the base of the tree confirmed this and that data was subsequently found to be of limited value in determining hot layer levels. The other thermocouple tree, however, yielded useful data.

4.2 Summary of Trial No. 4

The fire size was increased to approximately 70 kW (one 450 mm x 450 mm x 100 mm deep tray with 1 litre of methylated spirits) with an expected duration of 4 minutes. Smoke was again introduced and the observations were similar to trial 3. The smoke alarms at the kitchen end of the hallway and in the closed bedroom were activated at 24 and 206 seconds respectively.

The visual record of the descending smoke level in bedroom 1 correlated well with that indicated by the recorded temperatures.

4.3 Summary of Trial No. 6

Trial No. 6 was a repeat of trial No. 4 with the 48 kW fire source, except that the door to bedroom 2 was wedged open 100 mm. Smoke was again introduced and the observations were similar to trials 3 and 4. The smoke alarms at the kitchen end of the hallway and in the partly open bedroom were activated at 28 and 36 seconds respectively.

In all trials, the recorded data (both visual and by instrumentation) and the output obtained from modelling the fire scenarios on CFAST showed encouraging agreement. Some problems were encountered with calculation of the hot layer interface, particularly in the first minute when stratification of hot and cold layers had not been fully established, at which stage the calculation method (Cooper et al, 1982) is sensitive to small temperature differences in the recorded data. Improvements in the recording and processing of data minimised these problems in subsequent trials.

5. COMPARISON WITH THE CFAST MODEL

An extensive comparison between the recorded data and the output from a computer model CFAST was not warranted at this stage of the project. However, sufficient analysis was undertaken to address problems in processing of the data and comparing that data with the model that the remainder of the project could be undertaken with confidence. Some brief examples follow to illustrate that confidence.

Trial No. 6 has been selected for this comparison because the retarding effect on smoke movement of the partially open door is illustrated, and a four-compartment scenario is slightly more complex than for three compartments.

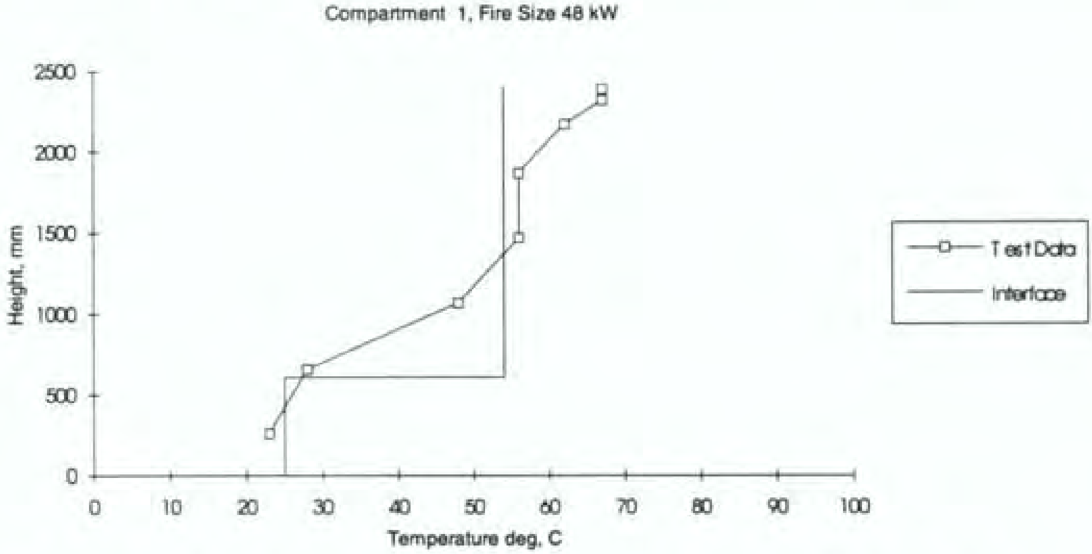


Figure 5: Calculation of hot layer interface and upper and lower layer temperatures for bedroom 1 at 60 seconds (Trial No.6).

Figure 5 is a snapshot of the trial data taken on a thermocouple tree in bedroom 1 at 60 seconds. The relationship of the temperatures to height is used to determine the interface between the hot and cold layers (Cooper et al,1982). The mean temperatures in the two layers are calculated by numerically integrating over their respective heights. The interface height and the mean upper and lower layer temperatures are represented by the single horizontal and two vertical lines, respectively, on the graph. This process is repeated for every time interval and was used in the construction of Figure 6.

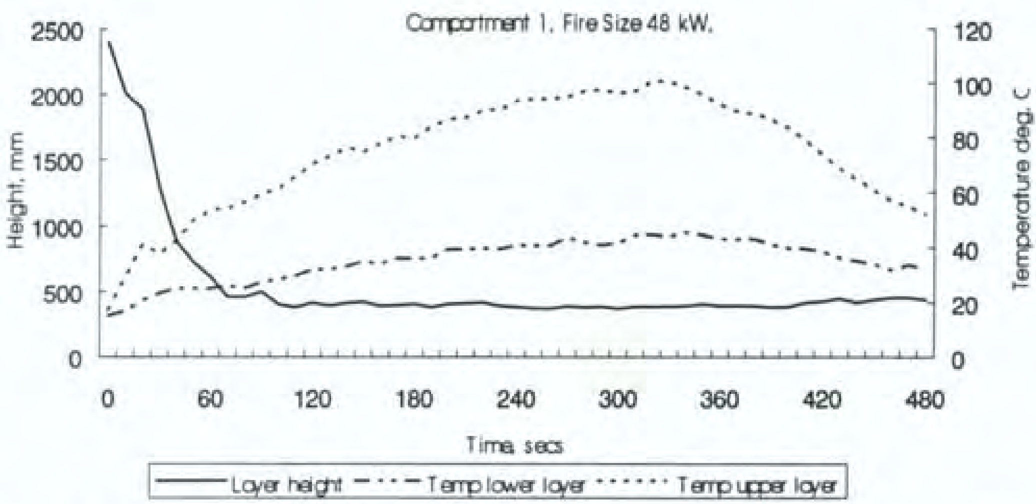


Figure 6: Interface height, upper and lower layer temperatures in burn room (Trial No.6).

Figure 7 shows a comparison between the measured temperatures in bedroom 1 (burn room) and the equivalent temperatures predicted by the model (CFAST). Very good agreement is obtained for the lower layer, but since the temperature does not rise significantly a large difference would not be expected. For the temperatures in the upper layer, the maximums achieved are very close, but the rates of increase show some differences. Possible explanations for this include: uncertainties over the actual heat output of the methylated spirit fire, and heat loss from the hot gases through the walls, ceiling, windows and into cupboards by conduction, convection or leakage. Issues such as the above will need to be addressed in the remainder of the project to reduce uncertainties.

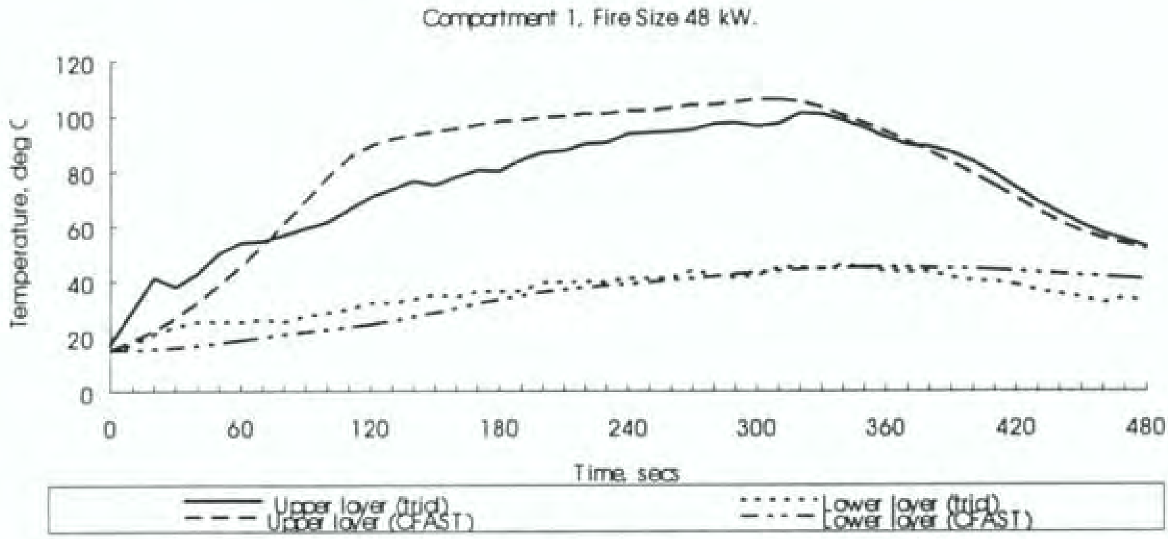


Figure 7: Comparison of measured and predicted temperatures in upper and lower layers of burn room (Trial No.6).

A comparison of interface levels is displayed in Figure 8. Generally, good agreement between the model and the recorded data is obtained, at least for limited periods of the duration of the trial. Obvious disagreements occur in the first minute, where calculation of the layer height is very sensitive to small variations in temperatures recorded on the thermocouple trees and this accounts for the wide fluctuations for compartments 2 and 4. Once there is a definite temperature gradient from floor to ceiling this calculation is more reliable.

The model predicts that the interface level drops to floor level in all compartments, but the trial data recorded clearly showed that there was a cooler layer on the floor of approximately 400 mm in depth where the temperature had only risen by 10 to 15°C, as shown in Figure 7.

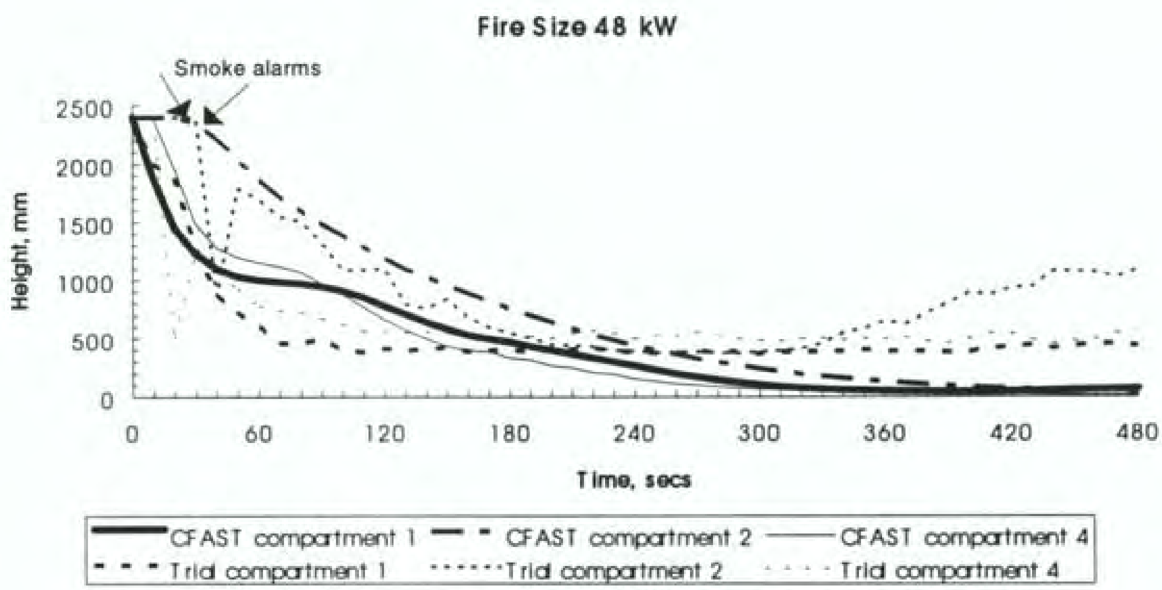


Figure 8: Comparison of measured and predicted interface height in the burn room, the hallway and bedroom 2 with smoke alarm activation (Trial No.6).

The activation of the two smoke alarms is indicated by the arrows in Figure 8. If it is assumed that a detector should operate when the hot layer (including smoke) descends to the same elevation, then the detector at the end of the hallway activated about 15 seconds later than expected as indicated by the recorded data. This is probably due in part to it being situated at the far end of the hallway from the burn room. The detector in bedroom 2 responded closer to the time expected and as indicated by the hot layer measurement.

Visual observation of the smoke levels against graduations marked on the walls in the various compartments showed general agreement with the calculated levels. However, problems with the artificial smoke varying in density with temperature made accurate determination of the smoke height difficult using this method. In spite of the uncertainty, this measurement technique provided a useful and inexpensive check on smoke height, confirming the validity of the method of Cooper et al (1982).

6. CONCLUSIONS

6.1 Part 1 of Project

The first stage of this project was successfully completed before the second stage was undertaken. Useful experience was gained by commissioning the house as an experimental rig, and a few teething problems were discovered and corrected before the experiments in Part 2 were conducted. The most significant of these was in the datalogging software, where improvements were made to reduce the uncertainty and instability in the thermocouple tree measurements and subsequent calculations.

7. PART TWO: FULL-SCALE EXPERIMENTAL WORK

7.1 Introduction

The remainder of the project comprised setting up some more realistic fire scenarios and measuring heat outputs for correlation with temperature rises in the various compartments, as well as measuring oxygen depletion and carbon monoxide production. The effectiveness of the domestic sprinkler system, smoke alarm and heat detectors was tested in realistic fire scenarios as well as against measured heat input fires using methylated spirits.

As a consequence of two furniture fires the reaction of the wall and ceiling linings to fire was also measured, but is not reported at this stage.

Valuable data was collected for comparison with fire models, which in future will be an integral tool in the application of the performance-based New Zealand Building Code (BIA, 1992).

The experimental runs conducted are listed in Table 2. Not all the trials produced useable results due to problems with commissioning the weighbridge and getting the best results out of the calorimeter. Those trials marked by an asterisk warranted closer analysis and these are presented in this report.

Table 2: Experimental Trials Conducted In Part Two Of Programme

Trial #	Duration (secs)	Fire Source	Fire Peak W	Fire Loca-tion	Fire load kg	Temp Max C	Heat Detector secs	Com-part-ments	Venting windows open	Wind km/hr, direction
10	1410	meths	26	1	1.40	125	164	1,3,4	nil	0-7,S
11	690	meths	91	1	1.00	318	72	1,3,4	1,40%at 540s	0-7,S
12*	1570	meths	110	1	1.75	126	-	1,3,4	1,40%at 630s	0-7,S
13*	2550	meths	39	1	1.68	168	-	1	nil	0-7,S
14	790	meths	120	1	1.70	219	-	1,3,4	nil	0-7,S
15	750	meths	120	1	1.67	232	-	1,3,4	nil	0-7,S
16*	1400	wood crib	45	1	3.72	133	252	1,3,4	nil	10-12 NW
20*	150	chair etc	<20	5	-	65	-	5	all open, 40+%	0
21*	500	sofa etc	1 MW+	5	-	700	119	5	all open, 40+%	0
22*	980	meths	90	1	1.38	110	128	1-5	1,3,5,15%	6-8 N
23*	1070	meths	80	1	1.80	134	-	1-5	1,15%	6-8 N
24*	240	meths	63	1	0.66	95	99	1-5	1,15%	6-8 N
25*	650	meths	62	1	0.57	94	-	1-5	1,15%	6-8 N
26*	640	meths	91	1	1.27	139	-	1-5	1,15%	6-8 N
27*	600	chair	~250	1	15	837	160	1-5	1,15%	0

* Subjected to analysis

***Note to Table**: For each series of trials the numbering started at 10 or 20 to separate them from the previous series, so there were no trials 7, 8, 9 etc. Temperature maximum refers to the maximum indicated temperature on an individual thermocouple rather than the layer average, and differs from the mean upper and lower level* *temperatures shown on the following graphs as used for comparison with the CFAST model. The venting column shows the extent that windows and doors are open in the various compartments. The individual digits represent the compartment numbers with vents open the exterior, followed by the percentage that the vent is open. The size of the vent can be found in the sample input file for CFAST in Appendix C. In trial 22 the vent that is 15% open is the sliding door (HVENT 5 7 1 in Appendix C). In trials 20 and 21 the vents in compartment 5 were wide open, accounting for 40 to 45% of the total vent area as not all windows opened. This figure increased further once glass began to shatter with the elevated temperature. Trial 20 was extinguished by sprinklers, while trial 21 continued beyond flashover before being extinguished. Measurements of wind strength and direction were taken for input into the CFAST model.*

The ceiling-mounted heat detector actuation times, where shown, indicate closely when the actuation temperature of 57°C as recorded by the data logger was exceeded. Unfortunately, the heat detectors failed to reset on occasions when trials were too close together to permit adequate cooling.

The results of the mass loss rate of the methylated spirits and heat flux at the wall were compared, and showed that the earlier assumption for trials 1 to 6, that the heat output was nearly constant, was incorrect. The heat output increased over a period of time and then decayed as the liquid fuel was exhausted. Heat flux incident at the point of measurement was related back to the heat output at source using the method described by Drysdale (1992).

8. RESULTS AND ANALYSIS

The heat output results for trials 12, 13 and 16 are plotted in Figures 9, 14 and 18. The heat output is clearly not constant and could crudely be described as triangular in shape, on the basis that the heat output increases from zero to a peak and then decays to zero. The agreement between the weigh-bridge and calorimeter measurements for trials 12 and 13 were encouraging, although it is important to realise that the calorimeter reading tends to lag behind the weigh-bridge measurement. In trial 13 the hook supporting the fuel pan deformed, due to the elevated temperature, allowing the pan to touch the floor after 70 seconds, invalidating the remaining weighbridge data. In trial 16 the calorimeter readings were considerably less than the weighbridge, over the period up to 960 seconds. Based on observations, the flaming was obscured within the wooden crib and was therefore not registered by the calorimeter until the decay phase, when the crib was completely engulfed in flames, after which only glowing embers remained.

Factors which should be taken into consideration when comparing the two measurement methods and their outputs are as follows:

1. The weighbridge is recording the mass loss of fuel from the pan as it is consumed while burning. An assumption of the burning efficiency of the fuel is required, as unburnt fuel does not contribute to the heat release rate to the compartment.

2. The calorimeter, in these trials, was mounted flush with the wall, a horizontal distance of 1.9 metres from the burning fuel. It registered the radiative heat from the flames and surfaces as well as the convective heat from the heated gases flowing over its surface.

8.1 Trial 12

For trial 12 the heat inputs recorded are shown on Figure 9. The calorimeter reading, adjusted for distance from the fire source, lags behind that for the weighbridge due to the time taken for the airspace and surroundings to heat up. Similarly, during the decay phase the calorimeter reading lags behind due to heat stored in the airspace and surroundings. The heat input follows the same general shape as the temperatures of the upper and lower layers shown in Figures 12 and 13.

The gas species recorded (Figure 10) in the lower level at a height of about 500 mm in compartment 1 (the fire compartment), show a small reduction in oxygen content, down to about 17%, while the carbon monoxide increases steadily. The step-wise increase is due to the resolution of the equipment being in the order of several parts per million or an uncertainty of ±5 ppm. These low levels are by no measure life threatening. Since all external windows were closed, and remained intact during the trial, and leakage by other means was considered negligible, the consumed oxygen was not replaced nor could the carbon monoxide escape.

Compartments 1, 3 and 4 were exposed to the fire conditions while compartment 2 was behind a closed door. The hot layer levels (Figure 11) all rapidly descended to an equilibrium level of about 400 mm. Small temperature differences between the upper and lower regions in the period 0 to 90 seconds account for fluctuations in the calculated level height.

8.2 Trial 13

For trial 13 the door to compartment 1 was closed as well as the window. A small tray (250 mm x 250 mm) of methylated spirits on the weighbridge was allowed to burn until it was consumed.

After about 60 seconds the suspension hook on the weighbridge failed, allowing the tray to touch the floor. From this time onwards the readings were invalid and only the calorimeter readings are considered. Figure 14 indicates the rapid rise in heat input to the compartment, followed by a slow decay due more to reducing oxygen content than fuel supply. The rising carbon monoxide level (Figure 15) peaking at 119 ppm is not dangerously high. The maximum safe level for long-term exposure is 1700 ppm (NIST,1991). The oxygen content dropping to 12.9% (see Figure 15) is likely to be more hazardous, as is the temperature of 150°C.

When it appeared the fuel was totally consumed (at 1650 seconds), judged by there being no visible flaming, the door to compartment was opened briefly and flaming ensued until the remaining fuel was consumed. Figures 15 and 16 show the rapid drop in carbon monoxide, the restoration of oxygen and the drop in room temperatures. Such a door opening is typical of an occupant investigating the possibility of a fire and Figure 17 illustrates the consequences in the adjoining compartment (the hallway) due to mixing gases and possible spread of the fire. The hot layer interface has been omitted from Figure 17 as it proved to be sensitive to small variations in temperature, leading to an erroneous result.

8.3 Trial 16

This trial used a wooden crib, suspended from the weighbridge, as the fire source. Compartments 1, 3 and 4 were involved.

The crib parameters were as follows:

Timber species:	Radiata pine
Weight:	3.72 kg
Section size:	35 x 35 mm
Section lengths:	200 - 400 mm
Moisture content:	12%
Timber density:	450 kg/m^3
Shape:	pyramid, six sections in height, with 35 mm horizontal spacing between sections.
Calorific value:	13 MJ/kg for 10% moisture content (Hadvig, 1981).

The heat-release characteristics were somewhat different to the alcohol fires of previous trials. As expected, the rate of increase of heat input into the compartment was slower and the rate of decay was very slow. At the same time glowing embers remained in the pan. Figure 18 shows a considerable difference between the two methods of measurement for the first 960 seconds of the trial. This could be explained by the different radiative properties of luminous flames and glowing embers. Also the crib itself would obscure some of the flames in the first part, and the initial heat output was caused by the 100 ml of alcohol used to ignite the crib initially. The weighbridge measurement more accurately reflects the observed behaviour of the fire and therefore heat input to the room, so this input was used for the CFAST model comparisons.

The consumption of oxygen shown in Figure 19 is not significant and shows a similar trend to trial 12, once an adjustment for heat input is made. The carbon monoxide concentration, however, increases up to 72 ppm, and although not significant in terms of life safety it does illustrate the difference that the fuel makes. The constituents of wood contain a greater content of carbon than does methylated spirits.

The layer heights and temperature rises in the compartments are shown in Figures 20, 21 and 22. The temperature rises continued for a short time after the fire peak and then decayed slowly.

8.4 Realistic Fire Scenarios

The fire scenario in trials 20 and 21 involved a rubbish bin with an assortment of paper contents placed beside a ceiling-to-floor curtain which was, in turn, adjacent to an item of lounge furniture. All windows in the fire compartment (5) were open to their full extent, which equated to 40 to 45% of window area. The sliding door was open 10 %, to allow adequate ventilation for the two fires to develop. The two doors joining the kitchen and the hallway were both closed for the trials.

8.4.1 Trial 20

With the sprinkler system charged and fast-response sprinkler heads with an RTI (Response Time Index) of 31 $m^{1/2}$ $s^{1/2}$ and an activation temperature of 68°C fitted, the contents of the rubbish bin were ignited. The closest sprinkler head to the fire plume was a distance of 1.8m. At 117 seconds flames had spread to the curtains; after 140 seconds the sprinkler system activated and extinguished the fire. The maximum gas temperature recorded by the data logger was 65°C, but the weighted mean temperature of the upper layer only reached 55°C. The layer height and temperatures in Figure 23 graphically record the brief sequence of events: the descent of the hot layer level and smoke, a rapid rise in temperature once the flames spread up the curtains, and the equally rapid drop in temperature once the sprinkler activated.

Figure 24 shows the gas species recorded for trial 20. An insignificant decrease in oxygen is noted, while the carbon monoxide content rose to a maximum of 50 ppm after the fire was extinguished.

The smoke alarm in the closed hallway (compartment 4) did not activate in this trial because the fire was extinguished before that could occur.

8.4.2 Trial 21

With the sprinklers turned off the scenario in trial 20 was repeated, with the damp chair exchanged for a dry sofa. Figure 25 illustrates the layer height and temperature rises as recorded by thermocouple tree 5T3, which was closest to the fire source. The curtains commenced burning 37 seconds after the contents of the rubbish bin were ignited and the fire spread to the sofa after 80 seconds. The ceiling-mounted heat detector in the kitchen area activated at 119 seconds, when the measured gas temperature exceeded the nominal activation temperature of 57°C. At 140 seconds the domestic smoke alarm located on the ceiling of the hallway, behind a closed door, activated an audible alarm by which time the lounge/dining/kitchen area was heavily logged with smoke. At 190 seconds, and when the temperature was about 275°C, the first window shattered and was rapidly followed by the others. A small decrease in temperature occurred as cooler air entered the compartment through the openings. Growth of the fire was fuel controlled and flashover occurred at approximately 400 seconds. Fully developed burning progressed for approximately 120 seconds before extinguishment by the Fire Service. As a training exercise by the Fire Service, the application of water was kept to a minimum, with the objective being to minimise water damage. This fire-fighting method proved successful, as evidenced by the rapid decrease in temperature.

The damage caused to the lounge/dining/kitchen room was as follows:

- In the area of fire origin the paper facing on the plasterboard lining on the walls and ceiling had completely burnt away, exposing the gypsum core. Cracks up to 1.5 mm wide ran vertically and horizontally the entire width and height of the sheets.

- The lining had pulled off over the nail heads in some places on the ceiling.

- The maximum temperature reached on the upper surface of the ceiling lining was 107°C.

- The extent of damage reduced further away from the seat of the fire. At the extreme corners of the compartment (6-8 metres away) the lining varied from heavily scorched at the upper level to slightly browned near the floor.
- On vinyl-covered chairs (6-8 metres away) the covering had melted where it faced the seat of the fire.
- All windows except one small one in the laundry had cracked and fallen out and the rubber gaskets in the aluminium frames had melted and burnt.
- The timber frames around the doors and windows had charred up to 1mm in depth.

8.5 Multiple Compartment Trials

Trials 22 to 27 involved 5 compartments - the three bedrooms, the hallway and the lounge/kitchen/dining room. The fires were: 5 alcohol fires and one involving a rubbish bin and chair. All were lit in bedroom (1).

8.5.1 Trial 22

An alcohol fire was set in the pan of the weighbridge in bedroom 1 and reached a peak output of 90 kW. The sliding door in the lounge was open to a gap of 200mm and windows in bedrooms 1 and 3 were open to a gap of 200mm also. A northerly wind of 11-15 km per hour was blowing. Figures 26 to 29 illustrate the measured layer height, temperatures and heat input for the compartments involved. The gas analysis data is not shown for this alcohol trial or any of the following alcohol trials because only very small quantities of carbon monoxide were produced and only a small depletion of oxygen occurred. The heat detector in the compartment of fire origin was activated at 128 seconds.

8.5.2 Trial 23

This was a similar scenario to trial 22 but all windows were closed with the exception of the one in the compartment of fire origin, which was open 200 mm. The wind remained constant at 11-15 km per hour from a northerly direction. The fire peak was 90 kW and the results are illustrated in Figures 30- 33.

8.6 Sprinkler Trials

The operation of the sprinkler system was tested in the trials 24 to 26.

8.6.1 Trial 24

With the sprinkler system charged and fast-response sprinkler heads with an RTI (Response Time Index) of 31 $m^{1/2} s^{1/2}$ and an activation temperature of 68 °C fitted, a 65 kW fire in bedroom 1 was set in a pan suspended from the weighbridge at a radial distance of 0.5m from the nearest sprinkler head. The sprinkler system activated 62 seconds after ignition, with the upper layer temperature reaching a maximum of 68 °C at 62 seconds after ignition. Figures 34-37 show the layer height, temperatures and heat output of the fire.

8.6.2 Trial 25

This involved the same scenario as trial 24 but with an 8 mm bulb standard-response sprinkler with an RTI of 170 and an activation temperature of 68 °C in the room of fire origin. This failed to activate even though the upper layer temperature just reached a maximum of 70 °C and remained over 60 °C for 2 minutes. Figures 38-42 show the layer height, temperatures and heat output of the fire.

8.6.3 Trial 26

Trial 25 was repeated with the fire heat output increased to 100 kW. This time the sprinklers activated when the temperature reached 100°C at 183 seconds after ignition. Figures 42-45 show the layer height, temperatures and heat output of the fire.

8.6.4 Trial 27

This was a more realistic fire scenario, with a rubbish bin containing waste paper placed beside a curtain draped over the arm of a 15 kg vinyl-covered foam rubber-filled chair in bedroom 1. The smoke alarm located on the hallway (compartment 4) ceiling activated at 52 seconds after ignition at the same time that the flames had just spread to the curtain. The ceiling-mounted heat detector in bedroom 1 activated at 110 seconds after ignition, when the derived average upper layer gas temperature had exceeded 57°C. Once the vinyl on the chair was alight fire spread was rapid, producing palls of black smoke filling the upper layer and flowing into the hallway, and from there to the other rooms. The increase in heat output (measured by two heat flux meters) was very rapid, following approximately a t^2 growth rate. The fire was allowed to continue and the windows shattered at 250 seconds from ignition. The sprinklers were manually activated at 260s to prevent further damage and the fire was completely extinguished at 350 seconds. When viewing Figures 46 to 50 it should be noted that ignition occurred 40 seconds into the data logging run.

Gas measurements were taken in the room of fire origin, at a typical nose height of 1.5 m. These are shown in Figure 49 where the oxygen content had reduced to 9% and the carbon monoxide level rose above 266 ppm (the meter reached a saturation level). Black acrid smoke filled the upper levels of the building leaving a relatively clear zone for a depth of about 1 metre above floor level in all rooms other than the room of fire origin.

The damage caused was as follows:

- Paper facing on plasterboard burned on the ceiling and the upper (hot layer) part of the walls.
- Wardrobe sliding doors burnt through the first layer to the honeycomb core and melted rollers on the track, allowing doors to fall inwards.
- Windows were broken in the room of fire origin only.
- Heavy soot deposition on surfaces throughout the house.

8.7 Comments on the Operation of Protection and Suppression Devices

8.7.1 Sprinklers

The fast-response sprinklers, with an RTI of $31m^{1/2}s^{1/2}$, activated before the average gas temperature had risen above 70 °C and were effective in extinguishing the fire. The standard- response sprinkler, with an RTI of $170m^{1/2}s^{1/2}$, required a higher temperature of up to 100 °C to activate and in the possible scenario of a slow growth fire may not operate early enough to bring it under control, as the fire may have spread beyond the spray pattern of the operational sprinkler head.

In general, sprinklers used in a domestic building have the potential to provide a complete protection package when fitted with an audible alarm to alert the occupants to the presence of a fire whether it has already been extinguished or not. If the fire has not been extinguished then the Fire Service will be called if there is a brigade connection. In any case the fire damage is likely to be limited, and the only disadvantage is likely to be the possibility of water damage. The risk to life is likely to be significantly reduced.

8.7.2 Smoke alarms

The domestic ionisation type smoke alarm located on the hallway ceiling gave very early warning of fire.

In trial 21, when the hallway door connecting the lounge was closed, and a rubbish bin fire next to the curtains and the sofa was set, the time for activation of the smoke alarm was only 140 seconds after ignition. At this time it was not possible to visually detect the smoke in the hallway that had leaked under the soffit to trigger the alarm. The fire continued to develop for a further 360 seconds, before Fire Service intervention. Afterwards only a thin smoke haze was visible in the hallway and there was evidence of the passage of hot gases having charred the soffit and the top of the door. Clearly the combination of the closed door and the early warning of the smoke alarm would have alerted occupants and provided time to escape. In this case the most desirable means of escape would have been via the windows at ground level as both external doors connect compartment 5, where the fire originated.

In trial 27, a similar scenario in compartment 1 (bedroom) with all connecting doors to the 5 compartments open, the ceiling mounted smoke alarm in the hallway provided audible warning after 52 seconds. Flashover did not occur for another 160 seconds, but smoke was rapidly filling the other compartments 60 seconds after the smoke alarm activated, presenting a risk to life. This presence of smoke is evident by the hot layer levels shown in Figure 46, and visual observations confirmed that even at the fire peak the smoke layer descended to a level 1 metre clear of the floor in the lounge/dining room (compartment 5). This is significant in that a crawling level escape route was available below what was an extremely dense and potentially toxic upper layer.

Finally, the reliable performance of smoke alarms is dependent on their installation being in accordance with the manufacturers' instructions, with particular attention to their being ceiling mounted. This is because hot gases, including smoke, will fill a compartment from the ceiling downwards. Figure 46 shows a descent in the layer height in the hallway (4), as detected by the thermocouple trees, which commenced 20 seconds prior to the smoke alarm activation. At the same time the temperature in the hallway (4) has not shown any noticeable increase in Figure 47.

8.8 Heat Detectors

The heat detectors were wired into the data logger and the time at which they switched to open circuit, when their activation temperature was exceeded, was recorded. The heat detector response in all cases was consistent with the upper layer temperature in the compartment exceeding 57 °C and the times to activation are shown in Table 2. It was evident that these devices have a very low thermal inertia or RTI. In some cases the detectors did not activate, but this can be perhaps be best explained by there being insufficient time for the device to reset following its exposure to elevated temperatures in the previous trial.

Although smoke alarms provide the earliest warning of fire, in locations such as kitchens where cooking smoke could be responsible for many false alarms, the heat detector offers the protection required. Heat detectors are available in a range of activation temperatures (57 °C is the lowest) to cater for various risk situations.

The performance of the heat detectors is illustrated in Figures 21, 25, 27 and 35. With the exception of trial 21 (Figure 25) the activation of the heat detector coincides with a temperature of 57 °C being exceeded. In trial 21, the ceiling-mounted heat detector in the kitchen was a distance of 6 metres away from the seat of the fire in the lounge and was also shielded by a partition, which accounts for the temperature in the vicinity of the fire reaching 160 °C before activation. The instrumentation in the kitchen, adjacent to the heat detector, confirmed that the heat detector activation closely followed 57 °C being exceeded.

9. MODELLING OF SELECTED EXPERIMENTAL RESULTS

A selection of experimental results was used for comparison purposes with the CFAST (NIST, 1992) model for fire and smoke transport, and the operation of the sprinkler system was compared with Firecalc (CSIRO, 1992). CFAST is now available in the updated version of Hazard 1 (NIST, 1991) (as version 1.2). Table 3 indicates which parameters of the various experimental runs were modelled. Some trials, in particular those where alcohol was used for the fuel, did not provide any useful data for toxic gas analysis, but valuable temperature data was produced and this is compared with CFAST.

Table 3: Modelling Of Experimental Results

Trial No.	CFAST: layers heights and temperatures	CFAST: gas species	Firecalc: sprinklers
12	X		
13	X		
16	X	X	
20			
21	X	X	
22	X		
23	X		
24			X

25	No analysis	No analysis	No analysis
26			X
27	X	X	

For each modelling run using CFAST, the heat input data that was recorded in the particular trial being modelled was used in the CFAST input data along with the relevant hydrogen to carbon ratio (HCR) for the fuel under consideration. A sample of input data for CFAST is listed in Appendix C.

9.1 Trial 12

The hot layer levels for the experimental run and model are illustrated in Figures 11 and 51. The minimum level is reached at approximately 120 seconds in each case and, at least for the fire compartment (1), this is 400 to 500mm above the floor. CFAST predicts a lower level for compartments 3 and 4, but observations indicated a cooler layer of a depth of 400 to 500 mm throughout the compartments involved.

The maximum temperatures (Figures 52 and 53) attained in the upper and lower level during the trial did not reach those predicted, and fell short by 25 to 35 °C (15 to 25%) in the compartment of fire origin. Agreement improved for the rooms further away from the room of fire origin and, in general, the times at which peak temperatures were reached were in agreement.

A difficulty encountered in preparing the CFAST input files was in accounting for the large areas of glass through which heat was lost by conduction. Particular care was taken to prepare accurate physical data for the wall and ceiling assemblies which matched the products actually used, but the CFAST software makes no allowance for heat loss through closed windows. Once windows have broken and become vents this is of little consequence, but in the context of the preliminary trials this may account for the differences.

Modelling of the gas species is not reported here, since an alcohol fire was used and the main product is water, followed by carbon dioxide and an insignificant quantity of carbon monoxide.

9.2 Trial 13

This trial was primarily intended as a single compartment trial to monitor oxygen consumption. Similar trends to trial 12 were noted, with a 15 to 20% over-prediction of the layer temperatures. The hot layer interface (Figure 54) was predicted at 600 mm as against the 400 mm recorded (Figure 16), but this method of layer height measurement is unreliable at low levels due to the bottom thermocouple being 260 mm above the floor, effectively generating an asymptote at about 400 mm, below which the layer interface cannot be registered.

The predicted oxygen consumption followed the general trend of the measured result and a comparison can be obtained between Figures 15 and 57. Any variation between the experimental and CFAST data is likely to have arisen because of the location of the sample point being at a height of 550 mm above floor level, which was chosen on the basis of nose height if occupants are either sleeping or crawling to escape. The intention was to make comparisons of the upper level gas species. The consumption of oxygen shows a similar downward trend. In the case of the CFAST prediction, when the oxygen content descends below the programmed limiting oxygen index of 12% the heat output from the fire (Figure 56) drops significantly. Observations of the burning fuel during trial 13 indicated that the rate of burning reduced markedly, but unfortunately the weighbridge measuring the mass loss rate had failed by this time and the heat flux measured by the calorimeter obviously included a significant proportion of heat from the walls and air, which would have masked the true heat input. The general trends of the level of carbon monoxide, while not life threatening, were in sufficient agreement that future predictions can be relied upon to assess the risk to life.

When the door to the fire compartment (1) was opened at 1650 seconds, CFAST accurately predicted (Figure 55) a brief temperature rise up to 70 - 80 °C in the hallway before the heat was dissipated throughout the remaining compartments.

9.3 Trial 16

For trial 16, with the wood crib fire, the maximum predicted temperatures (Figure 60) in the upper layer are 5 - 10 °C higher than recorded (Figure 21), and because CFAST (Figure 59) is indicating that the layer height descends to floor level, instead of the 400 mm recorded (Figure 20), the significance of the lower layer temperature is doubtful.

The gas species prediction in Figure 62 agrees reasonably with the trend recorded (Figure 19) up to the time that the gas analysis recorder tripped out due to a filter blockage. It is questionable whether the samples were being taken from the upper or lower layer, and the layer height in compartment 1 (Figure 20) certainly passes through the 550 mm level that the samples were being taken at.

9.4 Trial 21

The input data for the fire source for trial 21 was developed from the database in CFAST and involved a rubbish bin, curtains and sofa. A scenario was developed which matched the sequence of events described in the earlier section under results and analysis. The contribution of the remaining fire load in the lounge/dining/kitchen area was ignored, as the fire was extinguished once flashover had occurred and the contribution of the remaining contents was minor. Another problem arises because the fire scenario input is limited to 20 steps, and that number were already being used. Extending the duration would have required compromises to be made which would have conflicted with the objective of modelling the actual fire as closely as possible. Comparing Figures 25 and 63 the curves for the upper layer temperature are quite different. The closest agreement is the maximum temperature reached, of 700 to 800°C. The time at which the maximum temperature was reached is easily dictated by the design of the fire scenario, which was of course based on what occurred in the trial.

Other areas of disagreement can be explained by difficulties in accurately describing the true venting through the windows. The CFAST input file requires that for each vent the amount of opening be expressed as a fraction (0 to 1) of the total opening area, and that fraction refers to a vertical strip the entire height of the vent. This is not too difficult for hinged and sliding doors or vertically hinged windows but problems arise for horizontally hinged windows (opening bottom edge outwards for instance) for which it can be quite difficult converting rectangular and triangular openings around the edges to the equivalent vertical strip, especially when the height parameter makes a greater contribution to the flow. It is evident in comparing the layer heights in Figures 25 and 63 that the venting configuration is exerting a substantial influence. In trial 21 the windows, which were all initially open 200 to 300 mm, began shattering and falling out in a random fashion once the temperature in the hot layer had exceeded 275°C. The venting created did not in all cases extend to the window soffits and this restricted the flow of hot gases from the compartment, forcing the hot layer closer to the floor to maintain the required outflow. Observations certainly confirmed this. The ideal case is as modelled by CFAST, and shown in Figure 63, where openings no matter how restrictive extended to the window soffits. Indeed, the hot layer level barely descends below the 2000 mm level of the soffits. When the windows began breaking at 190 seconds an upward turn in the layer height was evident as more hot gases flowed out of the compartment. A similar trend with the layer height is barely detectable in the actual experimental results, although the in rush of cooler air does momentarily reduce the upper layer temperature prior to flashover.

Once flashover had occurred, at a hot layer temperature of 300 to 700°C, the lower level temperature rose to 300°C, making survival for occupants still in the compartment highly unlikely. The CFAST model shows a barely detectable rise to 100°C at the same time, but this is not unexpected as the model is not intended to be used for post-flashover conditions.

The gas species modelled in Figure 64 indicate life-threatening conditions, with oxygen content plummeting to 5% and carbon monoxide rising to 3500 ppm which, on its own, would be expected to be lethal after 30 minutes exposure (NIST, 1991).

A more positive aspect of the CFAST model is that the activation of the ceiling-mounted smoke alarm in the hallway can be predicted with the exercise of some judgement. The hot layer level in the hallway (compartment 4), beyond the closed door but with door leakage equivalent to 1% open, begins to descend at 80 seconds, and the temperature begins to rise at 100 seconds. Given that the ceiling-mounted smoke alarm activated at 140 seconds, this corresponded with a predicted temperature rise of 4°C at the same time that the measured temperature started to increase. This agreement is quite encouraging considering the sensitivity, to the results, of small vent openings. A 1% opening of the door was included to allow for leakage around its perimeter, and the gap would be likely to increase further due to warping as the temperature increased. As a rule of thumb, for modelling purposes, it could be predicted that 20 to 30 seconds after the layer level begins to descend, or the temperature begins to rise, a smoke alarm will activate. Most important of all, however, is the need to factor in some leakage around the perimeter of closed doors to get realistic modelling results in this type of situation.

9.5 Trial 22

Introducing wind conditions into CFAST did not work. This feature is not working in CFAST, although it does work in the earlier version FAST (the fire and smoke transport model utilised in HAZARD 1.1 (NIST, 1991). For this reason the 3.5 m/s northerly wind which was blowing at the time of the trial could not be incorporated into the modelling.

The experimental results in Figures 26 to 28 compared with the modelling in Figures 64 to 67 show distinct differences which can, in part, be attributed to the wind effects not being included. Quite clearly the wind had the effect of blowing the hot gases through the house and out of the open window in compartment 1 (bedroom 1), reducing the temperatures reached in all rooms. A consistent trend between the experimental results and the model showed that for compartment 2, with a closed window and thus considered as a dead space, the hot layer level descended closest to the floor.

9.6 Trial 23

This was a repeat of trial 22, but with the window and sliding door to compartments 3 and 5 respectively closed to negate the effect of the wind. The window to compartment 1 was open and the fire set was slightly larger than in trial 22. The comparison of results was markedly different this time.

The CFAST prediction of the hot layer level (Figure 69) shows it settling at a level of about 1m above the floor, probably due to the open window, while in all other compartments the hot layer descended to floor level. This is matched by the experimental results in Figure 30 where the hot layer level for compartment 1 is highest at about 750 mm, with the other compartments grouped around 500 mm.

The temperature in compartment 1 is over-predicted by 30°C, but for all other compartments agreement is within 5°C and the times at which the peaks are reached are consistent.

9.7 Modelling of Sprinkler Operation

The operation of the sprinkler system is compared with the predictions of Firecalc (CSIRO, 1992), where the input parameters are:

- the ceiling height (and sprinkler head height) in metres
- distance of sprinkler from axis of fire in metres
- initial room temperature in °C
- detector activation temperature °C
- detector response time index (RTI) in $m^{1/2}\ sec^{1/2}$
- heat release rate of the fire in kW.

The output is given as a predicted activation time along with a graphical representation of the heat release and temperatures of the air and detector (sprinkler head) against time.

9.8 Trial 24

This trial used a fast-response sprinkler head with an RTI of $31m^{1/2}sec^{1/2}$ in compartment 1. The measured heat output in Figure 24, taken as an average between the weighbridge and calorimeter outputs, was input to Firecalc. An activation time of 62 seconds was predicted (Figure 78) with an actual time of 62 seconds. It is perhaps coincidental that the times agree so closely considering that the sprinkler algorithm applies to an unbounded (by walls) ceiling instead of one where the hot gases are somewhat contained to the level of the soffits of the doors and windows.

9.9 Trial 25

A different sprinkler head was fitted, this time an 8mm bulb standard-response type with an RTI of $170m^{1/2}sec^{1/2}$. The fire in this trial was insufficient to activate the sprinkler, even though a heat output of 60 kW was exceeded for 2 to 3 minutes and the temperature reached the actuation temperature of 68°C briefly, as is shown in Figure 39. Firecalc (CSIRO, 1992) indicated that the sprinkler would not activate under the above exposure conditions.

9.10 Trial 26

Trial 25 was repeated with an increased fire load to provide sufficient heat and duration to activate the sprinkler. The heat output according to Figure 45 was about 90 kW and the temperature rose to 100 °C in the upper layer. Under these conditions the sprinkler activated at 183 seconds after ignition. The Firecalc (CSIRO, 1992) prediction for activation was 154.6 seconds and is shown in Figure 79. This is somewhat earlier than actually occurred.

9.11 Trial 27

The CFAST modelling of this realistic scenario matched the hot layer descent in the fire compartment (1) to a level of about 600mm above the floor. For the other compartments (2 to 5) it had the hot layer level descending to floor level, whereas it was observed that there was actually about 1 metre of relatively clear air at floor level. Temperatures were under-predicted, but followed the general trend. It is assumed that the actual heat output of the fire, as measured by the calorimeters, must be greater than the input to the CFAST model.

10. SUMMARY AND CONCLUSIONS

10.1 CFAST Model

The following summary of the conclusions gained from this study is intended to provide the reader and user of the CFAST software with guidance on which input parameters are likely to need adjustment to gain maximum benefit from the model. The experimental results can be used to compare output data from the model, and a sample input programme is included in Appendix C. The user can then vary the openings/vent sizes to suit, and introduce the appropriate fire source.

1. Predictions of layer height are more reliable and useful in determining the time when the initial descent occurs than the final level reached. The major benefit here is in determining when smoke alarms are likely to be activated. It is advisable to also check that an initial temperature rise in the upper layer (2 to 4°C is sufficient) has occurred, as a further indicator that hot gases and, of course, smoke are present.

2. It is unlikely that the hot layer descends all the way to the floor level. A cool layer of at least 300 mm has been observed in trials and is likely to remain up until flashover has occurred.

3. Activation of heat detectors or sprinklers can be confidently determined by the initial temperature rise in the upper layer.

4. The effect of open vents, especially doors, can be reliably modelled, provided account is taken of the equivalent open area. Closed doors can be modelled if the gaps around the perimeter are measured and a leakage allowance is included in the model input.

5. Some judgement is needed with windows breaking in a fire, as 100% opening is never reached and neither is the full height, at least not until window frames are completely burnt out.

6. Computer models are more useful for reconstruction of fire scenarios than for predicting possible outcomes beforehand. This is because clues as to the progress of a fire, as well as the extent of broken windows and venting, are likely to be available and these can be used in modelling.

7. From trials 21 and 27 it appears that windows commence breaking once upper layer temperatures of 300°C are reached, although this is more likely to be the result of the difference in temperature across or within the pane of glass, and is determined by the type of glass. However, this provides a useful datum point for increasing the ventilation in CFAST trial runs.

10.2 General Fire Development

Three different fuel types were used for the trial fires.

1. The methylated spirit pan fires, while completely artificial in terms of realistic fire scenarios, did provide valuable and easily monitored heat input to the compartments. The rates of heat output were characterised by rapid growth, followed by a slow decay, and this data was used primarily to validate the CFAST predictions. The species generated were mainly water, carbon dioxide and, generally, a very small yield of carbon monoxide and no soot. Oxygen content in the case of test 13 when all vents were closed, dropped to 13%, which almost extinguished the fire. Accordingly, the carbon monoxide content increased appreciably, but to nowhere near a dangerous level.

2. The single wood crib fire was slower in development and decay compared with the methylated spirit fires. The yield of carbon monoxide was correspondingly higher, for the oxygen consumed, but never reached a dangerous level.

3. The two fires involving items of furniture provided the only realistic scenarios. Both of these were permitted to develop to a stage where the temperature exceeded 500°C, providing valuable data on smoke transport and gas species production for comparison with CFAST. Both of these fires were extinguished before any serious damage to the building occurred, as the building used here is required for further fire experiments.

10.3 Effectiveness of Smoke Alarms, Heat Detectors and Sprinklers

1. The ionisation-type smoke alarms gave a very early indication of the presence of smoke and proved an effective means of early warning of fire, even when separated from the fire source by closed doors. Smoke alarms represent the most economical and easily installed protection device that may be installed in domestic housing, provided they are maintained in working order. For rental accommodation hard-wired smoke detectors may be the preferred option.

2. The response of the ceiling-mounted heat detectors was consistent with the rise in temperature of the upper layer exceeding the activation temperature of 57°C. These devices, with a very low RTI, are a viable protection option in areas such as kitchens where cooking vapours could cause false alarms if smoke alarms were the option chosen.

3. In the trials conducted on the sprinkler system with fast-response sprinkler heads fitted, their activation was reliably predicted by Firecalc (CSIRO, 1992). The standard-response heads, however, were slow to activate and although it was not proven by the two tests, a genuine concern is acknowledged that a fire may spread beyond such a sprinkler's spray pattern before it activates. The effectiveness of the fast-response sprinklers was convincingly demonstrated in both rapid activation and extinguishment of a furniture fire. This system represents a viable domestic fire protection option and, provided the regulations applying to the security of water supply can be easily met, their widespread use should be encouraged.

10.4 General Comments

This study has strengthened the already compelling case supporting the benefits of smoke alarms and heat detectors as an economical and effective fire safety strategy. The role of domestic sprinklers, while not an inexpensive option, was shown to be equally decisive as a means of limiting hazard to life and fire damage.

The confidence gained in the application of computer models will encourage their usage in the assessment of hazard situations, producing more cost-effective solutions to building problems where fire safety is an issue.

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Figure 9: Heat output methylated spirits pan fire, test 12

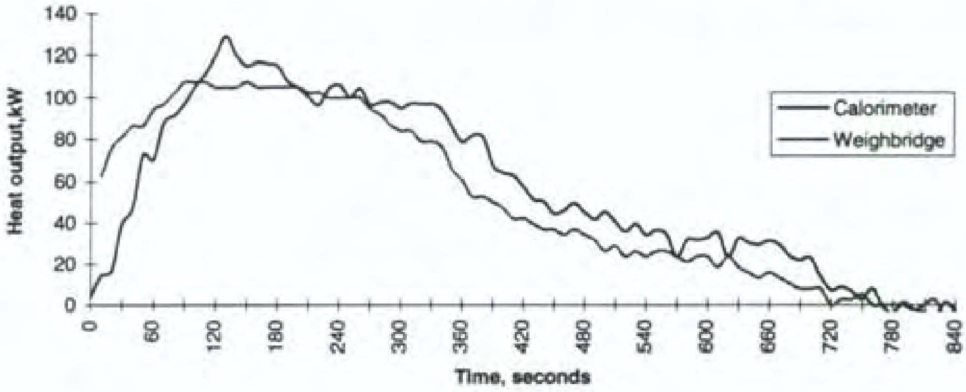

Figure 10: Gas species in lower level, test 12

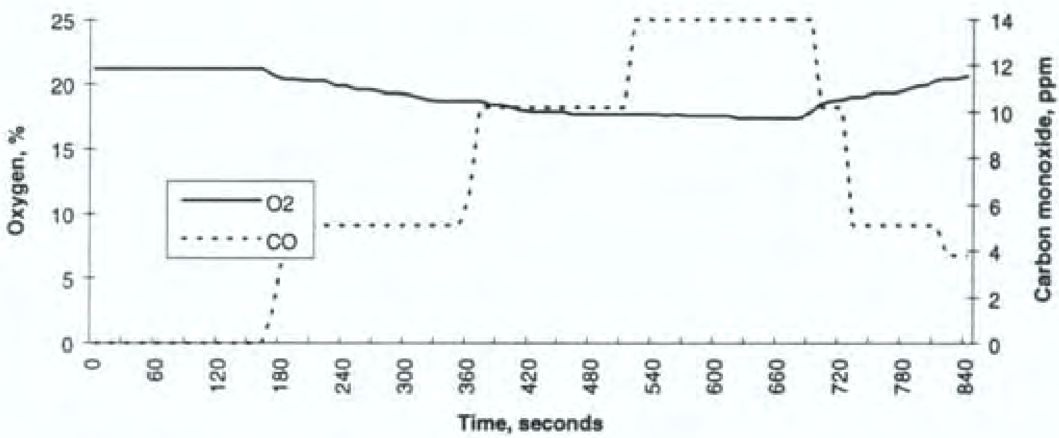

Figure 11: Hot layer level, test 12

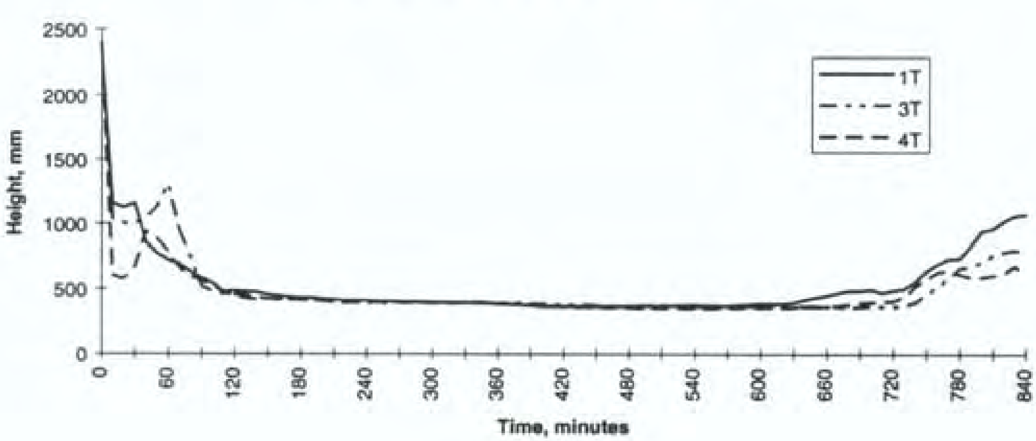

Figure 12: Upper layer temperatures, test 12

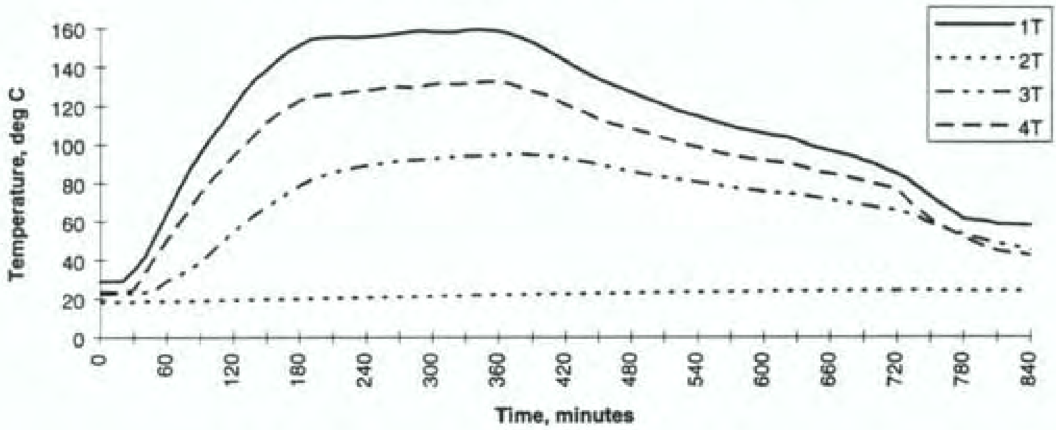

Figure 13: Lower layer temperatures, test 12

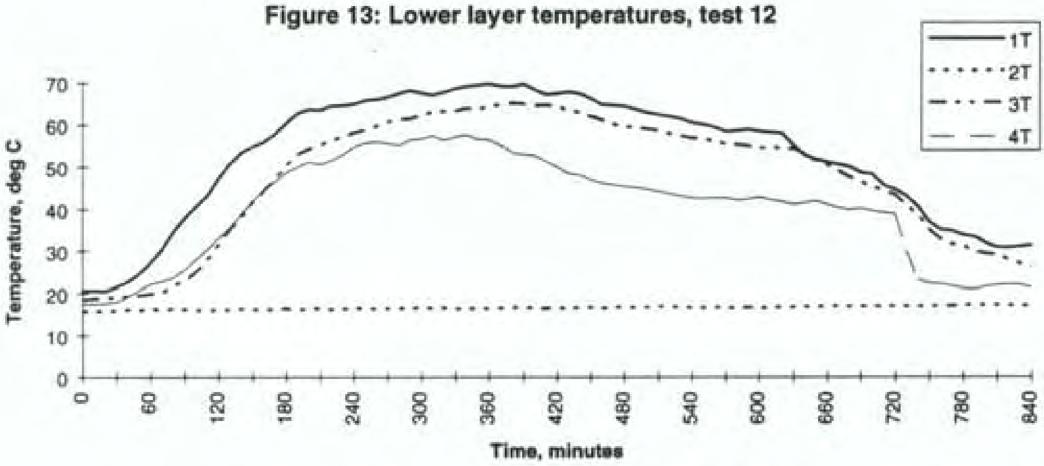

Figure 14: Heat output test 13.

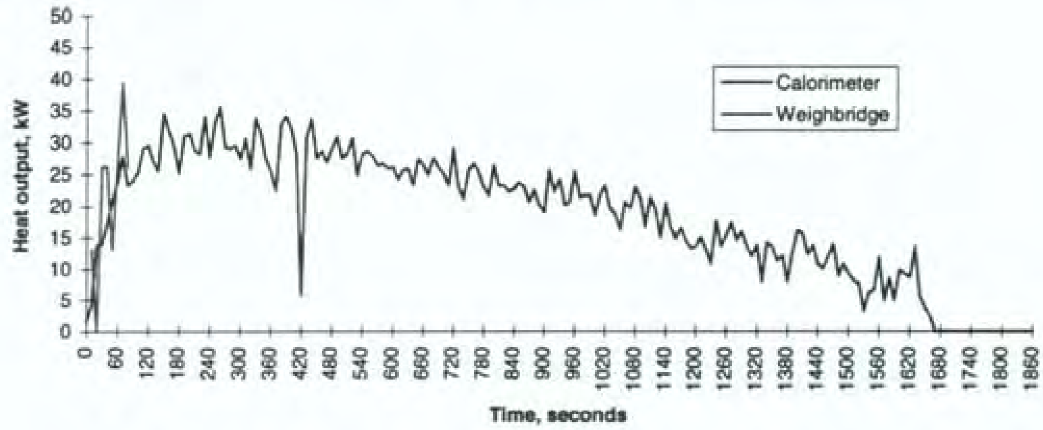

Figure 15: Gas species in lower level, test 13

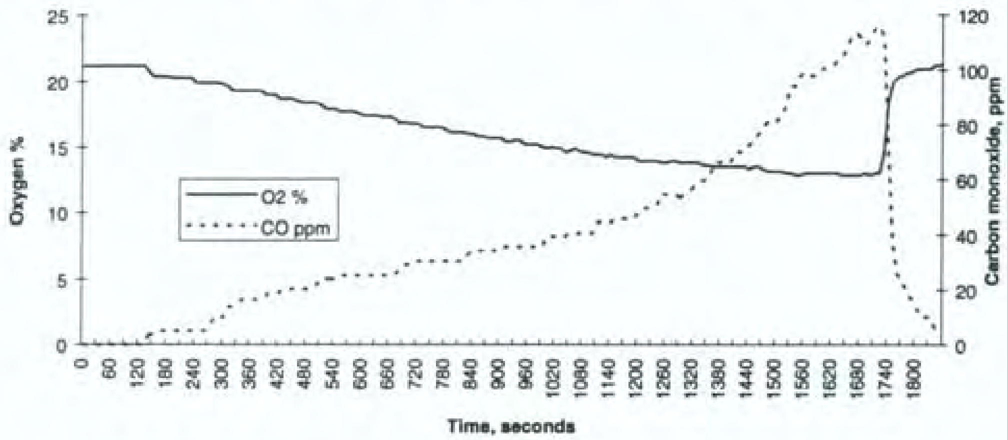

Figure 16: Layer height and temperatures, test 13

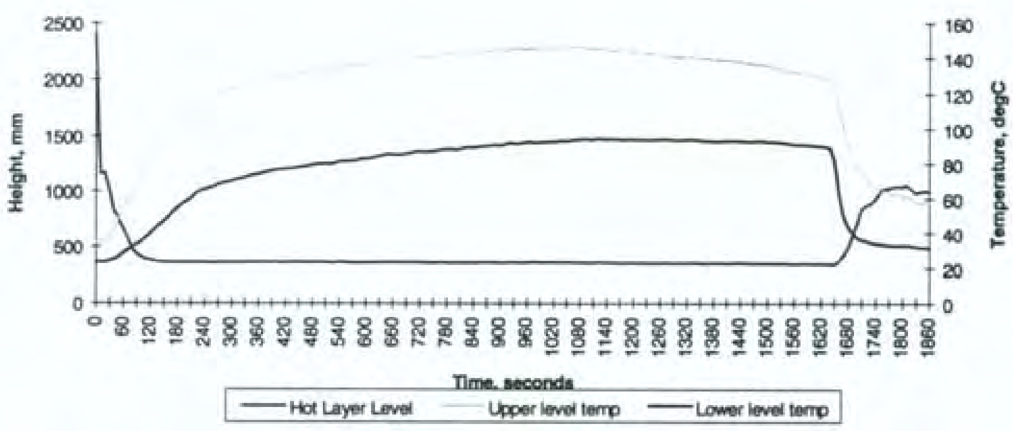

Figure 17: Temperatures in hallway, test 13

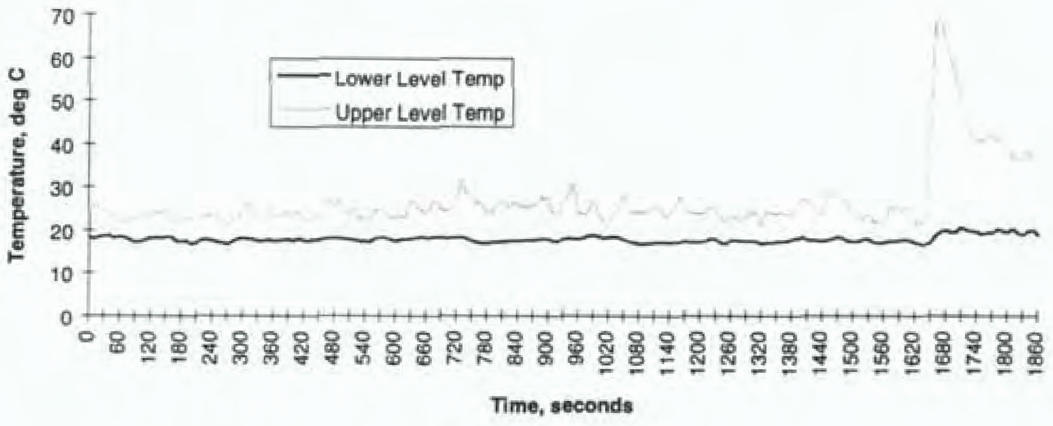

Figure 18: Heat input, test 16

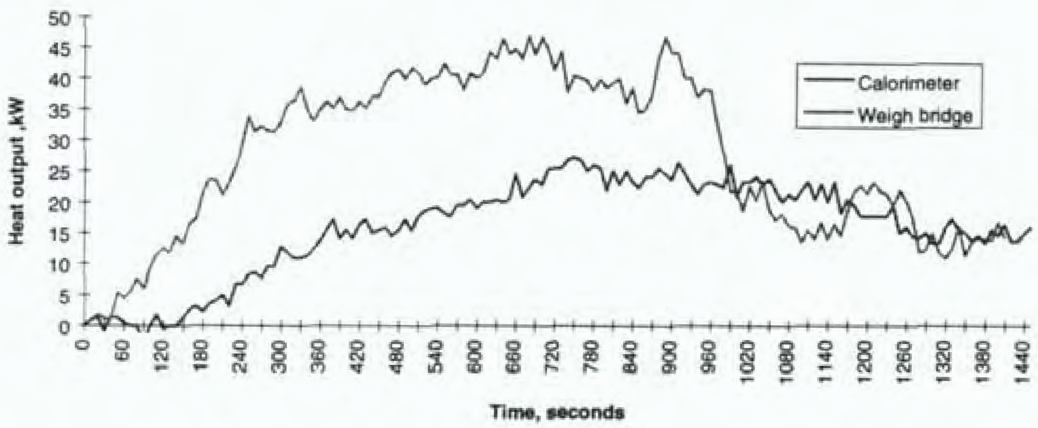

Figure 19: Gas species, test 16

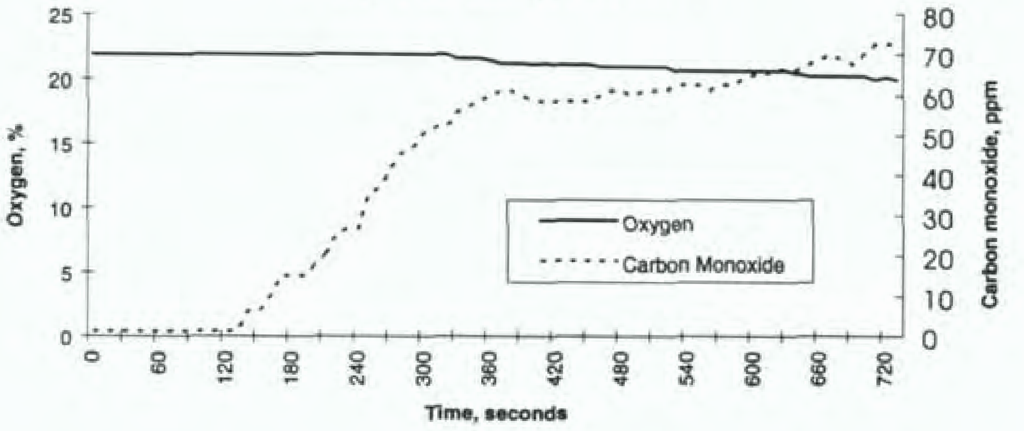

Figure 20: Layer heights, test 16

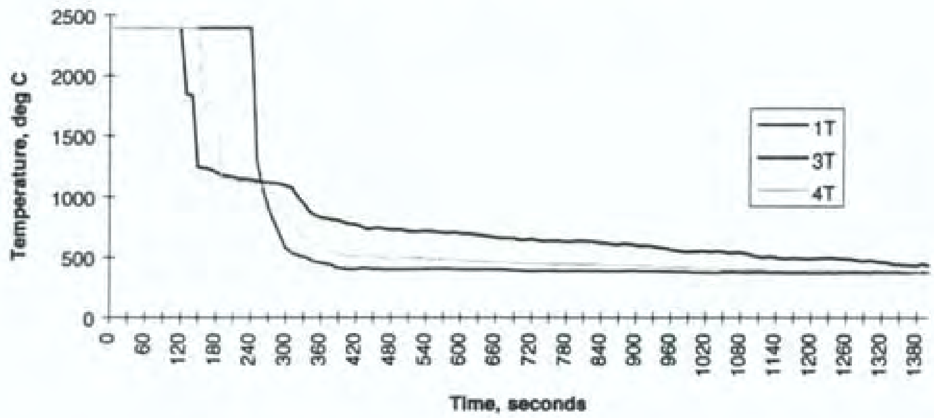

Figure 21: Upper layer temperatures, test 16

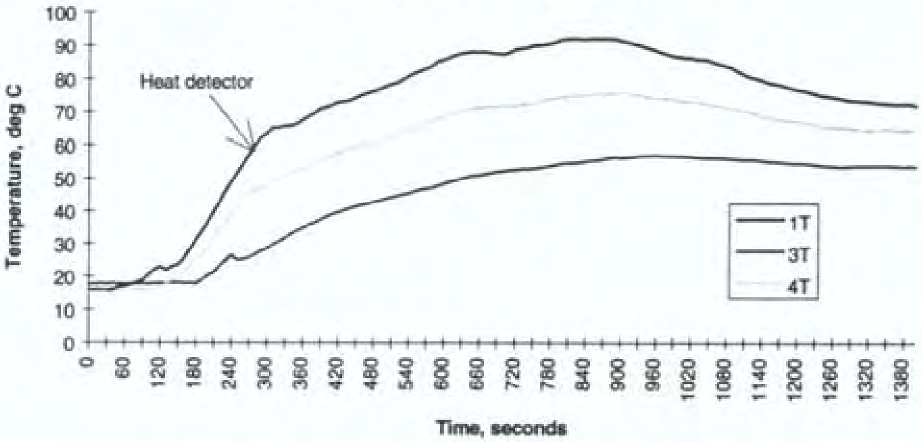

Figure 22: Lower layer temperatures, test 16

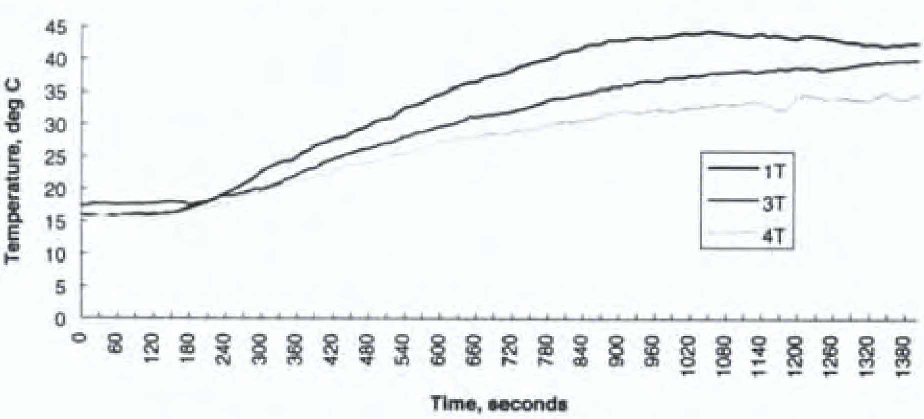

Figure 23: Layer height and temperatures, test 20

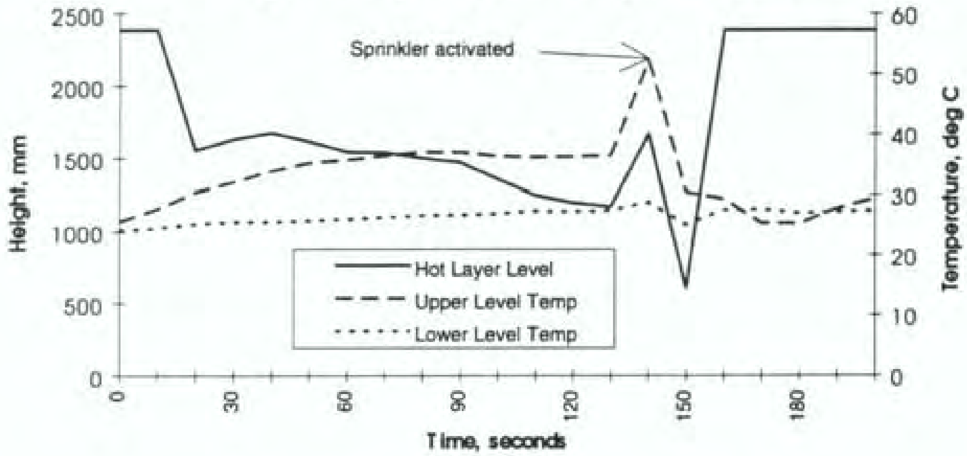

Figure 24: Gas species, test 20

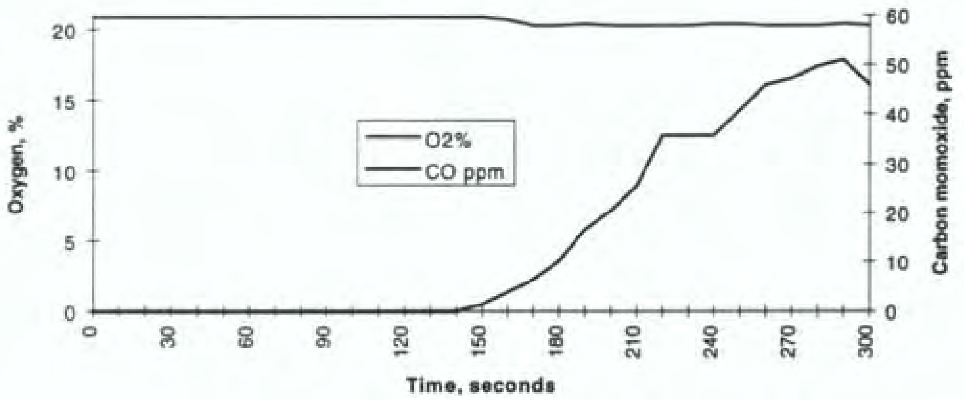

Figure 25: Layer height and temperatures, test 21

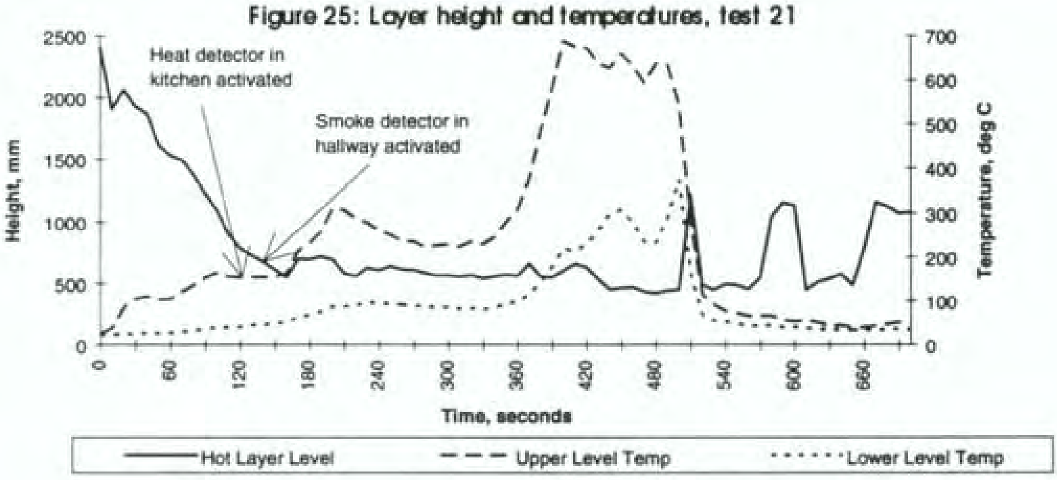

Figure 26: Hot layer level, test 22

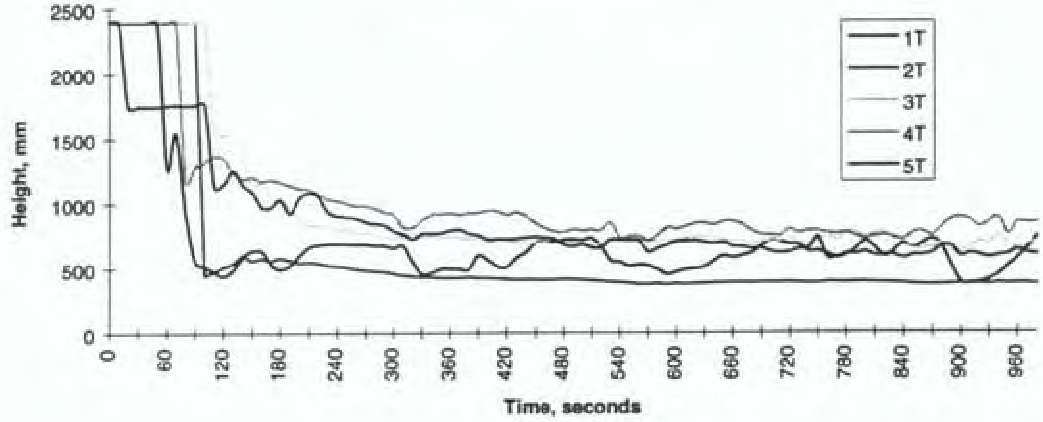

Figure 27: Upper layer temperature, test 22

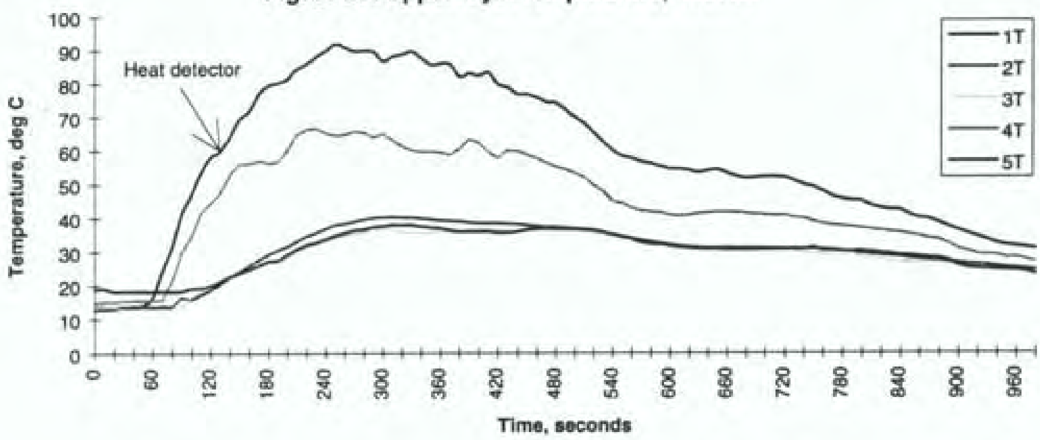

Figure 28: Lower layer temperatures, test 22

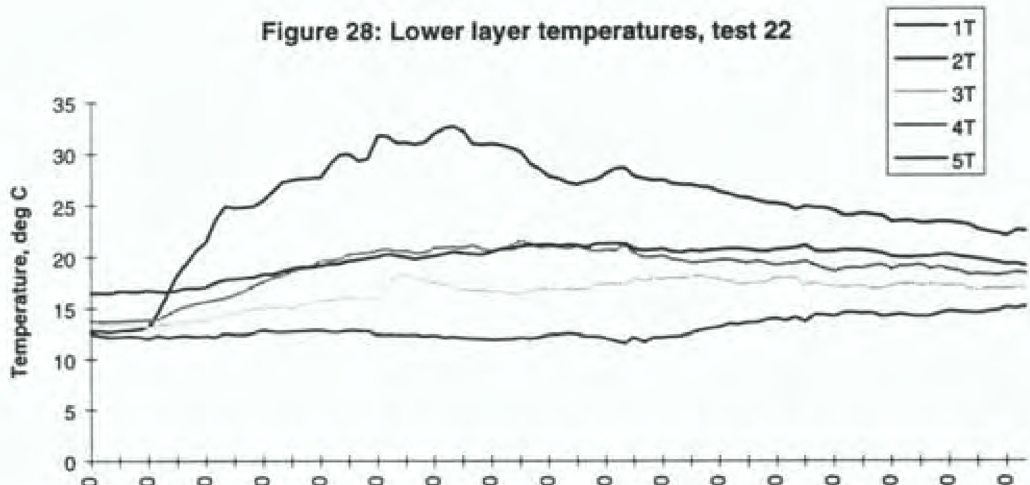

Figure 29: Heat output methylated spirits pan fire, test 22

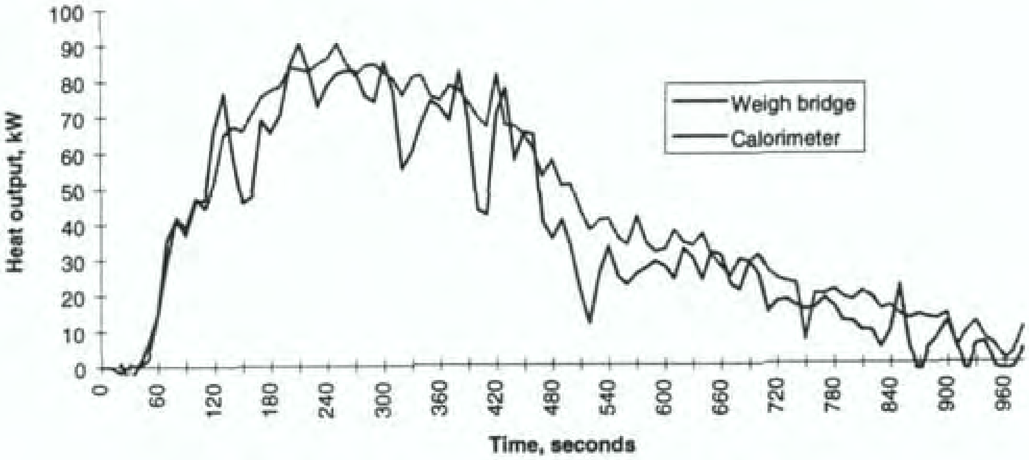

Figure 30: Hot layer level, test 23

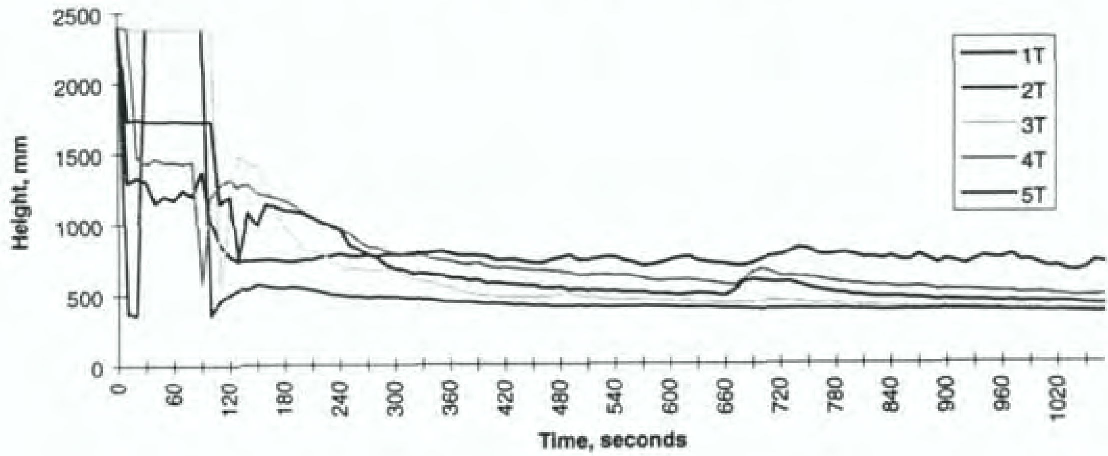

Figure 31: Hot layer temperatures, test 23

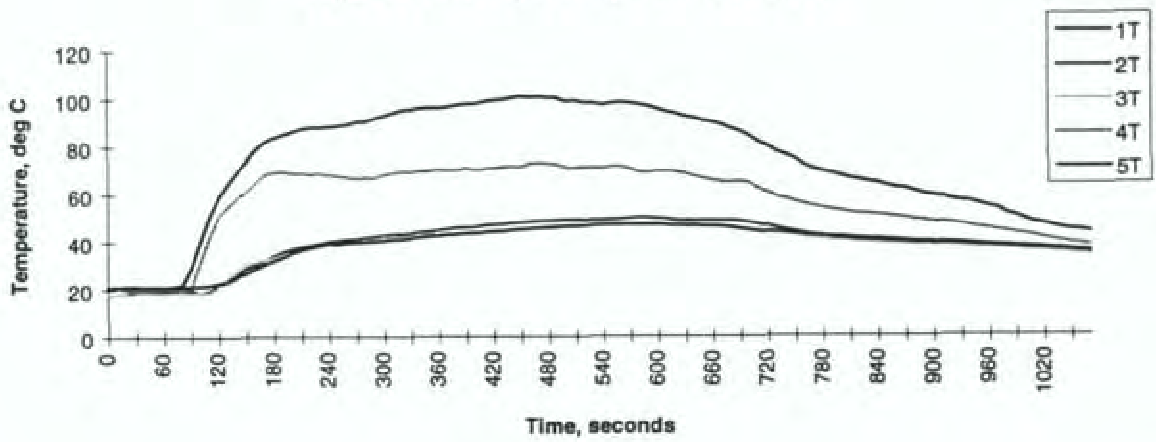

Figure 32: Lower layer temperatures, test 23

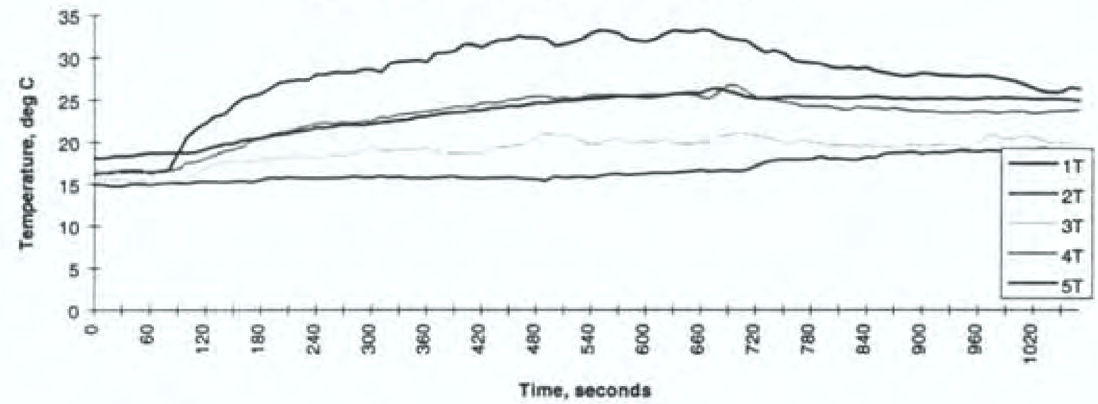

Figure 33: Heat output methylated spirit pan fire, test 23

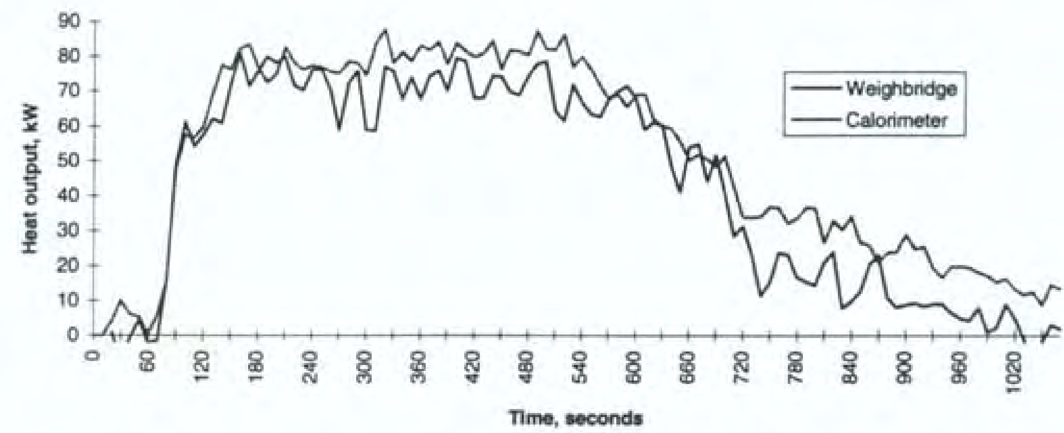

Figure 34: Hot layer level, test 24

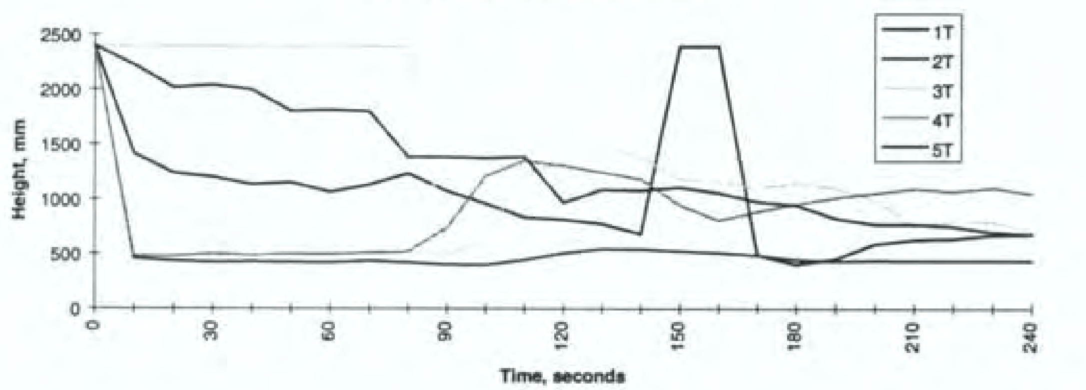

Figure 35: Hot layer temperatures, test 24

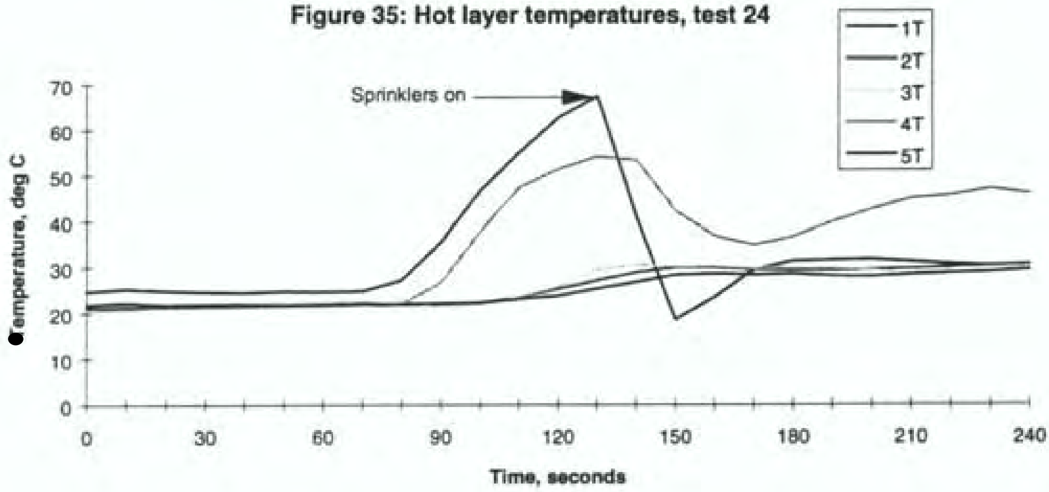

Figure 36: Lower level temperatures, test 24

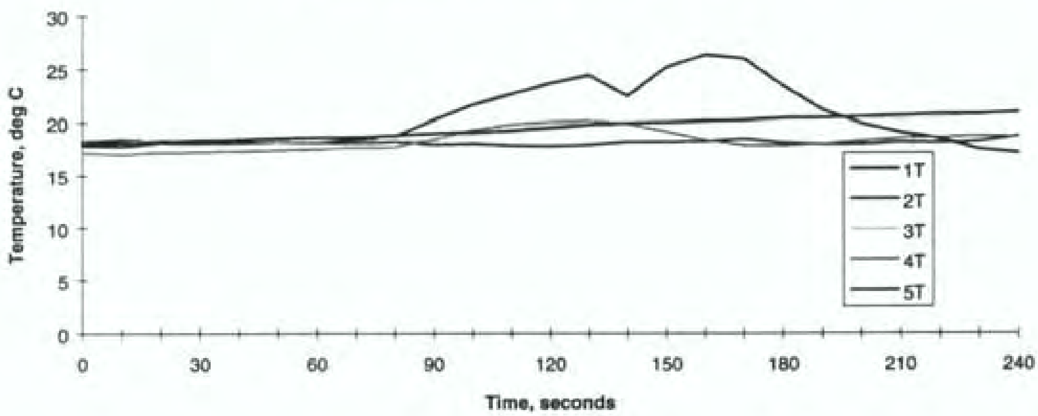

Figure 37: Heat output methylated spirits pan fire, test 24

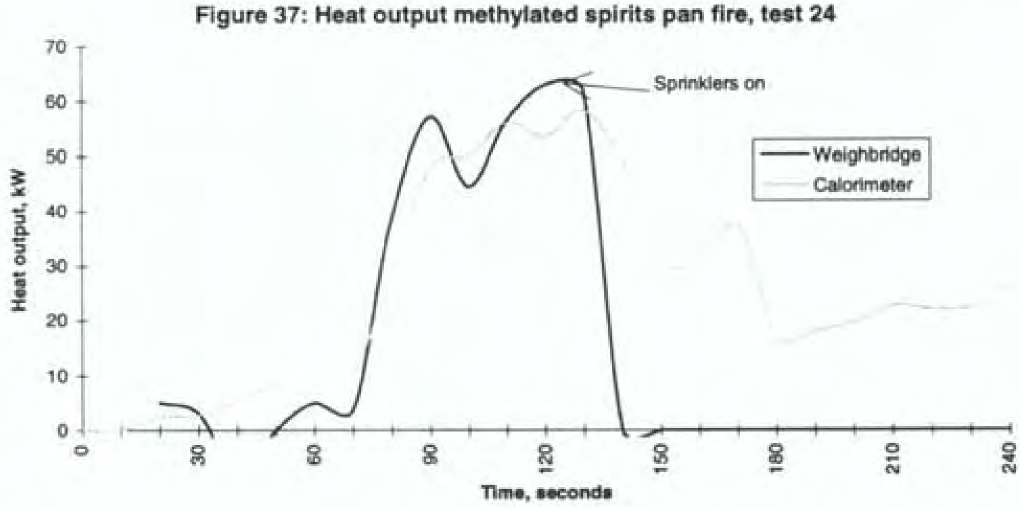

Figure 38:Hot layer level, test 25

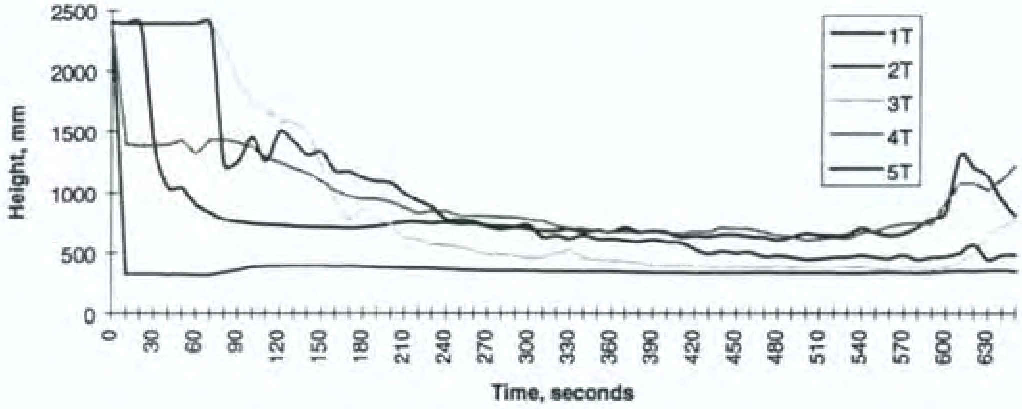

Figure 39: Upper layer temperatures, test 25

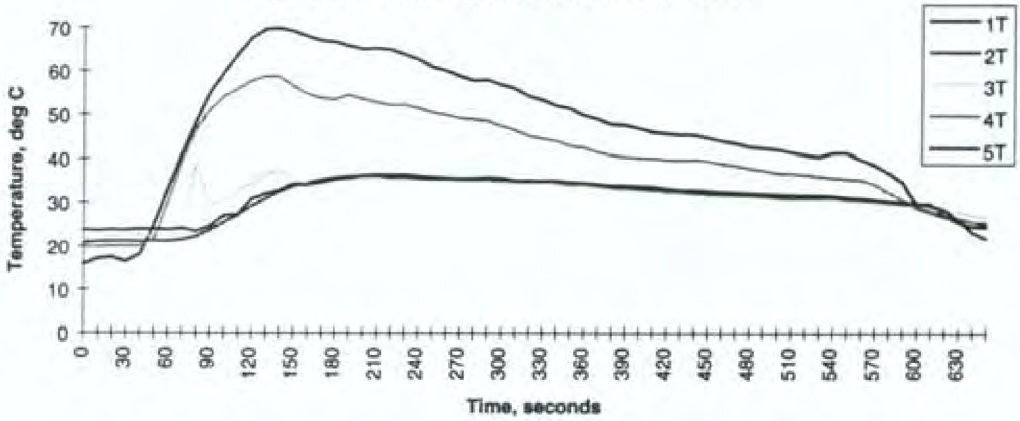

Figure 40: Lower layer temperatures, test 25

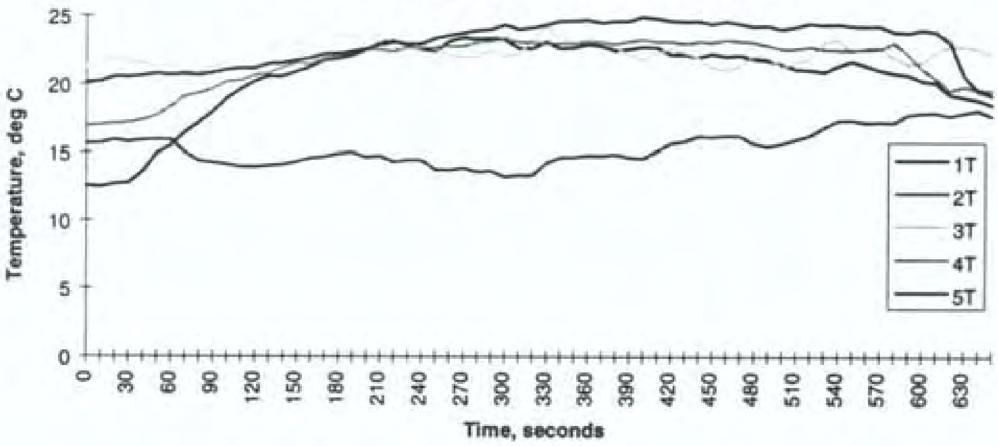

Figure 41: Heat output methylated spirit pan fire, test 25

Figure 42: Hot layer levels, test 26

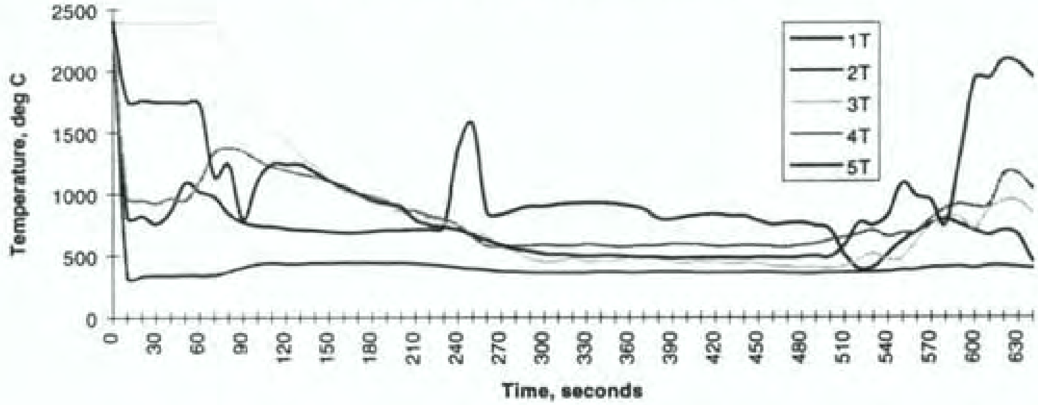

Figure 43: Upper layer temperatures, test 26

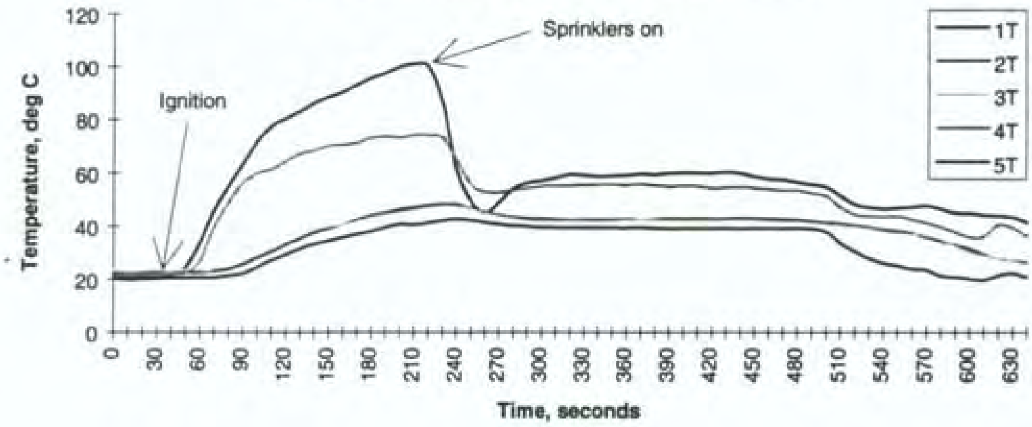

Figure 44: Lower layer temperatures, test 26

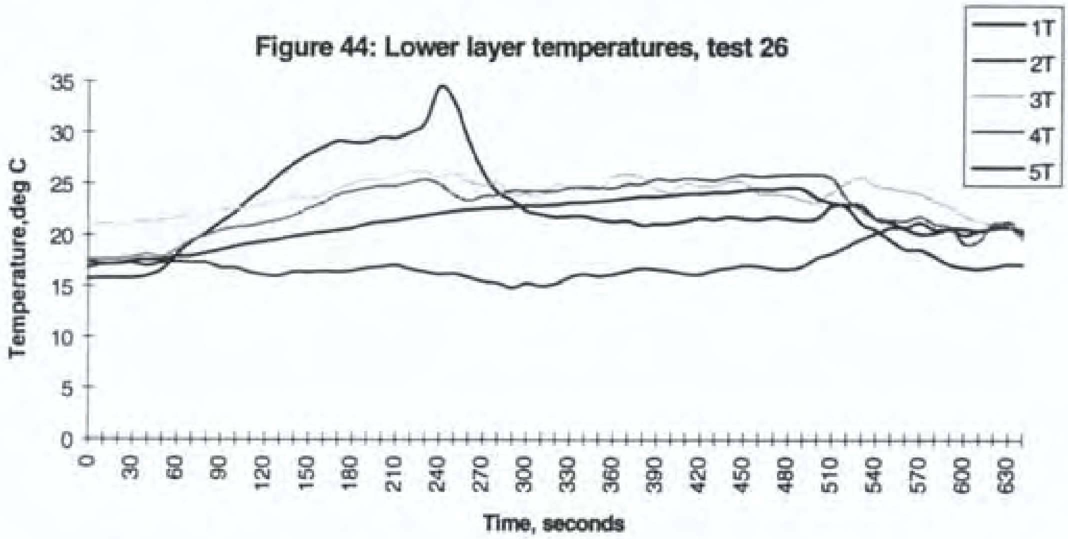

Figure 45: Heat output methylated spirits pan fire, test 26

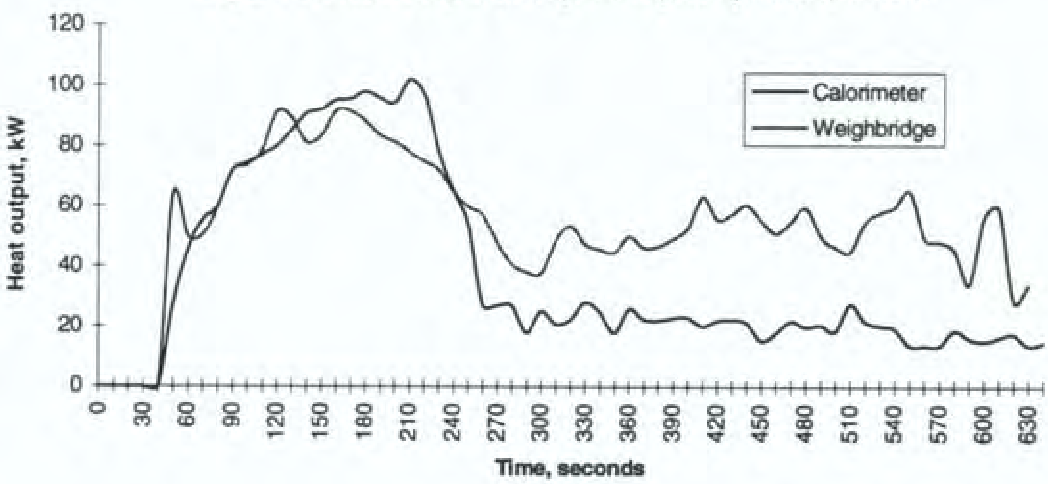

Figure 46: Layer heights, test 27

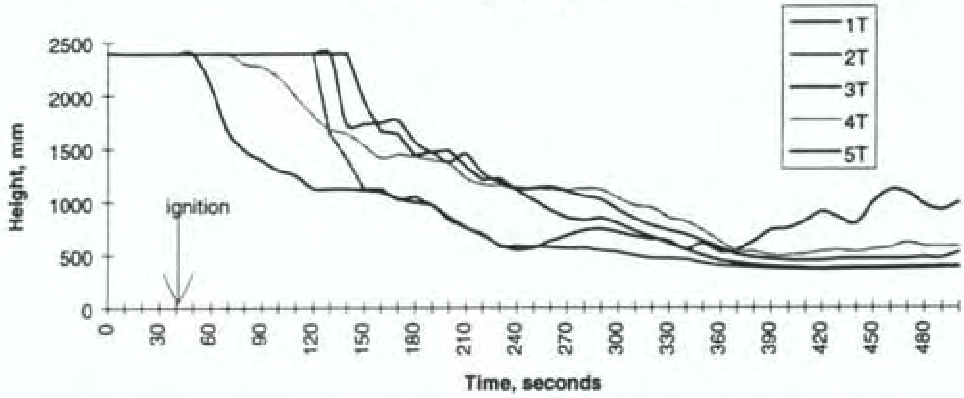

Figure 47: Upper layer temperatures, test 27

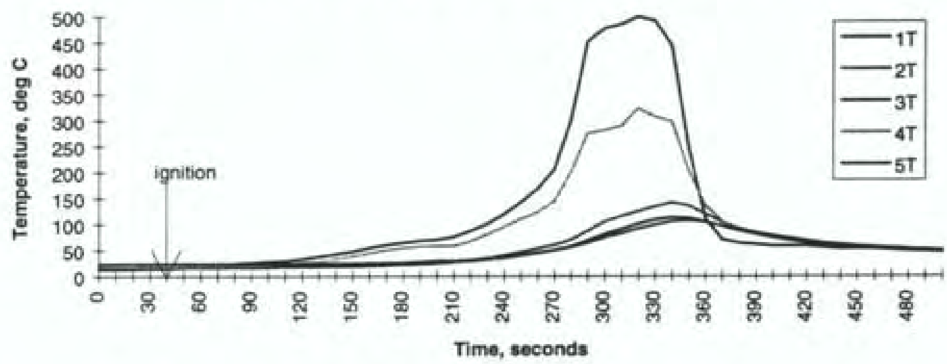

Figure 48: Lower layer temperatures, test 27

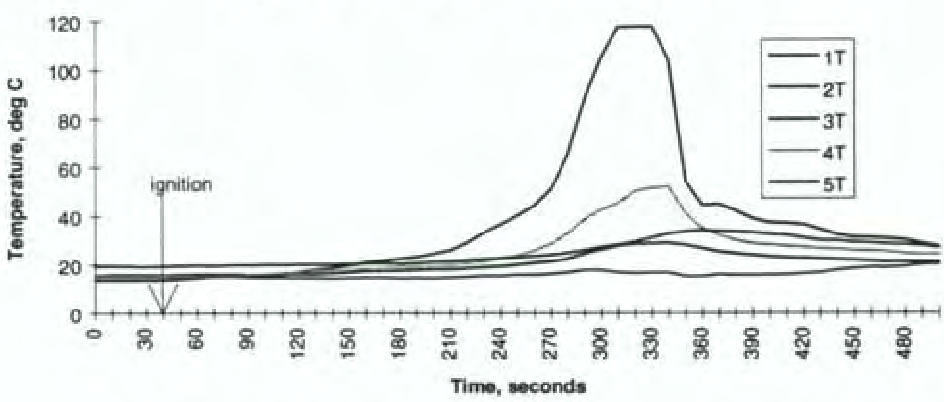

Figure 49: Gas species, test 27

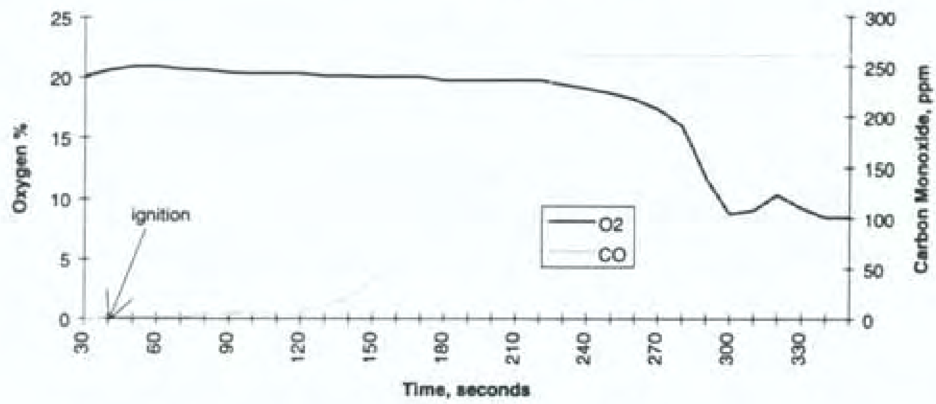

Figure 50: Heat output vinyl-covered polyurethane chair fire, test 27

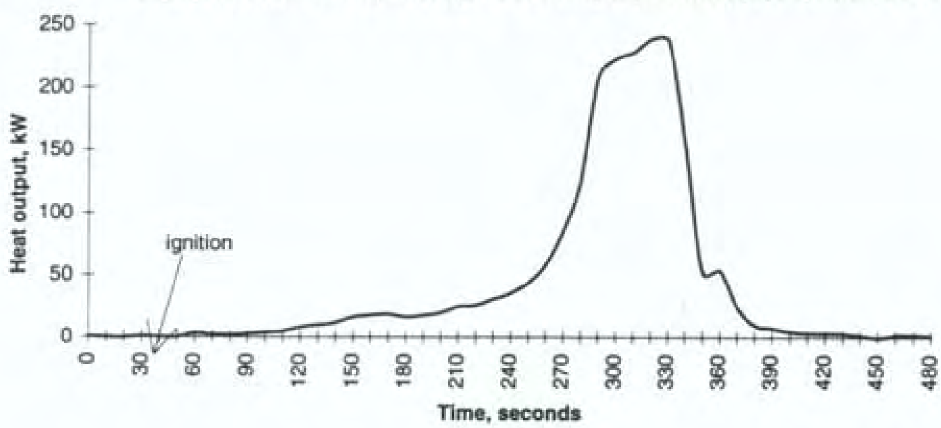

Figure 51: Hot layer levels, CFAST 12

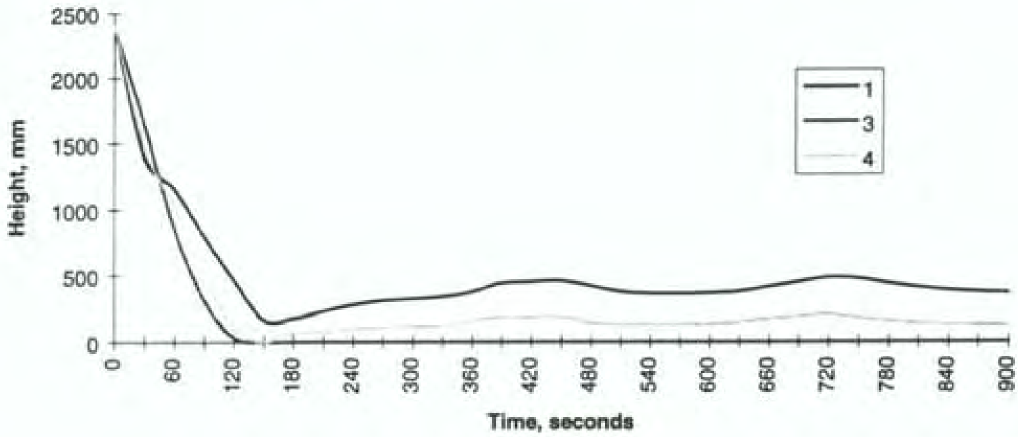

Figure 52: Upper layer temperature, CFAST 12

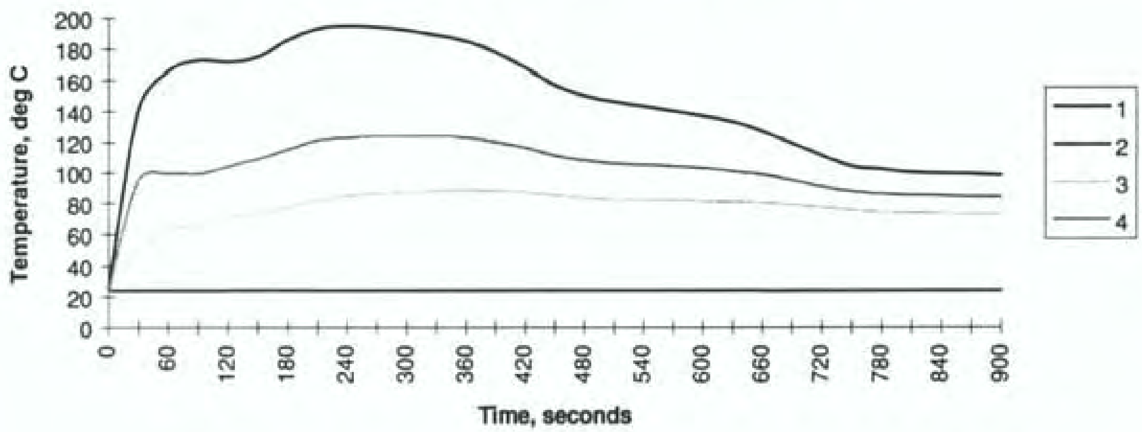

Figure 53: Lower layer temperatures, CFAST 12

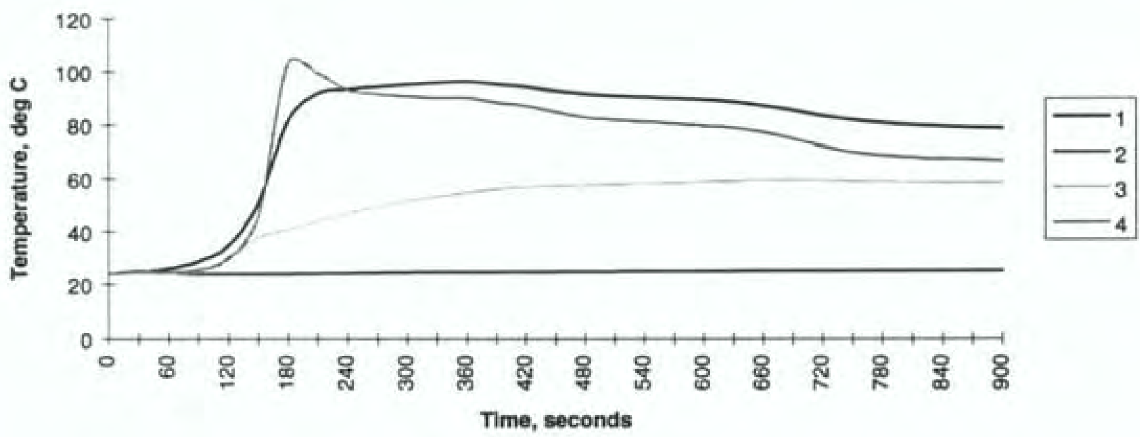

Figure 54: Layer height and temperatures, CFAST 13

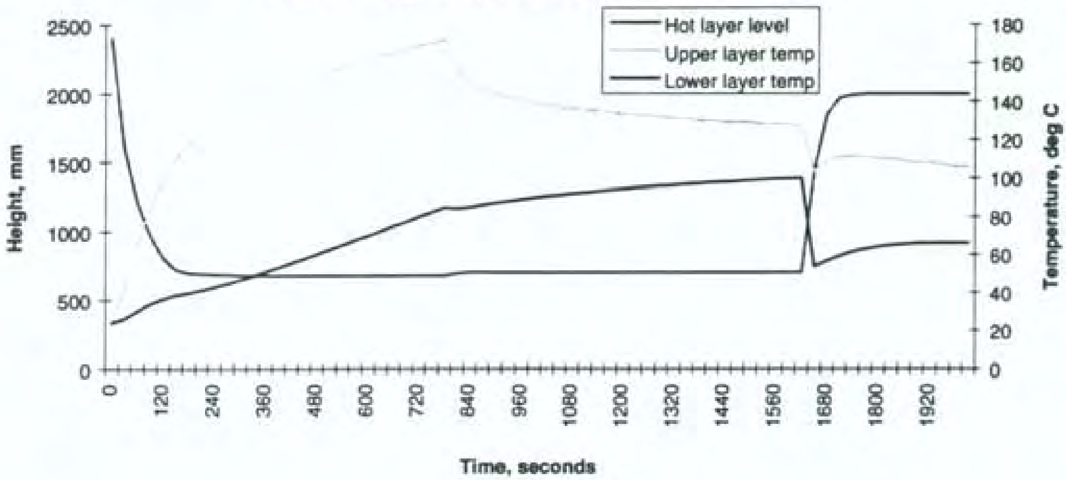

Figure 55: Temperatures in hallway, CFAST 13

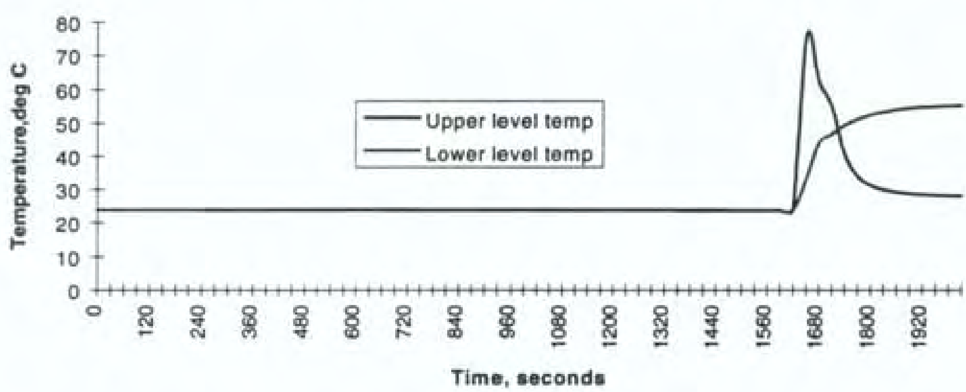

Figure 56: Heat output methylated spirits pan fire, CFAST 13

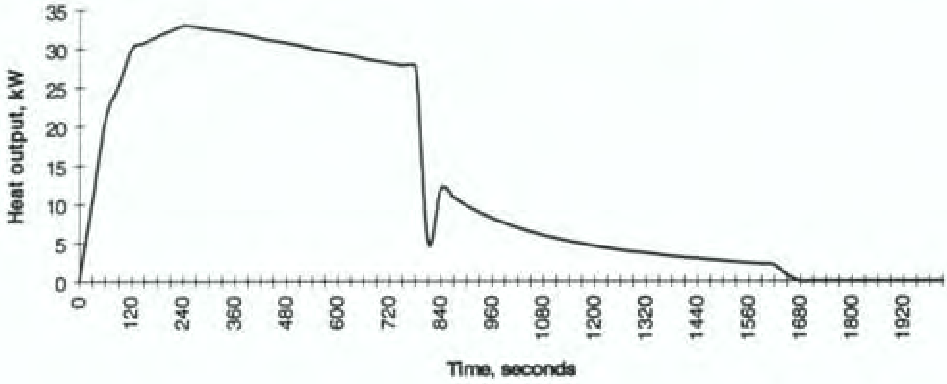

Figure 57: Gas species, CFAST 13

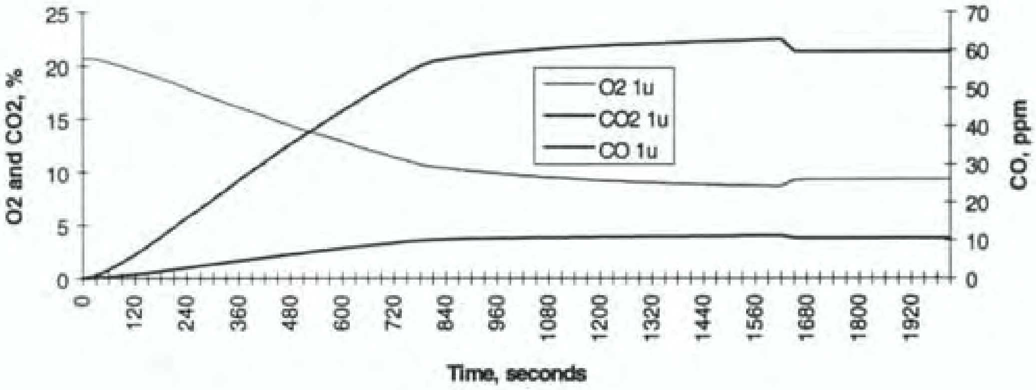

Figure 58: Heat output wood crib fire, CFAST16

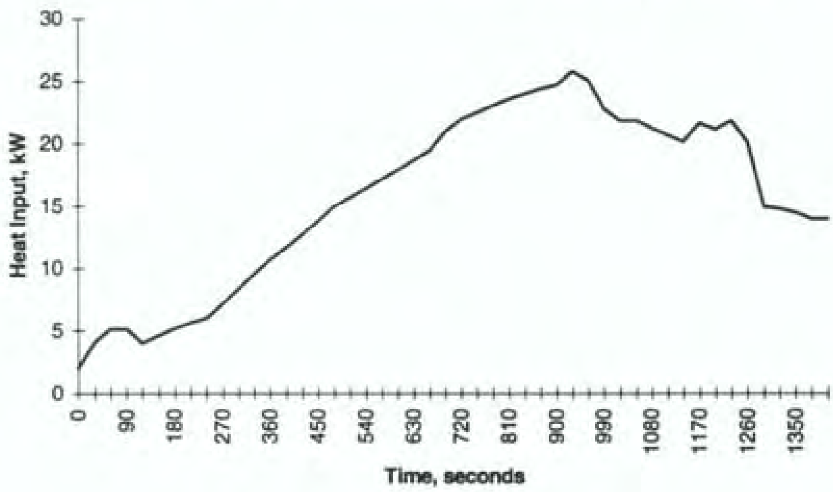

Figure 59: Layer height, CFAST 16

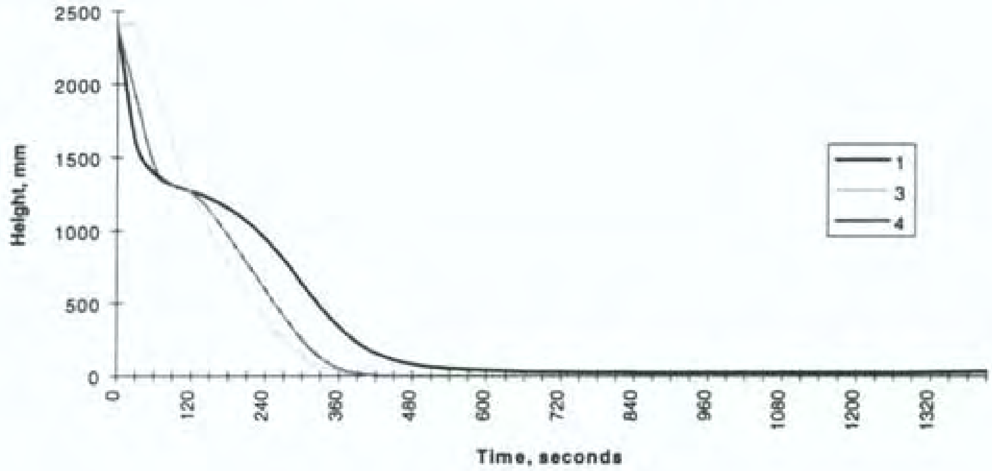

Figure 60: Hot layer temperatures, CFAST 16

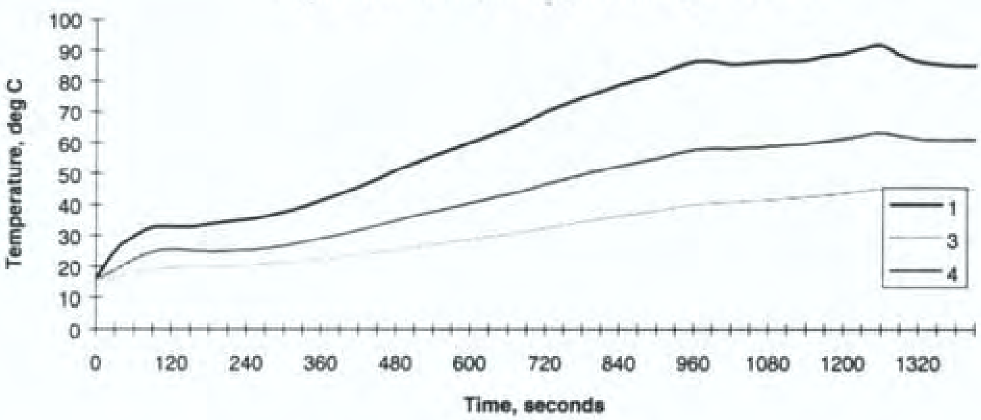

Figure 61: Lower layer temperatures, CFAST 16

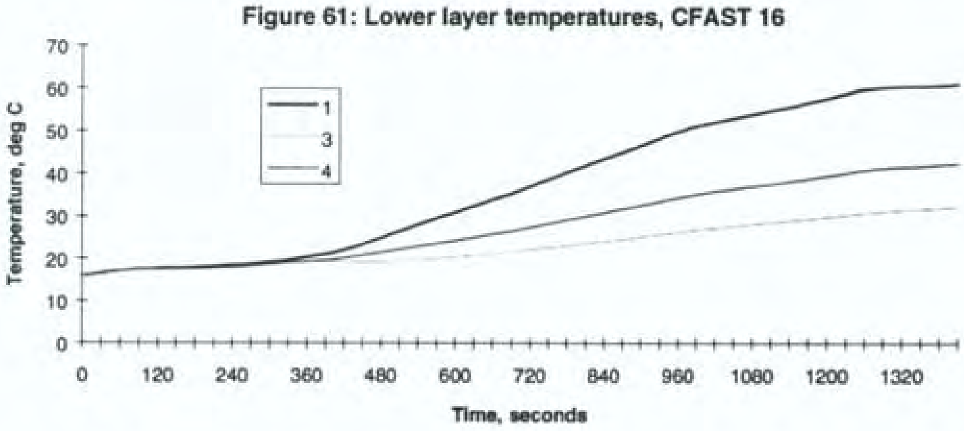

Figure 62: Gas species, CFAST 16

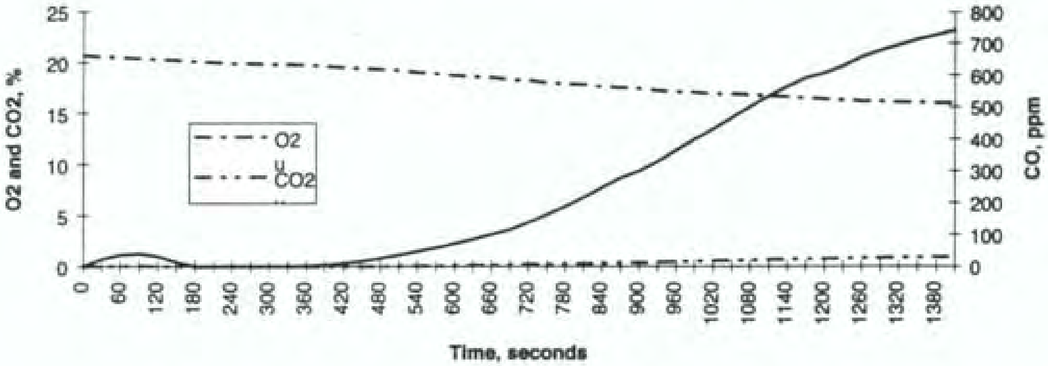

Figure 63 : Layer height and temperatures, CFAST 21

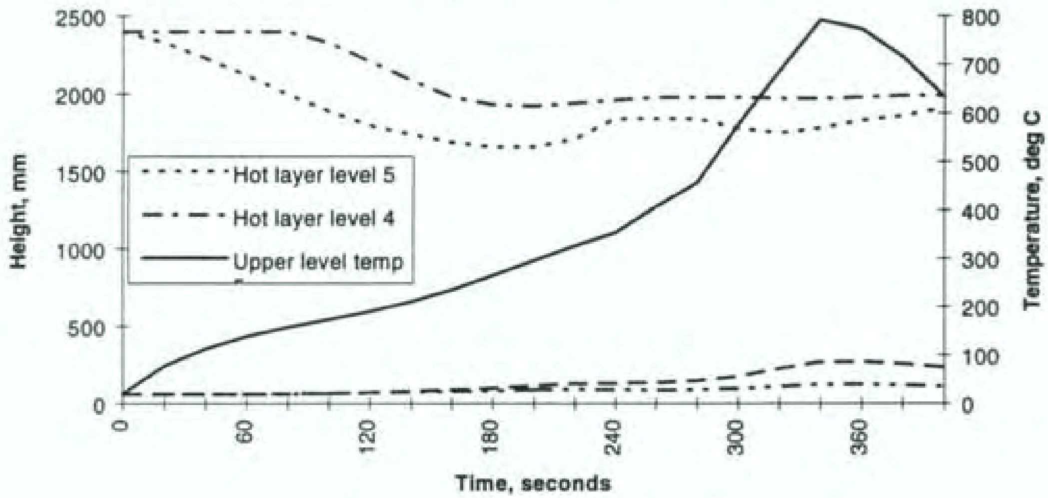

Figure 64: Gas species, CFAST 21

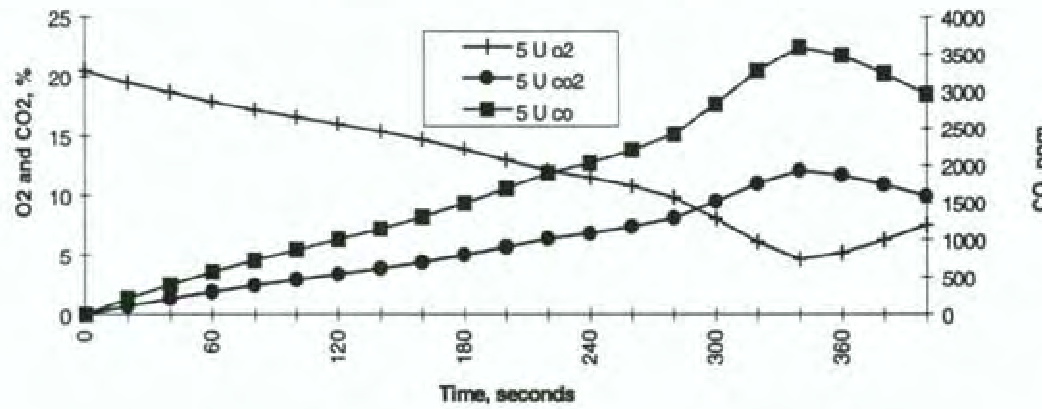

Figure 65: Hot layer levels, CFAST 22

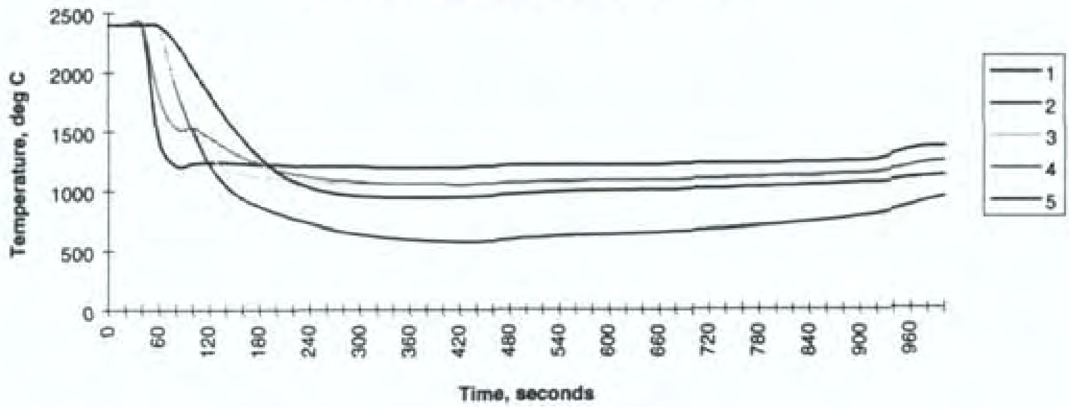

Figure 66: Upper layer temperature, CFAST 22

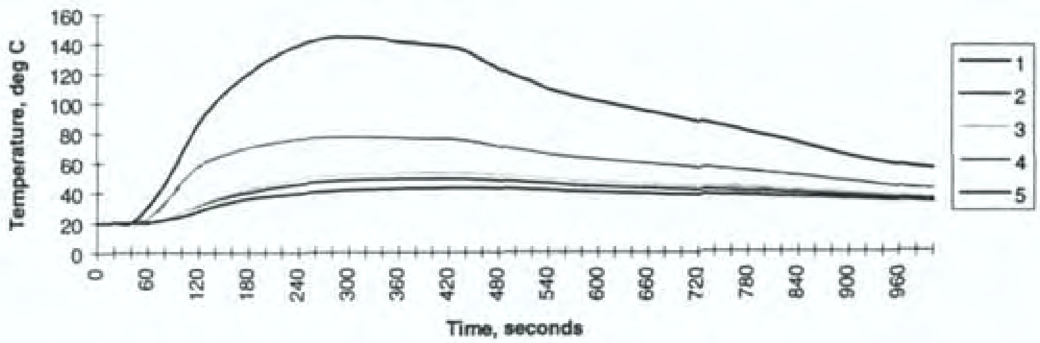

Figure 67: Lower layer temperatures, CFAST 22

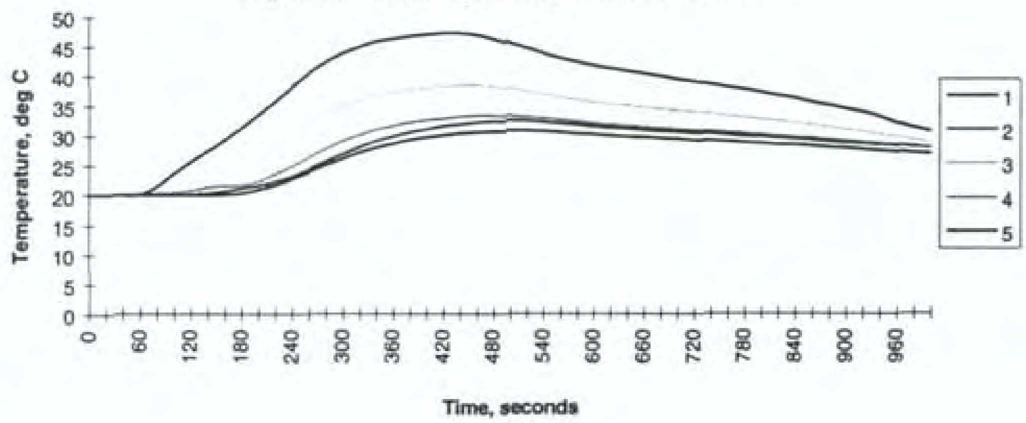

Figure 68: Heat output, CFAST 22

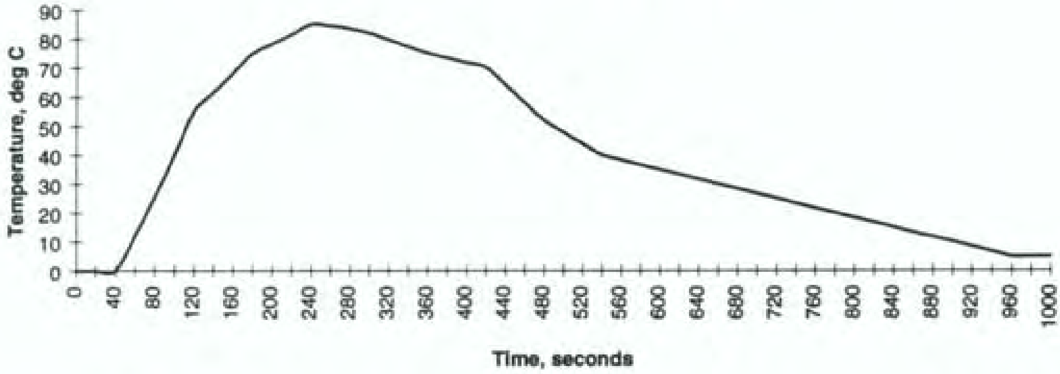

Figure 69: Hot layer level, CFAST 23

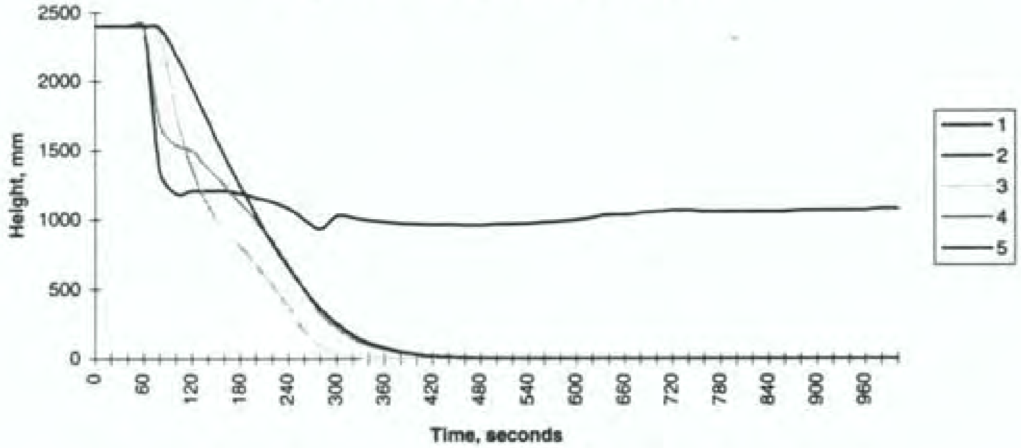

Figure 70: Upper layer temperatures, CFAST 23

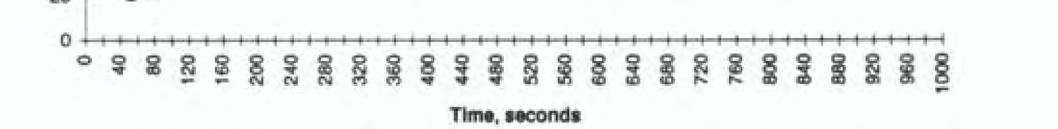

Figure 71: Lower layer temperatures, CFAST 23

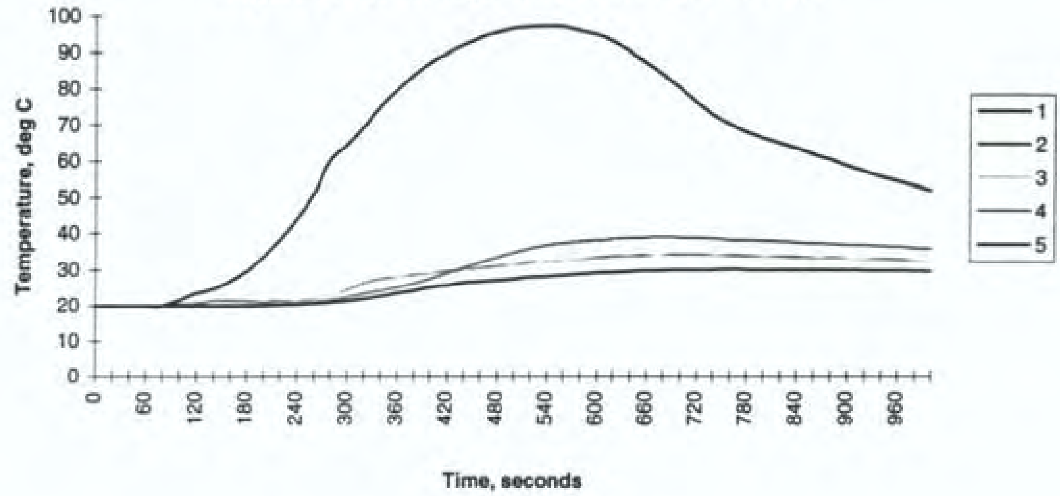

Figure 72: Heat output, CFAST 23

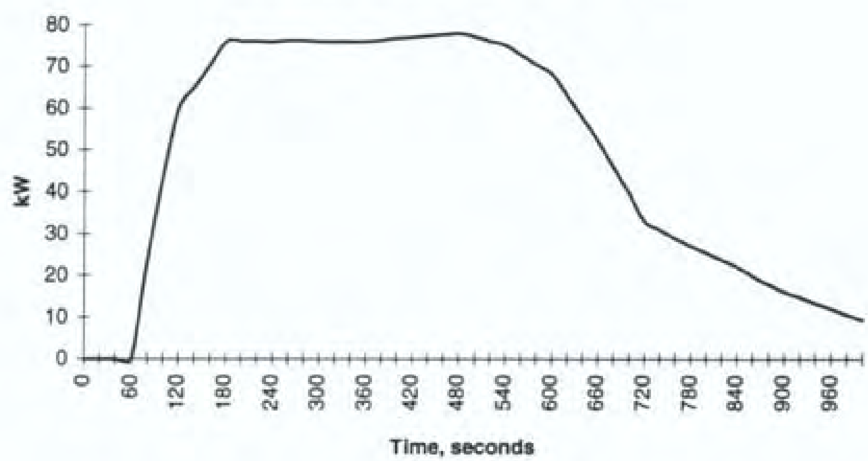

Figure 73: Hot layer levels, CFAST 27

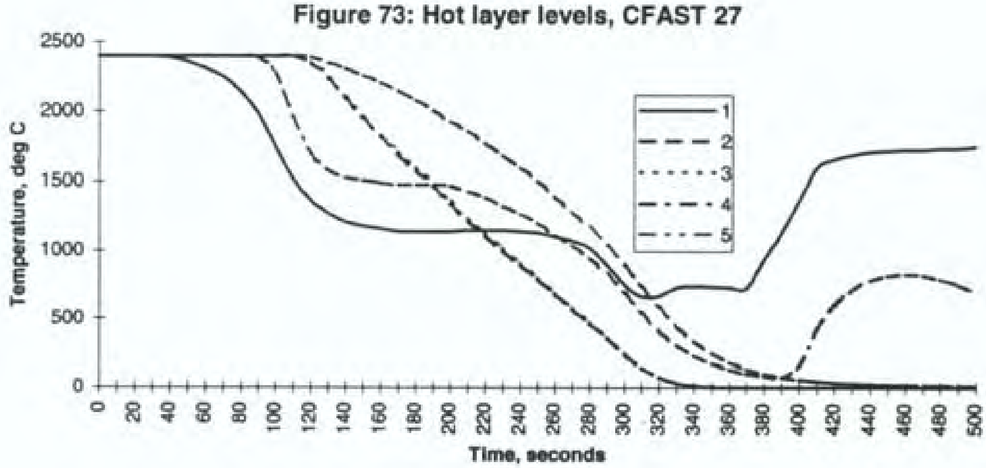

Figure 74: Upper layer temperatures, CFAST 27

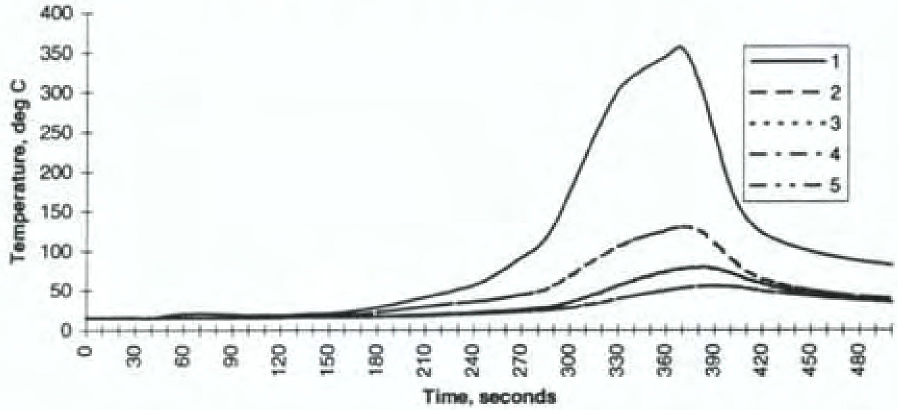

Figure 75: Lower layer temperatures, CFAST 27

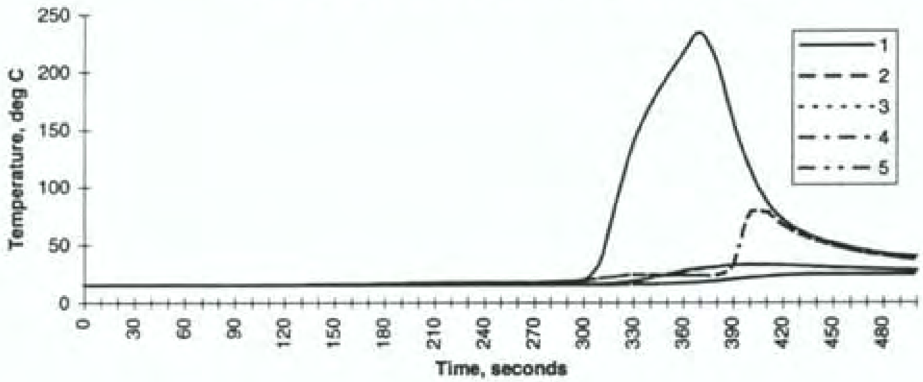

Figure 76: Gas species. CFAST 27

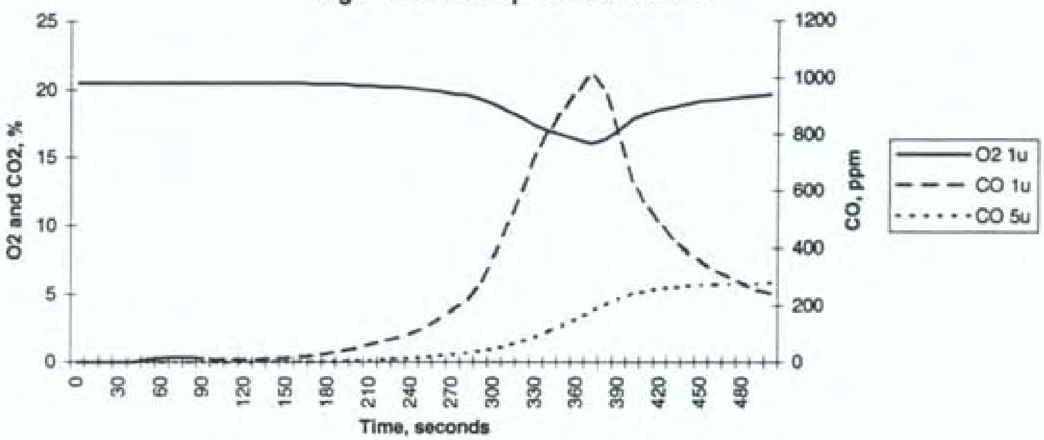

Figure 77: Heat output

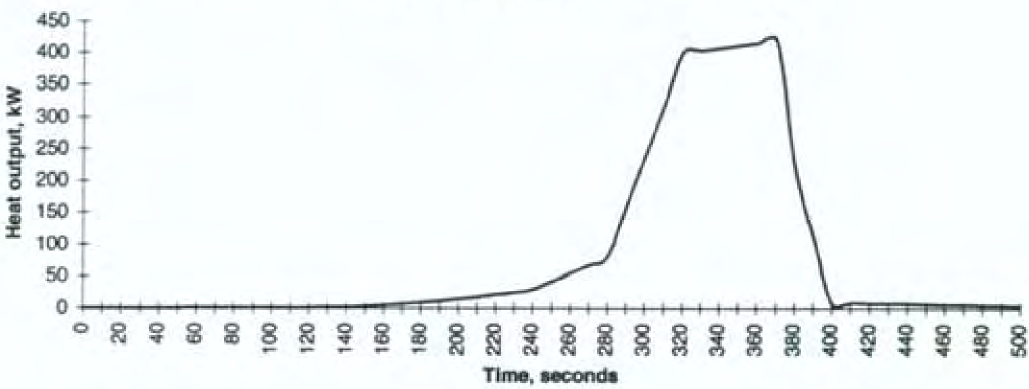

Figure 78: Sprinkler activation, Firecalc prediction trial 24

FIRECALC, v.2.3, update 30 June 1993
(C) CSIRO, div. BCE, North Ryde, N.S.W., Australia
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Program SPRINKLER

Height of ceiling above fuel 2.4 m
Distance of detector from axis of fire 0.5 m
Initial room temperature 20 °C
Detector Actuation Temperature 68 °C
Detector Response Time Index (RTI) 31 $\sqrt{m.s}$
The smallest detectable fire intensity is 50 kW

Heat release
Temperatures:
Air flow
Detector

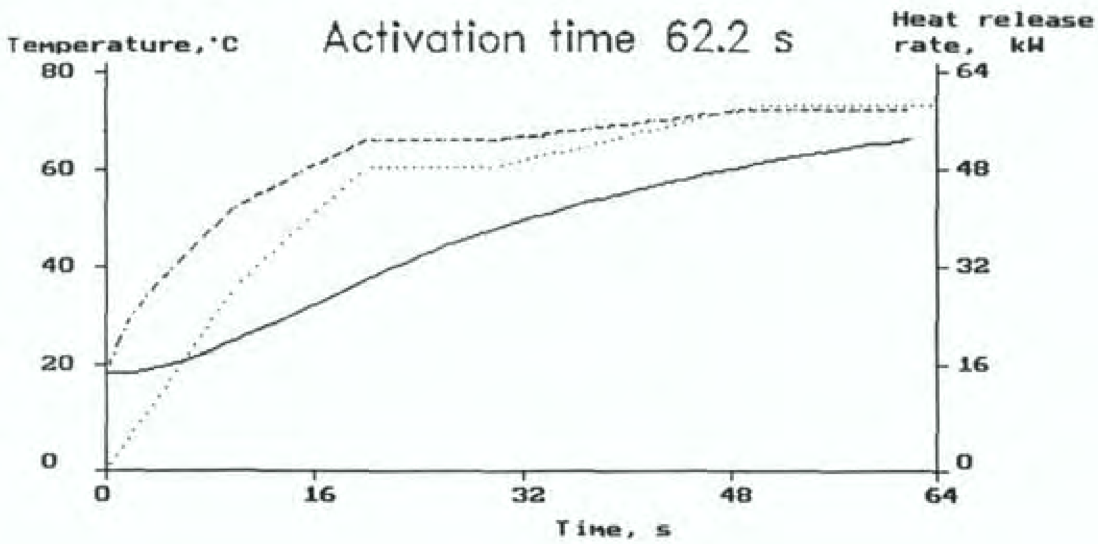

Figure 79: Sprinkler activation, Firecalc prediction trial 26

FIRECALC, v.2.3, update 30 June 1993
(C) CSIRO, div. BCE, North Ryde, N.S.W., Australia
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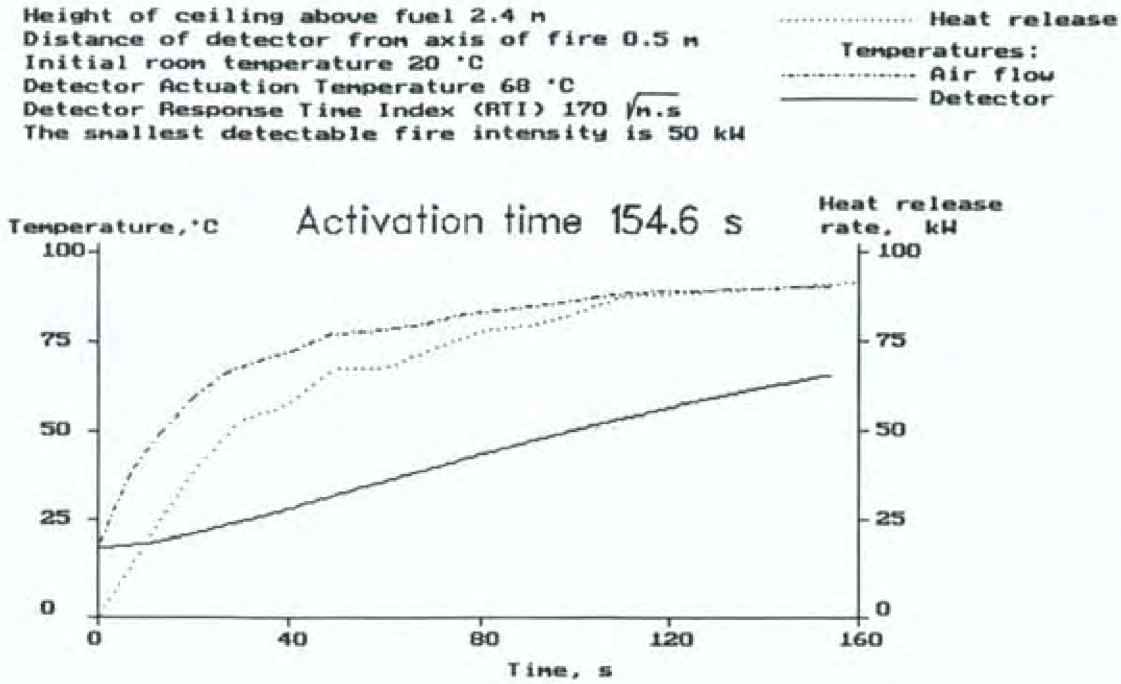
Program SPRINKLER



APPENDIX A: Specification Of Materials Used In Construction (all dimensions in mm)

Floor joists:	150 x 50 at 450 centres Radiata pine
Wall framing, external:	100 x 50 Radiata pine
Wall framing, internal:	75 x 50 Radiata pine
Wall lining:	9.5 mm Standard Gibraltar board
Ceiling lining:	9.5 mm Standard Gibraltar board
Floor lining:	20 mm Pynefloor particleboard
Wall cladding:	6 mm, 240 smooth exterior fibre cement cladding by James Hardie & Co Pty Ltd
Roof:	15 deg pitch, galvanised corrugated steel roofing, with plastic spouting and downpipes
Trusses:	R41 at maximum 1050 centres Radiata pine
Ceiling battens:	70 x 40 at 400 centres Radiata pine
Insulation:	fibreglass batts / polyester batts by INZCO
Doors, internal:	paint grade interior doors with cardboard honeycomb cores and slimline jambs, by Plyco
Doors, exterior:	aluminium and glass, by Vantage Aluminium Joinery
Windows:	aluminium, with condensation channels and double tongue catches, by Vantage Aluminium Joinery
Wall finishing:	none
Ceiling finishing:	none
Plumbing:	none
Electrical wiring:	none
Sprinkler system:	fast-response sprinkler heads (68°C) GEM 990 by Grinell with steel pipework, installed by Wormalds Ltd.
Smoke alarms:	model DT950 ionization type by Goldair

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

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

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

APPENDIX B. Schedule Sensors Connected To Each Data Logger Channel

House data logging points	Test No

Channel	Code	Compartment	Elevation, mm	Instrument type
1	1T18	1	2390	thermocouple
2	1T17	1	2320	thermocouple
3	1T16	1	2170	thermocouple
4	1T15	1	1870	thermocouple
5	1T14	1	1470	thermocouple
6	1T13	1	1070	thermocouple
7	1T12	1	660	thermocouple
8	1T11	1	260	thermocouple
9	1T28	1	2390	thermocouple
10	1T27	1	2320	thermocouple
11	1T26	1	2170	thermocouple
12	1T25	1	1870	thermocouple
13	1T24	1	1470	thermocouple
14	1T23	1	1070	thermocouple
15	1T22	1	660	thermocouple
16	1T21	1	260	thermocouple
17	2T18	2	2390	thermocouple
18	2T17	2	2320	thermocouple
19	2T16	2	2170	thermocouple
20	2T15	2	1870	thermocouple
21	2T14	2	1470	thermocouple
22	2T13	2	1070	thermocouple
23	2T12	2	660	thermocouple
24	2T11	2	260	thermocouple
25	3T18	3	2390	thermocouple
26	3T17	3	2320	thermocouple
27	3T16	3	2170	thermocouple
28	3T15	3	1870	thermocouple
29	3T14	3	1470	thermocouple
30	3T13	3	1070	thermocouple
31	3T12	3	660	thermocouple

32	3T11	3	260	thermocouple
33	4T18	4	2390	thermocouple
34	4T17	4	2320	thermocouple
35	4T16	4	2170	thermocouple
36	4T15	4	1870	thermocouple
37	4T14	4	1470	thermocouple
38	4T13	4	1070	thermocouple
39	4T12	4	660	thermocouple
40	4T11	4	260	thermocouple
41	4T28	4	2390	thermocouple
42	4T27	4	2320	thermocouple
43	4T26	4	2170	thermocouple
44	4T25	4	1870	thermocouple
45	4T24	4	1470	thermocouple
46	4T23	4	1070	thermocouple
47	4T22	4	660	thermocouple
48	4T21	4	260	thermocouple
49	1T19	ceiling 1	2410	thermocouple
50	1T29	ceiling 1	2410	thermocouple
51	2T19	ceiling 2	2410	thermocouple
52	3T19	ceiling 3	2410	thermocouple
53	4T19	ceiling 4	2410	thermocouple
54	4T29	ceiling 4	2410	thermocouple
55	WA3	wall cavity	2000	thermocouple
56	WA2	wall cavity	1200	thermocouple
57	WA1	wall cavity	400	thermocouple
58	WB3	wall cavity	2000	thermocouple
59	WB2	wall cavity	1200	thermocouple
60	WB1	wall cavity	400	thermocouple
61	WC3	wall cavity	2000	thermocouple
62	WC2	wall cavity	1200	thermocouple
63	WC1	wall cavity	400	thermocouple
64	5T39	ceiling	2410	thermocouple
65	WD3	wall cavity	2000	thermocouple
66	WD2	wall cavity	1200	thermocouple
67	WD1	wall cavity	400	thermocouple
68	WE3	wall cavity	2000	thermocouple
69	WE2	wall cavity	1200	thermocouple

70	WE1	wall cavity	400	thermocouple
71	5T29	ceiling	2410	thermocouple
72	5T19	ceiling	2410	thermocouple
73	5T18	5	2390	thermocouple
74	5T17	5	2320	thermocouple
75	5T16	5	2170	thermocouple
76	5T15	5	1870	thermocouple
77	5T14	5	1470	thermocouple
78	5T13	5	1070	thermocouple
79	5T12	5	660	thermocouple
80	5T11	5	260	thermocouple
81	5T28	5	2390	thermocouple
82	5T27	5	2320	thermocouple
83	5T26	5	2170	thermocouple
84	5T25	5	1870	thermocouple
85	5T24	5	1470	thermocouple
86	5T23	5	1070	thermocouple
87	5T22	5	660	thermocouple
88	5T21	5	260	thermocouple
89	5T38	5	2390	thermocouple
90	5T37	5	2320	thermocouple
91	5T36	5	2170	thermocouple
92	5T35	5	1870	thermocouple
93	5T34	5	1470	thermocouple
94	5T33	5	1070	thermocouple
95	5T32	5	660	thermocouple
96	5T31	5	260	thermocouple
97	Calorimeter	1	-	calor1
98	Calorimeter	1	-	calor2
99	Fuel bridge	1	-	strain
100	not used		-	
101	Htd 1	1	2400	Heat detector
102	Hdt 2	5	2400	Heat detector
103	not used			
104	not used			
105	not used			
106	not used			
107	not used			

108	not used			
109	not used			
110	not used			
111	6T19	bath ceiling, 6	2410	thermocouple
112	Ambient	external .		thermocouple
113	not used			
114	not used			
115	not used			
116	not used			
117	not used			
118	not used			
119	not used			
120	not used			
121	not used			
122	not used			
123	not used			
124	not used			
125	not used			
126	not used			
127	not used			
128	not used			

The code used for the thermocouples in the thermocouple trees is as follows:

1. Under code, 4T25 means compartment 4, tree no.2, and themocouple 5. Where the last digit is a 9, this signifies a thermocouple on the upper side of the ceiling lining directly above a thermocouple tree.

2. Under code, WA1 is a thermocouple mounted onto the lining in the wall cavity. This data was not used in any of the analyses.

   The elevation refers to the height of the instrument above floor level. Stud height throughout building was 2400mm.

APPENDIX C: Example Of An Input File For CFAST Test 21

The names (BTCEIL and BTWALL) used for the ceiling and wall barriers were developed specifically for the materials used in the house and are not part of the CFAST data base. Using the GYPSUM data in the programme produces similar results.

```
VERSN  1                    BTL HOUSE21
TIMES  1200   0  20  20   0
TAMB  293.  101300.   0.
EAMB  293.  101300.   0.
HI/F   0.00  0.00  0.00  0.00  0.00  0.00
WIDTH   2.80  2.46  2.46  0.85  6.00  1.75
DEPTH   3.20  2.86  2.99  3.50  5.00  1.60
HEIGH   2.40  2.40  2.40  2.40  2.40  2.40
HVENT  1 4 1  0.760  2.000  0.000
HVENT  1 7 2  1.420  2.000  0.600  0.000
HVENT  2 4 1  0.760  2.000  0.000
HVENT  2 7 2  1.420  2.000  0.600  0.000
HVENT  3 4 1  0.760  2.000  0.000
HVENT  3 7 2  1.420  2.000  0.600  0.000
HVENT  4 5 1  0.760  2.000  0.000
HVENT  4 6 1  0.760  2.000  0.000
HVENT  5 7 1  1.800  2.000  0.000  0.000
HVENT  5 7 2  4.250  2.000  0.600  0.000
HVENT  5 7 3  1.720  2.000  0.800  0.000
HVENT  5 7 4  0.800  2.000  0.000  0.000
HVENT  6 7 1  0.600  2.000  1.000  0.000
CVENT  1 4 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  1 7 2  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00 0.00  0.00  0.00  0.00  0.00  0.00
CVENT  2 4 1   0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00 0.00  0.00  0.00  0.00  0.00  0.00
CVENT  2 7 2   0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00 0.00  0.00  0.00  0.00  0.00  0.00
CVENT  3 4 1  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1.00  1.00  1.00  1.00  1.00  1.00  1.00
CVENT  3 7 2   0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00 0.00  0.00  0.00  0.00  0.00  0.00
```

```
CVENT 4 5 1 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01
CVENT 4 6 1 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00
CVENT 5 7 1 0.10 0.10 0.10 0.10 0.10 0.50 0.50 0.50 0.50 1.00 1.00 1.00 1.00
1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 5 7 2 0.10 0.10 0.10 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.70 0.80 0.90
1.00 1.00 1.00 1.00 1.00 1.00 1.00
CVENT 5 7 3 0.10 0.10 0.10 0.10 0.10 0.20 0.20 0.20 0.20 0.30 0.40 0.40 0.40
0.40 0.50 0.50 0.60 0.70 0.80 0.90
CVENT 5 7 4 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.50 0.50 0.50 0.50 0.50
0.50 0.50 0.50 0.50 0.50 0.50 0.50
CVENT 6 7 1 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00 0.00 0.00
CEILI BTCEIL BTCEIL BTCEIL BTCEIL BTCEIL BTCEIL
WALLS GLASS GLASS GLASS GLASS GLASS GLASS
FLOOR FIBERB FIBERB FIBERB FIBERB FIBERB FIBERB
CHEMI 16. 50. 12.0 18100000. 288. 388. 0.
LFBO 5
LFBT 2
FPOS 0.00 0.00 0.00
FTIME 80. 140. 180. 215. 230. 240. 280. 330. 340. 350. 405. 450. 530. 600. 640.
680. 750. 980. 1020.
FMASS 0.0000 0.0064 0.0112 0.0166 0.0214 0.0202 0.0229 0.0340 0.1036 0.1188 0.1059 0.0350
0.0255 0.0091 0.0088 0.0085 0.0084 0.0074 0.0051 0.0049
FHIGH 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00 0.00 0.00 0.00
FAREA 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.50 0.00 0.00
0.00 0.00 0.00 0.00 0.00
FQDOT 0.00 9.00E+04 1.57E+05 2.42E+05 3.17E+05 3.05E+05 3.58E+05 5.78E+05 1.87E+06
2.14E+06 1.91E+06 6.31E+05 4.61E+05 1.67E+05 1.62E+05 1.58E+05 1.56E+05 1.38E+05
9.20E+04 8.87E+04
CJET OFF
CT 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 1.000 0.000
0.000 0.000 0.000 0.000 0.000
HCR 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.080 0.333
0.333 0.333 0.333 0.333 0.333
CO 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.019 0.000
0.000 0.000 0.000 0.000 0.000
```

```
OD    0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.013 0.000
0.000 0.000 0.000 0.000 0.000
DUMPR BTL21D.HI
WINDOW     0    0 -100 1280 1024  1100
GRAPH 1  100.  050.  0.  600.  475.  10.  3 TIME  HEIGHT
GRAPH 2  100.  550.  0.  600.  940.  10.  3 TIME  CELSIUS
GRAPH 3  720.  050.  0.  1250. 475.  10.  3 TIME  FIRE_SIZE(kW)
GRAPH 4  720.  550.  0.  1250. 940.  10.  3 TIME  OID2IO(%)
INTERFA 0 0 0 0 1   1 U
TEMPERA 0 0 0 0 2   1 U
HEAT   0 0 0 0 3   1 U
O2    0 0 0 0 4   1 U
INTERFA 0 0 0 0 1   2 U
TEMPERA 0 0 0 0 2   2 U
HEAT   0 0 0 0 3   2 U
O2    0 0 0 0 4   2 U
INTERFA 0 0 0 0 1   3 U
TEMPERA 0 0 0 0 2   3 U
HEAT   0 0 0 0 3   3 U
O2    0 0 0 0 4   3 U
INTERFA 0 0 0 0 1   4 U
TEMPERA 0 0 0 0 2   4 U
HEAT   0 0 0 0 3   4 U
O2    0 0 0 0 4   4 U
INTERFA 0 0 0 0 1   5 U
TEMPERA 0 0 0 0 2   5 U
HEAT   0 0 0 0 3   5 U
O2    0 0 0 0 4   5 U
INTERFA 0 0 0 0 1   6 U
TEMPERA 0 0 0 0 2   6 U
HEAT   0 0 0 0 3   6 U
O2    0 0 0 0 4   6 U
```

Note: The files BTCEIL and BTWALL were specifically prepared using the actual configuration properties of the materials used in the construction of the ceiling and walls. The difference in results was not significant and using GYPSUM, as in the CFAST database, for CEIL and WALLS will give satisfactory results.

APPENDIX D: Photographs Of Fire Sources And Damage Caused

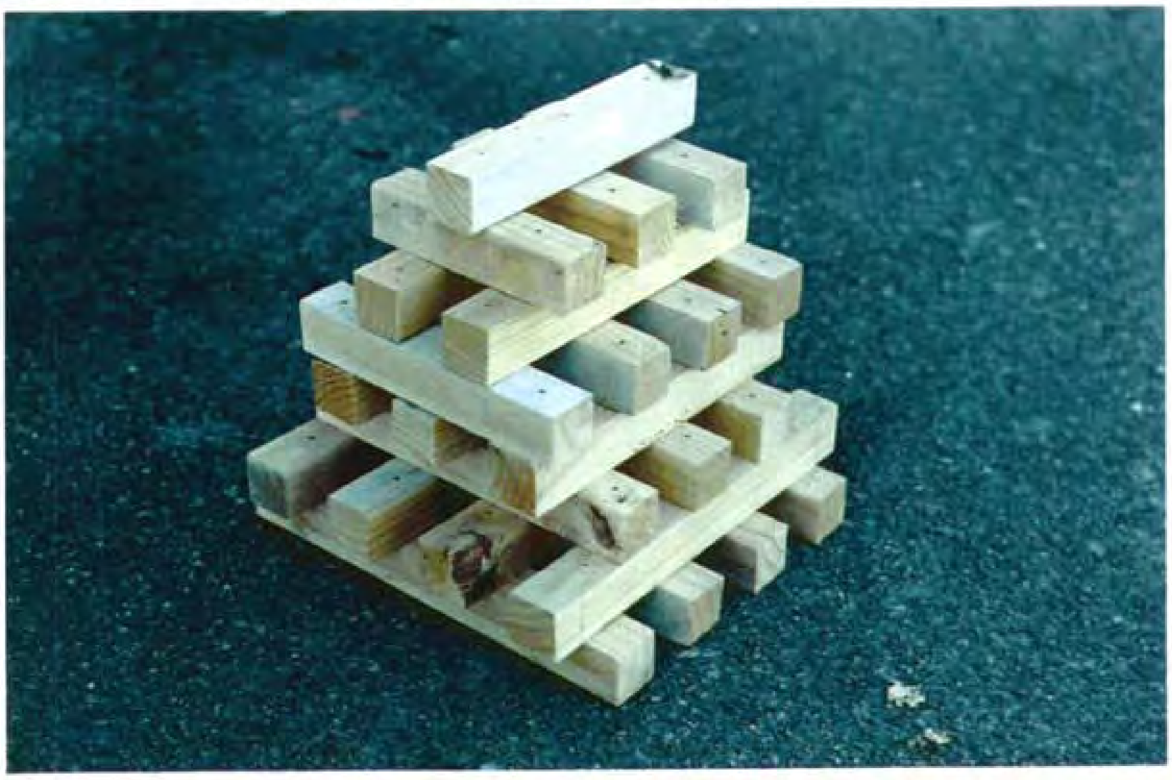


Figure 80: Wooden crib fuel source, as used in trial 16.

Figure 81: Fire source prior to trial 20.

Figure 82: Fire source prior to trial 21.

Figure 83: Damage after the fire was extinguished, trial 21.

Figure 84: Hallway door (lounge side) after trial 21.

Figure 85: Hallway door (hall side) after trial 21, note slight charring on soffit.

Figure 86: Close-up hallway door (lounge side) after trial 21, note honeycomb core.

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