BUILDING RESEARCH ASSOCIATION OF NEW ZEALAND

CI/SfB				(K4)
Date: January 1997				

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REPRINT

No 142 (1997)

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From: Fire Technology, Vol.32
No.3, 1996

RESTRICTED

Funding for the work presented here was provided by the Foundation for Research, Science and Technology from the Public Good Science Fund, and by the Building Research Levy.

ISSN: 0111-7459

From *Fire Technology*, Vol. 32, Number 3, 1996

Fire in a Residential Building: Comparisons Between Experimental Data and a Fire Zone Model

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Abstract

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

A series of experiments in a three-bedroom dwelling were conducted and included both a nonflashover and a flashover fire, and a selection of experimental results were analyzed to determine smoke and gas movement together with temperature rises in the various rooms. These results were compared to the predictions of the CFAST fire and smoke transport computer model.

Introduction

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- and smoke-transport computer model. It was also intended to develop valuable understanding of fire development and behavior in a fully instrumented building under controlled conditions.

Statistics show that New Zealand, with its population of 3.5 million, has an annual average of 30 deaths by fire in buildings, and of these, 90% occur in residences. A disproportionately high number of these deaths occur in rented accommodations.[1] Also contributing significantly to the statistics are fire deaths occurring in rest homes for the elderly. In all situations, the greatest cause of death is smoke inhalation. This project shows how the relative hazards to life develop and demonstrates the value of computer modeling in predicting those hazards and of detection and suppression devices.

It has been some years since an instrumented experimental fire has been conducted on an actual building in New Zealand, and since then, there have been considerable advances internationally in fire-growth modeling 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 in New Zealand and worldwide. This study has attempted this validation and verification using construction methods, materials, and furnishings common to New Zealand housing stock. Instrumentation and monitoring included records of air temperatures within rooms and wall and ceiling cavities, smoke spread, gas species concentrations (oxygen, carbon monoxide), and heat radiation.

This research has assisted in the practical application and understanding of computer fire models, leading to more certainty and confidence about their use and applicability in New Zealand. This will enable better quantitative assessment of fire hazards, providing a greater level of confidence in fire safety designs, mainly by comparing alternative designs and quantifying their respective performance.

Experimental House

The building chosen for the experimental work was a modern, three-bedroom, single-story New Zealand dwelling, with a floor area of 69 m^2. The layout of the house (see Figure 1) comprised a hallway connecting the three bedrooms, a bathroom, toilet, and combination lounge/dining room/kitchen. Exits were via a sliding glass door from the lounge and a hinged door from the kitchen. The method of construction was light timber framing clad with fiber-cement planks and roofed with corrugated steel. The floor was of particle board and the walls were lined with paper-faced gypsum board. External walls and ceiling were insulated with a mixture of fiberglass and polyester batts. A sprinkler system with fast response heads was also installed throughout the house.

Instrumentation and Temperatures

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

The thermocouple trees had eight thermocouples each to measure the hot layer stratification and smoke-layer depths using Cooper *et al.*'s method.[2] The remaining 26 disc-type thermocouples were installed in the wall cavities 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 2.

Fuel Mass Loss

A weigh bridge based on a cantilever beam was designed and built to measure the rate of fuel consumption. 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 former provided a relatively steady heat output, while the latter produced an example of a triangular heat output. The rate of mass loss measured was used to estimate the rate of heat input to the compartment.

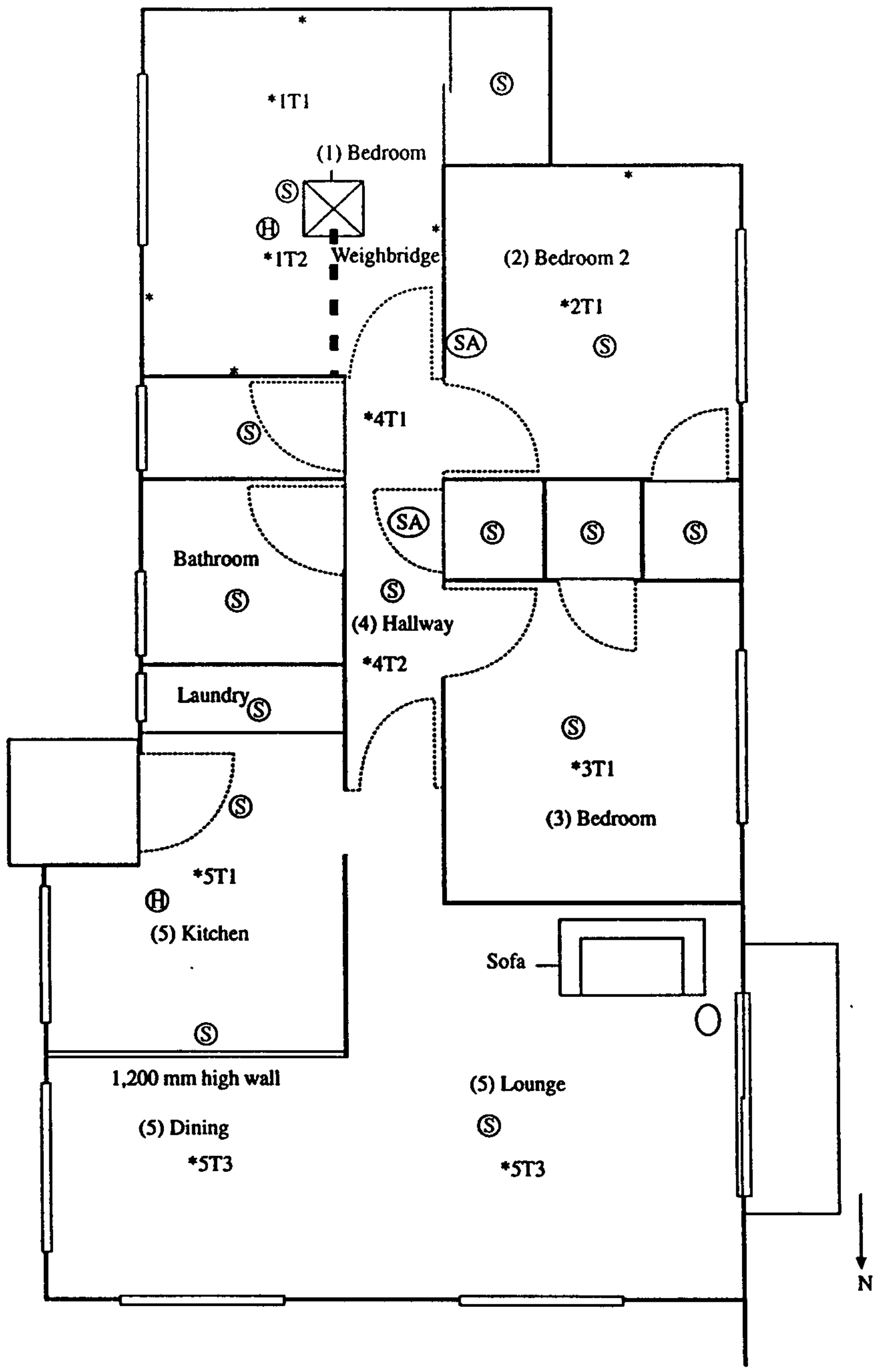

Figure 1. Floor plan of the house.

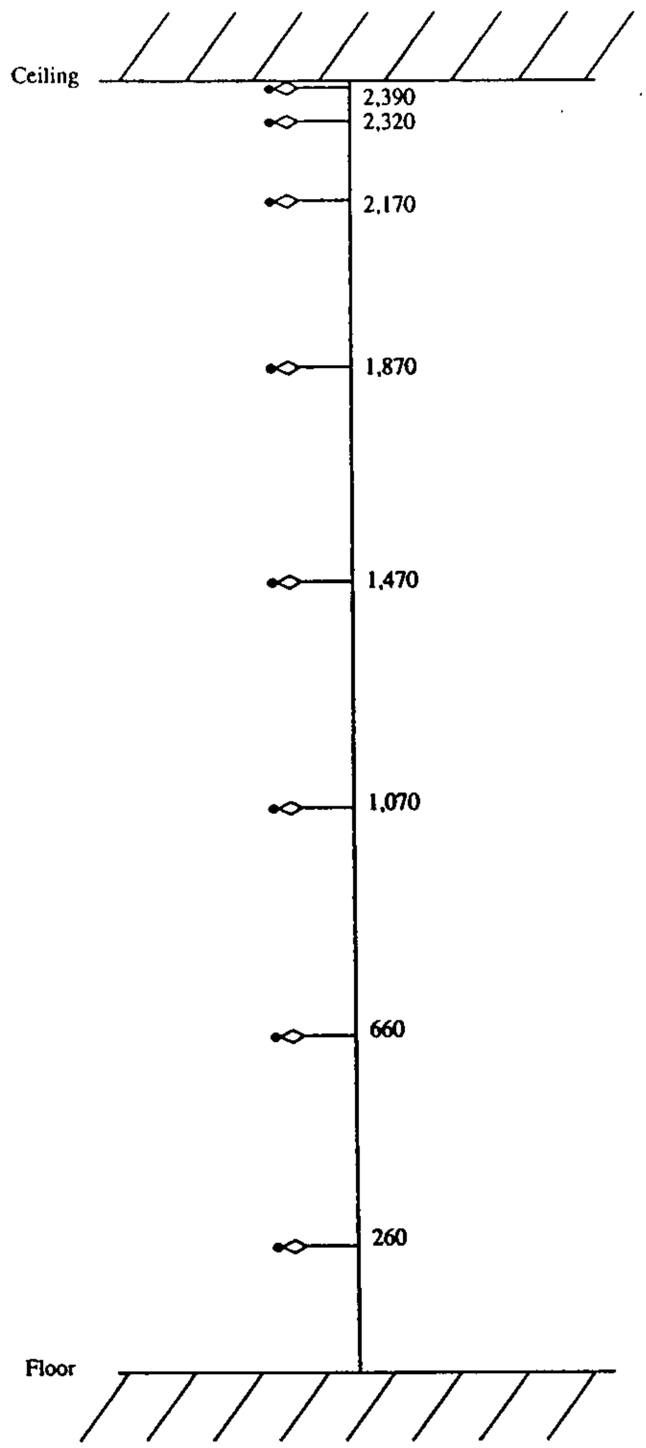

Figure 2. Thermocouple tree with elevations in mm above floor.

Heat flux

Heat flux measurements of the fire sources were taken using Gardon-type heat flux meters or calorimeters. The heat flux meter measured the radiation. This measurement was compared with the heat input determined by the mass loss rate of the fuel and offered an improved input to the software modeling package used to predict fire outcomes. Estimates of the radiant heat output from fire sources were calculated using the geometric relationship for radiation between the flame and receiver presented by Drysdale.[3]

Gas Analysis

Oxygen and carbon monoxide in the room of fire origin were recorded at various heights ranging from 500 mm to 1,500 mm above the floor using a portable gas meter, and the results were later downloaded into the data-logging PC for subsequent analysis.

Recording Data

All data, with the exception of the gas analysis, was averaged over 10 second intervals and recorded on an IBM-PC compatible with a 128 channel data-logging system. This allowed the data to be written to ASCII files for later retrieval and analysis. Comparisons were made of the recorded data with those predicted by a room fire model.

Experimental Program

A total of 21 experimental trials have been conducted to date. Of the 13 preliminary trials, 12 used methylated spirits as the fuel, and 1 used a 3.7 kg wooden crib. The rate of heat input to the compartments for these trials was purposely limited to below 100 kW—temperatures did not exceeding 160°C—to avoid damaging the building. With the essentially steady state and measurable heat input to the compartments, it was possible to record some useful comparisons between the actual temperature rises and those predicted by CFAST.[4] Artificial smoke from a generator was introduced to aid visualization of the hot layer. Visual observations were correlated with layer height calculations based on the method of Cooper *et al.*,[2] which uses the vertical temperature profile within a compartment. Figure 3 shows a temperature profile recorded in one of the preliminary tests: The square markers represent temperatures recorded on the thermocouple tree (Figure 2) at the various elevations; the horizontal line of the stepped trace is the calculated layer interface; and the vertical lines are the weighted mean of the lower and upper layer temperatures.

Figure 3 is a snapshot of the trial data taken on a thermocouple tree in compartment 1 at 60 seconds. The relationship of the temperatures to height is used to determine the interface between the hot and cold layers.[2] The mean temperatures in the two layers are calculated by numerically integrating over their respective heights. This process is repeated for every time interval and is used in the construction of the time/temperature and time/layer height graphs in the following figures.

In all trials, the data recorded both visually and by instrumentation, and the output obtained from modeling the fire scenarios on CFAST showed encouraging agreement. Some problems were encountered calculating the hot-layer interface. This was usually the case during the first minute, when stratification of hot and cold layers had not been fully established, and at which stage the calculation method[2] is sensitive to small temperature differences in the recorded data. Improvements in the recording and processing of data minimized these problems in subsequent trials.

Data from three experimental runs involving burning items of furniture have been selected for analysis in this paper and are listed in Table 1.

Fire Scenarios

The fire scenario in Trials A and B involved a rubbish bin containing an assortment of paper located beside a ceiling-to-floor curtain which was, in turn, adjacent to an item of lounge furniture. The position of the fire source in the lounge/dining room/kitchen is indicated in Figure 1. The door to the hallway was closed, and the doors connecting bedrooms 1 to 3 and the hallway were all open. All windows in the lounge/dining room/kitchen were open.

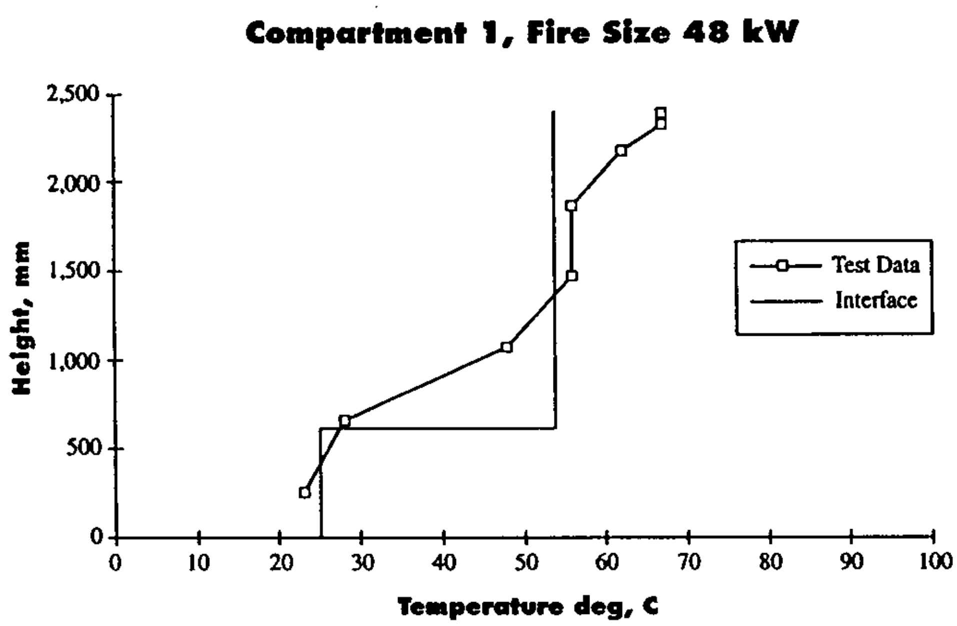

Figure 3. Comparison of experimental data calculation of hot-layer interface and upper- and lower-layer temperatures for compartment 1 at 60 seconds.

TABLE 1
Experimental Trials

Trial	Fire Source	Maximum fire size (kW)	Fire compartment and location	Sprinkler activation (s)	Heat detector activation (57°C)(s)	Smoke alarm in hallway activation (s)
A	rubbish bin and chair	<20	5— lounge	140	—	—
B	rubbish bin and sofa	MW+	5—lounge	—	119	140[1]
C	rubbish bin and chair	~250	1—bedroom	—	160	52

[1] smoke detector behind closed door (see Figure 1 for house layout)

The Trial A fire was extinguished by sprinklers. The Trial B fire was extinguished by the fire service. And the Trial C fire was left to develop and then was extinguished by manually operated sprinklers.

For Trial C, a similar scenario to Trials A and B was repeated in bedroom 1, with all doors between the bedrooms, hallway and lounge/dining room/kitchen fully open. External windows were all closed, except in bedroom 1.

With the sprinkler system charged in Trial A and fast response sprinkler heads with a Response Time Index (RTI) 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 1.8 m away. At 117 seconds, flames had spread to the curtains, and 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 4 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 are all shown.

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

With the sprinklers turned off in Trial B, the scenario in Trial B was repeated, with the chair exchanged for a sofa. Figure 5 illustrates the layer height and temperature rises as recorded by thermocouple tree 5T3, which was closest to the fire source. The curtains started 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 hallway ceiling behind a closed door, activated an audible alarm, by which time the lounge/dining room/kitchen 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, and fire-growth was fuel-controlled due to adequate ventilation, which was increased by breaking the windows. Flashover occurred at approximately 400 seconds and was characterized by an improvement in visibility as some of the unburnt pyrolysates in the dense smoke were consumed and other items of furniture and curtains ignited. Fully developed burning progressed for approximately 120 seconds before the fire service extinguishes it. As a fire service training exercise, application of water was kept to a minimum, with the objective of minimizing water damage. This fire-fighting method proved successful, as shown by the rapid decrease in temperature.

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 over 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 lessened further from the seat of the fire. At the extreme corners of the compartment (6–8 m away) the lining varied from heavily scorched at the upper level to slightly browned near the floor. On vinyl covered chairs (6–8 m away) the covering had melted where it faced the seat of the fire. All windows, except one small one in the laundry room, had

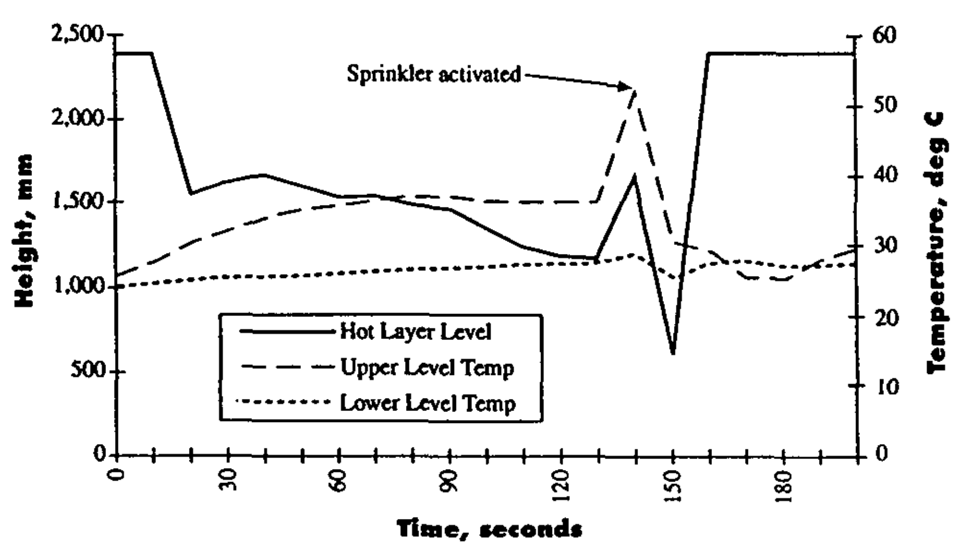

Figure 4. Layer height and temperatures, Trial A.

cracked and fallen out, and the rubber gaskets in the aluminum frames had melted and burnt. Finally, the timber around the doors and windows had charred to a depth of 1–2 mm.

Trail C used a similar fire scenario of a rubbish bin containing waste paper placed beside a curtain draped over the arm of a 15 kg vinyl-covered polyurethane foam rubber–filled chair in bedroom 1. The smoke alarm located on the hallway ceiling (compartment 4) activated at 52 seconds after ignition, at the same time that the flames started to spread to the curtain. In Figure 6, the activation of the smoke alarm coincided closely with the recorded descent of the layer height in the hallway (compartment 4). The ceiling-mounted heat detector in bedroom 1 activated at 110 seconds after ignition, when the derived average upper-layer gas temperature had exceeded 50°C, as shown in Figure 7. The maximum individual temperature in the upper layer had exceeded the activation temperature of 57°C. Once the vinyl on the chair was alight, fire spread was rapid, producing palls of black smoke that filled the upper part of room, flowed into the hallway, and from there, flowed 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 260 seconds to

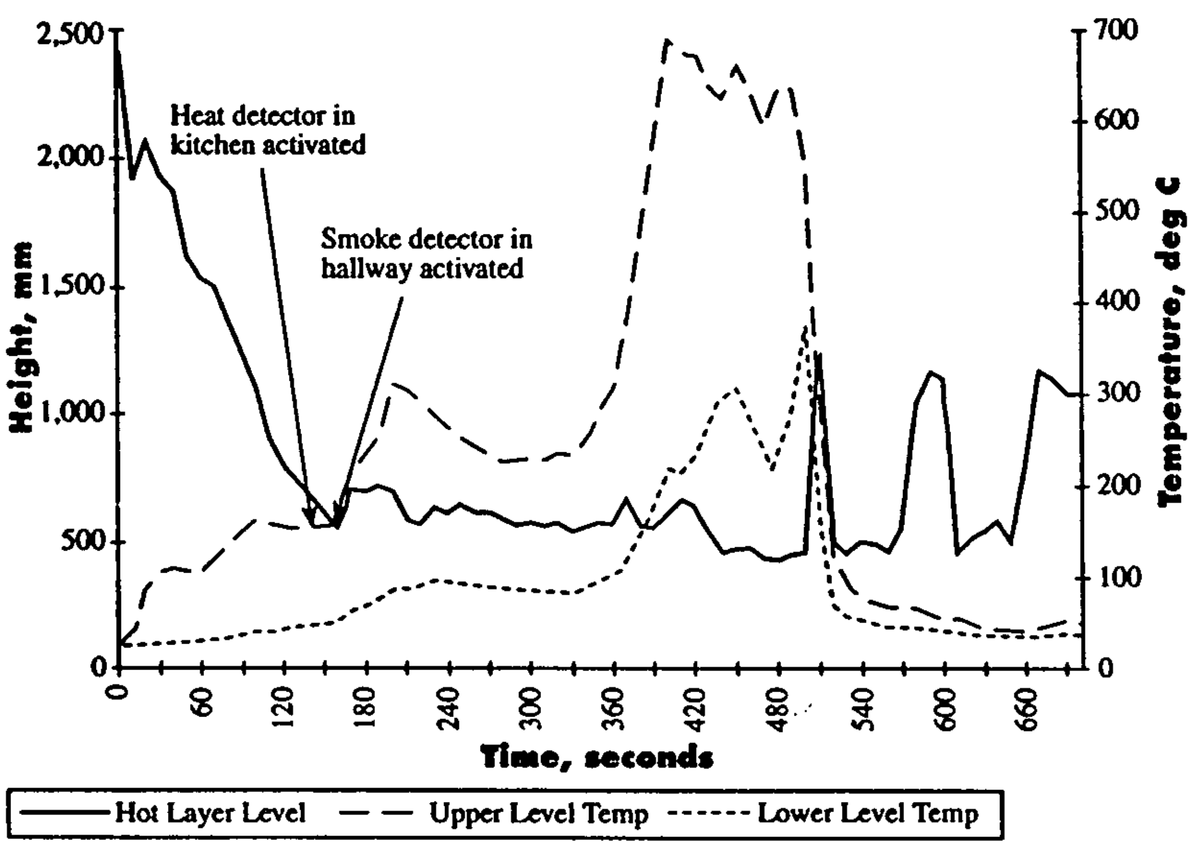

Figure 5. Layer height and temperatures, Trial B.

prevent further damage, and the fire was completely extinguished at 350 seconds.

Figures 6 to 9 show that ignition occurred 40 seconds into the data-logging run. The numbers in the legend refer to the number of the compartment where the temperature was recorded, and the *T* signifies that the data was obtained from a thermocouple tree.

Gas measurements were taken in the room of fire origin at a typical nose height of 1.5 m, and these are shown in Figure 9 where the oxygen content is reduced

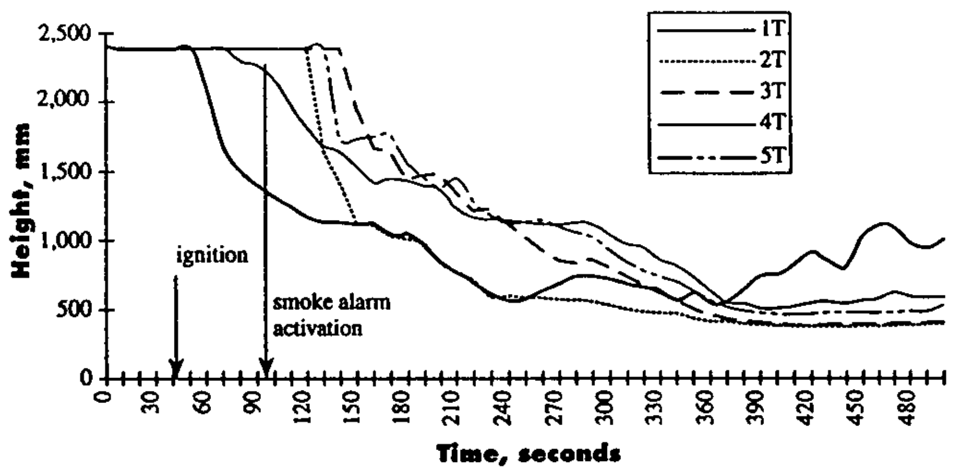

Figure 6. Hot-layer heights, Trial C.

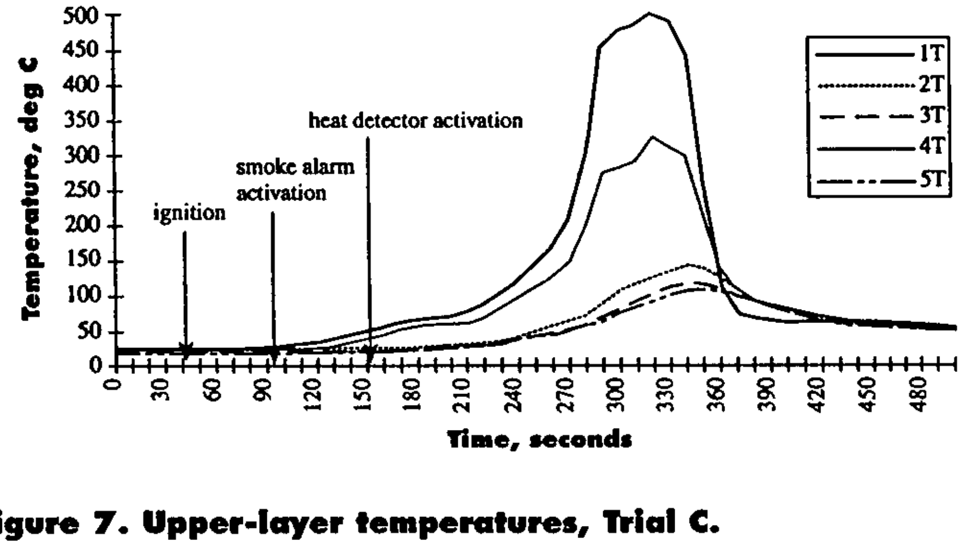

Figure 7. Upper-layer temperatures, Trial C.

to 9% and the carbon monoxide level rose above 266 ppm (the meter reached saturation level). Estimates using the CFAST model show that the carbon monoxide concentration may have exceeded 3,500 ppm. Black smoke filled the upper levels of the building, leaving a relatively clear zone for a depth of about 1 m above floor level in all rooms other than the room of fire origin.

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

The Operation of Protection and Suppression Devices

In Trial A, a single fast response sprinkler with an RTI of 31 $m^{1/2}s^{1/2}$ and activation temperature of 68°C activated when the gas temperature at the ceiling had risen to 65°C and was effective in extinguishing the fire. The maximum temperatures reached in the remainder of the lounge/dining room/kitchen (compartment 5) at the time of sprinkler operation were 65°C in the dining area (see Figure 1) and 42°C in the kitchen. The door to the hallway was closed during Trial A, preventing passage of hot gases and temperature rises in the remainder of the house.

The domestic-type ionization smoke alarm located on the hallway ceiling gave very early warning of fire. In Trial B, when the hallway door connecting the lounge was closed and a rubbish bin fire next to the curtains and the sofa was ignited, the smoke alarm activated only 140 seconds after ignition. At this time, it was not possible to see the smoke in the hallway that had leaked under the soffit to trigger the alarm. The fire developed for 360 seconds more before the fire service extinguished it. Afterwards, only a thin smoke haze was visible in the

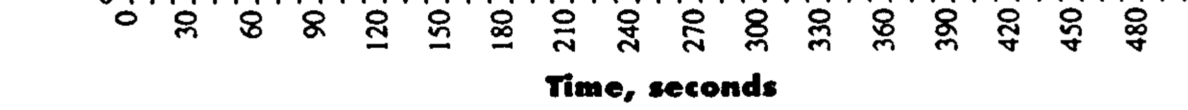

Figure 8. Lower-layer temperatures, Trial C.

hallway, and there was evidence that passing hot gases had charred the soffit and the door top. Clearly, the combination of the closed door—even if only a cardboard-cored door—and the early warning of the smoke alarm would have alerted occupants and allowed them time to escape. In this case, the most desirable means of escape would have been through the windows at ground-floor level, as both external doors were in compartment 5, where the fire originated. This raises the question of the viability of using ground-floor windows to escape in situations where burglar-proof catches may be installed and/or a disabilities prevent occupants from using that means of escape.

Trial C used a similar scenario in compartment 1 (bedroom 1). 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 6, and visual observations confirmed that even at the fire peak, the smoke layer descended to a level 1 m clear of the floor level in the lounge dining room (compartment 5). It's significant that a crawling level escape route is available below what was an extremely dense and potentially toxic upper layer. Fortunately, the temperature in the crawl zone did not rise significantly outside the compartment of fire origin (Figure 8). Figure 6 shows a descent in the layer height in the hallway (4T), as detected by the thermocouple trees, which started 20 seconds before the smoke alarm activation. At the same time, the temperature in the hallway (4T) had not shown any noticeable increase in Figure 7.

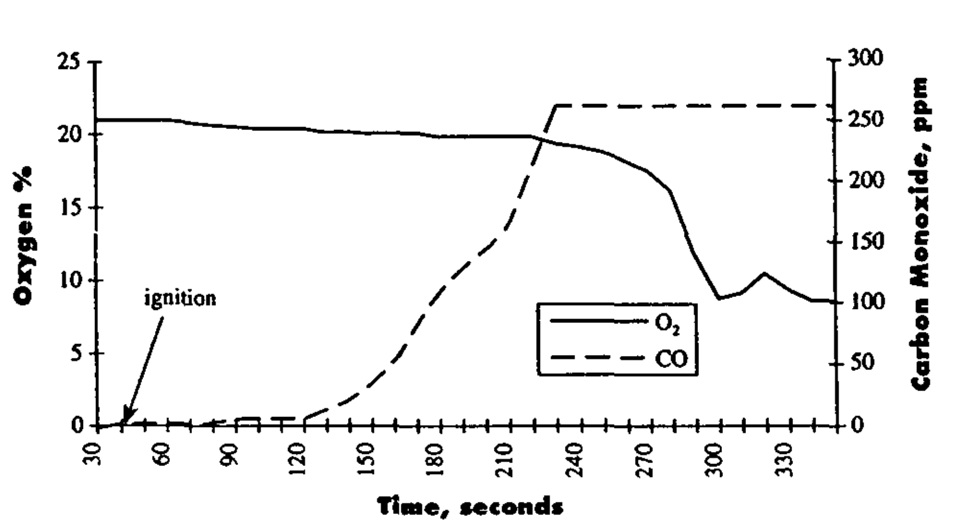

Figure 9. Gas species, Trial C.

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 1. It was evident that these devices have a very low RTI. Heat detectors are available in a range of activation temperatures (57°C is the lowest) for various risk situations.

The performance of the heat detectors is illustrated in Figures 5 and 7. With the exception of Trial B (Figure 5) heat detector activation occurred immediately after the gas temperature exceeded 57°C. In Trial B, the ceiling-mounted heat detector in the kitchen was 6 m away from the seat of the fire in the lounge, and it was also shielded by a partition, which accounts for the temperature in the vicinity of the fire reaching 160°C before activating. The instruments in the kitchen, adjacent to the heat detector, confirmed that the heat detector activation closely followed the 57°C being exceeded.

Modeling

Comparisons of the operation of the sprinklers in Trial A with Firecalc[5] differ depending on fire size and position, detector position, and whether the ceiling jet is unconfined by boundary walls closer than 2–4 ceiling heights. Unfortunately, the compartments in the house are below that limit, and although application of the algorithm agrees quite closely with the result in Trial A and the other trials conducted, strictly speaking, Firecalc would be expected to overestimate the activation time.

The input heat release data for the fire source for Trial B was developed from the database in CFAST and involved a rubbish tin, curtains, and sofa. A scenario was developed that matched the sequence of events in the fire scenarios described. Since the fire was extinguished once flashover had occurred, the contribution of the remaining fire load in the lounge/dining room/kitchen was minor, and thus, it was ignored.

Another problem arose because the fire scenario input is limited to 20 steps, which were already being used for input. Extending the duration would have required compromises that would have conflicted with the objective of modeling the actual fire as closely as possible. A comparison of the curves for the measured and predicted upper-layer temperature (Figure 10) shows they are quite different, the closest agreement being the maximum temperature reached of 700 to 800°C. The time at which the maximum temperature was reached is dictated by the design of the fire scenario, which was based on what occurred in the trial.

Other areas of disagreement can be explained by the difficulties in accurately describing true venting through the windows. The CFAST input file (Appendix A) requires that for each vent, the amount of opening be expressed as a fraction between 0 and 1 of the total opening area and that the fraction refer 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—those that open bottom edge outward, for instance—for which it can be quite difficult converting rectangular and triangular openings around the edges to the equivalent vertical strip. This is especially difficult when the height parameter makes a greater contribution to the flow.

Comparing the layer heights in Figure 10, it is clear that the venting configuration is exerting a substantial influence. In Trial B, the windows, which were all initially open 200 to 300 mm, began shattering and falling out randomly once the temperature in the hot layer had exceeded 275°C. The venting created by the broken windows was more random than the fractionally open, full-height, rectangular vents (or vertical strips) modeled by CFAST. Because the available venting did not extend the full height to the window soffits, the gases and smoke in the hot layer descended closer to the floor before they were able to flow out of the compartment.

The ideal case, as modeled by CFAST and shown in Figure 10, has openings that, no matter how restrictive, extend to the window soffits (that is, the total height of vent available to set up flow), and the hot-layer level barely descends 2,000 below the soffits. When the windows begin breaking at 190 seconds, an upward turn in the layer height is shown as more hot gases flowed out of the compartment. A similar trend with the layer height was detectable in the actual experimental results, although the in flow of cooler air did momentarily reduce the upper-layer temperature before flashover.

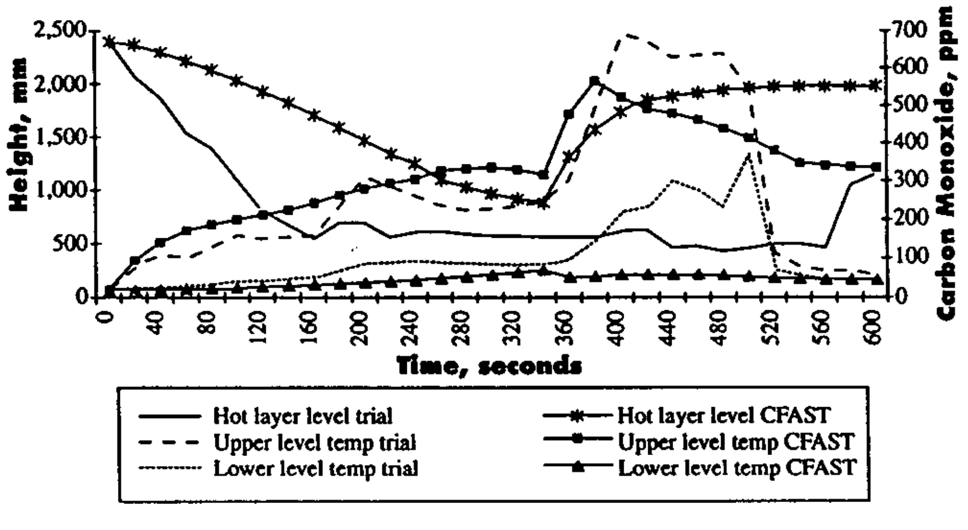

Figure 10. Layer height and temperatures, CFAST prediction of Trial B.

Once flashover had occurred at a hot-layer temperature of 600 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 less significant 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 modeled in Figure 11 indicate life-threatening conditions, with oxygen content falling to 5%. The effect of the carbon monoxide level rising to 3,500 ppm is not as insignificant—30 minutes exposure at this level would be be lethal.[6]

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 judgment. The hot-layer level in the hallway (compartment 4) beyond the closed door and with leakage equivalent to 1% open begins to descend at 80 seconds, and the temperature begins to rise at 100 seconds (Table 2). Given that the ceiling-mounted smoke alarm activated at 140 seconds, the CFAST prediction of 4°C corresponded with actual experimental results.

The measured temperature showed a similar increase to correspond with the activation of the smoke alarm. While the operation of the smoke alarms is independent of temperature rise, a temperature rise indicates that combustion products necessary for activating the smoke alarms are present. 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

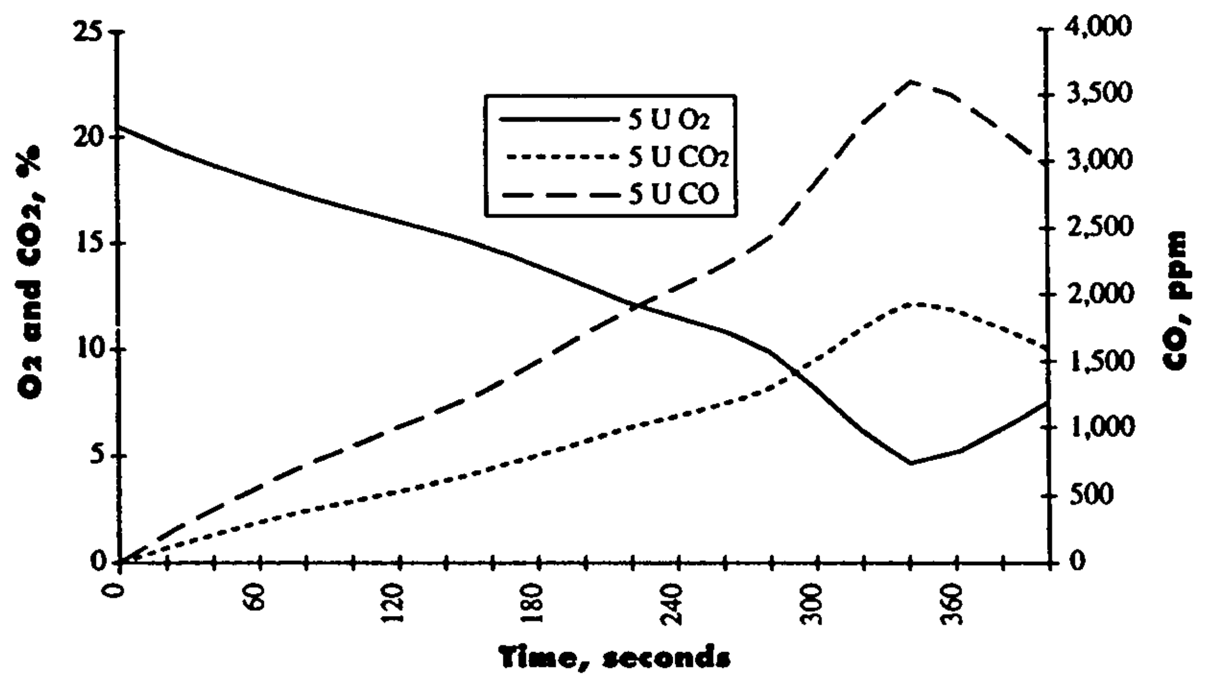

Figure 11. Gas species, CFAST prediction of Trial B.

TABLE 2
Temperature Rise in Hallway, Trial B: CFAST vs. Measured Temperature Rise

Time (s)	80	100	120	140	160
Temp °C, CFAST	0	1.5	2.8	4.0	5.3
Temp °C, Trial B	0	0	1	2	3.5

perimeter, and the gap would likely increase further, due to warpage, as the temperature increased. As a rule of thumb for modeling purposes, it's predicted that a smoke alarm will activate 20 to 30 seconds after the layer level begins to descend, or when the temperature begins to rise by 2 to 4°C. Most important of all, however, is the need to factor in some leakage around the perimeter of closed doors to get realistic modeling results in this type of situation.

The heat output of the fire in Trial C was estimated from the radiation recorded by the heat flux meters.[3] It was assumed that 33%[7] of the heat output was radiation and that the remainder was convection in the form of hot gases evolved and entrained air. Figure 12 shows the heat output assumed for Trial C, based on the received radiation at the heat-flux meter and the heat output derived from the database included in CFAST.

The CFAST modeling of this scenario matched the hot layer descent in the fire compartment (bedroom 1) to a level of about 600 mm above the floor (Figure 13a). CFAST predicted the rapid rise of the hot layer to 1,900 mm at 345 seconds when the fire is extinguished. This represents an almost total displacement of hot gases by ambient air up to window-soffit level. This effect is not matched in the trial run, where the use of sprinklers in mixing the upper and lower layers minimized the temperature differential that would have allowed the flow regime to continue. For the other compartments, CFAST predicted the hot layer level descending to floor level, whereas it was observed in the trials that there was actually about 1 m of relatively clear air above floor level (Figures 13b and c). Temperatures in the upper levels (Figures 14a, b and c) were underpredicted but followed the general trend. Lower level temperatures were overpredicted (Figures 15a, b and c), with the exception of the fire compartment. This is misleading because CFAST predicts that the hot-layer level descends almost to the floor, which effectively means that the lower level does not exist.

Modeling the decay phase of the fire by operating the sprinklers manually, was achieved in the CFAST input by reducing the heat output to zero. The cooling effect of the sprinkler spray on the air temperature could not be modeled, so cooling is the result of ventilation, radiation losses, and so on.

CFAST predictions of the gas species (oxygen and carbon monoxide) in the upper layer (compartment 1) followed the trial results, although the same practical problems that occurred in Trial B were repeated. Figure 16 shows that the observed drop in oxygen content down to 8.5% was not matched by the CFAST modeling, although agreement up to 280 seconds was very good. The carbon monoxide levels agree quite closely until the meter reached a saturation level (266 ppm). A possible reason for the difference in oxygen levels beyond 280 seconds may be accounted for by the same problem encountered with modeling the venting in Trial B. The random breaking of the window glass prevents the full window height from being available for ventilation. When modeling the venting, a fraction of the width and the total height is used to match the venting area. This creates a situation where, area for area, the equivalent venting has a greater effect in the CFAST simulation, increasing the exchange with ambient air, and appears to compensate for oxygen consumption by diluting the products of combustion.

Summary and Conclusions

The following findings from this study may be used as a guide for CFAST users. It is most important that the user apply a degree of judgment in selecting the input parameters in order to achieve what is considered a logical program output or prediction and gain the maximum benefit from the model.

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 also advisable to check that a 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.

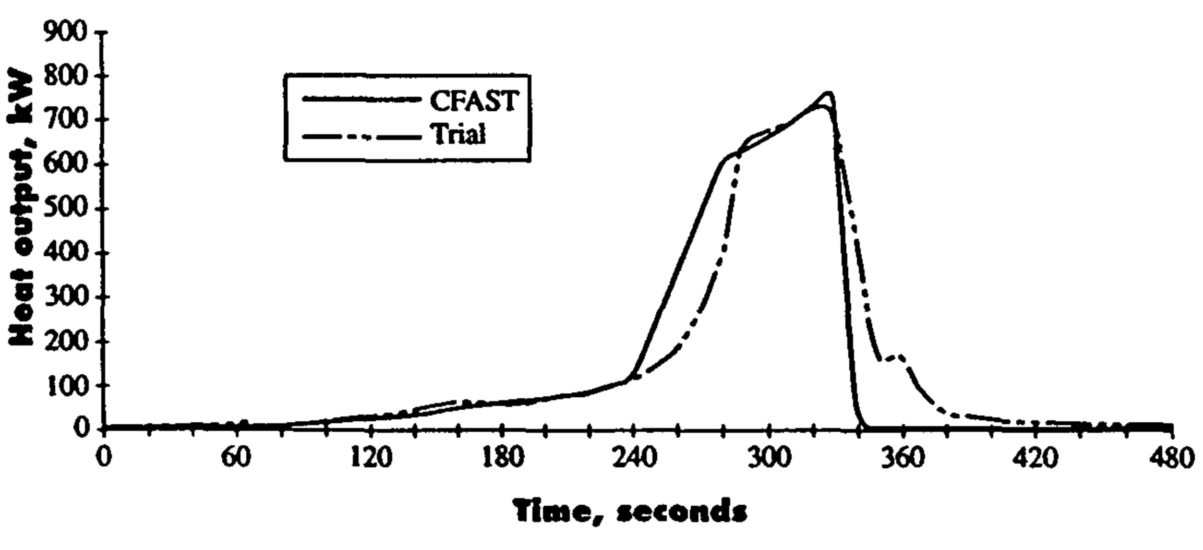

Figure 12. Heat outputs, CFAST input based on trial result for Trial C (bedroom 1).

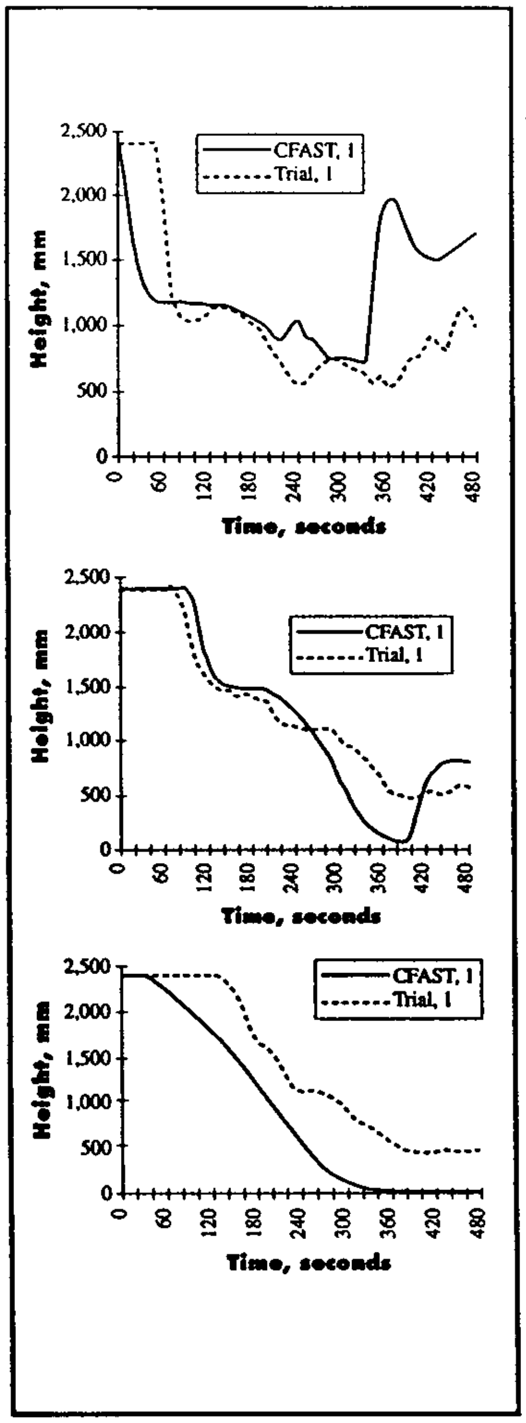

Figure 13. Hot layer levels, CFAST prediction and result for Trial C in compartment 1 (top), compartment 4 (middle), and compartment 5 (bottom).

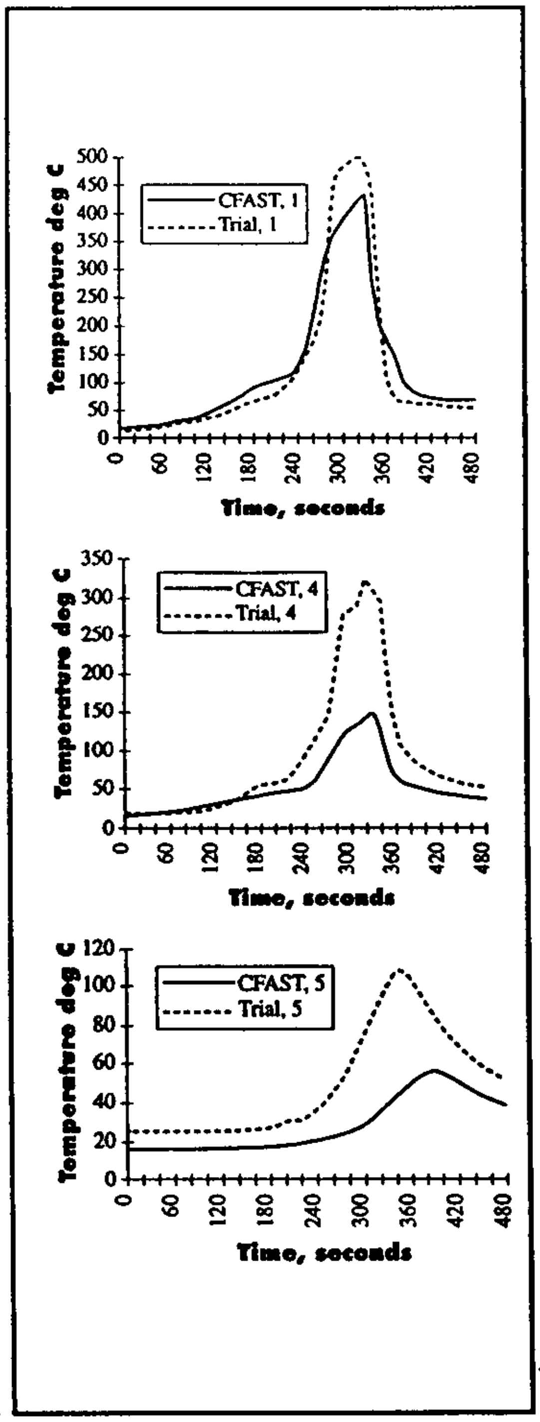

Figure 14. Upper layer temperatures, CFAST prediction and result of Trial C in compartment 1 (top), compartment 4 (middle), and compartment 5 (bottom).

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 until flashover has occurred.

3. Activation of heat detectors and fast-response sprinklers can be confidently determined by the temperature rise in the upper layer.

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

5. Some judgment 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.

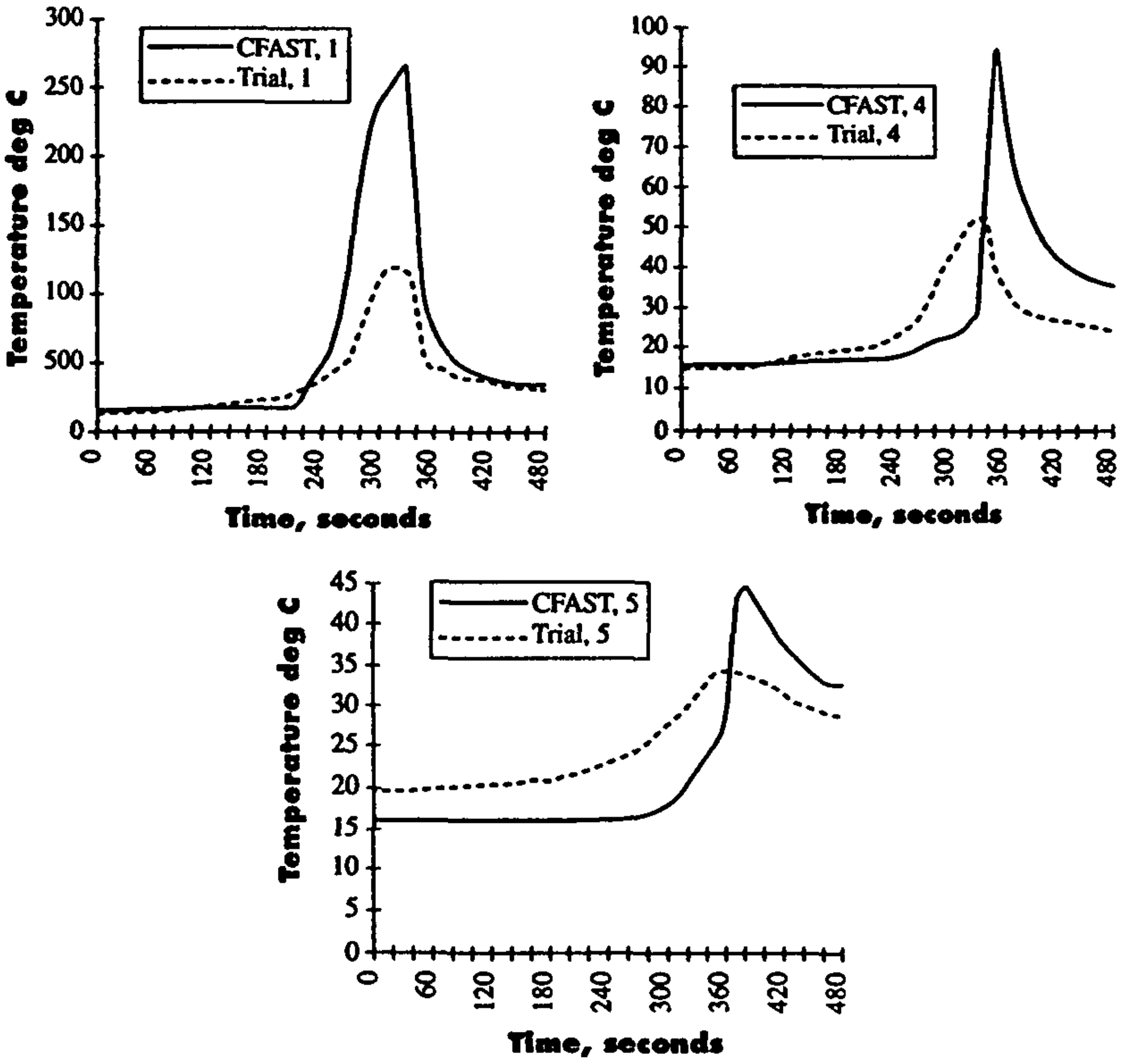

Figure 15. Lower layer temperatures, CFAST prediction and Trial C result in compartment 1 (top left), compartment 4 (top right), and compartment 5 (bottom).

6. Computer models are a valuable tool for reconstructing fire scenarios as well as predicting possible outcomes beforehand. This is because clues to the progress of a fire are likely to be available to confirm model predictions. The extent of broken windows would also allow more accurate input of the venting parameters.

7. From Trials B and C, it appears that windows start breaking once upper layer temperatures of 300°C are reached, although this more likely results from the difference in temperature across or within the pane of glass and determined by the type of glass. However, this finding provides a useful datum for increasing the ventilation in CFAST trial runs.

Two fires involving items of furniture provided realistic scenarios, both of which 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.

These conclusions were made about the effectiveness of smoke alarms, heat detectors, and sprinklers:

1. The ionization 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/detection device for residential buildings, provided they are maintained. For rental accommodation hard-wired smoke detectors may be the preferred option.

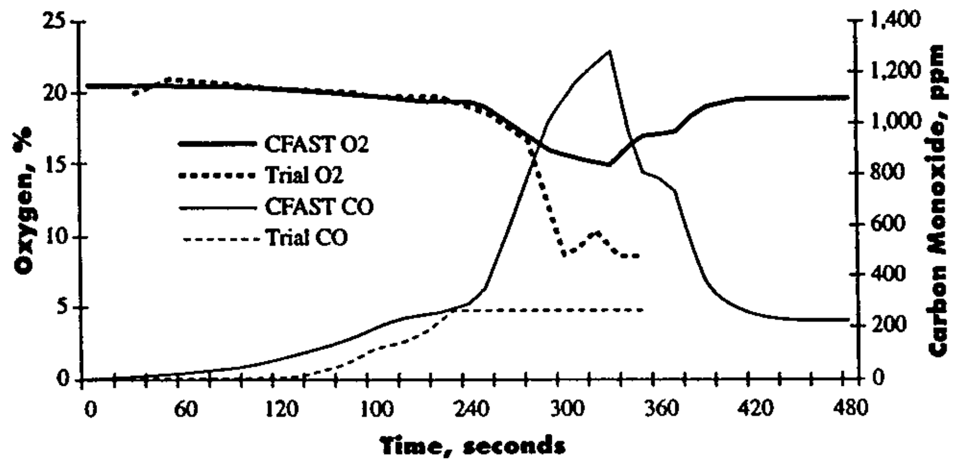

Figure 16. Gas species, CFAST prediction and trial result for Trial C (bedroom 1 sampled at a height of 1.5 m above floor level).

2. The response of ceiling-mounted heat detectors closely followed 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 smoke alarms would be prone to false alarms due to cooking vapors.

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

In addition, the confidence gained in applying computer models will encourage their use in the assessment of hazard situations producing more cost-effective solutions to building design where fire safety is an issue.

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3. Drysdale, D., *An Introduction to Fire Dynamics,* John Wiley & Sons, New York, 1992, pp. 143–145.

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5. *Firecalc, Computer Software for the Fire Engineering Professional,* CSIRO Division of Building, Construction and Engineering, North Sydney, Australia, 1992.

6. *Hazard 1.1, Fire Hazard Assessment Method,* National Institute of Standards and Technology, Gaithersburg, Maryland, 1991.

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Appendix A: Example of an Input File for CFAST Test 21

```
VERSN  2                   BTL HOUSE21
TIMES  600    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  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00  0.00  0.00  0.10  0.30  0.50  0.60  0.70  1.00  1.00  1.00
1.00
CVENT  5 7 2  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00  0.00  0.00  0.10  0.20  0.40  0.60  0.70  1.00  1.00  1.00
1.00
CVENT  5 7 3  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00  0.00  0.10  0.20  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
0.00  0.00  0.10  0.20  0.30  0.50  0.60  0.70  1.00  1.00  1.00
1.00
CVENT  6 7 1  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
```

```
0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.00
CEILI GYP1/2  GYP1/2  GYP1/2  GYP1/2  GYP1/2  GYP1/2
WALLS GYP1/2  GYP1/2  GYP1/2  GYP1/2  GYP1/2  GYP1/2
FLOOR PARTBDHD PARTBDHD PARTBDHD PARTBDHD PARTBDHD PARTBDHD
CHEMI  16.  50. 12.0  18100000. 288. 388. 0.000
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  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50
0.50  0.50  0.75  0.75  0.75  0.75  0.75  0.75  0.75  0.75
FAREA  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50  0.50
0.50  0.50  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
STPMAX 5.00
DUMPR BTL21.HI
DEVICE 1
WINDOW 0  0. -100. 1280. 1024. 1100.
GRAPH  1 100.  50.  0. 600. 475.  10. 3 TIME HEIGHT
GRAPH  2 100. 550.  0. 600. 940.  10. 3 TIME CELSIUS
GRAPH  3 720.  50.  0. 1250. 475.  10. 3 TIME FIRE_SIZE(kW)
GRAPH  4 720. 550.  0. 1250. 940.  10. 3 TIME O|D2|O(%)
HEAT 0 0 0 0 3 1 U
HEAT 0 0 0 0 3 2 U
HEAT 0 0 0 0 3 3 U
HEAT 0 0 0 0 3 4 U
HEAT 0 0 0 0 3 5 U
HEAT 0 0 0 0 3 6 U
TEMPE 0 0 0 0 2 1 U
TEMPE 0 0 0 0 2 2 U
TEMPE 0 0 0 0 2 3 U
TEMPE 0 0 0 0 2 4 U
TEMPE 0 0 0 0 2 5 U
TEMPE 0 0 0 0 2 6 U
INTER 0 0 0 0 1 1 U
```

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

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