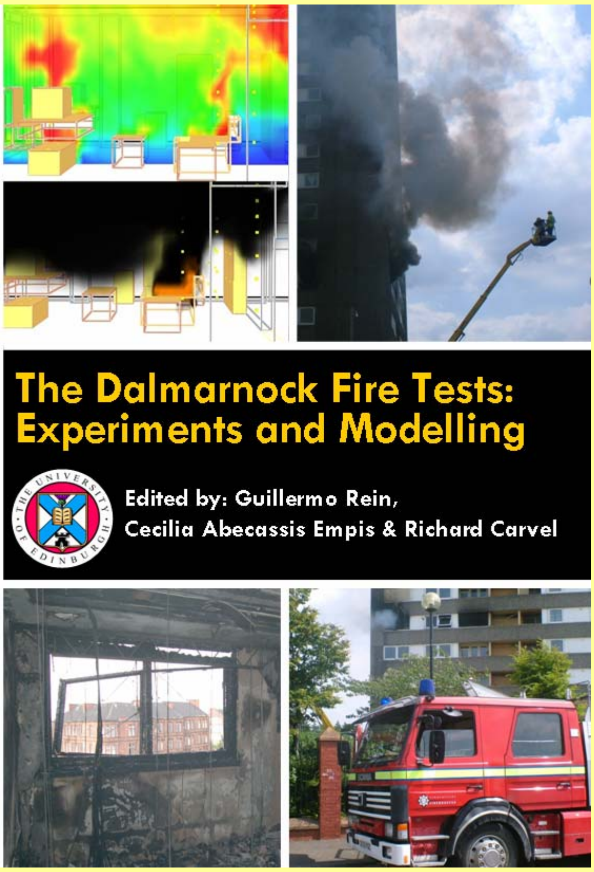
The Dalmarnock Fire Tests: Experiments and Modelling
Edited by G. Rein, C. Abecassis Empis and R. Carvel



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4. Test Two: The 'Controlled Fire'

By Adam Cowlard, Thomas Steinhaus,
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Introduction

The main objective of Test Two was to demonstrate the effectiveness of ventilation changes and smoke management on the growth of a compartment fire and to display the potential for these techniques to be incorporated into an automated fire fighting system. The compartment furniture and sensory equipment was set up in an almost identical configuration to that of Test One as described in detail in Chapter 2 and in Abecassis Empis *et al.* (2007). The windows and doors leading to the fire compartment, and the front door of the apartment, were fitted with mechanisms enabling remote opening and closing thus permitting general control over the compartment's ventilation. With the aid of live video streams, the ventilation was altered remotely during the fire to allow the outflow of any smoke accumulated within the compartment; the intention being to interrupt the positive feedback loop associated with a stratified compartment fire, thus delaying the fire growth rate and maintaining tenable conditions within the compartment. A substantial but enforced change to the ventilation conditions from Test One, given the circumstances, was the placing of a large hole in the wall from the fire compartment to the adjacent bedroom. This provided an escape route for a cameraman filming in the compartment while the fire remained localised. The major events and a characterisation of the output from this experiment are detailed below.

Major Events

Test Two was initiated by the same method as Test One, with a blow torch used to ignite a wastepaper basket containing crumpled newspaper, in this case soaked in 300ml of heptane. Slightly less accelerant was used than in Test One and the time delays between pouring the accelerant and igniting the fire also varied, but this difference is not significant to the general behaviour over the timescale of the fire as the accelerant only contributed to the momentary ignition of each fire and was fully consumed within seconds. The different ignition protocol was defined to establish the robustness of ignition conditions after results from laboratory tests (*cf.* Chapter 6). Its impact on the main timeline of the fire, as will be described later, is minor.

The fire quickly spread from the bin over a blanket draped over the side of the sofa. Upon igniting the bin the technician left the flat, and the two doors to the fire compartment and

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a third, the front door from the apartment to the communal corridor, were closed by remote control from outside the building. Members of the Strathclyde Fire Brigade and a cameraman remained inside the apartment. The smoke detection systems activated at 12 s post ignition. A further 16 s later, the windows of the fire compartment were opened by remote control to allow the smoke to vent out. Around 90 s post ignition, the sofa was burning at the end nearest the ignition source. By this stage a clearly perceptible, light grey smoke layer, characteristic of a localised fuel-controlled fire, had formed to a depth below the top of the compartment's door frames. At this time, the door from the fire compartment to the kitchen was opened to allow smoke to vent via the kitchen to the outside. Some 20 s after this intervention, the quantity of smoke in the room had been visibly reduced. The fire on the sofa was growing steadily and three minutes post ignition, the cushions on the sofa were fully involved in the fire. The door linking the fire compartment to the corridor was thus opened to allow ventilation through the two bedrooms, and a minute after this, the apartment's front door was also opened to allow further ventilation to the communal corridor. This final alteration to the ventilation conditions occurred four minutes after the ignition of the wastepaper basket.

Figure 1. Left - Cameraman films the fire spreading from the sofa arm to the cushions at 11:57:04. Right - Fireman exits right as fire transitions towards flashover at 11:59:33.

The fire spread from the sofa to the nearby bookcase and later across the sofa until it was fully involved in the fire. Once the bookcase ignited the smoke layer began accumulating despite the abundant ventilation. The growth rate of the fire continued to rise rapidly and ceiling jet flames were seen to travel across the compartment in what appeared to be the beginning of a transition to flashover and away from a fuel-controlled fire (Drysdale 2002). As the fire compartment became rapidly untenable the cameraman evacuated through the hole in the wall leading to Bedroom 1 followed immediately by a fire fighter. Meanwhile a thicker, blacker smoke layer, more indicative of a ventilation-controlled fire descended rapidly. Upon evacuation of the occupants, fire fighters immediately began to extinguish the fire through the hole from Bedroom 1 and subsequently from the fire compartment itself. The detailed times of the major events described here are shown in Table 1 below.

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Major Events Observed	Time [h:m:s]	Time from Ignition [s]
ignition	11:54:09	0
blanket ignited	11:54:10	1
Smoke detection system activates	11:54:21	12
Technician leaves and apartment door starts closing	11:54:27	18
Fire compartment / kitchen door closes	11:54:35	26
Fire compartment / corridor closes	11:54:36	27
Windows begin to open	11:54:37	28
Apartment door fully closed	11:54:44	35
Windows fully opened	11:54:53	44
Sofa ignited	11:55:39	90
Smoke accumulation in the room	11:55:51	102
Fire compartment / kitchen door opened	11:55:53	104
Substantial amount of smoke has left the room	11:56:12	123
Sofa cushions fully burning	11:57:04	175
Fire compartment / corridor door opened	11:57:08	179
Apartment front door opened	11:58:12	243
Shelf begins to burn	11:58:37	268
The sofa is fully involved	11:59:25	316
Cameraman begins to exit the fire room	11:59:33	324
First ceiling jet flame occurs	11:59:35	326
Fire Fighter intervention	11:59:41	332

Table 1. Timing of the Major Events as per camera footage.

Data Processing

Sensor Calibration

A detailed description of all the instruments used in this test is given in Chapter 2 and their locations relative to fuel in the fire compartment are shown in Figure 4. As some of the sensors were constructed specifically for these experiments, they required varying levels of calibration to produce meaningful results and several of these processes took place at the University of Edinburgh. Thin-skin calorimeters constructed from copper discs and thermocouples were used to measure incident heat flux to the fire compartments ceiling and kitchen wall. Laser smoke obscuration sensors consisting of a laser emitter and receiver diode were used to measure light obscuration. These data were then used to provide indicative values of extinction coefficients, required for use in the methodology followed for correcting thermocouple temperature readings for radiation, in to true gas-phase temperature. All these sensors were calibrated as per the processes described in detail in Chapters 2 and 3. Unlike in Test One, Test Two had no air velocity probes present in the fire compartment's doorways and window; therefore, no heat release rate curve is produced for this Test. These devices were omitted as the fire was never intended to grow to a fully developed, post-flashover, ventilation-controlled stage where these sensors are most effective, and also due to the complexity of installation alongside the automated windows and doors.

Smoke Layer and Extinction Coefficients

The extinction coefficients for Test Two were calculated using the same method as described for Test One in Chapters 2 and 3. The most reliable data obtained from the laser smoke obscuration sensors in Test Two came from the three vertical sensors, as the horizontal sensors were unexpectedly defected. It was therefore necessary to use the depth of the smoke layer for the path length (L) as the air between the sensor's emitter and receiver was not always completely smoke filled and contributing to levels of obscuration. An estimation of the variation of the smoke layer depth with time was calculated from thermocouple measurements, under the assumption that the smoke and hot layers were coincident, and averaged over the whole compartment, *i.e.* all vertical columns, and is shown in Figure 2 below. This was verified against camera footage to ensure the timing of the steep descent in smoke layer was congruent. The extinction coefficients that these measurements subsequently yielded are shown below in Figure 3. While there are some limitations with the accuracy of the vertical laser measurements (*cf.* Chapter 3), the vertical laser obscuration sensor placed closest to the window is thought to have yielded the most reliable readings as its photodiode receiver was shielded from the direct line of sight of the flame. Hence measurements from the remaining two vertical sensors were used to create an upper and lower bound range of possible extinction coefficients. Since these latter sensors were placed close to the main seat of the fire, they were affected by infrared radiation from the flaming, in effect yielding a lower extinction coefficient than that characteristic of the smoke layer. This explains the intermittent dips into negative extinction coefficients in the lower bound solution.

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Although this is not physically possible (*i.e.* visibility of the smoke layer can not be 'clearer' than the absence of smoke layer) it provides a range of bounds within which the actual extinction coefficient of the smoke layer might fall. The difference between the extinction coefficient measured close to the window and the lower bound solution was also used to define the upper bound range. This also accounts for the range of possible values of average extinction coefficient of the smoke layer, since only localised measurements were taken. These bounds can be used to check for the significance of the accuracy needed in the extinction coefficient of the smoke layer when applied to the thermocouple-to-gas-phase temperature correction process.

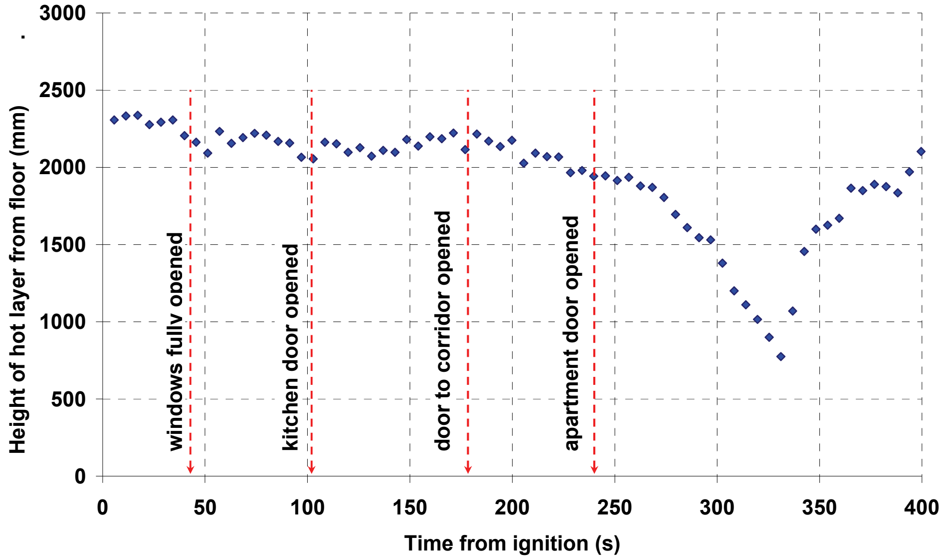

Figure 2. Smoke layer height (mm) variation within the experimental compartment derived from thermocouple data.

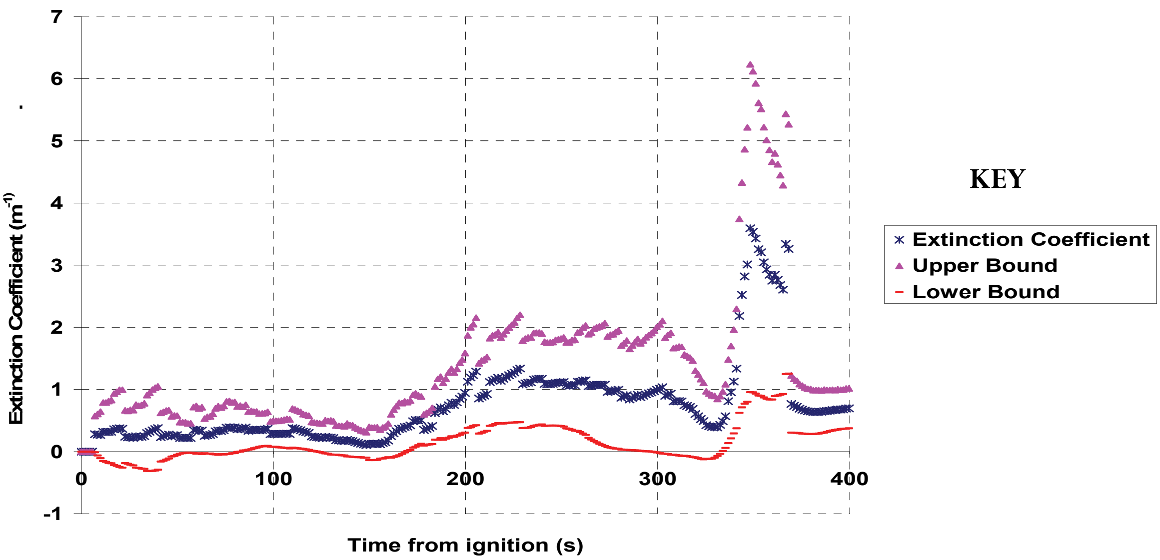

Figure 3. Extinction coefficient (m^{-1}) vs. time (s)

Thermocouple-Temperature Correction to Gas-Phase Temperature

Thermocouple corrections were performed according to the method described by Welch *et al.* (2007). Analysis of the initial, steadier period of burning until the period of rapid growth, around 300 s post ignition, showed the corrections to be negligible. The largest temperature correction to any of the thermocouples during this period was 10.78°C, with an average correction of ± 0.45°C. These values were deemed negligible as it is comparable to the errors inherent in the measuring process itself. Post 300 s, when the fire is undergoing rapid growth together with descent of the smoke layer, some localised maximum corrections are in the vicinity of the flaming region, as expected, and of the order of ~200°C. Nevertheless the average of maximum temperature correction for all thermocouples during this period is still relatively low at ± 29.6°C. Upper and lower bound coefficients, shown in Figure 3, were also used to determine respective temperature corrections and compared to the standard values obtained using the best-fit extinction coefficient. The maximum differences between the maximum upper bound and lower bound corrections, and the standard correction values were -8.03°C and 7.85°C respectively. The average maximum upper and lower bound corrections of the raw thermocouple readings were ± 0.5°C and ± 0.49°C respectively, which again were deemed negligible.

Characterisation of the Fire

The average gas-phase temperature-time curve (Figure 5) represents the general behaviour within the compartment with indications of the major events affecting the fire. In order to fully characterise the fire, selected Time Steps indicative of key stages of the fire were chosen for comparison of different data sets throughout the event. Time Step 1 represents a period 90 s after ignition where a localised fire was present on the arm of the sofa nearest the ignition source. The compartment windows had previously been opened after activation of the fire alarm but all other entrances to the compartment remained closed. Time Step 2, 200 s after ignition, comes once the fire has spread to the sofa cushions and the doors to the compartment have been opened. This instance is just prior to the onset of a slight but prolonged, steady rise in average room temperatures. The third time step, at 268 s post ignition, represents all sources of ventilation opened and a second major fuel source, a corner bookcase, now involved in the fire. Time Step 4, at 325 s, comes after a sudden increase in the size of the fire and the presence of ceiling jets protruding from the tops of the bookcases. It was just after this stage that the fire fighters extinguished the fire.

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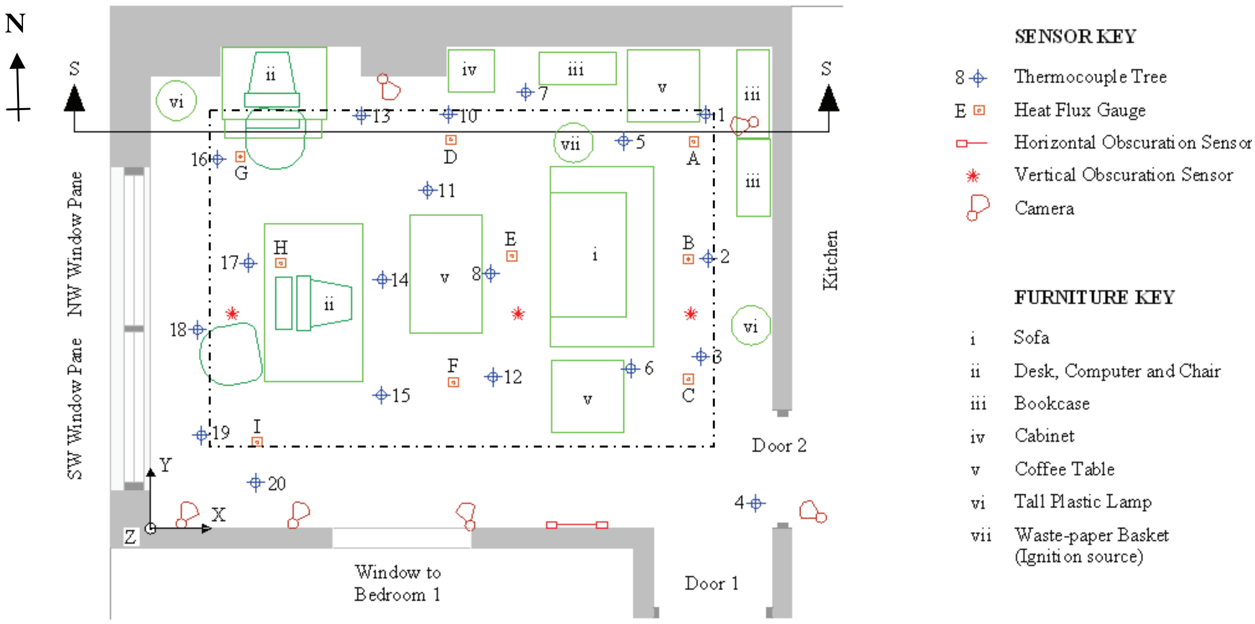

Figure 4. Plan View of the Test Two experimental compartment showing slice place section S-S relative to furniture layout (to scale) and sensor locations. The boxed region indicates the area corresponding to ceiling Heat Flux plots. The global coordinate system origin is also indicated.

Average Temperature-Time Curve

The plot of the average compartment temperature *vs.* time provides an overview of conditions within the compartment. Figure 5 shows this relationship along with some of the major events observed, as described above (Table 1). It also indicates the standard deviation throughout thereby giving an indication of temperature homogeneity throughout the compartment. It shows how for a large period of time post ignition the average room temperature remains low with a small standard deviation. This indicates a small localised fire and also shows how the room temperatures are constrained by automated venting of the smoke. When a door or window is opened there is generally a slowing in the rise of, and sometimes decrease in, the average room temperature. This plot demonstrates that while the fire is initially confined to one major fuel source, in this case the sofa, the venting is beneficial in limiting the increase in overall room temperatures but when the fire eventually spreads to a second major source of fuel, in this case the bookcase, it begins to grow rapidly and out of control of the effects of the remotely controlled ventilation. Correspondingly the standard deviation grows with the size of the fire indicative of larger temperature gradients generated throughout the compartment.

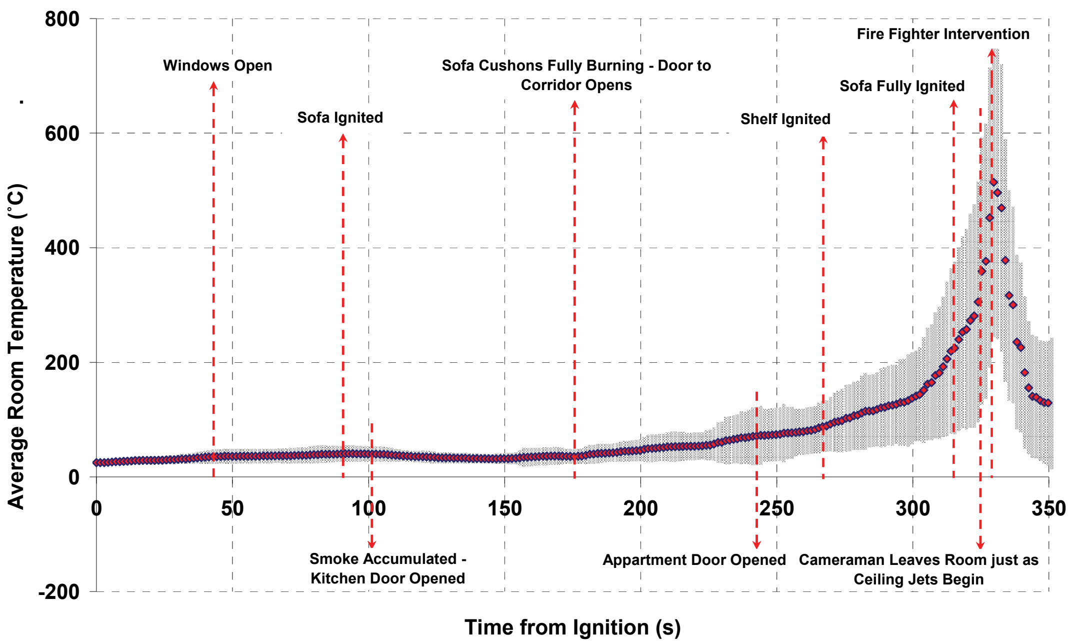

Figure 5. Average room temperature (°C) variation in time (s) during Test Two with indication of standard deviation. Times of some major events are indicated.

This trend of rapid growth upon ignition of the fuel laden NE corner was also observed in Test One. This highlights an objective of the design of the furniture arrangement which was intended to provide a level of repeatability. The positioning and nature of the ignition source adjacent to a fuel laden corner was intended to ensure secondary ignition of the bookcases irrespective of the presence of a smoke layer. Potential ignition of secondary items is discussed in depth by Babrauskas (1981). A comparison of the two tests is shown in Figure 6. The average temperature in Test Two is seen to remain below 40°C for the first three minutes whereas by contrast, Test One had reached an average room temperature of slightly over 100°C by this point. In both cases there is a sudden peak in temperature immediately following the ignition of the bookcases. Throughout the period of burning in each test involving only a localised fire on the sofas, the standard deviation was far smaller in Test Two. This is likely to be due to the lesser smoke layer in Test Two in this period. As the fire grows and the smoke layer becomes beyond the control of the externally operated ventilation, the standard deviation increases. Once the bookcases are involved, and the fire grows rapidly, the standard deviation for Test Two becomes comparable to that of the similar point in the fire growth of Test One.

As mentioned before, there was a small variation in the ignition protocol of both tests additional to the ventilation changes. Nevertheless, Figure 6 provides evidence that the ignition methodology and set up of the furniture is robust enough to guarantee a consistent timeline for both tests. Therefore these variations allow for an assessment of

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the bounds of repeatability of the test (i.e. in the form of comparison between outcomes of both tests) associated with a potential range of environmental conditions.

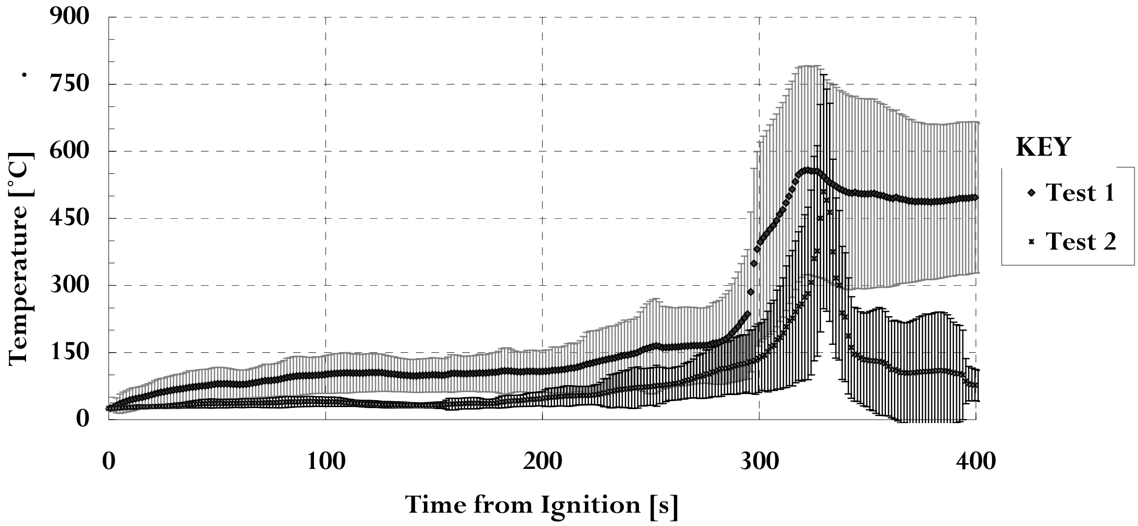

Figure 6. Comparison of the average room temperature (°C) variation in time (s) of Test One (up to 400 s only) and Test Two

Temperature Contour Plots

Temperature contour plots, representing a Y-plane section of the room indicated as S-S in Figure 4 are shown below in Figure 7. These plots encompass six thermocouple trees (Trees 1,5,7,10,13, and 16) with eleven gas-phase thermocouples per tree between the heights of 450-2400mm, the uppermost thermocouple in each tree being in contact with the ceiling and hence, not included. At Time Step 1, localised elevated gas phase temperatures can be seen in the area closest to the fire which is confined to the wastepaper basket and nearby arm of the sofa. A hotter upper layer is beginning to form above the fire seat but further away nearer the window, temperatures are hardly affected. Time Step 2, almost two minutes later, shows only a slight progression from Time Step 1 with regards to the formation of a hot layer below the ceiling. Despite the gap between the two time steps, the fire scenario has not vastly progressed which can be attributed to the controlled venting of the smoke to the rest of the apartment. The fire is still localised, confined to part of the sofa and its cushions, whilst near ambient temperatures still prevail in large areas of the room near the windows.

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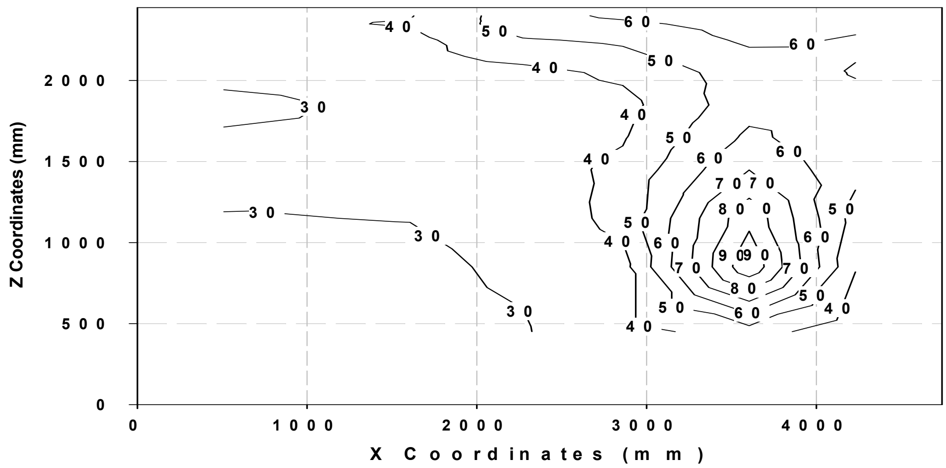
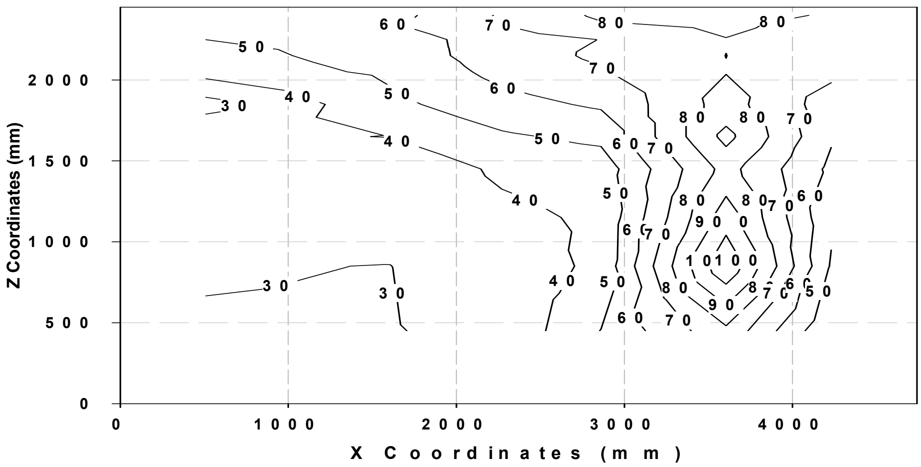
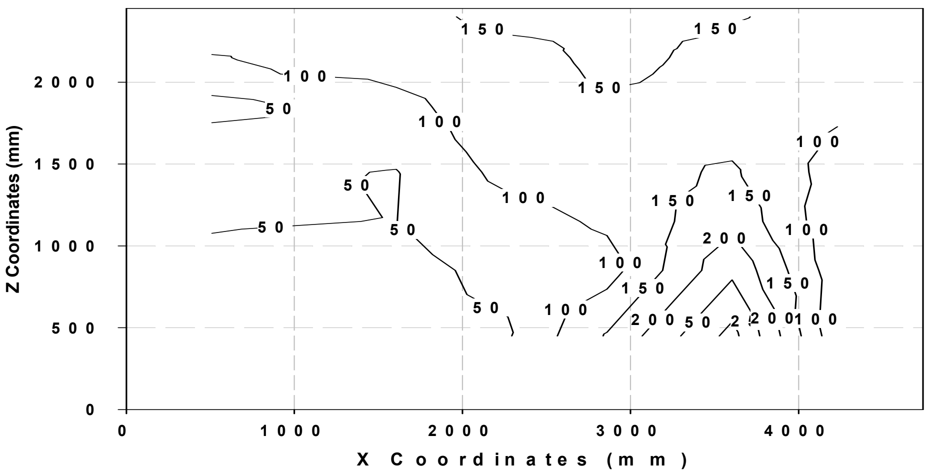


1) 90 Seconds



2) 200 Seconds



3) 268 Seconds

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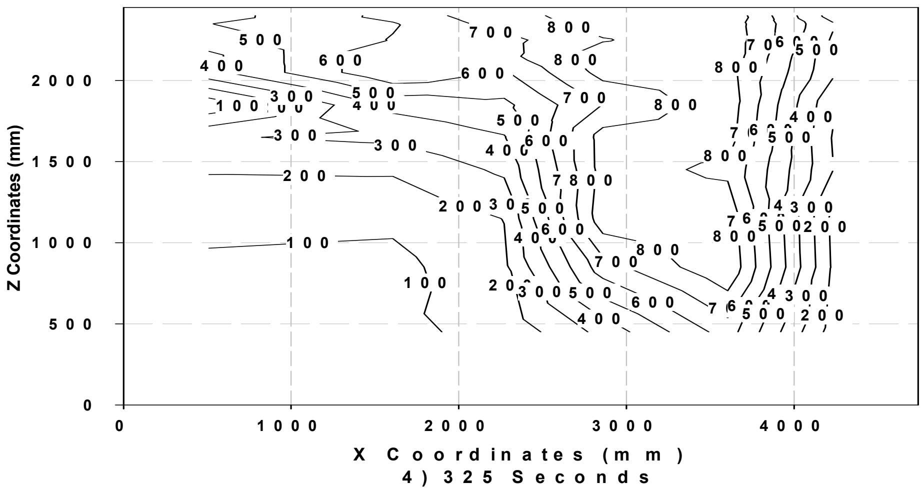


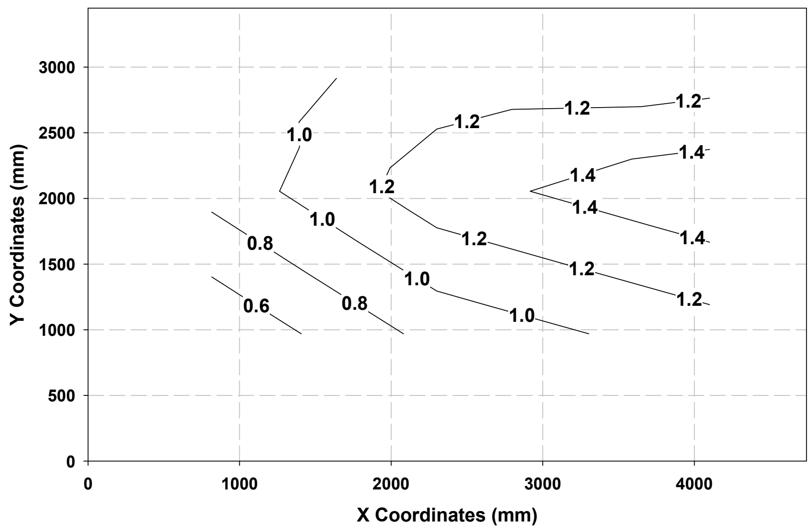
Figure 7. Temperature contours (°C) along Section S-S at 1) 90 s, 2) 200 s, 3) 268 s, and 4) 325 s from ignition. Axes values read distances from the global origin (*cf.* Figure 4).

Figure 7-3 shows the immediate effect that the bookcase ignition has had on the temperatures throughout the compartment. There is a distinctly hotter upper layer and the sofa fire has increased in magnitude with the impact from the bookcase. The temperatures around the compartments windows that before had not increased much beyond ambient temperature have now risen notably. The fourth time step shows the dramatic change that has occurred in approximately one minute since the bookcase initially ignited at Time Step 3. The size of the fire has increased dramatically, ceiling jets are now present, and there are steep temperature gradients throughout the compartment, with a notable increase in the depth of the smoke layer.

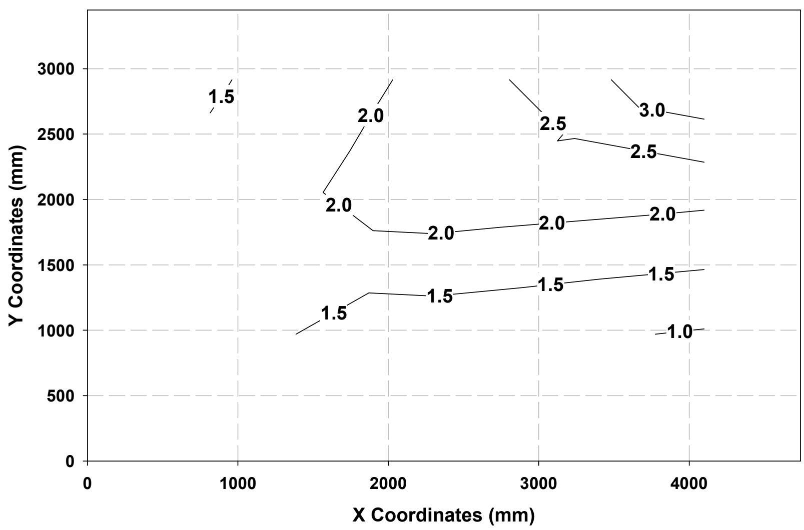
Comparisons have also been made between the contour plots in Figure 7 and corresponding plots (in time) from Chapter 3 on Test One. Comparison between Time Step 2 above and Chapter 3 Figure 6a, both around 200 s from ignition, clearly indicates the influence of the administered ventilation in Test Two. While both fires are localised and confined to the sofa near the ignition source, the temperatures are greater and a more stratified and hotter gas layer has formed beneath the ceiling in Test One. Approximately a minute later, shown in Figure 7-3 above and Figure 6b (*cf.* Chapter 3) in Test One, the temperatures of both fires have risen only slightly and the profiles of the contour plots remain very similar. The last comparable contour plots are Time Step 4 above and Figure 6c (*cf.* Chapter 3) in Test One, about 5-6 mins into the respective fires, where the average room temperatures reach a peak and the scenarios are far removed from those of the previous time steps. The greatest temperatures are situated around the seats of the fires and there are large temperature gradients across the compartments corresponding to the notable increase in standard deviations shown in Figure 6 above.

Heat Flux Contour Plots

Contour plots of the incident heat flux impingent on the ceiling of the fire compartment have been analysed and compared to the temperature contour plots and average compartment temperature-time curve. Again the heat flux plots show similar trends to those previously observed. During the initial three minutes there is very little growth, as indicated by the similarity in heat flux values shown in Time Steps 1 and 2. Time Step 3 shows the immediate effect of the bookcase involvement in the fire, raising the heat flux impingent on the ceiling. The profile of the contours changes from being centred close to the sofa to encompassing the area above both the sofa and the bookcases too. Time Step 4 clearly indicates the massive rise in heat flux to the ceiling corresponding to the global rise in compartment temperatures at this time seen in Figures 5 and 7-4. Once again a steep gradient exists from the kitchen wall to the windows with the uppermost fluxes coming from the sofa and bookcases. The ceiling heat flux contour plots have also been compared to the corresponding plots from Test One, where identical relationships can be seen between the Time Steps as those observed with the temperature contours. Similar plots were compiled for heat flux incident on the kitchen partition wall.



1) 90 Seconds



2) 200 Seconds

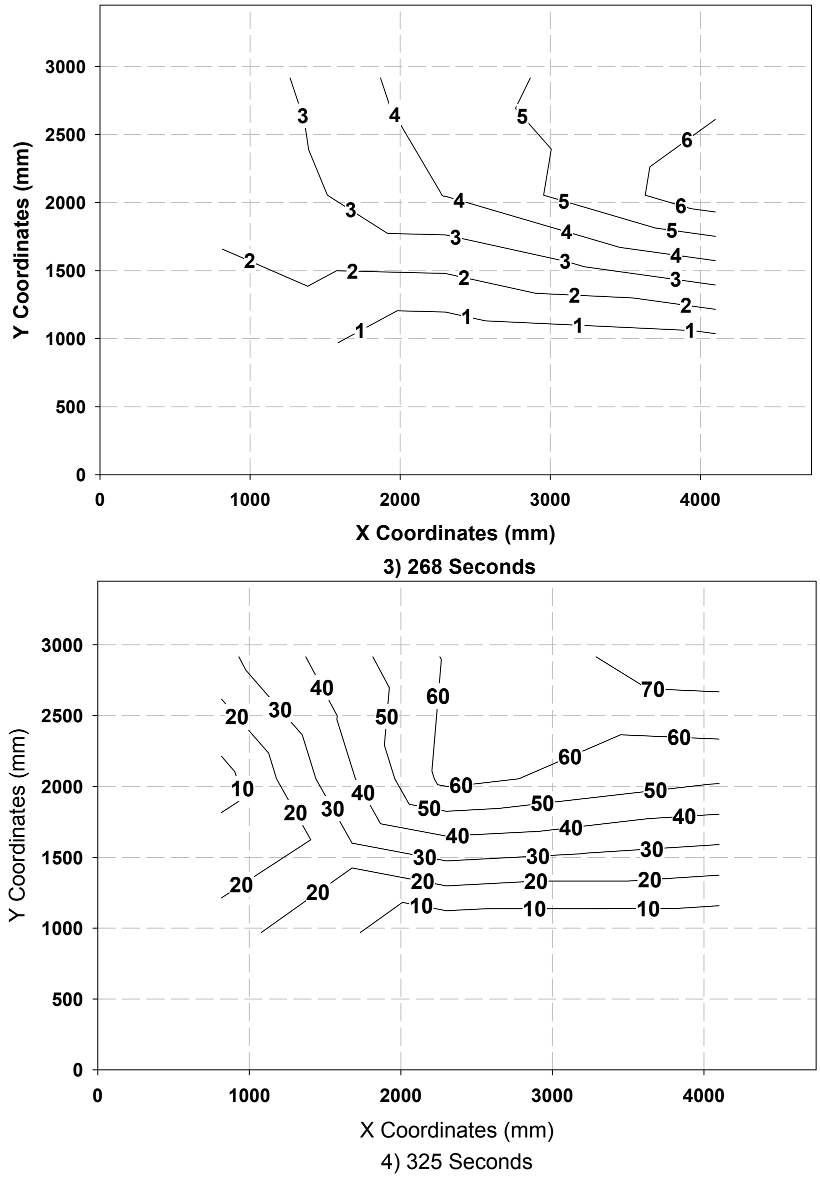


Figure 8. Contour plots of incident heat flux (kW/m²) on fire compartment ceiling region indicated on Figure 4, at 1) 90 s, 2) 200 s, 3) 268 s, and 4) 325 s from ignition. from ignition. Axes values read distances from the global origin (*cf.* Figure 4).

Summary

Test Two has successfully demonstrated the potential effectiveness of automated venting of smoke to hinder the build up of a smoke layer in a compartment fire. This in turn inhibits the positive feedback loop commonly associated with smoke layer build up and subsequent growth in fire size towards flashover. The average gas-phase temperature in Test Two remained reasonably low and conditions were generally more tenable than in Test One until the period just prior to the bookcase ignition. Hence this test also serves to highlight the importance of limiting the fire to one significant fuel source in order to further prolong the period of tenability.

The second objective of the tests, to create a repeatable large scale test scenario, was also successfully demonstrated. Despite the lower average room temperatures for the duration of the fuel-controlled periods of these fires, the transition towards a fully developed compartment fire occurred at an almost identical time post ignition and at an almost identical rate. The combination of the heat flux from both the ignition source and sofa, coupled with their close proximity to the large fuel load provided by the bookcases in the NE corner, leaves the situation extremely liable to a secondary ignition regardless of the levels of smoke built up. Given the excess of highly combustible constituents of the shelves and their corner configuration it is also highly likely that ignition of these items will initiate a transition to flashover. Comparison with the characteristics of Test One verifies this tendency towards repeatability, irrespective of ventilation conditions. This provides results particularly useful for validation of tools for modelling smoke and ventilation control. In addition, the sensor density equivalent to that in Test One, provides further data that is ideal for field model validation.

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