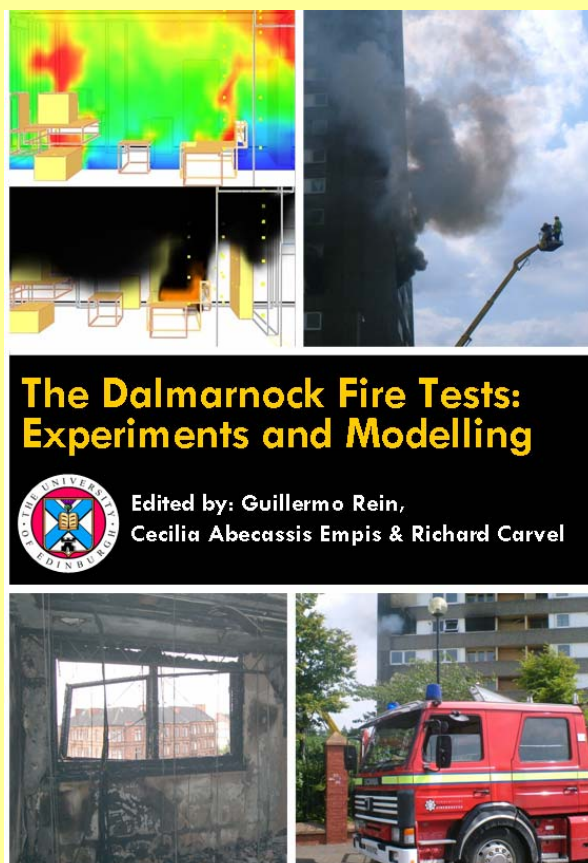


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10. A Priori Modelling of Fire Test One

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Introduction

Fire modelling is frequently used in contemporary fire safety engineering practice but discussions have been ongoing for many years now about its accuracy and reliability.

Fire modelling was first developed as a research tool in the 1970's (Emmons 1978) after the surge of computer resources. It reached its first applications to real fire engineering problems in the late 1980's (Cox *et al.* 1989), and now is widely used (Novozhilov 2001) in virtually all possible aspects of fire sciences, including forensic investigations, performance and risk assessments, life safety, smoke movement, sprinkler performance, structural behaviour, and safety engineering design. It is being used to model fire dynamics in enclosures and to simulate flames, plumes, hot layers and smoke movement during every stage of the fire development, from ignition and flame spread to flashover and extinction.

Modelling is among the fastest developing areas in fire safety science and receives much attention from both the research and engineering communities. However, its ability to reproduce fire phenomena lags our empirical understanding by about 10 years (McGrattan 2005). A key aspect for the discipline is the proper evaluation of the results from fire modelling. Many papers and standards addressing the verification and validation of fire models have been published recently (ASTM 2005, NUREG 2007, Salley *et al.* 2007, Wen *et al.* 2007) and many more are expected in the near future. In general, these aim at determining the level of accuracy and the range of applicability of given fire models by means of comparison to certain experiments. This evaluation is essential but what remains to be further explored is the evaluation of the entire process of fire modelling, in which the mathematical model is only a component. The assumptions made by the users, the collection of data for the input, the selection of the many parameter values available in the literature, and the expected or assumed accuracy in the output are crucial parts leading to the creation of the input file and the interpretation of the results. It seems reasonable to say that the current state-of-the-art of the technique is reflected not only in the mathematical model's inherent capabilities, but also in what is done during these stages. Thus, in order to understand the strengths and limitations of the whole process,

the complete process of fire modelling needs to be investigated. That is the objective of this study.

Generally, studies that have been conducted comparing modelling results to experiments find them in reasonable agreement with the test data. However, the great majority of the simulations are done after the test and with access to the resulting experimental data; thus, the comparisons are not blind and the level of bias may not be explicitly reported. Only a few blind prediction studies are available (Hakkarainen *et al.* 1995, Miles *et al.* 2000, Wang *et al.* 2001, Reneke *et al.* 2001) but these are for rather simple scenarios, which do not include features such as multiple fuel packages, flame spread, window breakage, etc. Very little research has been done comparing models with real scale fire tests, and none of these studies are blind (Pope & Bailey 2006, Reneke *et al.* 2001).

This Chapter reports the results obtained in a round-robin exercise to model the large-scale Dalmarnock Fire Test One (Chapter 3). The results are made public to encourage debate and exchange of views regarding the process of fire modelling.

Round-Robin Studies in Fire Science

A round-robin involves the analysis of a common scenario by several independent teams. In fire safety science the most famous round robin was that conducted by Emmons (1968) after his trip around the world visiting 40 fire laboratories to compare flammability ratings of a common set of materials. His results illustrated the lack of agreement among the tests resulting from a lack of basic fire science (Beyler 1999). In fire modelling, only two round-robins can be found in the literature. CIB organized and conducted a large and international round-robin (Hakkarainen *et al.* 1995) but the results were not made publicly available. A few teams published their own results (Miles *et al.* 2000, Wang *et al.* 2001). It seems natural to expect that these results were potentially among the teams that got the lowest discrepancy with the experimental results. The validation exercise published in NUREG (2007) could be viewed as a round-robin study with different teams and fire models, but it was not conducted to be a blind exercise. The lack of round-robin studies in fire modelling is a pending issue of the discipline.

The round robin presented here was organized with a pool of participants composed of international teams, all working in fire and using fire modelling as part of their professional practice. There are representatives from all the branches of fire modelling, from fundamental and applied research to final engineering 'real world' design. Due to the wide range of participants the results pertain to a wide range of users and allow certain conclusions to be made that reflect on the state-of-the-art of discipline as a whole. The participants worked independently and had access to a large common pool of data regarding the initial conditions just prior to fire. Each provided one or more simulations that represented their best prediction of the process according to their *a priori* knowledge.

The Dalmarnock Tests were performed in a way to simulate real fire conditions, which involve multiple fuel packages, flame spread, and result in a fire growth that is not readily obvious.

The objective is to compare all the modelling results, providing a range of predicted behaviours and a sense of the robustness, consistency and sensitivity of current fire modelling and the assumptions used. The results are also compared to the experimental measurements of the Dalmarnock Fire Test One to allow further conclusions on the accuracy and effectiveness of these tools. In spite of the fact that the Dalmarnock Test was designed to maximize its repeatability, this is always a concern in fire development (for both laboratory and real scenarios) and thus, the experimental measurements are not taken as the only true fire development but as a very realistic representation characterizing the scenario. Comparison of the results from Test One and Test Two (Chapter 4) later confirmed that the repeatability of the tests was high.

For all the aforementioned reasons, this study can be considered an assessment of the state-of-the-art of fire modelling in realistic enclosure scenarios.

Common Description of the Scenario

All teams were given access to a common pool of information about the test setup¹. Each team was free to use this information as they saw fit according to the best knowledge and criteria. There were no limitations for the team to consult the literature and search for additional data regarding other fire experiments or similar tests. Any missing information, unclear information or additional details were supposed to be complemented by the team's assumptions, research and external sources, as in any other fire modelling work they frequently conduct.

The teams were given all the details available up to the very ignition of the fire and some general overviews related to the aftermath. This included the geometry and dimensions of the flat; a detailed and measured layout of the room furniture (Figure 2); 50 photographs of the whole compartment final set-up, windows, fuel packages and instrumentation; individual descriptions, material, dimensions and photographs of each furniture element; and the heat release rate of a replica of the sofa and a wastebasket ignition source, which had been measured in the laboratory furniture calorimeter. Detailed description and analysis of this and other supporting laboratory tests are presented in Chapter 6. The information on the ventilation conditions included size, photographs and status of the windows and doors. The main compartment window was externally forced to break at 840 s after ignition, and this information was also provided to the teams. Metrological data from two nearby stations were also available. Media coverage was inevitable and thus the teams were provided copies of some news articles and footages which included photographs and journalist descriptions of the event as seen from outside. A 5-min video recorded with a hand-held camera summarizing the event, the compartment before and after the fire, and the fire as seen from outside the building was provided as part of the round-robin as well.

¹ In order to avoid biases in the predictions from The University of Edinburgh team, the modellers were kept separated from the experimentalists and created their input file before the actual test was conducted.

The study only considers the first test (the ‘uncontrolled fire’), held in a two-bedroom single family flat where the fire was allowed to grow past flashover conditions. A description of the test compartment and the fuel layout is presented in Chapter 2, but an overview is included here for quick reference. The main experimental compartment was the flat’s 2.45 m high, 3.50 m by 4.75 m living room, with a 2.35 m by 1.18 m set of windows (two panes) on the west-facing wall, 1.11 m above the floor (see Figure 1). The experimental compartment was furnished as a regular living room/office. The general layout was such that most of the fuel was concentrated towards the back of the compartment, away from the window, with a fairly even fuel loading throughout the rest. The main source of fuel was a two-seat sofa but the compartments also contained several items typical of office buildings. The fuel load density in the main compartment was estimated to be 32 kg/m² (Chapter 2) of wood equivalent, whereas a typical value for office buildings is 25 kg/m². The test was designed and conducted in a way such that it maximized repeatability of the fire development. Comparison of the results from Test One and Test Two (Chapter 4) later confirmed that the repeatability of the tests was indeed high.

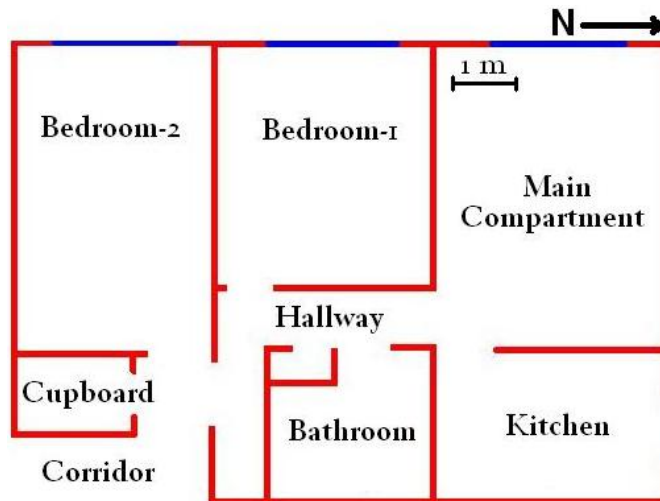


Figure 1: Flat layout showing basic dimensions (to scale), rooms and windows (Chapter 2).

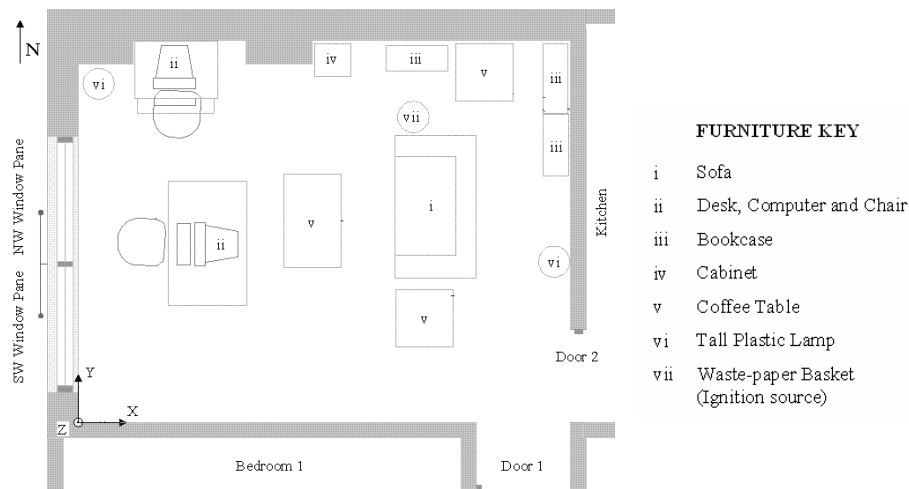


Figure 2: Furniture layout in the main compartment (see Chapter 2).

During the experiment all the doors of the flat were left open, except the bathroom's and cupboards' doors. The front entrance door communicating to the floor corridor was also open. Windows of all compartments excluding the kitchen and bedroom-2 were closed. The kitchen window was left partially open, producing an opening at the top and bottom due the pivoting mechanism of the pane.

The test was designed with an instrumentation density high enough to provide measurements with time and spatial resolutions compatible to that typical of field models (Chapter 2). However, the team were asked to provide results in three ascending levels:

- 1) General fire behaviour and time to major events (*e.g.* ignition of nearby objects, windows breakage, flashover, burn-out). This level suits all models, especially analytical ones.
- 2) Transient fire behaviour by zones (*e.g.* temperature of different layers and rooms, growth of smoke layer, ignition of other items). This level suits zone and field models.
- 3) Transient fire behaviour by fields, both in space and time (*e.g.* temperature, flow and species concentration fields). This level suits field models only.

The process of converting the data from field models to zone model-type and the assumptions made were a decision of each team and considered part of the round robin. The conversion of the point measurements to zone-type was done assuming that the smoke layer interface is located near the 150 °C isotherm. A sensitivity study for this criterion was conducted and results provided include isotherms in the range from 90 °C to 250°C.

Input Files for the Simulations

In total, ten simulations were submitted; eight field models using FDS (McGrattan and Forney 2006) and two zone models using CFAST (Peacock *et al.* 2000). No limitations or suggestions were given regarding the fire model to be used. Each team was completely free to choose their favourite or most adequate model for the task. The organizers tried to have in the round robin as many different models as possible, but users of other codes declined the invitation to participate. The fact that only freely available codes were selected is a reflection of the wide, extended and international use of NIST codes in fire engineering.

Table 1 condenses the most important aspects of each simulation in the round robin, and the following sections describes in detail each of the input files. Unless otherwise stated the default parameters of the base model were utilized. The ventilation conditions in the simulations were those in the experiments unless specified otherwise. All models include the forced breakage and falling out of the south pane window in the main compartment around 840 s, as provided in the round-robin data.

#	Fire Model	ERT* [h]	Grid [mm]	General description of input to for the simulation
A1	CFAST	0.01	-	Domain includes all the rooms in the flat. Total HRR partially predicted. Ignition source modelled using the HRR from NIST sofa. Individual item's HRR curves were prescribed and ignition was predicted by ignition temperature.
A2	FDS 4	153	50	Domain includes only the main compartment. Total HRR partially predicted. Ignition source prescribed using the HRR from NIST sofa. Material parameters were used for other burning items and ignition is predicted by ignition temperature.
B	FDS 4	23	5-500	Domain includes the whole flat. Total HRR partially predicted. Ignition source prescribed with measured HRR of sofa replica and mass left introduced into domain and allow to further burn. Ignition of secondary items predicted by ignition temperature and material properties.
C	CFAST	0.01	-	Domain includes the whole flat and floor corridor. Ignition source prescribed with measured HRR of sofa replica as given. Ignition of secondary items predicted by ignition temperature and material properties.
D1	FDS 4	19	100	Domain includes the whole flat. HRR is fully prescribed using the onset of external flaming as the peak value at each stage. Ignition source is a t^2 fire.
D2	FDS 4	128	50-100	Domain includes the whole flat. Total HRR is partially predicted. Ignition source prescribed using the measured HRR. Ignition of secondary items predicted by ignition temperature and material properties.
E1	FDS 4	55	100	Domain includes the whole flat. Total HRR is predicted. Ignition source is a basket fire. Ignition of secondary items predicted by ignition temperature and material properties.
E2	FDS 4	33	100	Domain includes the whole flat. Fully prescribed HRR using t^2 law and plateaus based on ventilation conditions.
F1& F2	FDS 4	170	90	Domain included main compartment, kitchen, bedroom-1 and hall. Total HRR partially predicted. Ignition source prescribed with measured HRR of sofa replica but extrapolated with a t^2 law. The peak HRR is raised by 20% in F1 and by 40% in F2. Ignition of secondary items predicted by ignition temperature and material properties.

Table 1. Condensed information about each simulation

* Estimated Running Time in the computer

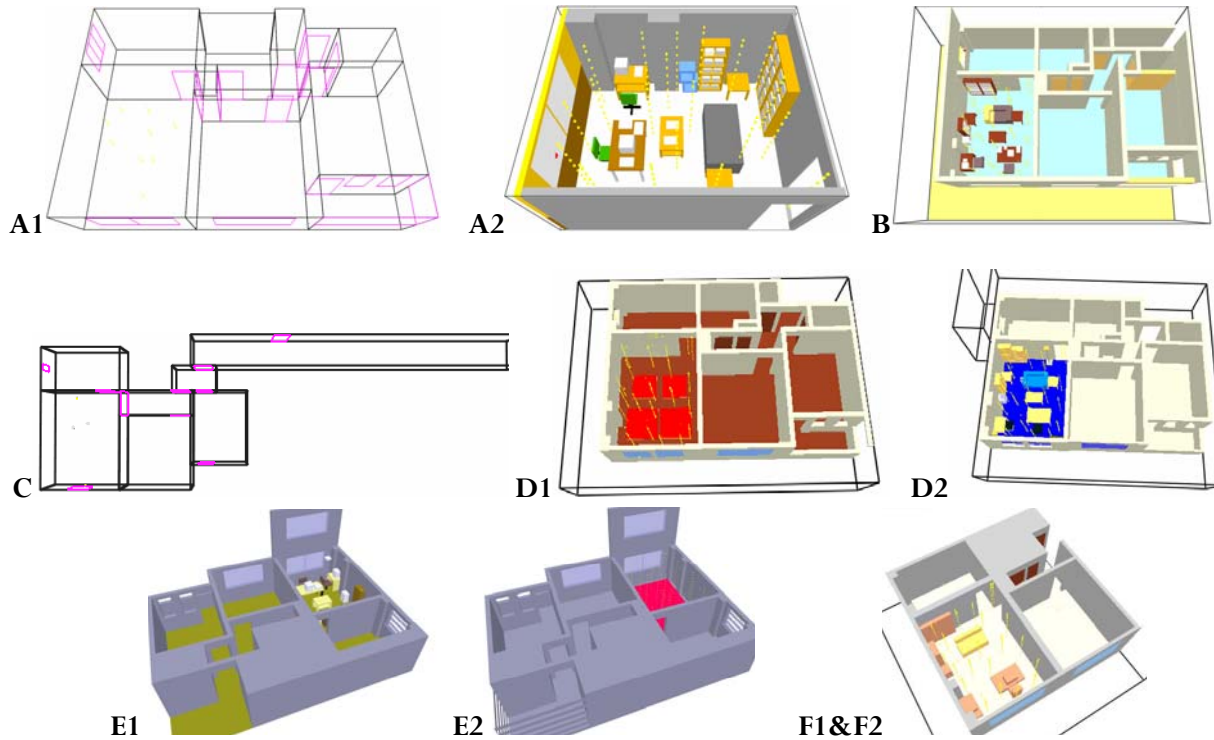


Figure 3: Full computational domain for each of the simulations

Simulation A1

The model used was CFAST 6. The geometry included all the rooms of the flat (Figure 3) using eleven compartments. The walls and ceiling were assumed of concrete and floor was hardwood.

The ignition source was prescribed following the NIST sofa curve (Lawson *et al.* 1983). The HRR curve of the Dalmarnock sofa replica was deemed too low and not used. For the other fuel elements, the HRR curves provided in CFAST database were used. For example, a TV-set curve was used for the low table and twice a TV-set curve for the coffee table (this curve peaks at 280 kW after 720 s). A panel workstation curve, with a peak of 6.7 MW at 550 s, was used for the two desks. A wardrobe curve was used for the bookcases. The criterion for ignition of all fuel items was a wood ignition temperature of 240 °C (Babrauskas 2001).

The machine used was a Pentium 4 CPU 3.40 GHz processor and the calculations required a computer time of only a few seconds.

Simulation A2

The model used was FDS 4. The domain only included the main compartment (Figure 3). The other pane of the window in the main compartment was predicted to break when a heat detector reached 100 °C. The walls and the ceiling are given the properties of concrete. The global chemical reaction used was that of polyurethane.

The ignition source was prescribed following the NIST sofa curve (Lawson *et al.* 1983). The HRR curve of the Dalmarnock sofa replica was deemed too low and not used in the simulation. The burning parameters to model the furniture items correspond to the burning experiments in (Metral *et al.* 2001) resulting in an imposed HRR curve with a peak of 243 kW/m² at 575 s. The parameters to model the computers and other plastic materials were taken from Madrzykowski and Walton (2004). Criteria for ignition of the room items was the ignition temperature (326 °C for plywood and 200 °C for the plastics).

Conversion to zone-type data was conducted following the methodology in FDS (McGrattan and Forney 2006).

The total computational domain is 4 x 5 x 2.5 m with a total number of 400,000 cells. The side of a grid cells is 5 cm in all directions. The machine used was dual-CPU Xeon 3.40 GHz processor. The calculations required a computer time of about 153 h (one week).

Simulation B

The fire model used was the FDS 4. The domain included the whole flat extended several metres beyond the building structure (Figure 3) and extended one storey above the level of the flat. Several preliminary simulations were performed at reduced grid resolutions to investigate the fire dynamics, and find the dependency with the grid size. Each window was set to break at 650 °C, with the exception of the main compartment window which was forced to break at 960 s into the simulation. The other windows broke when flashover was achieved shortly after. The global reaction utilized was that of polyurethane.

The properties of concrete for the walls and other materials utilized in the simulation were taken from the FDS database and literature (Babrauskas 2003, SFPE Handbook 2002, Grosshandler *et al.* 2005). The material properties collected included ignition temperature and heat of vaporization which governed the ignition and combustion for the simulation. A combination of prescribed and predicted HRR was used. The HRR was prescribed initially to simulate the ignition source following the provided HRR of the sofa replica (Chapter 6). To account for the sofa mass left, this was introduced into the compartment and allowed to burn based on ignition temperature and heat of vaporization.

Field data for layer height and layer temperatures were converted from the field data using the built in functions in FDS.

The numerical grid utilized for the simulation varied and ranged in size from 5 mm within the main compartment to 500 mm furthest away from the combustion area. The total number of cells utilized was 500,302. The simulation was performed on a 2 GHz Pentium M machine. The running time was approximately 23 h.

Simulation C

The fire model used was CFAST 6. The domain included the whole flat as well as a section of the floor corridor outside the flat (Figure 3). In addition to the given

ventilation conditions, a doorway from the corridor was opened at 600 s. The walls and ceilings are made of gypsum and the floors of hardwood and concrete.

The measured heat release rate curve of the sofa replica was used, as given. In addition, a wastebasket fire was added using a heat release rate of 40 kW for the first 300 s, then decay linearly to burnout at 600 s. The other fuel items were modelled using the CFAST database properties for plywood.

The machine used had an Intel U2500 processor at 1.2 GHz and the calculations required a computer time of only a few seconds.

Simulation D1

The fire model used for both simulations was FDS 4. The whole flat was modelled and some external space was added to the domain (Figure 3). The material properties used for the flat were the FDS 4 database values of gypsum board for the walls, glass for the windows, ceiling tile for the ceiling and spruce for the doors and floor. The second pane of the main compartment was assumed to break and fall at 960 s (rough estimate of a few minutes after the other).

The heat release rate was fully prescribed. The ventilation parameters of the main compartment are not readily obvious and calculations of the maximum HRR due to ventilation control conditions gave unrealistic values (about 12 MW using correlations Karlsson and Quintiere 2000). Thus, a different approach was sought. Exploratory simulations were run varying the heat release rate to determine the actual value that ensures the majority of the flames to be internal to the flat. This was done to avoid the tendency of FDS to predict flames outside the compartment of origin once ventilation-limited conditions are reached. The maximum heat release rate was determined as 2.5 MW before window breakage, 4.7 MW after the first window broke, and 6.9 MW after the second window broke. The fire load was distributed across the floor in four separate burners. The first two burners, which were located in the kitchen end of the main compartment, contributed to the first peak. The third and fourth burners, which were located on the window end of the main compartment, turned on at 780 s and 960 s (the times to window breakage), respectively. The growth rate used was a standard fast t^2 fire (Karlsson and Quintiere 2000).

Conversion of field data to zone type was conducted following the methodology of He *et al.* (1998).

The total computational domain is 12 m x 9 m x 2.5 m with a grid size of 100 mm in each direction. The calculations were conducted in two networked Intel Pentium 4 at 2.66 GHz, and required a computer time of 19 h.

Simulation D2

The fire model used for both simulations was FDS 4. The whole flat was modelled and some external space was added to the domain (Figure 3). The ventilation conditions were identical to those specified in the round robin data, except that the bathroom's and

cupboards' doors opened. The material properties used for the flat were the FDS 4 database values of gypsum board for the walls, glass for the windows, ceiling tile for the ceiling and spruce for the doors and floor. The second pane of the main compartment was assumed to break and fall at 960 s (rough estimate of a few minutes after the other).

The intent of the simulation was to replicate flame spread and fire development throughout the geometry by using a blind prediction of the materials used in the experiment. Material properties for the furnishings such as sofas, chairs, curtains/drapes were extracted from experiments of similar materials that were used on a previous FDS analysis (material properties extracted using a similar approach to that in Lautenberger *et al.* (2006)). Although not the exactly the same (Dalmarnock materials were not available for small scale tests), these material properties were considered sufficiently similar to composition and orientation to the Dalmarnock interior finishes. New properties for all of the input constants required for flame spread modelling were used. For the initiating fire the free burn sofa data measured under the hood calorimeter was utilised as given.

Conversion of field data to zone type was conducted following the methodology of He *et al.* (1998).

The main compartment was divided into cells 50 mm in all directions. The rest of the flat had a grid resolution of approximately 100 mm in all directions. The domain had 723,280 cells. The simulation was runs in a cluster of 20 CPU's with speeds between 2200 GHz and 2800 GHz and took 128 h to complete.

Simulations E1 and E2

The fire model is FDS 4. The domain included the whole flat and several meters of the exterior around the building (Figure 3). The second pane of the main compartment was roughly assumed to break one minute after the other. The thermal properties of the walls and ceilings are those of concrete.

For the first simulation E1, the heat release rate was predicted and the fire load was modelled in a detailed manner. A trash-can fire was imposed with a constant HRR (135 kW) during 3 min (SFPE Handbook). The measured HRR curve of the sofa replica was not used because that experiment did not reached the peak value. Ignition and burning of secondary items was simulated based on material properties taken from the FDS default database (PMMA, upholstery, plastic commodity). The global chemical reaction used was that of polyurethane.

For the second simulation E2, the HRR was fully prescribed and the fire load was considerably simplified. For this simulation, it was decided to use the time to flashover predicted during the E1 simulation (*i.e.* 180 s), as input data to define a user prescribed heat release rate curve. Thus, the prescribed HRR curve is made of a t^2 , followed by a plateau until the half pane of main compartment window is broken. A new plateau is then reached and a linear decrease is applied when the fire-fighters intervene into the compartment. The typical values of HRR are here defined by ventilation conditions

(Drysdale 2002), by taking into account the main compartment window and the kitchen window.

The conversion to zone-type data was conducted using the built-in functions in FDS 4 (McGrattan and Forney 2006).

The numerical grid used was uniform with a cell size of 10 cm. A second much smaller numerical domain was employed to simulate external flames. The number of cells involved is 311,000 for the first domain and 17,300 for the second one. No grid effect study has been performed but, to the author knowledge, such a grid is sufficiently fine to simulate the case, at least with a prescribed HRR. The computing time required to solve for simulation E1 was 55 h using a Pentium Dual Core I 3.4 GHz, and for simulation E2 it was roughly 33 h using a Pentium Dual Core II 3.2 GHz.

Simulations F1 and F2

The fire model used was FDS 4. It included the main compartment, the kitchen, bedroom-1 and half of the hall-way (Figure 3). All windows were allowed to break following the criteria that 33 % of the glass will fall out when it reaches 100 °C. Walls, floors and ceilings are given the properties of concrete as listed in the FDS4 data base. Several preliminary runs were conducted first to investigate the maximum heat released rate available given the ventilation, the effect of a reduced flat domain and the grid size.

On the ignition HRR is prescribed and the burning of the rest of the items is predicted. The ignition source and the sofa fire were prescribed following the HRR curve measured in the sofa replica. This curve was extrapolated to reach complete consumption of the sofa mass using a t^2 law, which yields a peak of 800 kW after 20 min. To take into account the lack of thermal feedback from the fire in the laboratory experiment, the simulation F1 had this peak HRR raised by 20 % and simulation F2 by 40 %. These two simulations were seen as describing the range of the possible fire developments depending on possible variability of the ignition source. Other combustible items were the three bookshelves and two computer desks, modelled as a lumped general fuel the ignition temperature of paper 250 °C (Drysdale 2002) and the heat released per nit areas of plastic (500 kW/m²).

Conversion to zone-type data assumed that the smoke layer was located at 100 °C or at the maximum gradient when the maximum temperature is lower than this value.

The computational domain is 9 x 9.2 x 2.6 m with a grid of 300,000 cells. The grid is of made of uniform cells approximating cubes with a side of 90 cm. It took about 170 h (a week) to run in a 1.5 GHz multiprocessor Intel Itanium 2 machine.

Comparison of the results

The simulations shown in this section were conducted blindly. It is convenient to remind the words attributed to Sir Winston Churchill (circa 1945): *“I always avoid prophesying beforehand because it is much better to prophesy after the event has already taken place”*. Thus, the findings made after the comparison with the experimental data were unknown to the

modellers and it is an important part of this study to conclude on the implications of these findings.

The large data collected from the round robin participants greatly exceeds what can be presented in this Chapter. Thus, only a selection of the most important variables is presented here.

Table 2 shows the time and the experimental results for the maximum temperature in the compartment as well as the time to reach flashover. The predicted times to flashover fell into two groups, those at 800 ± 80 s (~ 13 min) – very close to the time for forced window breakage at 840 s – and those that predicted flashover before 180 s (3 min). One simulation predicted no flashover at all. The maximum predicted temperatures in the compartment varied between a 50 % overprediction down to a 72 % underprediction, but the average of the ten simulations is only 10 % higher than the measured maximum temperature.

Figure 4 shows the global heat release rate. The same legend for the simulation curves is used in all the subsequent figures (continuous line for field models, dashed line for zone models, and dots is for experimental data). Three stages are observed in all of them; initial growth, first post flashover until window breakage and second post flashover. The heat release rate (HRR) in the main compartment was measured during the test using the principle of oxygen depletion. This gave a rather steady 3 MW between flashover and the window breakage at 840 s and about 5 MW thereafter as plotted in Figure 4. Hand calculations using ventilation factors indicated good agreement with these values (see Chapter 3).

	Time to Flashover[s]	Maximum Smoke Layer Temp [°C]
A1	850	792
A2	780	1026
B	841	1070
C	no flashover	211
D1	200	720
D2	77	1153
E1	180	900
E2	180	1170
F1	720	590
F2	850	650
avg	591	828
exp	300	750

Table 2: Comparison of times to flashover and the maximum temperatures in the main compartment.

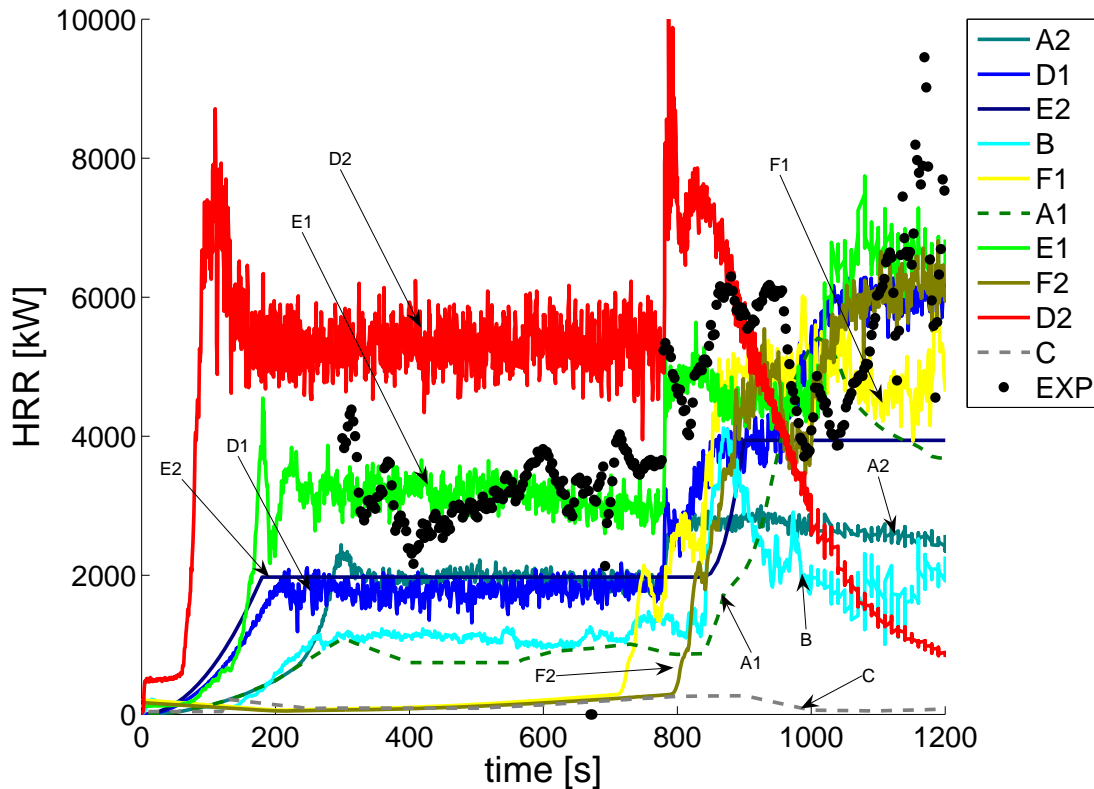


Figure 4: Predicted heat release rate in the whole compartment. Legend for the different curves; continuous line for field models; dashed line for zone models; and dots is for experimental data.

The HRR predictions show a wide scatter of fire behaviours. One simulation (D2) overpredicted the fire by 100 %, another (E1) provided quite good predictions and all the others underpredicted it in the range from 30 % to 90 %, with the average of all of them being about 30 % lower than the measured values. Note that two simulations (F1 and F2) compare poorly to the measurements but only in time, since the HRR levels are predicted well for the post flashover stages. Most simulations attempted to partially predict rather than fully prescribe the heat release rate. Only two models prescribed it completely (D1 and E2). For the two simulations that fully prescribed the HRR (D1 and E2), the prescribed values were not reached in the model due to unburned fuel leaving the domain via the vents. When a fire is ventilation limited, the underlying approximation of the mixture fraction model trend to over predict the external flaming in the domain. It is worth noticing that all expect one (D2) of the simulations predicting flashover before 3 min did not use the measured HRR for the sofa replica, as the users deemed it too slow for the growth stage or not complete. The best average results and lower scatter are obtained after the forced window breakage because users were informed of the time of this event.

The HRR curve is the single most global and comprehensive characteristic of fire development and results from the time evolution and interactions of many important mechanisms like pyrolyzate production rate, flame heat feedback, smoke layer built up, fire spread and ventilation boundaries, to name just a few. The wide range of simulated HRR demonstrates the difficulty in predicting and prescribing well this overall

characteristic in the case of non-trivial and realistic scenarios. Furthermore, the results also offer the possibility to investigate and quantify the implications of over and under predicting the HRR in *a priori* simulations by comparison of the gas phase and solid phase variables.

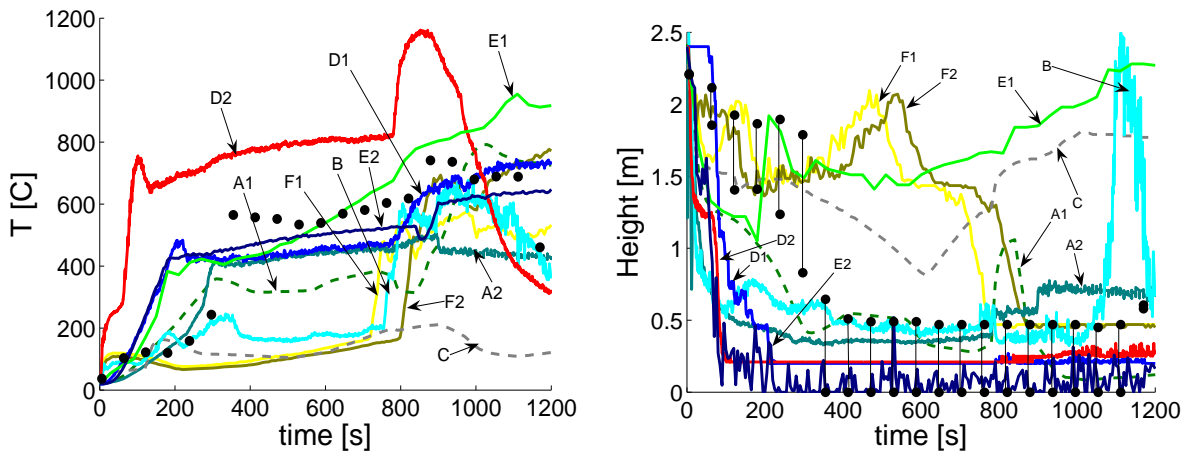


Figure 5: Transient results for the hot layer, right) temperature and b) height. Values derived from measurements assumed smoke layer started at isotherms from 90 °C to 250 °C.

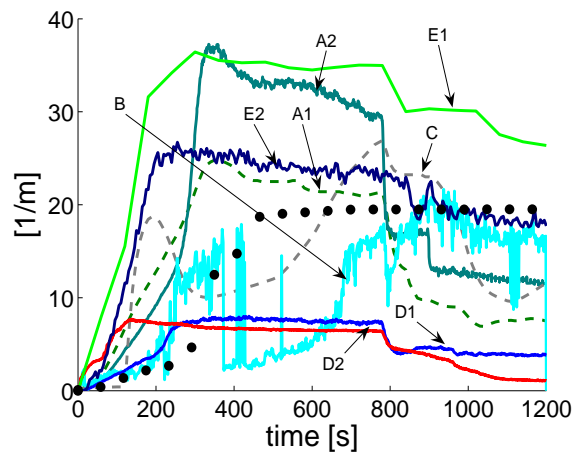


Figure 6: Transient results for the extinction coefficient in the hot layer.

The results averaged by zones are shown in Figures 5 and 6. Figure 5 shows the hot layer temperature and height. The experimental values are averaged over the entire smoke layer assuming this started at isotherms in the range from 90 °C to 250 °C. The smoke layer temperature averaged results were insensitive to variations within this range (less than 2%). Variations in the experimental smoke layer height to this criterion were significant during the growth period as presented in Figure 6. There is a wide scatter of modelling results in both figures, but especially in the height predictions. Most simulations underpredicted the hot layer temperature with four of them falling around

the 10 % to 40 % range. Regarding the smoke layer height, the very wide range of behaviours predicted reflects also on the influence of the user's assumptions converting field results to zones. It is worth highlighting that the simulation that performed the best predicting the HRR within 10 % (E1) predicted the hot layer temperature only within 30 % and is completely off in the smoke layer height. Figure 6 shows the results for the extinction coefficient in the smoke layer. The measurements lie in the middle of the range covered by the predictions, and there is no biased towards underprediction or overprediction.

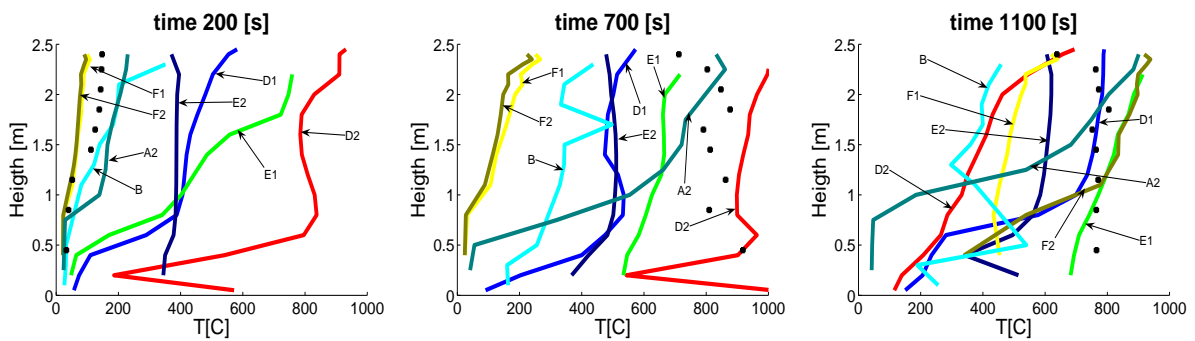


Figure 7: Gas-phase temperature vs. height on main compartment for different times at northeast corner, near sofa.

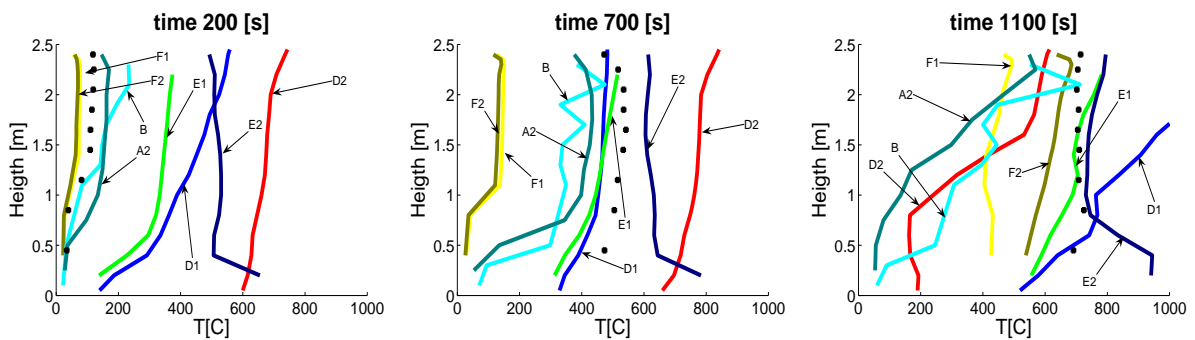


Figure 8: Gas-phase temperature vs. height on main compartment for different times at the southwest corner, near the window.

Local results by fields are shown in Figures 7 to 12. Figures 7 and 8 show the local gas-phase temperatures in the main compartment at different times and locations. Three times are chosen: during fire growth (200 s), first stage of the post flashover (700 s), and second stage post-flashover (1100 s), and two locations, near the sofa and near the window. In general, the range of temperature results is very wide (roughly $\pm 80\%$) with a biased towards underprediction. A relatively lower scatter is observed during the second stage of the post flashover and also near the window (away from the larger fuel load). The simulation that predicted the HRR within 10 % (E1), overpredicted local temperature by 200 % during the growth phase but during post flashover the disparity is reduced to 25 %.

Local results for the instrumented wall, east of the main compartment (see Figure 2), are shown in Figures 9 to 12. Figures 9 and 10 show the incident heat-flux at different times

and locations. In general, the scatter is large, especially during the growth phase and the lower heights, but it is lower at the higher heights during the post-flashover.

Figures 11 and 12 show the wall temperature at different times and locations. As with the heat flux, the general scatter is large, especially during the growth phase and the lower heights. However, the scatter is lower than that of the heat-flux.

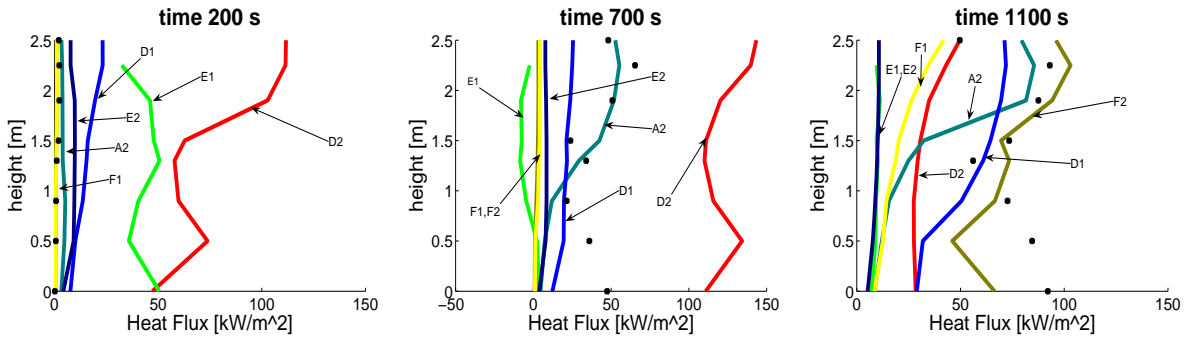


Figure 9: Local incident heat-flux vs. height on east wall of main compartment for different times.

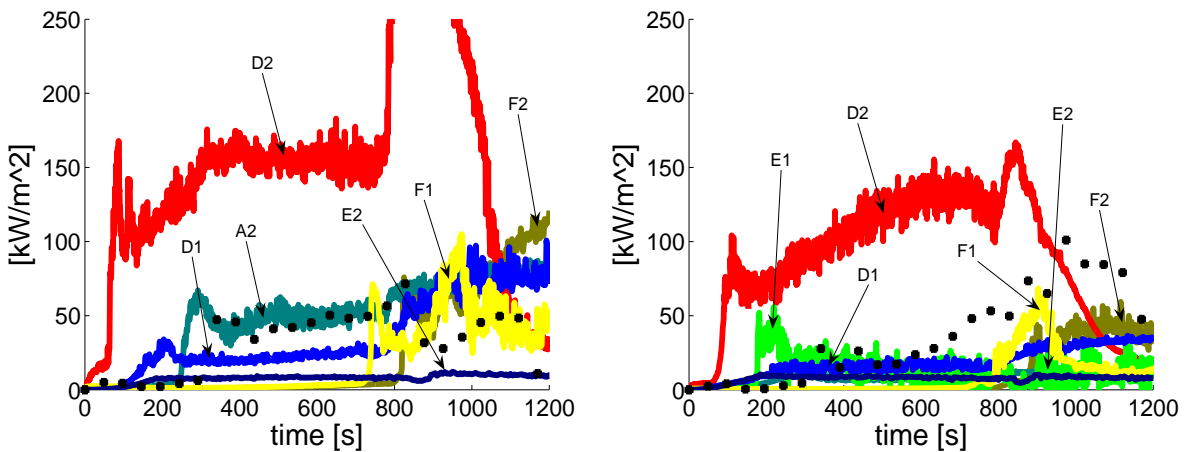


Figure 10: Local incident heat-flux vs. time on east wall of main compartment, at heights of (left) 250 cm; and (right) 50 cm from the floor.

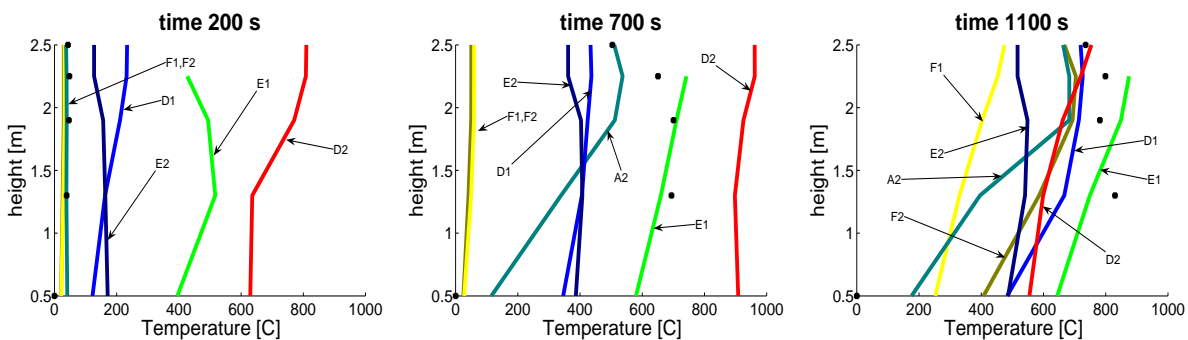


Figure 11: Local temperature vs. height of east wall of main compartment for three different times.

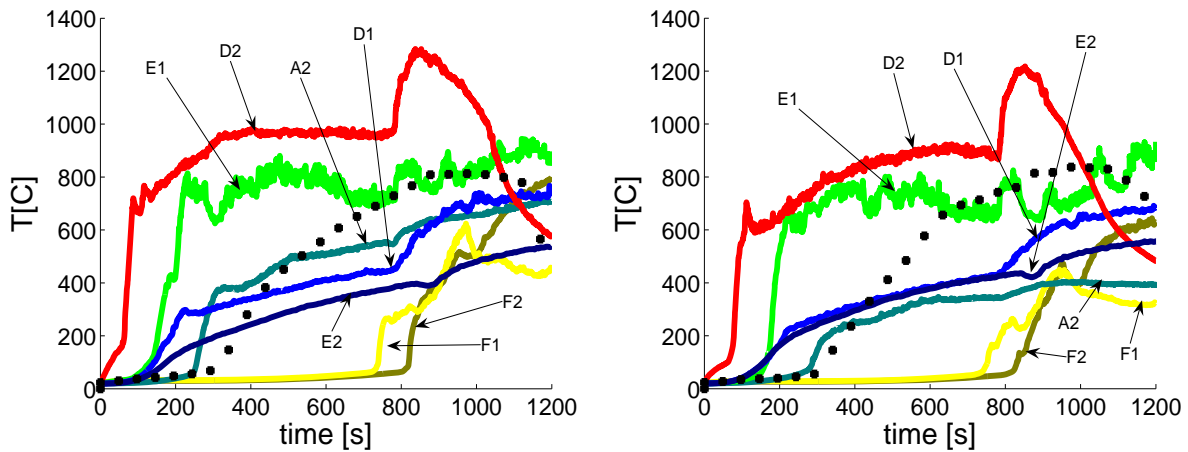


Figure 12: Local temperature vs. time on east wall of main compartment, at heights of (left) 250 cm; and (right) 50 cm from the floor.

Discussion of Results

The results indicate large scatter and considerable disparity between predicted fires, not only between themselves, but also differing from the experimental data. The scatter is biased towards the underprediction of the fire environment. The largest scatter is observed for predictions at long time-scales and small spatial-scales, with the lowest scatter away from the fire and during post-flashover conditions.

The stochastic nature of fire cannot be ignored and the uncertainty associated to the experimental repeatability was addressed during the design phase of the test set-up. Comparison of the results from Test One and Test Two (Chapter 4) later confirmed that the repeatability of the tests was high.

Although not the intent of this Chapter, the results could be used to point out that of the ten simulations presented for comparison, one provided very good results, four provided results that likely could be interpreted as being close to the experimental data and the rest did poorly. One simulation predicted HRR development and wall heat fluxes well, but deviated on some of the other predicted local quantities, while other simulations improved performance as they moved further from the area of the fire. Thus one of the conclusions that can be drawn is that, in addition to discrepancies between models and model users, good results for the average hot layer or the whole compartment do not necessarily correlate to good results in another fire variable or local quantity. This finding is corroborated in the *a posteriori* modelling presented in Chapter 11.

It was noticed that the main source of scatter is originated in the excess in degrees of freedom of the models, in especial to the parameters describing the ignition of the second item or flame spread, and the ventilation conditions. It is clear that the simulated fire evolution is sensitive to the way the heat release rate is predicted or prescribed. Specifically this is affected by the different ventilation conditions and predicted times for ignition of the secondary items (*i.e.* fire growth).

Nonetheless, the general behaviour captured by many of the simulations provides fire features that may be good enough to be applied towards simplified engineering objectives. These applications should take into account the expected level of accuracy and apply appropriate conservatism. A good example of the use of blind simulations to study the heating to the structure during post-flashover is presented in Chapter 7.

Concluding Remarks

A realistic fire test was conducted under conditions that are particularly relevant to field model validation. The study is an assessment of the state-of-the-art of fire modelling in a realistic enclosure scenario and evaluates the entire process of fire modelling as a whole, including the effect of combining the different assumptions and the user's interaction with the model.

The results provide a sense of the accuracy that could be expected from simulations of non-trivial real scenarios conducted in the absence of actual fire development data. The round robin emphasizes the known fact that there is an inherent difficulty in predicting fire dynamics. Enclosure fires involve complex dynamics driven by critical events, such as the ignition of secondary items, window breakage, flashover or fire-brigade intervention, etc. These events can change the course of the fire drastically due to the non-linear component of fire dynamics and make it even more difficult to predict fire phenomena at large time-scales. In order for models to be usefully applied to such complex, real scenarios, they require strong interactions with experiments in order to ensure that the obtained results are applicable.

Since most participants used the same field code, FDS, the range of predicted behaviours in the round robin is mainly originated by the different assumptions and input files. It should be remarked that we think that the general conclusions here would be applicable to the full suite of fire models in existence, not simply to those utilized in this study. The high number of degrees of freedom and the variability in literature values can lead to a large variance in the results, even from experienced users. The wide range of predictions is partly the result from the large uncertainty associated to the creation of input data for realistic and non-trivial fire scenarios. Thus, this must be taken into account when the model is applied to a specific task.

The Dalmarnock tests are used in Chapter 11 to show that it is possible to conduct *a posteriori* FDS simulations that reproduce in detail the observed fire behaviour quite satisfactorily. This can be achieved when sufficient experimental data is available to properly set up the input file for the model but requires a significant effort from the modeller. Regarding *a priori* modelling, a major lesson learnt from this study is that for obtaining accurate results in the simulation of non-trivial and realistic scenarios, like the Dalmarnock tests, the modelling should be conducted with the aid of experiments with similar fire development in order to provide input and validation.

The output from this study reflects on the strengths and limitations of current fire modelling in science and engineering. The results and conclusions are more important to

fire modelling practitioners than to code developers, and these are made public to encourage debate and exchange of views on the topic.

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