Reference : Spearpoint M J, Mowrer F W, McGrattan K. Simulation of a single compartment flashover fire using hand calculations, zone models and a field model. Proc. 3rd International Conference on Fire Research and Engineering, pp. 3-14, Chicago, 1999.

SIMULATION OF A COMPARTMENT FLASHOVER FIRE USING HAND CALCULATIONS, ZONE MODELS AND A FIELD MODEL

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ABSTRACT

A fully furnished compartment fire was conducted in a 5.2 m by 4.6 m by 2.4 m high room. Ventilation was provided through a single open doorway 0.9 m wide and 2.0 m high. Ignition of a pillow located on a loveseat was achieved with the halogen bulb of a torchiere lamp. The fire was confined to the pillow for approximately the first 5½ minutes of the test before spreading to the loveseat and thereafter taking about 4 minutes to reach flashover conditions. Temperature profiles at three locations and heat flux at floor level near the center of the room were measured. This paper discusses attempts to model the conditions within the compartment using three methods, including 1) hand calculations; 2) three zone fire models; and 3) a computational fluid dynamics model. Several fire growth scenarios were developed using visual observations and rate of heat release data from published sources. Predictions for flame height, upper layer temperature and layer interface height were developed for each methodology or model. These predictions are compared with experimental data obtained from the fire test.

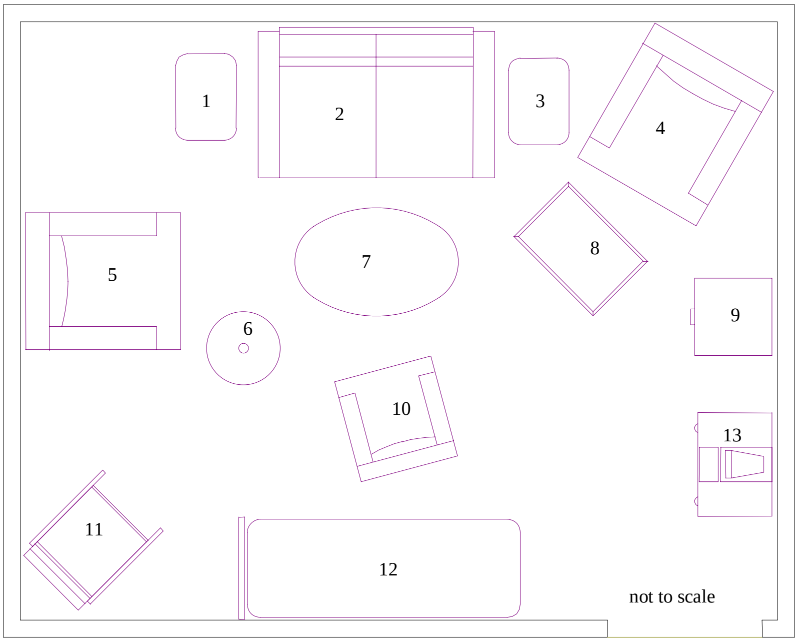
1. INTRODUCTION

A range of computational tools exists for calculating conditions resulting from fires in rooms and other enclosures [1]. These tools range from closed-form hand calculations, through relatively simple computer-based zone fire models, to very detailed and computationally intensive field models. This full range of tools is used to calculate conditions for a fire in a single naturally ventilated enclosure representative of a residential living room. These calculations are compared with data from the room fire test described in the next section.

The hand calculations used for comparison are those described by Mowrer [2] and extended by Joglar *et al.* [3]. The computer-based zone models used for comparison include Fire Simulator [4], FAST [5] and FIRST [6]. The field model used for comparison is the LES3D model [7].

2. THE ROOM FIRE TEST

The room fire test was conducted in the enclosure depicted in plan view in Figure 1. The room had nominal dimensions of 5.2 m by 4.6 m by 2.4 m high, with a single open doorway 0.9 m wide by 2.0 m high. The walls and ceiling linings were composed of a single layer of 12.5-mm thick gypsum wallboard painted with one coat of latex primer and two coats of interior latex paint. The floor covering in the room was carpet over concrete slab.



- Items 1 & 3, wooden side tables with lamps
- Item 2, loveseat with 2 cushions in the right-hand corner
- Items 4, 5, 10 and 11, various arm-chairs
- Item 6, torchiere lamp (shown upright)
- Item 7, coffee table
- Item 8, padded footstool
- Item 9, small chest of drawers with paperback books on top
- Item 12, futon
- Item 13, computer workstation

Figure 1. Plan view of room fire test facility (not to scale).

The room was furnished with a variety of furnishings representative of a residential living room. The furnishings included a number of pieces of upholstered furniture, including one loveseat, three chairs, an ottoman and a futon mattress, as well as a rocking chair, a desk with a computer, a file cabinet, a coffee table and two end tables with lamps. Pictures were hung on the walls behind the loveseat and behind the computer table. A freestanding torchiere lamp with a 500 W halogen bulb operating at fully intensity was located near the center of the room.

The fire was ignited by tipping over the torchiere lamp so that the halogen bulb was located near the center of the loveseat. A loose pillow on the loveseat was placed over the lamp, in contact with the halogen bulb. This caused ignition of the pillow. The ensuing fire appeared to involve only the loveseat pillow for a period of approximately 5½ minutes. During this period, the fire appeared to burn at a fairly constant rate, estimated to be approximately 10 kW. After this period, the loveseat cushions ignited, as evidenced by a change in the color of the smoke from a light gray to a darker gray and an accelerating escalation in the intensity of the fire. It took approximately 4 minutes following apparent ignition of the loveseat cushions for the fire to reach flashover conditions. Flashover was evidenced by a number of indicators, including radiant ignition of a crumpled sheet of newsprint located at floor level in the middle of the room, ignition and flame spread across the floor covering, ignition of chairs remote from the loveseat, and flame extension through the doorway. All of these events occurred within seconds of each other.

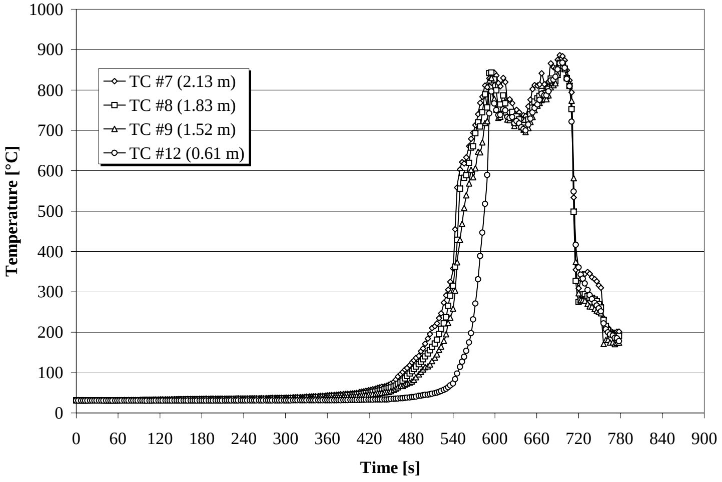


Figure 2. Center thermocouple tree measurements.

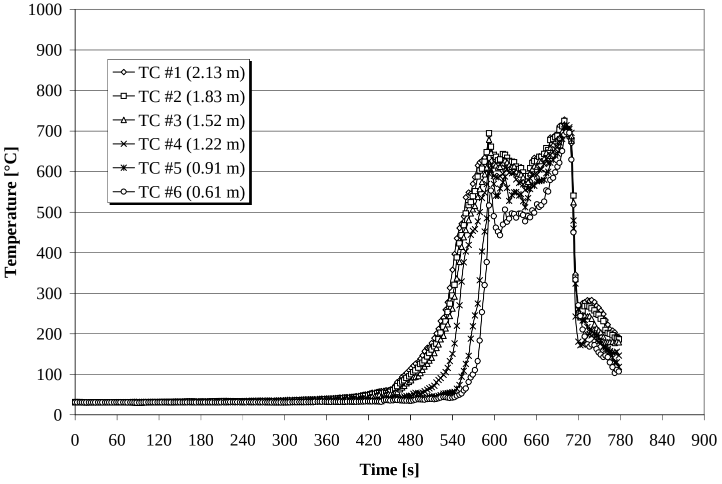


Figure 3. Doorway thermocouple tree measurements.

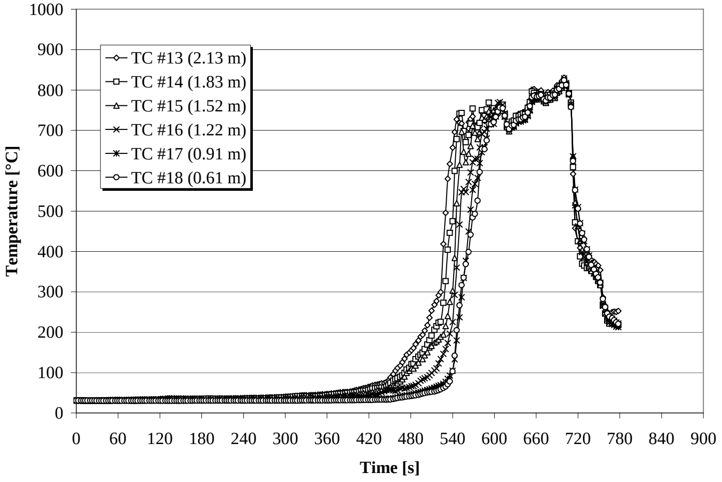


Figure 4. Rear corner thermocouple tree measurements.

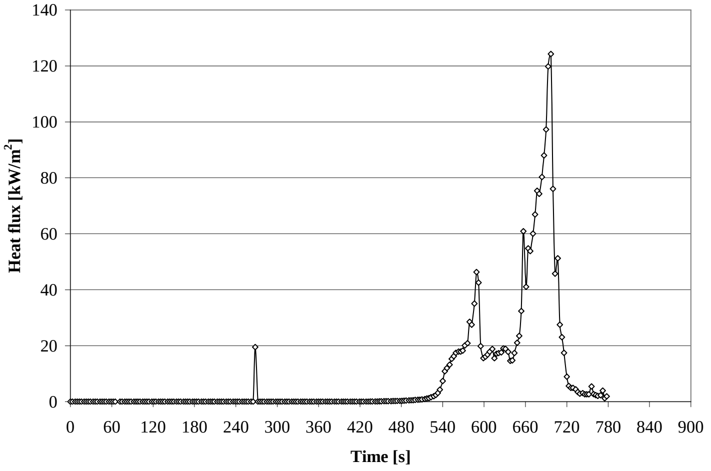


Figure 5. Heat flux measurements.

The room was instrumented with three thermocouple trees and a heat flux meter. A thermocouple tree was located near the doorway, near the middle of the room and near the corner opposite the doorway. Each tree included six thermocouples, which were located nominally 0.3 m apart with the highest thermocouple located 0.3 m below the ceiling. The heat flux meter was mounted to face upward; it was located just above floor level near the center of the room. Temperature data are shown in Figure 2 for the center tree, in Figure 3 for the doorway tree and in Figure 4 for the rear corner tree. Heat flux data are shown in Figure 5.

3. HAND CALCULATION COMPARISONS

The primary hand calculations used for comparison were developed by Mowrer [2] as part of the FIVE Methodology [7] and extended by Joglar, et al. [3], in the Fire Hazard Screening Methodology (FHSM). These calculations estimate average temperature conditions within an enclosure as well as in the fire plume and ceiling jet sub-layers. The basic FIVE methodology considers only closed, unventilated rooms, but auxiliary calculations were developed to address naturally and mechanically ventilated spaces as well. The natural ventilation calculations [9] are used for the present comparisons; they are applied in a quasi-steady way.

The hand calculations require knowledge or estimation of the fire location and heat release rate history, the fraction of heat released that is lost to enclosure boundaries and the size and shape of the wall vent. For the present comparisons, the heat release rate was assumed to be similar to the heat release rate history for a loveseat reported by NIST [10], once the loveseat cushions ignited after 5½ minutes. Before this time, the heat release rate was estimated to be a constant 10 kW. After 5½ minutes, the fire was assumed to grow as a t-squared fire to reach a peak intensity of 3.0 MW 9½ minutes after ignition. The actual heat release rate history of the loveseat and the simulated history used for the hand calculations are shown in Figure 6. The simulated history is based on an algorithm developed by Mowrer and Williamson [11].

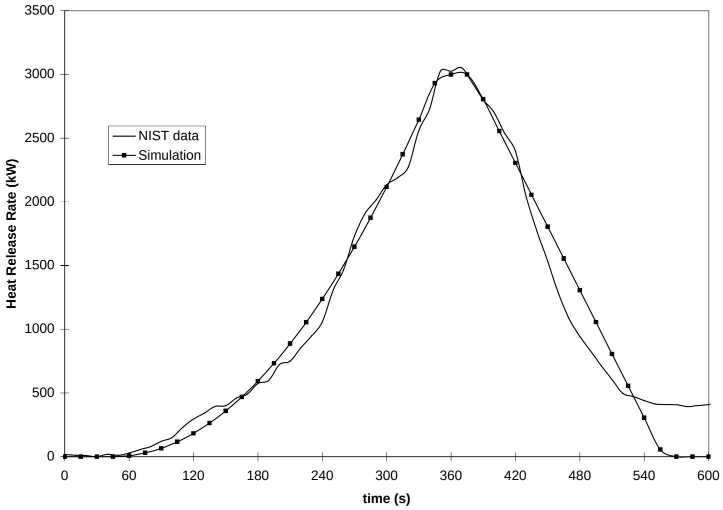


Figure 6. Actual and simulated loveseat heat release rates used for hand calculations.

The primary results of the hand calculations for the present purposes are the plume, ceiling jet and temperature histories in the room. These calculations are based on the simulated loveseat burning history only, they do not account for the ignition and burning of other items. Figure **7** shows the calculated average and ceiling jet temperatures with the measured temperatures for the middle thermocouple tree; temperatures were not measured in the plume, so they are not compared here. The calculated temperatures during the time period from approximately 360 s to 540 s exceed the measured temperatures. This may be the result of the simulated heat release rate developing more rapidly than in the actual fire test during this period or due to use of an incorrect heat loss fraction. Over the time period from approximately 540 s to 600 s, the calculated ceiling jet temperature matches the measured temperatures very well. During the period from about 600 s to 720 s, the calculated ceiling jet temperature is significantly higher than the actual temperatures, while the calculated average temperature is quite similar to the measured temperatures.

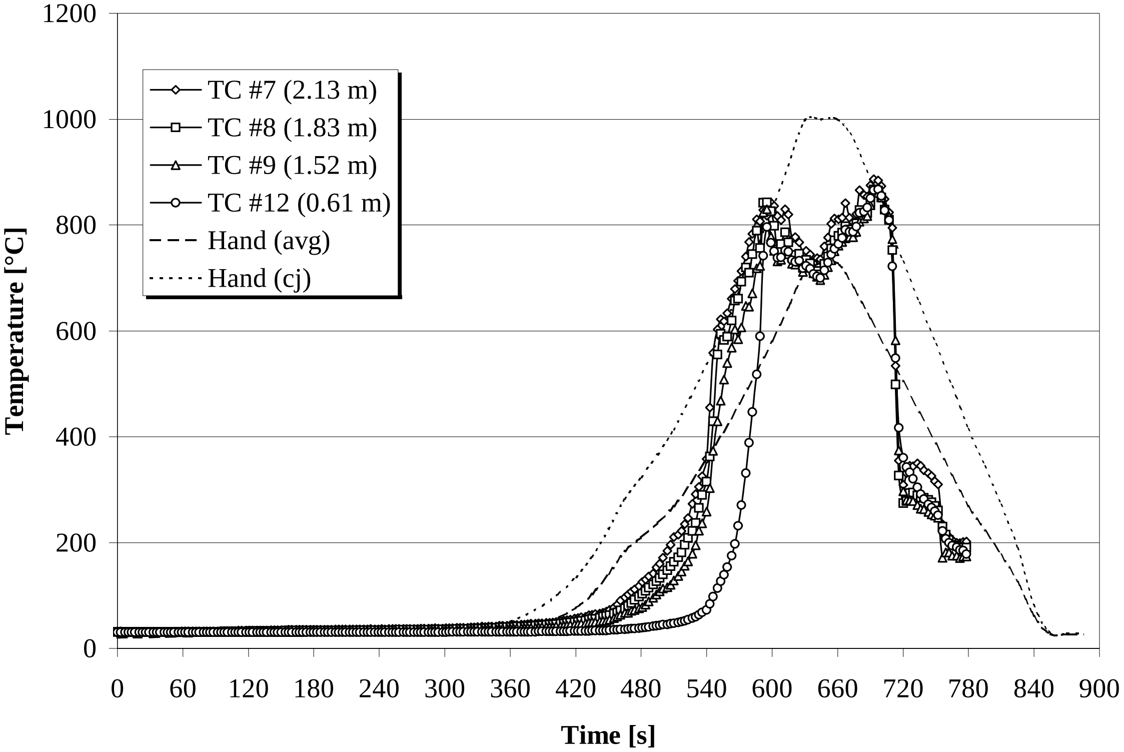


Figure 7. Comparison of middle thermocouple measurements and FHSM predictions.

Using 600°C as a criterion for flashover, flashover would be predicted at approximately 555 s based on the ceiling jet temperature and at about 600 s based on the average temperature. These results compare favorably with the actual time to flashover as well as with the times to flashover predicted by the zone models, as shown below in Table 1. Other parameters, including smoke layer interface height, detector temperature and target temperature, can be calculated with the FHSM, but these parameters were not measured during the room fire test, so they are not reported here.

4. ZONE MODEL COMPARISONS

4.1 Methodology

For the zone modeling analysis of the room fire test, several simulations were executed to examine the sensitivity of various modeling parameters. These parameters included material properties and rate of heat release history. Typical data from a simulation are presented in this paper in which the specified rate of heat release curve was a composite of data for a polyester-filled pillow [12] and a loveseat with polyurethane padding covered with a polyolefin fabric [13]. The two individual rate of heat release curves were summed with the curve for the loveseat offset from the curve for the pillow by 330 s. This offset was taken from an estimate of the time to ignition of the loveseat by the cushion during the test. The composite curve was then characterized (Figure 8) using selected points in order to reduce data input requirements to the zone models. Simulations would only require at most several minutes to complete when running on a mid-range Pentium based PC system.

4.2 Time to flashover

The calculated times to flashover from the zone models were compared with the estimated time to flashover of 570 s after ignition from the observations and from the thermocouple data (Table 1). The time to flashover using the thermocouple data of 566 s was found by taking the average temperature measured by the upper four probes on each tree and determining when that average exceeded 600 °C. All three models predicted a slightly earlier time to flashover than estimated from the test.

Experimental	Fire Simulator	FAST	FIRST
570 (observations) or 566 (thermocouples)	530	546	520

Table 1. Comparison of times to flashover.

4.3 Flame height

The calculated flame heights from the models were compared with the estimated flame height from the observations (Figure 9). In general, the calculated flame height exceeds the observed height particularly for FAST and Fire Simulator. This may be partly explained by the difficulty in estimating the flame height in the test once the smoke began to fill the compartment.

The correlation used in Fire Simulator calculates the height at which flames appear 50% of the time and this generally over-predicts heights compared with visual observations. If one considers the 10 kW steady rate of heat release estimated for the cushion and uses the Cox & Chitty flame height correlation (as provided in ASKFRS [14]), a steady flame height of 0.2 m and an intermittent flame height of 0.5 m is obtained. The steady value compares well with the visual height and the intermittent value is closer to the calculated values.

4.4 Layer interface height

The layer interface height in the test was found from the thermocouple data by examining the temperature profile for each tree at selected times. The layer interface height was then compared with the results from the three zone models (Figure 10). The models under-predict the layer interface height leading up to the ignition of the loveseat and also during the post-flashover stage. The estimation of the layer interface was subject to interpretation and therefore it appears that the three models all made a reasonable estimate of the layer interface height.

4.5 Upper layer temperature

The results for the upper layer temperature from the three models were compared with the thermocouple data. The temperature of the upper layer in the test was obtained by taking the average reading of all the thermocouples located above the layer interface height. The layer temperature at each thermocouple tree location as a function of time was obtained.

Figure 11 shows the comparison between the measured upper layer temperature and the results from the three models. The temperatures for the test show their rapid increase at a later time than the models predict. This result is consistent with the time to flashover comparison discussed above. The measured upper layer temperature in post-flashover conditions is comparable to the results from Fire Simulator and FAST although the temperature data from FAST continues to increase almost indefinitely whereas Fire Simulator reaches a stable temperature during this phase of the scenario. Overall all three models appear to make a reasonable attempt at predicting the upper layer temperature.

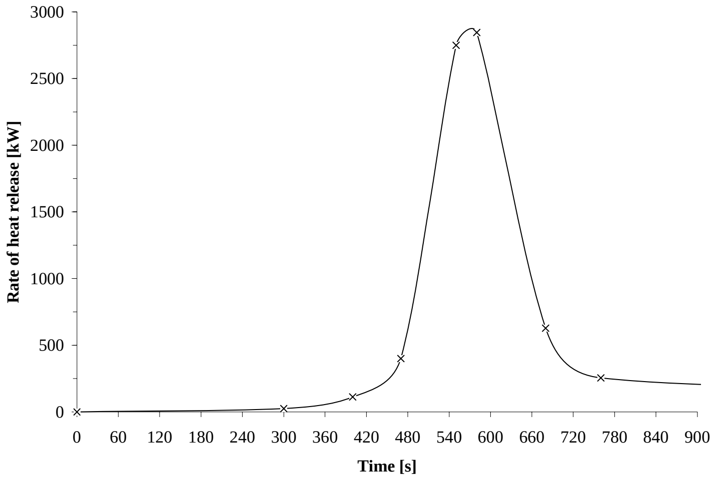


Figure 8. Composite rate of heat release curve.

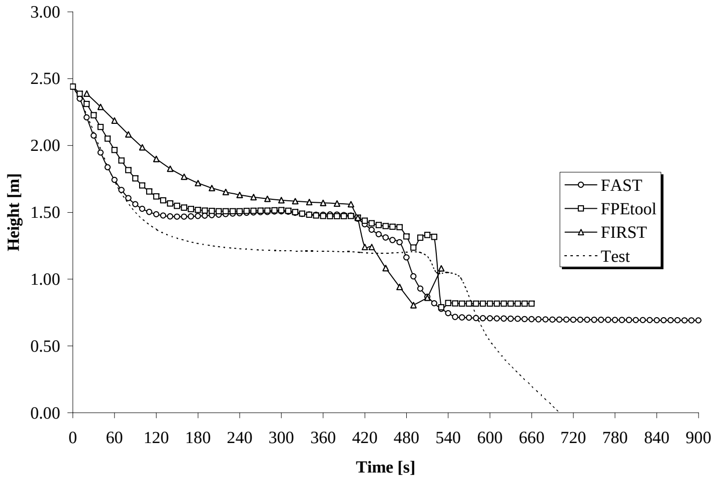


Figure 10. Layer interface height comparison.

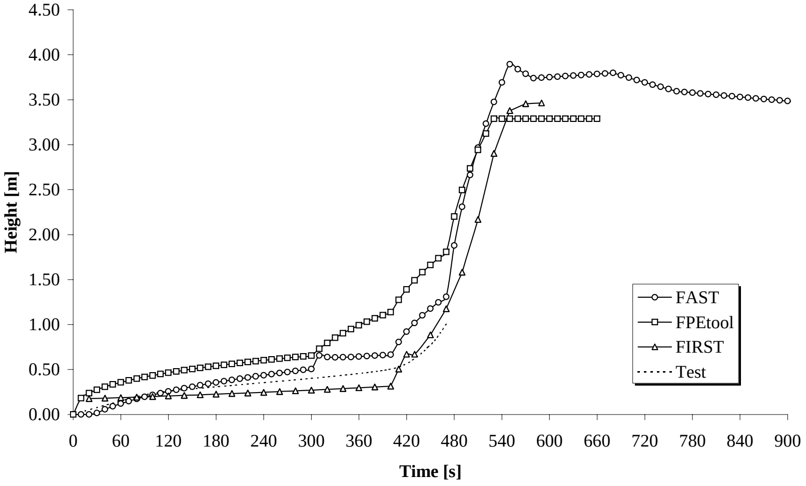


Figure 9. Flame height comparison.

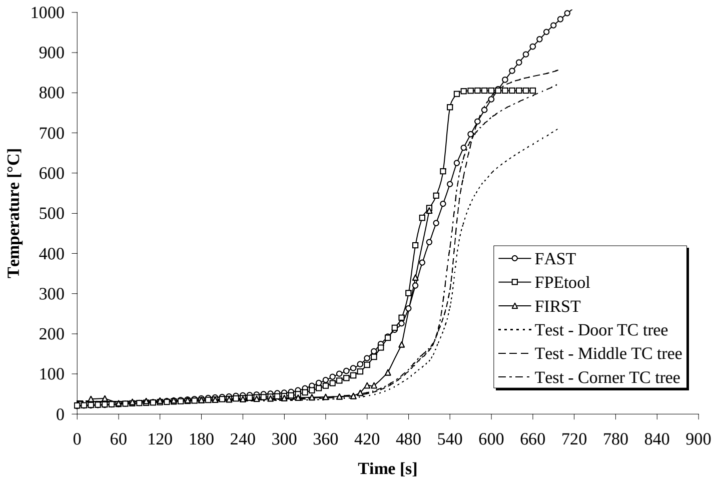


Figure 11. Upper layer temperature comparison.

5. FIELD MODEL COMPARISONS

Compared to the previous two techniques, simulating flashover in a compartment using a field model (or computational fluid dynamics (CFD) model) requires more detailed information about the thermal properties of the room contents. At a minimum, for each piece of furniture, plus the walls and carpeting, one needs to know the physical dimensions, thermal conductivity, thermal diffusivity, burning rate per unit area of exposed surface, and the heat of combustion of the material. Additional properties might include the smoke yield, and the yield of any other combustion products that would play a significant role in the emission or absorption of thermal radiation.

The calculation involves the convective transport of smoke and hot gases from the ignition source, plus the transport of thermal radiation to all surrounding surfaces and to any significant absorbing media. The convective transport is handled by solving a discretized form of the Navier-Stokes equations in which the volume of interest is divided into small cells in which mass, momentum and energy are conserved. The radiative transport can be handled in a variety of ways. The simplest is to trace randomly selected rays from the fire to the surrounding objects, transferring a given fraction of the chemical heat release rate from the fire to these surfaces. As flashover is approached, the transfer of heat from the fire and hot gases to the walls and floor and the re-radiation from these surfaces becomes the main mechanism of heat transfer. For a field model, this is the most difficult and computationally intensive part of the calculation.

To demonstrate the complexity of the problem, a field model under development at NIST called the Industrial Fire Simulator (IFS) was used to model the compartment flashover scenario described earlier. The convective transport was performed using the large eddy simulation (LES) technique described by McGrattan *et. al.* [7]. Radiative transport was performed by representing the fire as discrete particles, each of which has a prescribed rate of heat release based on the thermal properties of the fuel. A fraction of the energy released by these particles is redistributed on the surfaces of surrounding objects; and these objects heat up according to their prescribed thermal properties by means of a one-dimensional calculation of the heat equation within the solid. The rate of fire growth and spread is dependent on these thermal properties; for this scenario the properties were estimated based on data presented by Quintiere [15].

Figure 12 shows the layout of the calculation. The entire room plus a few feet outside the doorway is divided into a grid consisting of 24 by 24 by 12 cells. All objects within the room are represented by blocked cells. Each cell is roughly 0.2 m (8 in.) on a side. This grid is coarse because the calculation is mostly one of radiative, rather than convective, transport, and it was done as a classroom exercise, with the calculation performed on PCs of limited memory and speed. On the latest Pentium III processor (550 MHz), this calculation would require about 8 hours to simulate 10 minutes, and would require about 100 Mbytes of memory.

The calculation begins at the point in time where the loveseat pillow is fully involved and about to ignite the loveseat cushions. It is assumed that 35% of the 10 kW generated by the burning pillow is radiated to the surrounding loveseat cushions, whose thermal properties are estimated to be similar to those of polyurethane foam. This estimate leads to a more rapid progression of the fire than was recorded in the experiment (Figure 13). The entire loveseat becomes involved within minutes of the start of the calculation, as does the chair immediately to the right. Flashover occurs 130 s after the loveseat cushions ignite, as evidenced by the sharp rise in temperature of the thermocouples nearest the floor. This is due to the ignition of the carpet by thermal radiation.

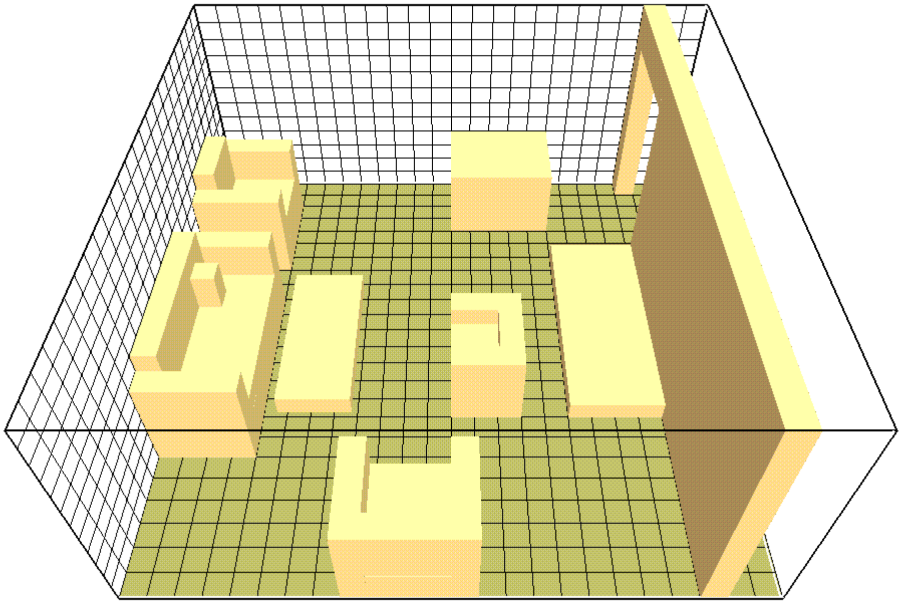


Figure 12. LES3D calculation mesh.

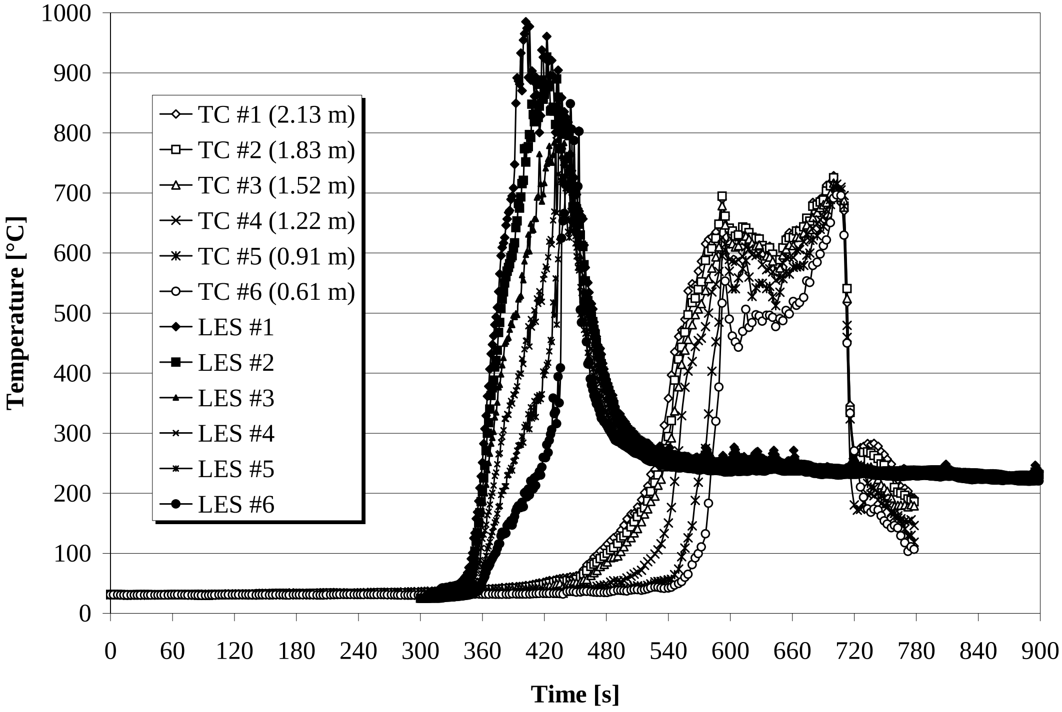


Figure 13. Comparison of doorway thermocouple measurements and LES3D predictions.

Figure 13 shows that the IFS calculation predicts faster fire spread on the loveseat and other furnishings than actually occurred. The inaccuracy of the current IFS calculation is due to a lack of detailed information about the thermal properties of the materials used in the test, as well as to inadequacy of the present versions of the radiation and oxygen consumption submodels in the IFS model. The solution to the first problem is to better characterize the materials used in fire tests if comparisons with detailed field models are desired. The radiation and oxygen consumption models are more difficult problems and are the subjects of study at NIST and elsewhere. Up to now CFD models have done a reasonably good job of predicting the transport of smoke and hot gases from a fire; but as flashover is approached the scenario begins to resemble a furnace more than an isolated fire plume and more work is needed to better characterize these conditions.

6. SUMMARY AND CONCLUSIONS

The results of this study might seem counterintuitive at first, with the hand calculations and zone models producing predictions closer to the actual data than the field model. But it must be remembered that the hand calculation and zone model results are based on a specified heat release rate history, while the IFS field model attempts to predict heat release rate as part of its computations. It would be unreasonable to expect a perfect match between model predictions and experimental data not only because any calculation method makes certain assumptions regarding the physics and chemistry of a fire scenario but also because the experimental data is also subject to interpretation.

The results from this study show that hand calculations and zone models are able to reasonably predict conditions within a residential-scale room where the development of a fire is already known and the geometry of the space is relatively simple. The hand calculations and the three zone models show similar trends in their predictions and appear to consistently match the experimental data. But again, the hand calculations and zone models do not attempt to model the development of the fire but rather rely on the user to supply a rate of heat release curve. Therefore a comprehensive database of heat release curves for a range of common items is required so that appropriate data can be selected and methods to integrate several heat release curves from separate items may also be necessary. This is a fundamental limitation with respect to the predictive capabilities of methods that rely on user-specified heat release rate histories.

In contrast to the zone models, the LES3D simulation attempts to model fire development at a more fundamental level by considering the thermo-physical properties of the materials rather than simply describing a rate of heat release history. This approach holds the promise of providing a better predictive tool where the development of the fire is undetermined. However, due to limitations in the current version of IFS and other field models, the match between the test data and the model predictions is not sufficient.

One current advantage of the zone models over the LES3D model is that they can be quickly executed on a mid-range Pentium PC compared with the higher specification system required by IFS (or any other CFD model). As computer power continues to grow, this should become less of a factor and other aspects such as accuracy, applicability and usability will be much more important.

7. ACKNOWLEDGEMENTS

The test fire was conducted at the Maryland Fire & Rescue Institute, University of Maryland on behalf of the Bureau of Alcohol, Tobacco and Firearms, Department of the Treasury.

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