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Verification of a Model of Fire and Smoke Transport*

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ABSTRACT

A set of comparisons between a comprehensive room fire model and a range of real-scale fire experiments is presented. For these comparisons, a zone-based model, CFAST ('consolidated fire and smoke transport' model) is used. The model predicts the evolution of a fire in a room and the subsequent transport of the smoke and toxic gases which result from this fire. These comparisons serve two purposes: to determine, within limits, the accuracy of the predictions for those quantities of interest to the users of the models (usually those extensive variables related to hazard), and to highlight the strengths and weaknesses of the underlying algorithms in the models to guide future improvements in this and other models. The predicted variables selected for comparison deal with both of these purposes. Although differences between the model and the experiments were clear, they can be explained by limitations of the model and of the experiments.

INTRODUCTION

Analytical models for predicting fire behavior have been evolving since the 1960s. Individuals have described in mathematical language the various phenomena which have been observed in fire growth and spread. These separate representations often describe only a small part of a fire experience. When combined, they create a complex computer code that estimates the expected course of the fire based upon given input parameters. These analytical models have progressed to the point of providing good predictions for some parameters of fire behavior. However, it is important to be able to state with confidence how close are the actual conditions to those predicted by the model. This is especially crucial since the actual use of the model often precludes an exact representation of the physical situation to be explored.

The Building and Fire Research Laboratory (BFRL) has a project to develop a methodology for the evaluation and accuracy assessment of fire models. Our goal is to define a mechanism by which the model predictions can be assessed so a model user can test the limits of model predictions. Earlier papers have dealt with the form[1] and availability[2] of experimental data for comparison with computer fire models. This paper presents a set of comparisons with a comprehensive room fire model. In the process, the strengths andd weaknesses of these models and of the comparison process become apparent.

BACKGROUND

Computer fire models

Many computer fire models have been developed. In a recent international survey,[3] 36 actively supported models were identified. Of these, 20 predict the fire-generated environment (mainly temperature) and 19 predict smoke movement in some way. Six calculate fire growth rate, nine predict fire endurance, four address detector or sprinkler response, and two calculate evacuation times. The computer models now available vary considerably in scope, complexity, and purpose. Simple 'room filling' models such as the available safe egress time (ASET) model[4] run quickly on almost any computer, and provide good estimates of a few parameters of interest for a fire in a single compartment. A special purpose model can provide a single function. For example, COMPF2[5] calculates post-flashover room temperatures and LAVENT[6] includes the interaction of ceiling jets with fusible links in a room containing ceiling vents and draft curtains. Very detailed models like the HARVARD 5 code[7] or FIRST[8] predict the burning behavior of multiple items in a room, along with the time-dependent conditions therein.

In addition to the single-room models mentioned above, there are a smaller number of multi-room models which have been developed.

These include the BRI (or Tanaka) transport model,[9] the HARVARD 6 code[10] (which is a multi-room version of HARVARD 5), CCFM,[11] FAST,[12] and the CFAST model[13] discussed below.

Mitler[14,15] and Jones[16] have reviewed the underlying physics in several fire models in detail. Most fire models are founded on fundamental physical laws—the laws of conservation of mass, momentum, and energy. (Most fire models conserve only mass and energy; the most complex models add momentum.) Errors arise in those instances where a mathematical short cut was taken, a simplifying assumption was made or an important phenomenon not included, intentionally or not.

Once a mathematical representation of the underlying science has been developed, the conservation equations are re-cast into predictive equations for temperature, smoke and gas concentration, and other parameters of interest, and are coded into a computer for solution. Because fires are constantly changing, the equations are typically cast in the form of *differential equations*. The set of equations can compute the conditions produced by the fire at a given time in a specified volume of air. The model assumes that the predicted conditions within the *control volume* are uniform at any time. Thus, the control volume has one temperature, smoke density, gas concentration, etc.

Different models divide the building up into different numbers of control volumes depending on the desired level of detail. The most common fire model, known as a *zone model,* generally uses two control volumes to describe a room—an upper layer and a lower layer. In the room with the fire, additional control volumes for the fire plume or the ceiling jet may be included to improve the accuracy of the prediction (see Fig. 1). This two-layer approach has evolved from the observation that such layering occurs in real-scale fire experiments. Hot gases collect at the ceiling and fill the room from the top. While these experiments show variation in conditions within the layer, these variations are often small compared to the differences between the layers. When this assumption of layer stratification holds, the zone model can produce a reasonable simulation of average layer temperature, density, and depth within a room.

Other types of models include *network models* and *field models.* The former use one control volume per room and are used to predict conditions in spaces far removed from the fire room, where temperatures are near ambient and this layering does not take place. The field model goes to the other extreme, dividing the room into hundreds or thousands of control volumes. Such models can predict the variation in conditions throughout the compartments,[17,18] but typically require far longer run times than zone models. Thus, they are used sparingly, when

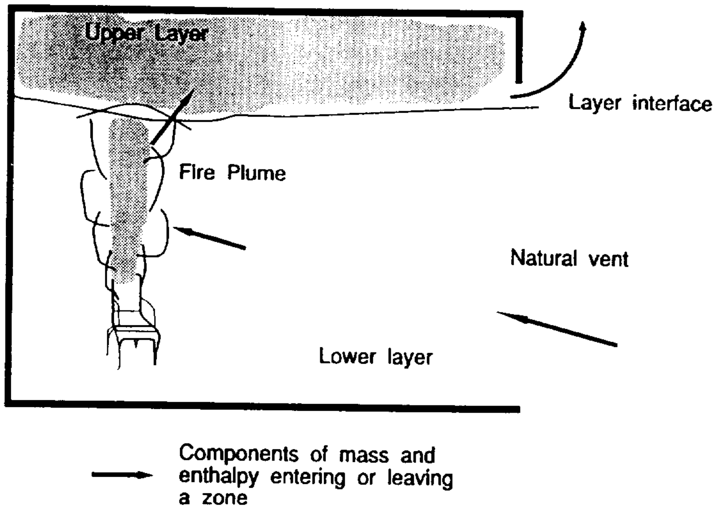


Fig. 1. Zone model terms.

highly detailed flow characteristics are essential. Neither of these types of models will be considered in this paper.

Jones and co-workers[12,13,19,20] have developed a zone-based model, CFAST ('consolidated fire and smoke transport' model) which predicts the evolution of a fire in a room and the subsequent transport of the smoke and toxic gases which result from this fire. The capabilities and known limitations of this model have been documented.[21] Version 1.2.1 of this model will be used as the basis for comparisons with several available experimental test results.

Available experimental data

Several systematic test series have been undertaken specifically to provide data for comparison with model predictions. In other cases, tests in which fire properties have been systematically varied (for various reasons) have been modeled using current computer fire simulations. In the first group are the study of Alpert *et al.*[22] for a single room connected to a short, open corridor, and that of Cooper *et al.*[23] and Peacock *et al.*[24] for gas burner fires in a room–corridor–room configuration. Although the second group is large, the works of Quintiere and McCaffrey,[25] and Heskestad and Hill[26] are particularly detailed.

Cooper *et al.*[23] reported an experimental study of the dynamics of smoke filling in realistic, full-scale, multi-room fire scenarios. A major goal of the study was to generate an experimental database for use in the verification of mathematical fire simulation models. The test space involved two or three rooms, connected by open doorways. During the study, the areas were partitioned to yield four different configurations. One of the rooms was a burn room containing a methane burner which produced either a constant heat release rate of 25, 100, or 225 kW or a time-varying heat release rate which increased linearly with time from zero at ignition to 300 kW in 600 s. An artificial smoke source near the ceiling of the burn room provided a means for visualizing the descent of the hot layer and the dynamics of the smoke filling process in the various spaces. The development of the hot stratified layers in the various spaces was monitored by vertical arrays of thermocouples and photometers. A layer interface was identified and its position as a function of time was determined. An analysis and discussion of the results including layer interface position, temperature, and doorway pressure differentials is presented. These data were later used by Rockett *et al.*[27,28] for comparison to a modern predictive fire model.[29]

Quintiere and McCaffrey[25] described a series of experiments designed to provide a measure of the behavior of cellular plastics in burning conditions related to real life. They experimentally determined the effects of fire size, fuel type, and natural ventilation conditions on the resulting room fire variables, such as temperature, radiant heat flux to room surfaces, burning rate, and air flow rate. This was accomplished by burning up to four cribs made of sugar pine or of a rigid polyurethane foam to provide a range of fire sizes intended to simulate fires representative of small furnishings to chairs of moderate size. Although few replicates were included in the test series, fuel type and quantity, and the room door opening width were varied. The data from these experiments were analyzed with quantities averaged over the peak burning period to yield the conditions for flashover in terms of fuel type, fuel amount, and doorway width. The data collected were to serve as a basis for assessing the accuracy of a mathematical model of fire growth from burning cribs.

Heskestad and Hill[26] performed a series of 60 fire tests in a room–corridor configuration to establish accuracy assessment data for theoretical fire models of multi-room fire situations with particular emphasis on health care facilities. With steady-state and growing fires from 56 kW to 2 MW, measurements of gas temperatures, ceiling temperatures, smoke optical densities, concentrations of CO, CO_2, and O_2, gas velocities, and pressure differentials were made. Various combinations of fire size, door opening size, window opening size, and ventilation were studied. To increase the number of combinations, only a few replicates of several of the individual test configruations were performed.

Except for the data of Cooper *et al.*[23] and Quintiere and McCaffrey[25] which are not available in machine readable form, the above data, along with other experimental results, have been reviewed by Peacock *et al.*[2] They provide a single consistent form for the experimental data from several series of experiments. Five sets of experimental data which can be used to test the limits of a typical two-zone fire model are detailed. Availability of ancillary data (such as smaller-scale test results) is included. These descriptions, along with the data should allow comparisons between the experiment and model predictions. The base of experimental data ranges in complexity from one-room tests with individual furniture items to a series of tests conducted in a multiple-story hotel equipped with a zoned smoke control system. These data will be used as the set of experimental results for comparisons in this paper.

Earlier comparisons of models and real-scale fires

Several researchers have studied the level of agreement between computer fire models and real-scale fires. These comparisons fall into two broad categories: fire reconstruction and comparison with laboratory experiments. Both categories provide a level of verification for the models used. Fire reconstruction, although often more qualitative, provides a higher degree of confidence for the user when the models successfully simulate real-life conditions. Comparisons with laboratory experiments, however, can yield detailed comparisons that can point out weaknesses in the individual phenomena included in the models. The comparisons made to date are mostly qualitative in nature. The level of agreement between the models and experiment is typically reported as 'favorable', 'satisfactory', 'well predicted', 'successful', or 'reasonable'. Some of the comparisons in the literature are reviewed below. The terms used to indicate agreement are those of the authors.

Fire reconstructions

Nelson[30] used simple computer fire models along with existing experimental data to develop an analysis of a large high-rise building fire. This analysis showed the value of available analytical calculations in reconstructing the events involved in a multiple-storey fire. Bukowski[31] has applied the FAST model (an earlier version of the CFAST model) in a litigation against the US Government. At the request of the Justice Department, the model was used to recreate a multiple-fatality fire in a residence. The analysis reproduced many details of the fire including conditions consistent with damage patterns to the building, the successful escape of three older children, and three fatalities including the locations of the bodies and the autopsy results. Emmons applied computer fire modeling to the MGM Grand Hotel fire of 1980. This work, conducted during the litigation of this fire was only recently published.[32] Using the HARVARD 5 model, Emmons analyzed the relative contributions of booth seating, ceiling tiles, decorative beams, and the HVAC system on the outcome of the fire.

Comparisons with laboratory experiments

Mitler and Rockett[33] utilized HARVARD 5 to model two in a series of eight well-instrumented full-scale room fires. The test fire room was 22 m^3 in volume with an open window or doorway. The fire source was two polyurethane slabs in opposing corners of the room. They reported 'good to excellent' agreement for most of the model variables studied. The most probable causes for disagreements were failure to account for heating of the lower gas layer, inadequacy of the burnout algorithm, and the lack of understanding of the CO production mechanism.

Rockett *et al.*[28] used the HARVARD VI multi-room fire model to simulate the results of real-scale, multi-room fire experiments. These experiments can be characterized by fire sizes of several hundred kW and total compartment volume of about 1000 m^3. While the model was generally found to provide 'favorable' simulations, several areas where improvements were needed were identified. They pointed out limitations in modeling of oxygen-limited burning, mixing of gases at vents, convective heat transfer, and plume entrainment.

Jones and Peacock[20] presented a limited set of comparisons between the FAST model and a multi-room fire test. The experiment involved a constant fire of about 100 kW in a three-compartment configuration of about 100 m^3. They noted 'slight over-prediction' of the upper layer temperature and satisfactory prediction of the layer interface position. Again, convective heating and plume entrainment were seen to limit the accuracy of the predictions. A comparison of predicted and measured pressures in the rooms showed good agreement. Since pressure is the driving force for flow between compartments, this agreement was seen as important.

Levine and Nelson[34] used a combination of full-scale fire testing and modeling to simulate a fire in a residence. The 1987 fire in a first-floor kitchen resulted in the deaths of three persons in an upstairs bedroom, one with a reported blood carboxyhemoglobin content of 91%. Considerable physical evidence remained. The fire was 'successfully simulated' at full scale in a fully-instrumented seven-room two-story test structure. The data collected during the test have been used to test the predictive abilities of two multi-room computer fire models: FAST and HARVARD VI. A coherent ceiling layer flow occurred during the full-scale test and quickly carried high concentrations of CO to remote compartments. Such flow is not directly accounted for in either computer code. However, both codes predicted the CO buildup in the room most remote from the fire. Prediction of the pre-flashover temperature rise was also good. Prediction of temperatures after flashover that occurred in the room of fire origin was less good. Other predictions of conditions throughout the seven test rooms varied from 'good approximations to significant deviations' from test data. Some of these deviations are believed to be due to phenomena not considered in any computer models.

Deal[35] reviewed four computer fire models (CCFM, FIRST, FPETOOL[36] and FAST) to ascertain the relative performance of the models in simulating fire experiments in a small room (about 12 m^3 in volume) in which the vent and fuel effects were varied. Peak fire size in the experiments ranged up to 800 kW. All the models simulated the experimental conditions including temperature, species generation, and vent flows, 'quite satisfactorily'. With a variety of conditions, including narrow and normal vent widths, plastic and wood fuels, and flashover and sub-flashover fire temperatures, competence of the models at these room geometries was demonstrated.

Duong[37] studied the predictions of several computer fire models (CCFM, FAST, FIRST, and BRI), comparing the models with one another and with large fires (4–36 MW) in an aircraft hangar (60 000 m^3). For the 4 MW fire size, he concluded that all the models are 'reasonably accurate'. At 36 MW, however, 'none of the models did well'. Limitations of the heat conduction and plume entrainment algorithms were seen to account for some of the inaccuracies.

Beard[38,39] evaluated four fire models (ASET, FAST FIRST, and JASMINE[40]) by modeling three well-documented experimental fires, ranging in scope from the same tests used by Mitler and Rockett[33] to a large-department-store space with closed doors and windows. He provides both a qualitative and quantitative assessment of the models ability to predict temperature, smoke obscuration, CO concentration, and layer interface position (for the zone-based models). In addition, the predicted 'time to hazard' was calculated with several selected criteria.

MODEL PARAMETERS SELECTED FOR COMPARISON

Comparisons of model predictions with experimental measurements serves two purposes: (i) to determine, within limits, the accuracy of the predictions for those quantities of interest to the users of the models (usually those extensive variables related to hazard); and (ii) to highlight the strengths and weaknesses of the underlying algorithms in the models to guide future improvements in the models. The predicted variables selected for comparison must deal with both of these purposes.

Most of the studies discussed above present a consistent set of variables of interest to the model user: gas temperature, gas species concentrations, and layer interface position. To assess the accuracy of the physical basis of the models, additional variables must be included. Pressure drives the movement of gases through openings. The pyrolysis rate, and heat release rate of the fire in turn, produces the gases of interest to be moved.

In this paper, we will consider all these variables for comparison:

- upper and lower layer gas temperature,
- layer interface position,
- gas species concentration,
- fire pyrolysis and heat release rate,
- room pressure, and
- vent flow.

Although there are certainly other comparisons of interest, these will provide evidence of the match of the model to the experimental data.

TESTS SELECTED FOR COMPARISON

A total of five different real-scale fire tests were selected for the current comparisons to represent a range of challenges for the CFAST model.

(1) A single-room test using upholstered furniture as the burning item was selected for its well-characterized and realistic fire source in a simple single-room geometry.[41] Figure 2 shows the room and instrumentation used during the test. Heat release rate, mass loss rate, and species yields are available for the test. This should allow straightforward application of the model. Peak fire size was about 2·9 MW with a total room volume of 21 m^3.

(2) Like the first test, this test is a single-room fire test using furniture as the fire source.[42] It expands upon that data set by adding the phenomenon of wall burning. Figure 3 shows the test

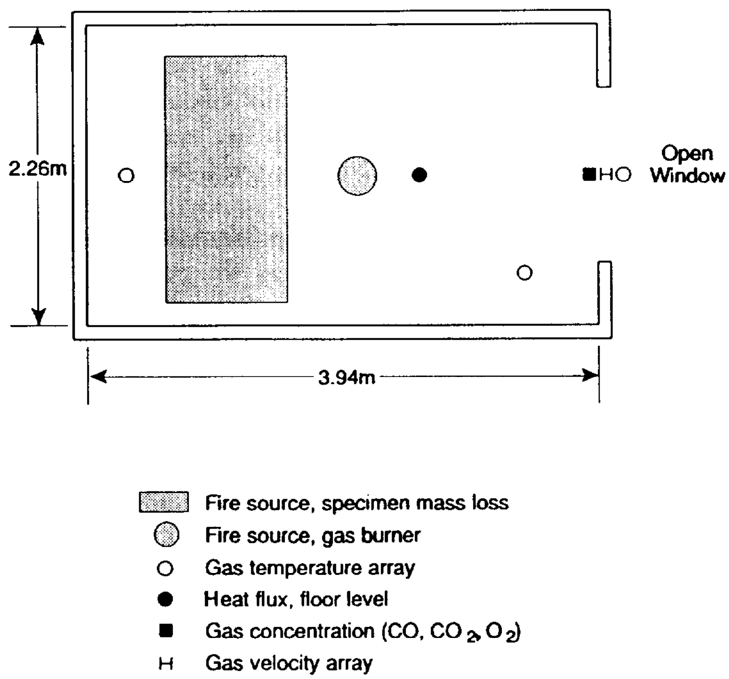


Fig. 2. Single-room furniture fire test.

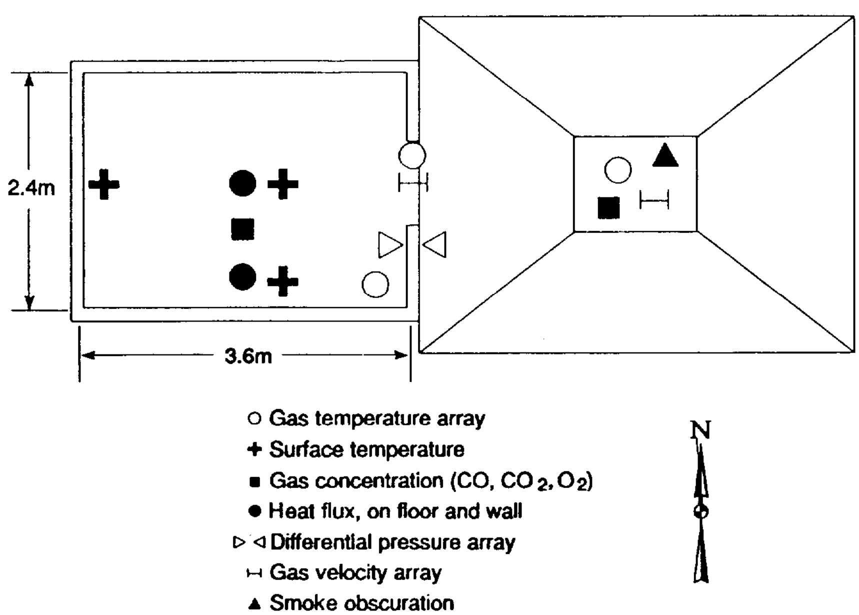


Fig. 3. Single-room furniture test with wall burning.

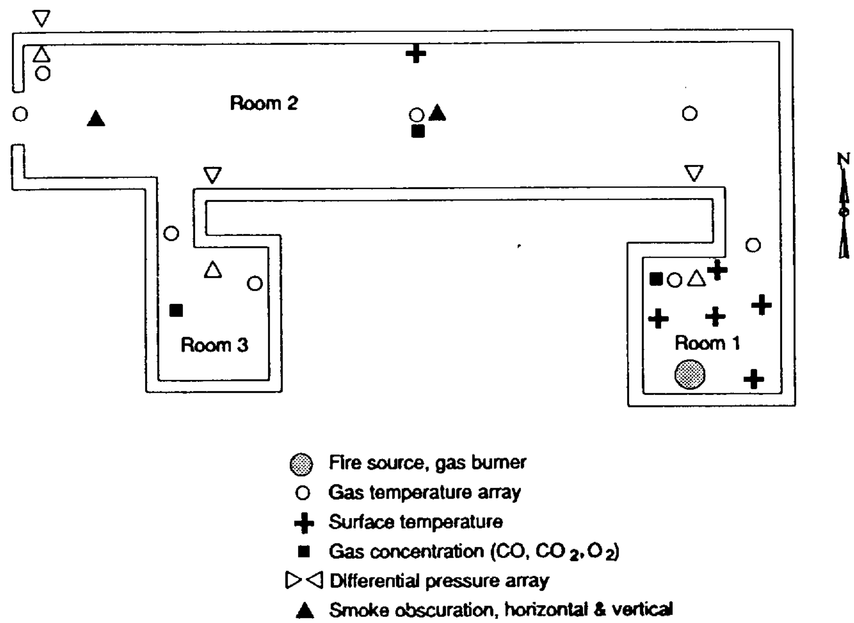


Fig. 4. Three-room gas burner tests with a corridor.

room and exhaust hood arrangement. Peak fire size was about 7 MW. Room size is similar to the first test.

(3) This data set is actually an average of a series of 11 replicate tests in a three-room configuration with simple steady-state gas burner fires.[24] Figure 4 shows the room configuration and instrumentation for the test. It provides a basic set of quantities that are predicted by current fire models for small to medium size fires. Since all fires were gas burner fires, simulation should be straightforward. It is of particular interest since it was undertaken as a part of a program to develop a methodology for the evaluation and accuracy assessment of fire models. Fire size was about 100 kW with a total volume of 100 m^3.

(4) This data set is part of a series of tests conducted in a multiple room configuration with more complex gas burner fires than the previous data set.[26,43] This study was included because it expands upon that data set by providing larger and time-varying gas burner fires in a room–corridor configuration. Figure 5 shows the room configuration and instrumentation for the test. Fire size was about up to 1 MW with a total volume of 200 m^3.

(5) By far the most complex test, this data set is part of a series of full-scale experiments conducted to evaluate zoned smoke

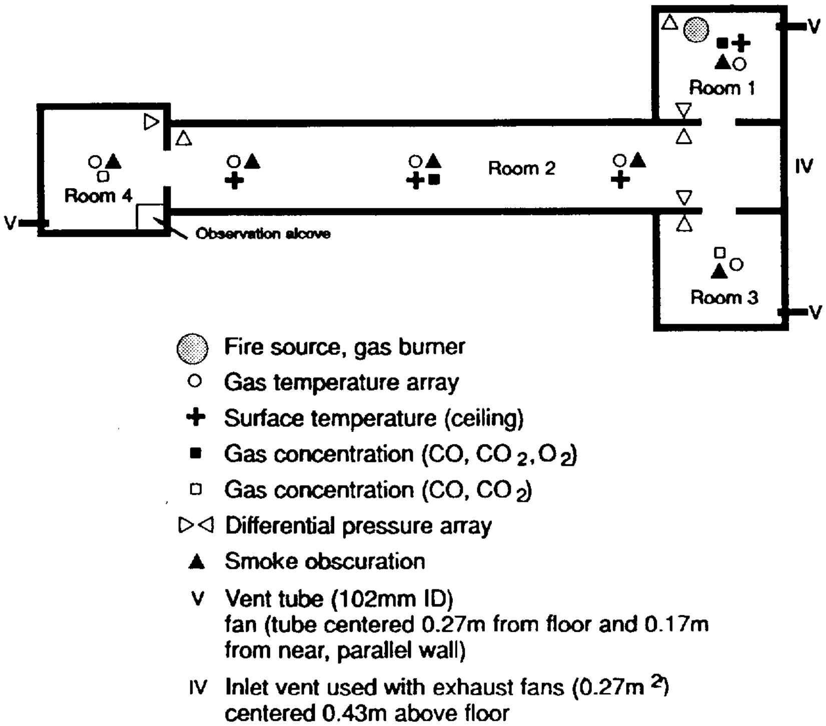


Fig. 5. Four-room gas burner with a corridor.

control systems, with and without stairwell pressurization.[44] It was conducted in a seven-story hotel (with basement) with multiple rooms on each floor and a stairwell connecting to all floors. Figure 6 shows the room configuration and instrumentation for one of the eight floors of the building. This data set was chosen because it would be considered beyond the scope of most current fire models. Measured temperatures and pressure differences between the rooms and floors of the building are extensive and consistent. Peak fire size was 3 MW with a total building volume of 140 000 m^3.

DISCUSSION

All of the simulations were performed with the CFAST model[13] on an MS-DOS† compatible computer. For each of the data sets, the model

† The use of company names or trade names within this report is made only for the purpose of identifying those computer hardware or software products with which the compatibility of the CFAST programs has been tested. Such use does not constitute any endorsement of those products by the National Institute of Standards and Technology.

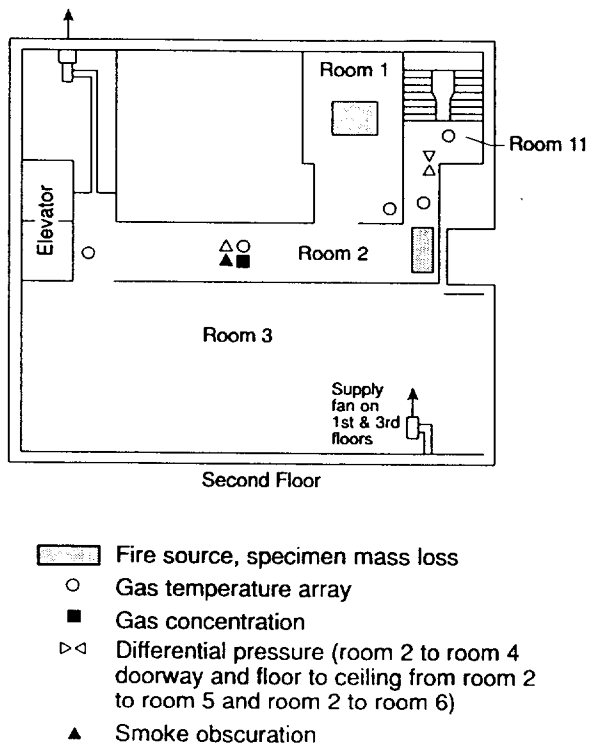


Fig. 6. Second floor for multiple-story building tests.

data were developed from the building and fire descriptions provided in the original reports. Obtaining building geometry, construction materials, and room interconnections was straightforward. Usually, description of the fire source was more difficult. At least two approaches are appropriate for different applications. For engineering design, an *a priori* approach is appropriate—developing the fire input without using data from the test to be modelled.[38] For fire reconstruction, this information is available *posteriori,* to varying extent, from information gathered from the fire or experiments conducted specifically to investigate the fire. In this paper, we take both approaches, depending upon the availability of experimental measurements. Where freeburn data were available, such data were used to describe the heat release rate, pyrolysis rate, and species yields. In other cases, estimates from similar materials or textbook values were used to determine missing quantities.

How to best quantify the comparisons between model predictions and experiments is not obvious. The necessary and perceived level of agreement for any variable is dependent upon both the typical use of the variable in a given simulation (for instance, the user may be interested in the time it takes to reach a certain temperature in the room), the nature of the experiment (peak temperatures would be of little interest in an experiment which quickly reached steady state), and the context of the comparison in relation to other comparisons being made (a true validation of a model would involve proper statistical treatment of many compared variables).

Insufficient experimental data and understanding of how to compare the numerous variables in a complex fire model prevent a true validation of the model. Thus, the comparisons of the differences between model predictions and experimental data in this paper are intentionally simple and vary from test to test and from variable to variable due to the changing nature of the tests and typical use of different variables. The graphical presentation of the results in the discussion below is meant to be typical of the set of comparisons for all of the tests. Graphs were omitted in the interest of brevity and those included represent a range of agreement. In some cases, experimental results were not available for comparison. These are noted in the captions for the figures.

Layer temperature and interface position

Arguably the most frequent question asked about a fire is 'How hot did it become?' Temperature in the rooms of a structure is an obvious indicator to answer this question. Peak temperature, time to peak temperature, or time to reach a chosen temperature tenability limit are typical values of interest. Quality of the prediction (or measurement) of layer interface position is more difficult to quantify. Although observed valid in a range of experiments, the two-layer assumption is in many ways just a convenience for modeling. From a standpoint of hazard, time of descent to a chosen level may be a reasonable criterion (assuming someone in the room will then either be forced to crawl beneath the interface to breathe the 'clean' atmosphere near the floor or be forced to breath the upper layer gases). Minimum values may also be used to indicate general agreement. For the single-room tests with furniture or wall burning, these are appropriate indicators to judge the comparisons between model and experiment. For the more-closely steady-state three- and four-room tests with corridor or the multiple-story building tests, a steady state average better characterizes the nature of the experiment.

Figure 8–10 and Tables 1–3 show typical upper layer temperature, lower layer temperature, and interface position for the tests studied. Like all zone-based fire models, CFAST calculates conditions within

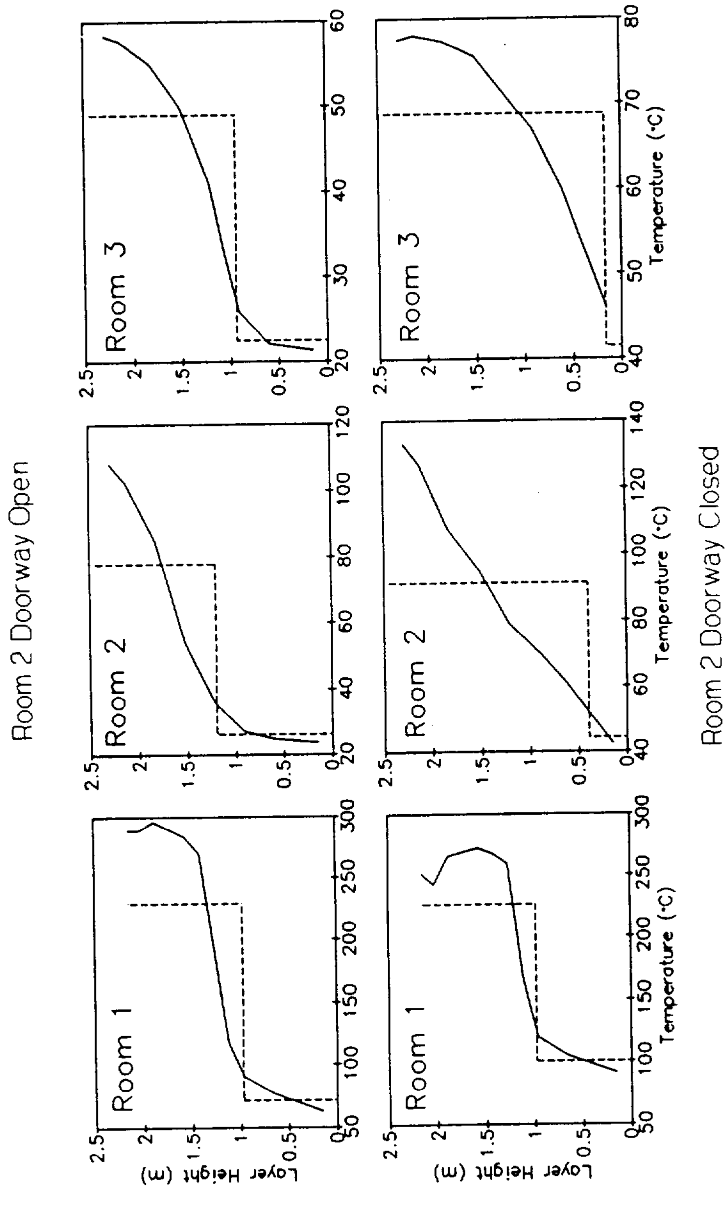
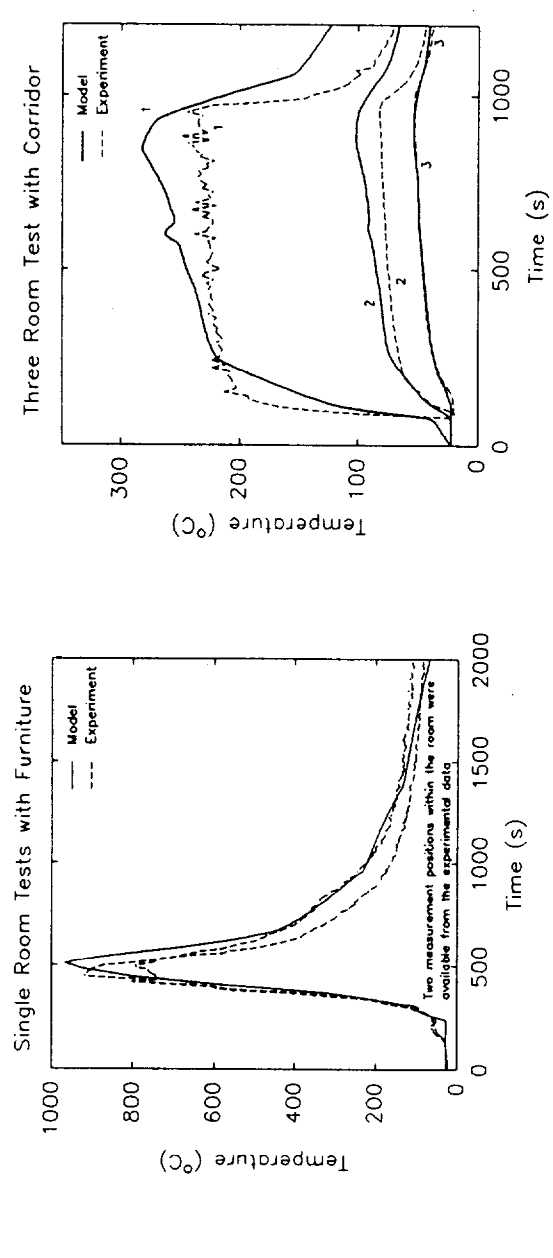


Fig. 7. Average two-layer temperature and interface position calculated from experimentally-measured temperature profiles in a three-room experiment.


Three Room Test with Corridor
Model
Experiment
Temperature (°C)
Time (s)
Single Room Tests with Furniture
Model
Experiment
Two measurement positions within the room were available from the experimental data
Temperature (°C)
Time (s)

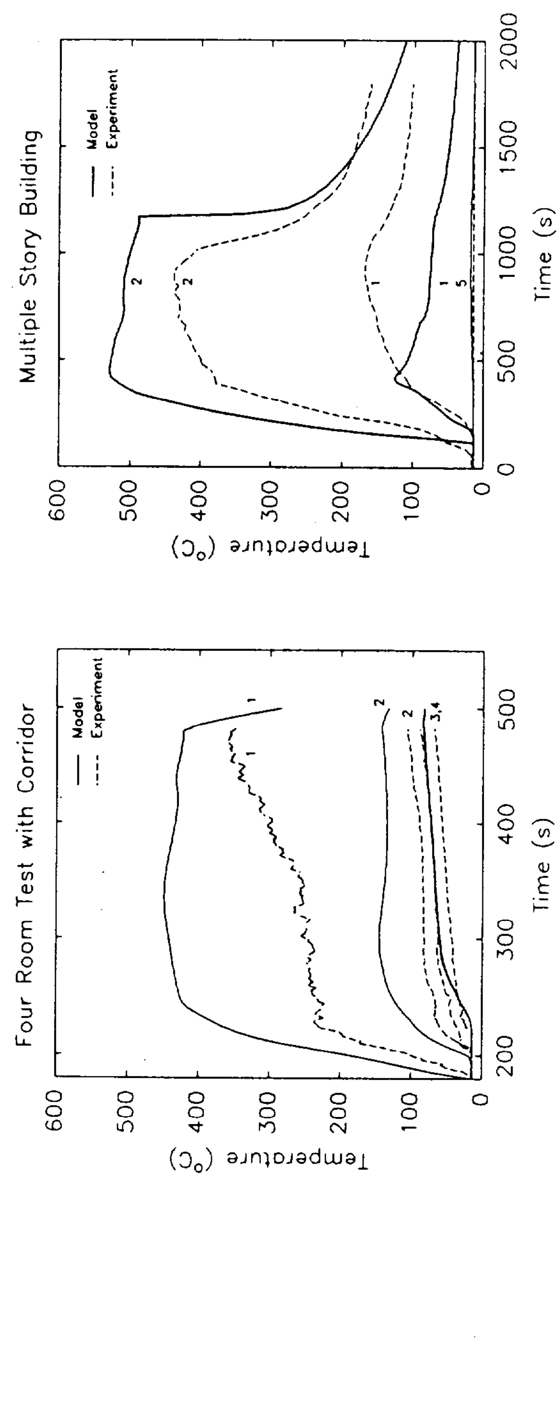


Fig. 8. Comparison of measured and predicted upper layer temperatures for several tests. (Numbers indicate comparable rooms in the test structure.)

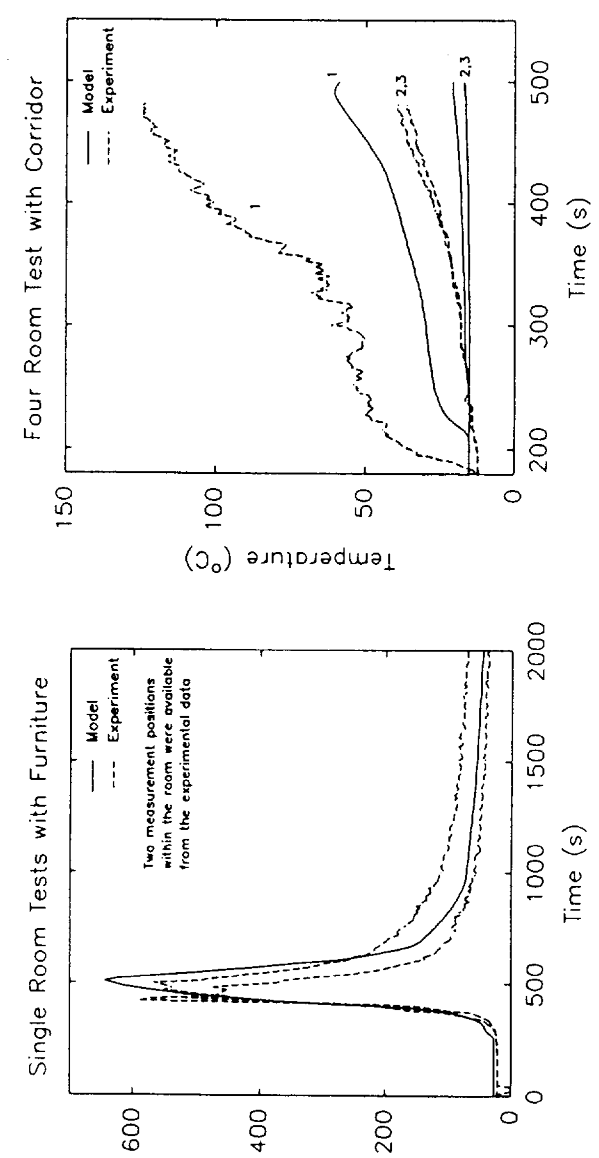


Fig. 9. Comparison of measured and predicted lower layer temperatures for several tests.

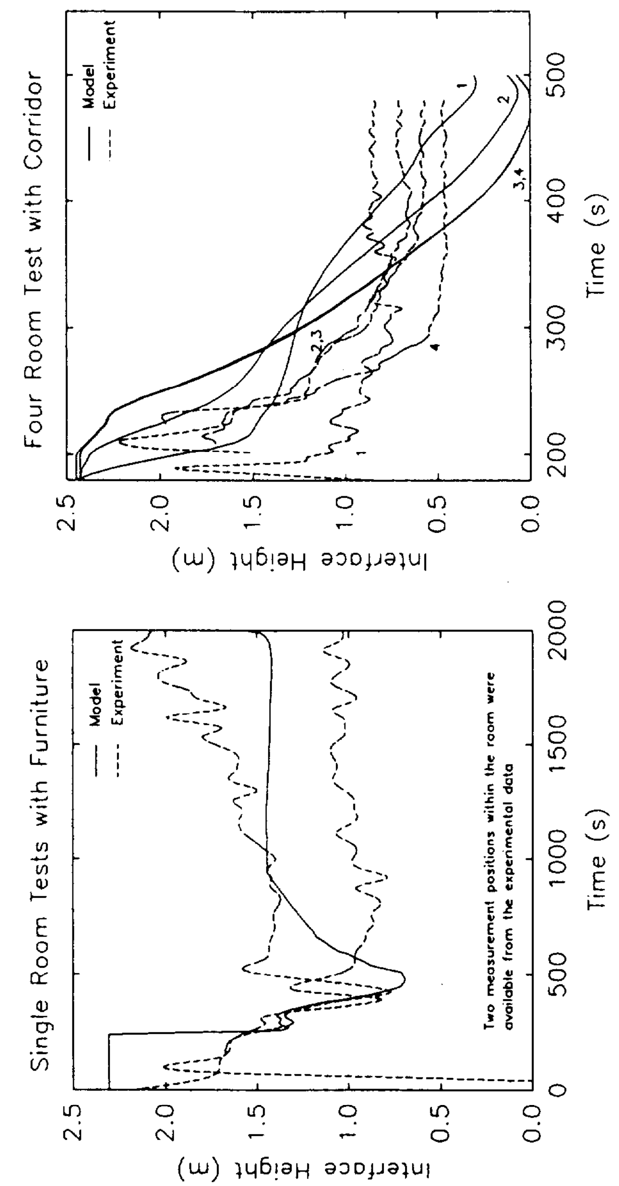


Fig. 10. Comparison of measured and predicted layer interface position for several tests.

TABLE 1
Comparison of Experimental Measurements and Model Predictions of Upper Layer Temperature (°C) for Several Tests[a]

	Peak value	*Time to peak*	*Time to 100 °C*	*Steady-state value*	*Similar shape?*
	790 (970)	500 (510)	290 (310)		
Single-room furniture tests[b]	920 (970)	450 (510)	290 (310)	—[b]	√
(Tests 1 and 6)	590 (790)	510 (510)	330 (340)	—	√
	900 (790)	510 (510)	330 (340)		
Single-room tests with wall	750 (710)	710 (700)	100 (120)	—	√
burning (Tests 1 and 2)	810 (1550)	520 (470)	100 (70)	—	√
Three-room tests with	—	—	100 (110)	230 (250)	
corridor[d] (SET 4, 11			830 (nr)[e]	75 (90)	
replicates)			nr	45 (45)	
			195 (190)	240 (470)	
			nr (270)	70 (110)	√
	—	—	nr	55 (35)	
Four-room tests with corridor[c]			nr	40 (35)	
(Tests 19 and 21)			200 (190)	260 (440)	
	—	—	nr (230)	80 (140)	
			nr	65 (60)	
			nr	50 (60)	
Multiple-story building	—	—	390 (375)	270 (340)	
(Test 7)			210 (150)	110 (65)	√
			nr	15 (15)	

[a] Numbers in parentheses are model predictions.
[b] Two measurement positions within the room were available from the experimental data.
[c] Not appropriate for the experiment.
[d] Multiple entries indicate multiple comparable rooms in the test structure.
[e] nr—Not reached.

each room as an upper and a lower volume (layer), each with uniform conditions throughout the volume at any instant of time. Thus, for the model, the temperature environment within a room can be described by an upper and lower layer temperature and by the position of the interface between these two layers. By contrast, experimental measurements often take the form of a vertical array of measurement points describing a profile of temperature. Techniques for collapsing these profiles to data that can be compared to zone fire models are available[1] and are used here to facilitate the comparison (see Fig. 7 for an example of the calculated and experimentally measured temperature profiles).

TABLE 2

Comparison of Experimental Measurements and Model Predictions of Lower Layer Temperature (°C) for Several Tests[a]

	Peak value	*Time to peak*	*Time to 100 °C*	*Steady-state value*	*Similar shape?*
Single-room furniture tests[b]	570 (650)	500 (510)	370 (380)	—[b]	√
	590 (650)	420 (510)	390 (380)		
	230 (340)	510 (510)	410 (440)	—	√
	590 (340)	500 (510)	390 (440)		
Single-room tests with wall burning	710 (250)	710 (700)	240 (220)	—	√
	700 (620)	520 (450)	290 (290)	—	√
Three-room tests with corridor[d]	—	—	nr[e]	70 (40)	
			nr	30 (30)	
			nr	23 (30)	
Four-room tests with corridor[d]			nr	75 (45)	
	—	—	nr	21 (19)	√
			nr	21 (15)	
	—	—	nr	70 (32)	
			nr	20 (17)	
			nr	20 (15)	
Multiple-story building	—	—	400 (nr)	40 (37)	
			nr	85 (70)	√
			nr	14 (16)	

[a] Numbers in parentheses are model predictions.
[b] Two measurement positions within the room were available from the experimental data.
[c] Not appropriate for the experiment.
[d] Multiple entries indicate multiple comparable rooms in the test structure.
[e] nr—Not reached.

For the single-room tests, predicted temperatures and layer interface position show obvious similarities to the measured values. Peak values occur at similar times with comparable rise and fall for most comparisons. Interface height for the single-room with wall burning is a notable exception. Unlike the model prediction, the experimental measurement does not show the rise and fall in concert with the temperature measurement. Peak values are typically higher for upper layer temperature and lower for lower layer temperature and layer interface position. For all the tests, including the single-room tests, times to peak values and times to 100 °C predicted by the model average within 25 s of experimentally measured values.

TABLE 3
Comparison of Experimental Measurements and Model Predictions of Layer Interface Position (m) for Several Tests[a]

	Peak value	*Time to peak*	*Time to 1 m*	*Steady-state value*	*Similar shape?*
Single-room furniture tests[b]	0·8 (0·7)	420 (480)	400 (400)	—[c]	✓
	0·8 (0·7)	450 (480)	(380) 400		
	0·8 (0·6)	480 (510)	420 (430)	—	✓
	0·9 (0·6)	460 (510)	430 (430)		
Single-room tests with wall burning	0·2 (0·7)	710 (230)	120 (210)	—	✓
	0·1 (0·6)	500 (410)	80 (280)	—	✓
Three-room tests with corridor[d]	—	—	360 (nr)[e]	1·0 (1·5)	
			1210 (nr)	12 (13)	✓
			90 (270)	0·9 (0·7)	
Four-room tests with corridor[d]	—	—	na[f]	0·7 (1·7)	
				1·0 (1·6)	
				1·0 (1·7)	
				0·7 (1·7)	
	—	—	na	0·8 (1·1)	
				0·9 (1·1)	
				0·8 (1·0)	
				0·6 (1·0)	
Multiple-story building	—	—	na	0·3 (1·8)	
				0·8 (2·1)	
				1·8 (1·8)	

[a] Numbers in parentheses are model predictions.
[b] Two measurement positions within the room were available from the experimental data.
[c] Not appropriate for the experiment.
[d] Multiple entries indicate multiple comparable room in the test structure.
[e] nr—Not reached.
[f] na—Not available.

Systematic deviations exist for the remaining three data sets. Differences between model predictions and experimental measurements change monotonically over time (rising for the three-room test and falling for the four-rooms tests). Modelling of heat conduction (losing too much or too little heat to the surfaces) or lack of modelling of leakage (rooms are presumed perfectly sealed unless vents are included to simulate leakage) may account for the trends. The comparison of interface position for the four-room test with corridor seems an anomaly. Although a nearly closed space, the roughly level interface position from the experiment seems more typical of a test more open to the ambient. The model calculations would appear to better represent the mixing which would occur in a closed volume. Again, leakage may be a factor. With some leakage in the space, lower temperatures for both the lower and upper layer and higher (and more uniform) interface position would be calculated.

In general, upper layer temperature and interface position predicted by the model are somewhat higher than experimental measurements, with the differences ranging from −46 to 230 °C for the temperature and −0·19 to 1·5 m for the interface position. Conversely, the lower layer temperature is somewhat lower for the model than for the experiments (−60 to 5 °C). Presuming conservation of energy (an underlying assumption in *all* fire models), these three observations are consistent. A higher interface position gives rise to a smaller upper volume (and larger lower volume) within a room. With the same enthalpy in a smaller upper volume, higher temperatures result. This lends credence to the assumption of energy conservation. Limitations inherent in the model also account partially for these trends. In the current version of CFAST, the lower layer is presumed to be clear. For the lower layer, energy is gained *only* by mixing or convection from surfaces. Adding radiative exchange to the lower layer would reduce the upper layer temperature and increase the lower layer temperature. Layer interface position is primarily affected by entrainment by the fire or at vents. Plume entrainment in CFAST is based on the work of McCaffrey[45] on circular plumes in relatively small spaces. For large fires in small spaces where the fire impinges on the ceiling (such as the single-room tests with wall burning) or very small fires in large spaces (such as atria), these correlations may not be as valid.

Gas species

The fire chemistry scheme in CFAST is essentially a species balance from user-specified species yields and the oxygen available for combustion. Once generated, it is a matter of bookkeeping to track the mass of species throughout the various control volumes in a simulated building. It does, however, provide another check of the flow algorithms within the model. Since the major species (CO and CO_2) are generated only by the fire, the relative accuracy of the predicted values throughout multiple rooms of a structure should be comparable. Figure 11 and Table 4 show measured and predicted concentrations of O_2, CO_2, and CO in two of the tests studied.

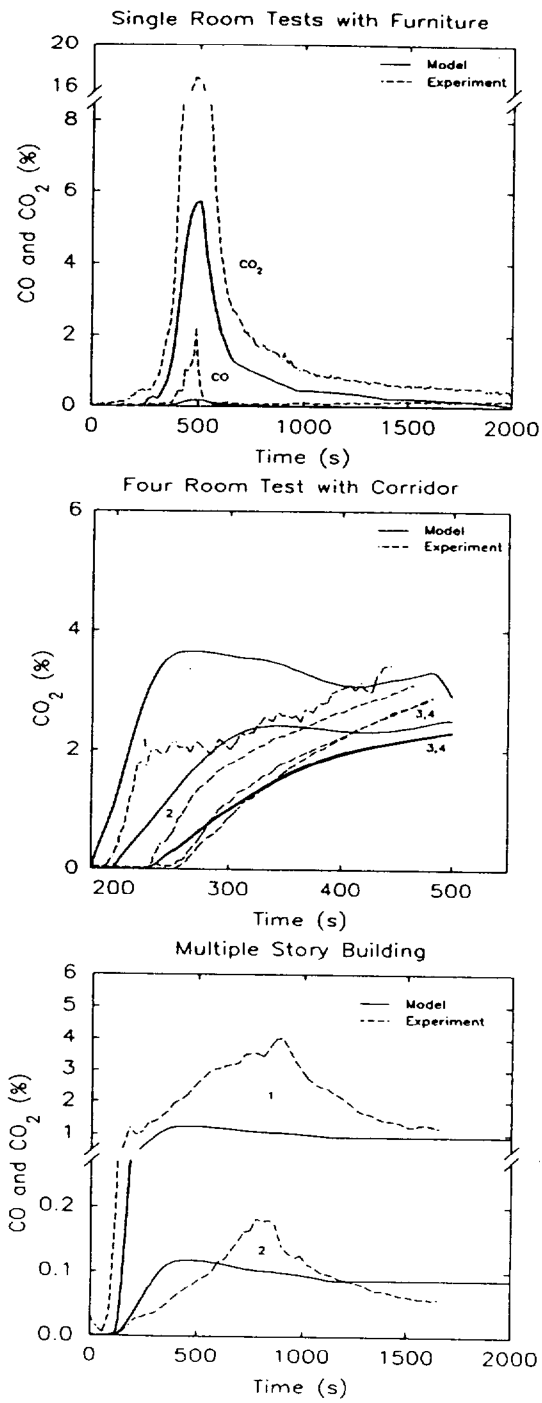


Fig. 11. Comparison of measured and predicted gas species concentration for several tests. Experimental measurements were not available for the single-room tests with wall burning or the three-room tests with a corridor.

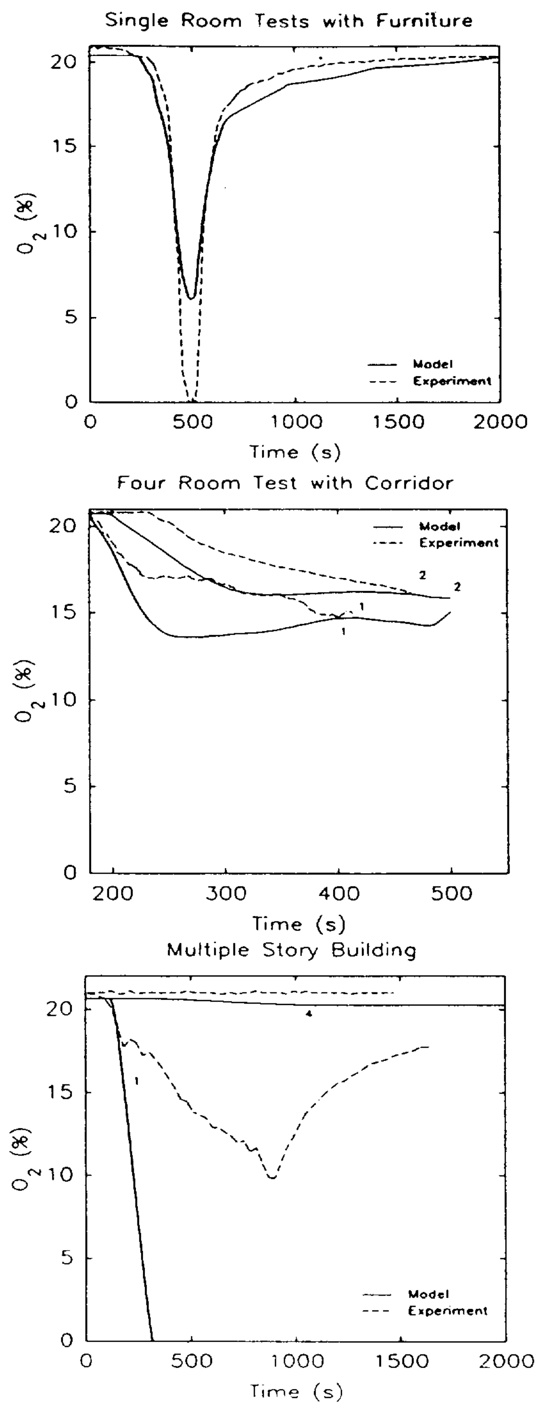

Single Room Tests with Furniture
20
15
10
5
0
O_2 (%)
0
500
1000
1500
2000
Time (s)
Model
Experiment
Four Room Test with Corridor
Model
Experiment
2
2
1
1
20
15
10
5
0
O_2 (%)
200
300
400
500
Time (s)
Multiple Story Building
4
1
20
15
10
5
0
O_2 (%)
Model
Experiment
0
500
1000
1500
2000
Time (s)

Fig. 11—*contd.*

TABLE 4
Comparison of Experimental Measurements and Model Predictions of Oxygen Concentration for Several Tests[a]

	Peak value	*Time to peak*	*Steady-state value*	*Similar shape?*
O_2 concentration				
Single-room furniture fire tests	0·01 (6·1)	510 (490)	—[b]	√
	6·9 (10·2)	490 (510)	—	√
Four-room tests with corridor[c]	—	—	17·9 (12·5) 18·0 (16·4)	√
	—	—	16·1 (14·0) 18·1 (16·5)	√
Multiple-story building test[c]	—	—	15.5 (2·9) 20·9 (20·4)	
CO_2 concentration				
Single-room furniture fire tests	17.0 (6.0)	480 (510)	—	√
	10.6 (4.2)	490 (510)	—	√
Four-room tests with corridor[c]	—	—	2·3 (4·3)	√
	—	—	2·4 (4·3)	√
Multiple-story building test[c]	—	—	2·0 (0·9)	
CO concentration				
Single-room furniture fire tests	2·2 (0·2)	490 (510)	—	√
	0·6 (0·1)	440 (510)	—	√
Multiple-story building test[c]	—	—	0·8 (0·8)	

[a] Numbers in parentheses are model predictions.
[b] Not appropriate for the test.
[c] Multiple entries indicate comparable rooms in the test structure.

For the single-room tests with furniture, the predicted concentrations are lower than those measured experimentally (averaging 5% low). This is probably due to the treatment of oxygen-limited burning. In CFAST, the burning rate simply decreases as the oxygen level decreases. A user specified lower limit determines the point below which burning will not take place. This parameter could be adjusted to provide better agreement with the experiment. For the present comparisons, it was always left at the default value.

For the four-room test with corridor, the asymptotic values of the gas concentrations agree quite well. At first glance, the model predictions reach this equilibrium more quickly. An appreciation of the differences between the modeled parameters and the experimental measurements put this in perspective. From Fig. 10, it takes about 100 s for the upper layer to descend to the level of the gas sampling port in the test. In addition, it is assumed that this point measurement is the bulk concentration of the entire upper layer. In reality, some vertical distribution not unlike the temperature profile (Fig. 7) exists for the gas concentration as well. Since this measurement point is near the lower edge of the upper layer for a significant time, it should underestimate the bulk concentration until the layer is large in volume and well mixed.

For the multiple-story building test, predicted values for CO_2, CO, and O_2 are far lower than measured experimentally. Both the lower burning rate limit as well as leakage in the 100-year-old structure probably contribute to the differences between the experiments and model. In addition, values for species yields were simply literature values since no test data were available.

Heat release and fire pyrolysis rate

Heat release rate and its initimately related fire pyrolysis rate are fundamental indicators of the fire hazard.[46] Peak values and time to reach peak values are typical scalar estimates used to represent the time-variant heat release rate and fire pyrolysis rate. For the single-room tests with furniture or wall burning, these are appropriate indicators to judge the comparisons between model and experiment. For the three- and four-room tests with corridor or the multiple-story building tests, a steady state average is more appropriate.

Table 5 and Fig. 12 compare measured and predicted heat release rates for the tests. In the CFAST model, the fire is specified as a series of straight line segments describing the pyrolysis rate, heat release rate, and species yields. For the four-room with corridor and multiple-story building tests, no experimental measurements were available for comparison. They were included in the graphs since the heat release rate is key to the prediction of the progress of a fire. Thus, the model predictions could be expected to agree quite well with experimental measurements. For tests where experimental data were available, the agreement is, not surprisingly, excellent—usually within 5% of the peak experimental values. Since this effectively just shows how well a series of line segments reproduces experimental measurement, this level of agreement is expected. Times to peak values are always close. For the four-room with corridor and multiple-story building tests, no experimental measurements were available. For two tests (the single-room with furniture and wall burning and the multiple-story building), the heat release rate in the room is limited by the available oxygen.

TABLE 5
Comparison of Experimental Measurements and Model Predictions of Heat Release Rate for Several Tests[a]

	Peak value	*Time to peak*	*Steady-state value*	*Similar shape?*
Single-room furniture fire tests	2450 (2200)	480 (480)	—[b]	√
	2600 (2350)	500 (510)	—	√
Single-room tests with wall-burning	2050 (2000)	230 (200)	—	√
	4000 (3150)	420 (370)	—	√
Three-room test with corridor	—	—	86 (87)	√
Four-room tests with corridor	—	—	nr[c]	√
	—	—	nr	√
Multiple-story building test	—	—	nr	√

[a] Numbers in parentheses are model predictions.
[b] Not appropriate for the test.
[c] nr—Not reached. Not available from experimental data.

Additional burning outside the room (seen in the single-room with furniture) accounts for the remainder of the heat released.

For the three-room test with corridor, multiple replicate tests put the agreement between the model and experiments in perspective. For all tests in the original study,[24] the coefficients of variation (the standard deviation expressed as a percentage of the mean) ranged from 4 to 52%. In another study, precision to within 15% for fires of 2·5 MW was noted.[41] Thus, the simplification of specifying the fire growth as a series of straight lines is easily justified with the expected accuracy of experimental measurements.

For the multiple-story building test, *no* pyrolysis rate or heat release data were available. Estimates of the 'steady-state' burning rate, time to reach 'steady-state', and duration of 'steady-state' burning were made from available correlations for wood cribs.[47,48] Although the comparisons for this test should be considered approximate, it was included since, if successful, the scope of the model is extended considerably to a large multiple-story building with mechanical ventilation.

Pressure

The differential pressure across an opening drives the flow through the opening. For each room, the CFAST model calculates a differential

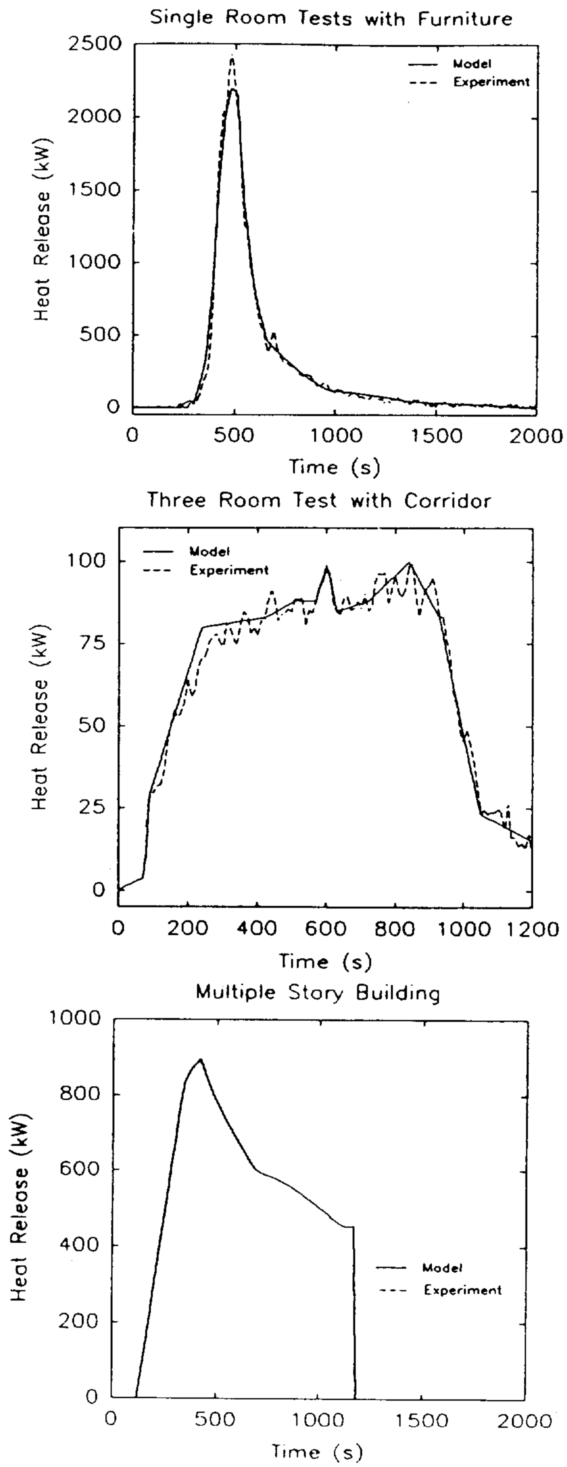


Fig. 12. Comparison of measured and predicted heat release rates for two selected tests.

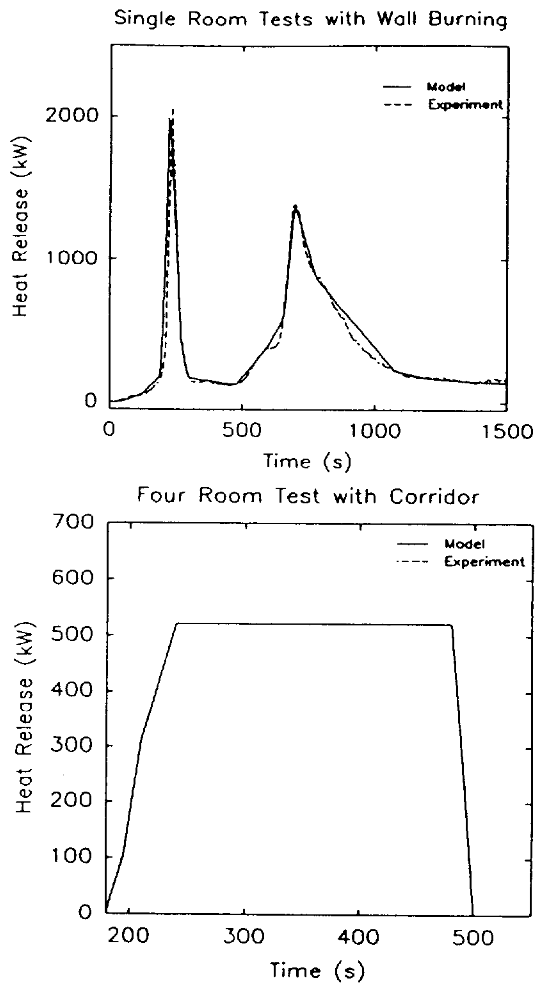


Fig. 12—*contd.*

pressure at floor level, referenced to ambient. Noting that the ambient pressure is approximately 100 kPa, typical pressure drops across openings induced by fires are but a small fraction of the ambient pressure—typically from less than 1 Pa to perhaps a few hundred pascals in well-sealed enclosures. The ability to model these extremely small differential pressures provides another check on the flow algorithms in the model. These are, however, expected to be difficult to model and measure accurately. Thus, agreement within a few pascals is often considered acceptable. In four of the five experimental test series, measurements (corrected to floor level) were available which could be compared to these predicted values (measurements were not available for the single room tests with furniture).

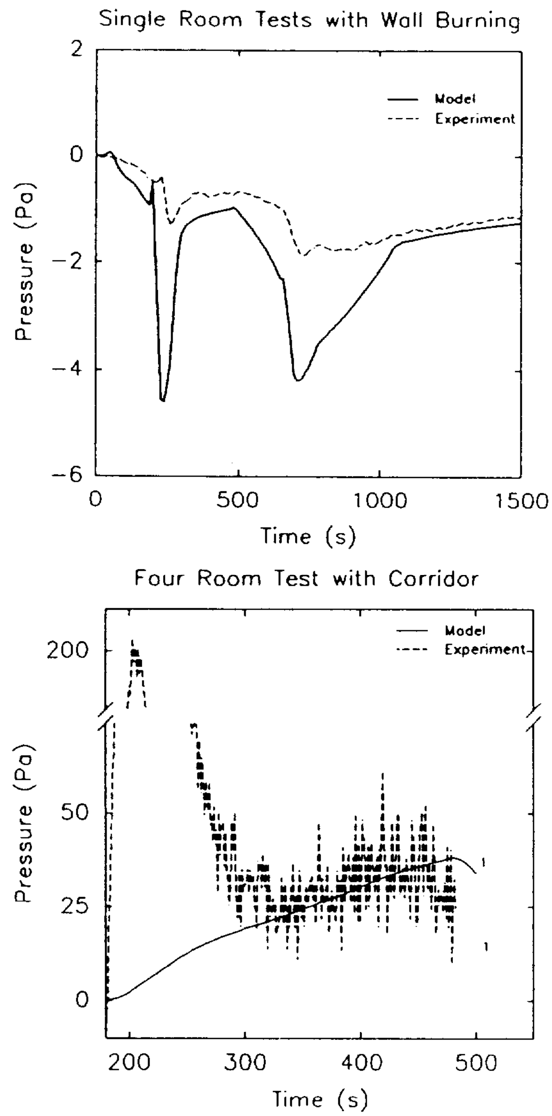


Fig. 13. Comparison of measured and predicted pressures for several tests. Experimental measurements were not available for the single-room tests with wall burning. the pressure shown for the multiple-story building is at floor level in the stairwell.

Figure 13 and Table 6 show the comparisons. For most cases, the agreement is reasonable, with the difference between measured and predicted values typically less than 2 Pa and for some experiments, less than 0·5 Pa. Trends displayed in the experimental data are replicated by the model predictions. Some interesting exceptions are apparent however. A combination of limitations in the model (damping) and

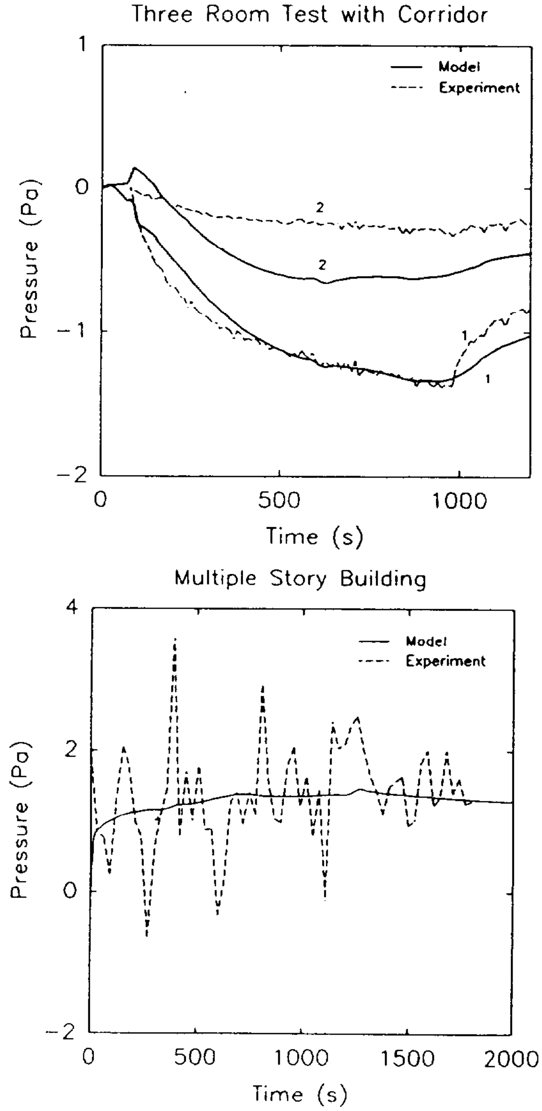


Fig. 13—*contd.*

quantities unknown in the experiments (leakage) accounts for much of the differences.

Flow through vents is governed by the pressure difference across a vent. Because pressure (and thus vent flow) vary most rapidly of all the source terms in the conservation equations in CFAST, they are most susceptible to uncertainty in the solution of the differential equations. To allow efficient solution with the current solver in CFAST, the

TABLE 6
Comparison of Experimental Measurements and Model Predictions of Room Pressure for Several Tests[a]

	Peak value	*Time to peak*	*Steady-state value*	*Similar shape?*
Single-room tests with wall-burning	−1·9 (−4·6)	730 (750)	—[b]	√
	−1·9 (−5·6)	520 (490)	—	√
Three-room test with corridor	—	—	−1·1 (−0·6)	√
			−0·2 (−0·5)	
Four-room tests with corridor	—	—	−1·0 (−2·1)	√
	—	—	36 (22)	
Multiple-story building test	—	—	2·4 (1·3)	√

[a] Numbers in parentheses are model predictions.
[b] Not appropriate for the test.

pressure and vent flow calculations include damping factors to lessen instability in the solution. In CFAST, the values for these constants are a compromise between numerical accuracy and calculation speed. For pressure, the constant takes the form of damping the rate of change of the pressure within a room. The four-room test with a corridor (test 21) illustrates this limitation with an average difference of −22 Pa out of a range of 210 Pa in the experimental measurements. This test is a nearly closed building (0·1 m^2 openings in each room). Not surprisingly, the pressure in the rooms builds to a positive value at ignition. In the experiment, an initial peak of about 200 Pa is not reproduced by the model due to the pressure damping. With the noise in the experimental data at later times, it is difficult to make conclusive observations about the remainder of the test.

Damping of the vent flow can also affect the pressure. In CFAST, flow through a vent below a certain threshold is presumed to be noise in the calculation. In addition, at low flows, the physics of the flow changes so the assumption of plug flow through the vent is no longer valid. If this presumed threshold is too high, vent flow will be underestimated. The model attempts to compensate for this effective lack of flow by forcing the pressure more negative to generate greater flow. The single-room tests with furniture and wall burning illustrate this limitation (with average differences nearly 50% of the range of experimental measurements). Although similar in shape, the model predictions show peak magnitudes much more negative than the experimental values.

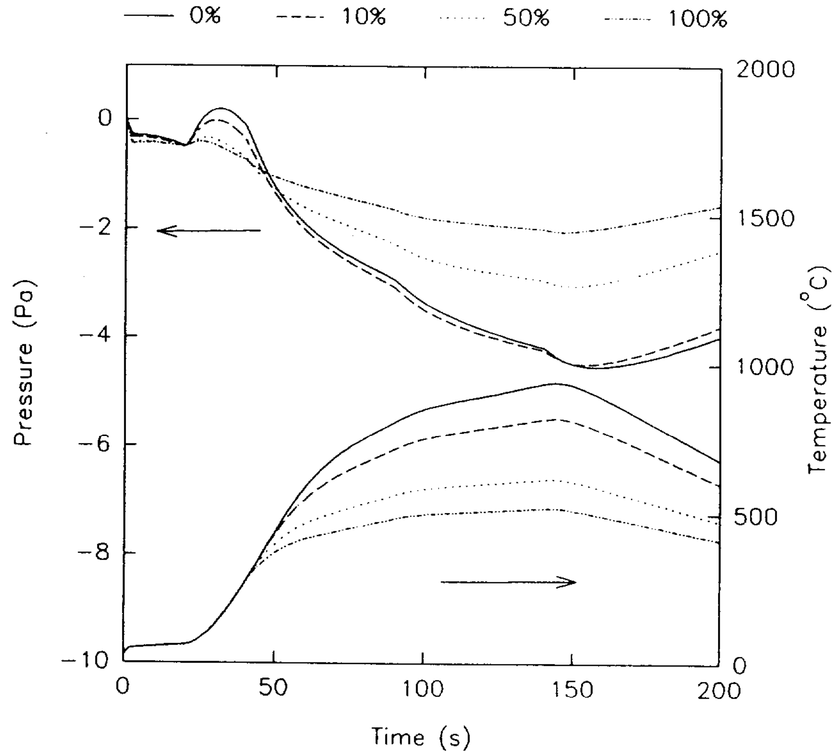


Fig. 14. Effect of leakage on calculated temperatures and pressures in an arbitrary single-room fire.

Not all of the onus for agreement should be placed on the model, however. Only one of the test series included any estimate of leakage through cracks in the buildings. Logically, unless directed otherwise, the model assumes *no* leakage from any room. This leakage can have a dramatic effect on the results predicted by the model. Figure 14 illustrates the effect of leakage for a single room with a single doorway and an upholstered chair used as the fire source. Leakage areas from 0 to 100% of the vent area were simulated with a second vent of appropriate size. Both temperatures and pressures are seen to change by more than a factor of two (other variables can be expected to change with similar variation). Temperature changes by about 20% with only a 10% leakage area. The effect on pressure is not quite as straightforward (for the smallest leakage rates, the numerical effects of the pressure damping may overwhelm the calculation more than the added area of the leakage), but for larger leakages changes in concert with the temperature. For the four-room tests with corridor, leakage from the

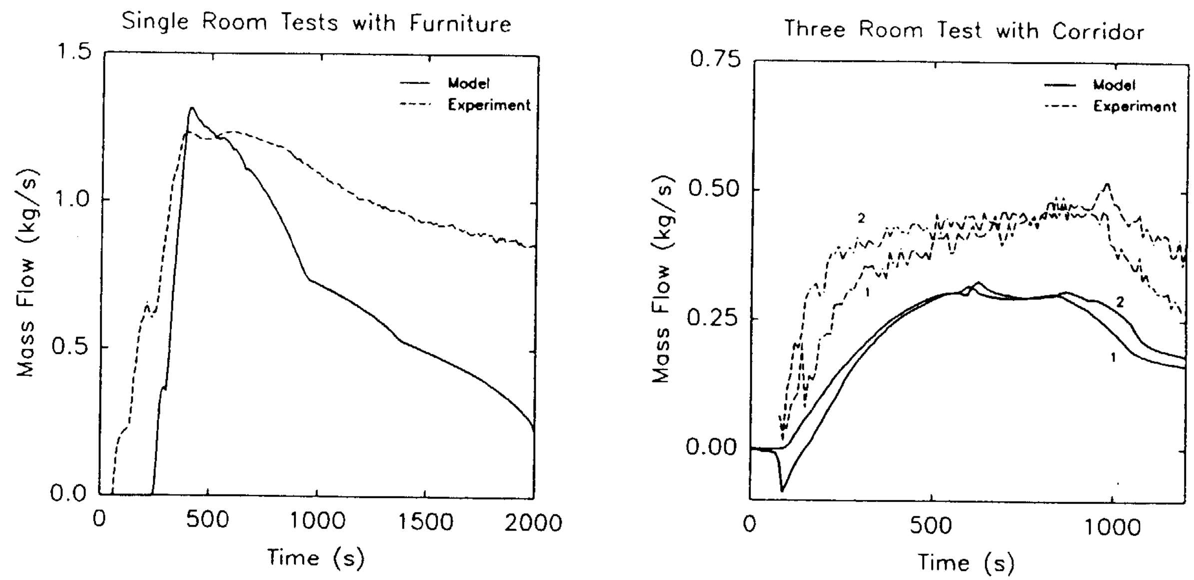


Fig. 15. Comparison of measured and predicted mass flow through vents for several tests. Experimental measurements were only available for the single-room tests with furniture and the three-room test with a corridor.

'well-sealed rooms' was estimated via measurement at not more than 25% of the total vent area.

Flow through openings

In the control volume approach, the differential form of the momentum equation for the zones is not solved directly. Rather, the momentum transfer at the zone boundaries is included by using Bernoulli's approximation for the velocity equation. This solution is augmented for restricted openings by using flow coefficients[49,50] to allow for constriction in vents. The flow coefficients allow for an effective constriction of fluid flow which occurs for vents with sharp edges. In CFAST, these coefficients are for rectangular openings in walls whose surfaces are much larger than the opening.

Figure 15 and Table 7 compare measured and predicted mass flows through doorways in two of the tests studied. For these calculations, measured pressure drops across the openings were used along with vertical temperature profiles to estimate mass flow in the experiments.[1] For the three-room test with a corridor, flow through two doorways of the same test are shown (one between the fire room and the corridor and one between the corridor and the outdoors). Not surprisingly, the flow is typically somewhat underpredicted by the model (from −0·14 to −0.58 kg/s). Like the pressure comparison discussed above, the flow calculation is affected by the flow damping. In addition, the vent flow in CFAST includes mixing phenomena at the vents. As hot gases from one compartment leave that compartment and flow into an adjacent compartment, a door jet can exist which is analogous to a normal fire plume, but with an extended flat plume similar to a waterfall. This places its use outside the normal range of the plume model[45] and

TABLE 7

Comparison of Experimental Measurements and Model Predictions of Mass Flow Through Openings for Several Tests[a]

	Peak value	*Time to peak*	*Steady-state value*	*Similar shape?*
Single-room furniture fire tests	1·2 (1·3)	380 (410)	—[b]	√
	1·9 (1·9)	560 (460)	—	√
Three-room test with corridor	—	—	0·4 (0·3)	√

[a] Numbers in parentheses are model predictions.
[b] Not appropriate for the test.

perhaps beyond its range of validity. However, no reliable correlation yet exists for the extended flat plume which occurs in vent flow.

Examining the trends of prediction of upper layer temperature in tests with multiple rooms (Tables 1 and 2), the typical over-prediction in the room of fire origin is far greater than for other rooms in the structures. The under-prediction of the mass flows probably accounts for this as a cascading effect as you move away from the room of fire origin.

CONCLUSIONS

For variables deemed of interest to the user of the model, the CFAST model provides predictions of the magnitude and trends (time to critical conditions and general curve shape) for the several experiments examined in this paper which range in quality from within a few percent to a factor of two to three of the measured values. Although differences between the model and the experiments were clear, they can be explained by limitations of the model and of the experiments. Thus, several areas which need additional research are apparent.

- *Numerical solvers*—newly available differential equation solvers could eliminate the need for the pressure and flow damping. With careful implementation, these would improve both the accuracy and speed of the calculation.
- *Entrainment*—fire plume and doorway jet entrainment are based on the same experimental correlations. The fire plume (for large spaces) and the doorway jet (in general) are often used outside the experimental range of validity of these correlations.
- *User specified fire*—the level of agreement is critically dependent upon careful choice of the input data for the model. A validated fire growth model would allow prediction of pyrolysis rate and species yields.
- *Leakage*—a better understanding of typical fire-induced leakage in buildings would facilitate more accurate description of the building environment.
- *Statistical treatment of the data*—presentation of the differences between model predictions and experimental data are intentionally simple. With a significant base of data to study, appropriate statistical techniques to provide a true measure of the 'goodness of fit' should be investigated.
- *Experimental measurements*—measurement of leakage rates,

room pressure, or profiles of gas concentration are atypical in experimental data. These measurements are critical to assessing the accuracy of the underlying physics of the models or of the models ability to predict toxic gas hazard.

The future development of the CFAST model will address these limitations. A new differential equation solver, flow algorithm, conduction algorithm, radiation algorithm, and flame spread model are under development and will be available in future versions of the model. Additional research is still needed in the areas of entrainment, leakage, and statistical treatment of model and experimental data.

As with any theoretical model, there are pieces which have been omitted and others which could be implemented more completely. However, with an understanding of the relative weaknesses and strengths of both the model and of the experiments, the user of the model can develop confidence in using such models for a wide range of simulations.

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