A Comparison of Three Models for the Simulation of Accidental Fires

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ABSTRACT: Assumptions made and results obtained when applying three fire modeling approaches to study three accidental fires that occurred in single-family dwellings are presented in this article. The modeling approaches used are: a simplified analytical model of fire growth, a zone model (CFAST), and a field model (FDS). The fires predicted are: a house fire of suspected initial location but of unknown ignition source, a small-apartment fire initiated by the ignition of a sofa, which extinguished due to oxygen depletion, and a one-story house fire started by a malfunctioning gas heater. The input to each model has been kept as independent as possible from the other models while consistent with the forensic evidence. The predictions from the models of the fires' characteristics are analyzed in the context of the forensic evidence for each accidental fire to compare the models' predictive capabilities. It is found that in spite of the differences in the sophistication of these three modeling approaches, the results are in relatively good agreement, particularly in the early stages of the fire. Simpler models can be used as a first step towards less approximate modeling or to confirm the order of magnitude of the results from more complex models. The results of this study can be used to reach conclusions about the complexity of the model required to describe a particular fire scenario.

KEY WORDS: fire modeling, analytical model, CFAST, FDS, accidental fires, fire investigation.

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INTRODUCTION

THE RESULTS FROM fire models as applied to the analysis of real accidental fires are rarely available for public scrutiny. This fact is unfortunate because much of the work conducted, particularly in product liability litigations, could be used as guides and templates for model verification or for model development. Moreover, review and critique of the objective for the modeling and the tenor of the assumptions made can indicate the validity of the application. The forensic evidence, as an indication of the fire environment, provides a realistic verification of the model results. If the evidence is abundant, the constraints on the assumptions are larger and the success simulating the true environment is potentially improved.

There are three main approaches to model compartment fires [1]. The simplest is to use basic expressions of physicochemical processes occurring in the fire to produce an analytical model of the fire development. Examples of this type of approach are the analyses of Lawson and Quintiere [2] and Alvares and Fernandez-Pello [3]. Analytical fire models can be set up quickly and are easy to use because of the limited mechanisms involved; however, results may only be correct within an order of magnitude. Nevertheless, these models can serve as a baseline for more sophisticated computer modeling. A more complex approach is the use of zone models [4], which consider the compartment as being composed of two gaseous layers, both interacting through the governing equations. Zone models are in general computer-based, such as FIRST [5] and CFAST [6]. They take more time to set up and to be solved, but on a modern desktop PC, the computational time is of the order of seconds. The main advantage of zone models is that this small computational time allows for extensive parametric studies. Since they take into account more physical mechanisms and make fewer simplifications, zone models have a strong potential to give better results than analytical models. However, fewer simplifications imply the need to know a larger number of fundamental parameters, to be extracted in general from experiments or forensic evidence, which is often associated with significant uncertainties and requires validation. The most complete approach is the use of field models [4], which solve numerically the 3D governing equations for a fire-driven flow in their differential form with varied levels of complexity. Examples of field models are JASMINE [7], SOFIE [8], and FDS [9]. They require a more significant setup effort and longer computational time, of the order of hours or days on a modern desktop PC. These models consider in more detail the most important fire mechanisms with the immediate advantage that the range of applicability widens, although this also implies an increase in the number of fundamental parameters required and therefore further calibration and validation is needed. With the ever-increasing computer power available, it is expected that field models will become more and more important in fire modeling and will eventually replace zone models.

Every model, as an approximate representation of an actual phenomenon, has limitations that constrain its use and narrow its range of applicability. Generally speaking, a more complete model implies more freedom and fewer limitations. However, it must be considered whether the model has been validated for the particular circumstances of interest.

Some examples of the application of fire models in the reconstruction of accidental fires using forensic evidence are: the MGM fire investigation and modeling of Emmons [10], the King's Cross fire simulations of Cox et al. [11], the examination of the nightclub fire in Göteborg by Yan and Holmstedt [12], and the fire and subsequent structural collapse of the World Trade Center Towers by McGrattan and Bouldin [13]. Also, some attempts at comparing directly the results from different models are available in the literature [12,14–16].

The objective of this study is to provide further direct comparison of fire models as applied to real accidental fires. Given a fire scenario to investigate, the decision of which model to use depends primarily on the available fire input-parameters, and the level of detail and accuracy that is desired in the analysis. For this purpose, it is helpful to have information about the predictive capabilities of the different models, what kind of input information is needed, and its impact on output results. Frequently, modelers are required to choose the input data from sources of experimental information that apparently contradict each other, or the modeler needs some properties that are not well determined. The effect of this datum inadequacy on the prediction capabilities of the fire model needs to be further explored.

To imitate the development process followed by a fire modeler who interacts with only one model at a time, the input to each model has been kept as independent from the others as possible. It is reasonable to affirm that the fire model chosen imposes conditions on the input data required (e.g., a field model could simulate the heat release curve by itself whereas an analytical model needs this entire information as input). Thus it is expected that different assumptions are made and different sources of information are consulted regarding the input data depending on the model being used, i.e., each model's input uses different sources of information while being kept consistent with the forensic evidence. Such real applications of fire modeling have practical implications that have been reproduced here.

This work is an extension of an earlier study [17] and presents the assumptions made and results obtained by applying all three fire-modeling approaches to predict three accidental fires that occurred in single-family dwellings. The predictions from these models of the characteristic fire parameters, such as heat release rate, ceiling layer depth, temperature, and smoke concentration at a particular point in the room, are studied in the context of the forensic evidence for each case to determine their predictive capabilities. The results of comparing fire models to the evidence left in accidental fires can be used to reach conclusions as to when models of increased complexity are needed to describe a particular scenario. The study also helps to elucidate, *a priori*, which models are suited for a given fire scenario, without the need to go directly to the most sophisticated one, when the effort might not be fully justified.

THREE-LEVEL MODELING ANALYSIS OF FIRES

This section presents a brief description of the three models used to simulate accidental fires.

Analytical Model

This model follows a similar methodology to that developed in [3], and is based on the application of overall mass and species conservation equations, together with a simple treatment of fire-plume air entrainment. Although improvements to this model are relatively easy to implement, it has been kept purposely simplified to give results quickly and to the correct order of magnitude.

Products of combustion together with the air entrained by the fire plume are considered to accumulate in the hot layer, which fills the ceiling volume and has uniform properties. Fire growth is either specified as a t^2 heat release rate with given strength or through a flame spread rate (which generally also produces a t^2 fire) and it is specially suited to describe early stages of a fire. The analysis provides the growth of the ceiling layer and variation of smoke and CO concentration in the layer with time.

First, the growth of the fire is described as:

$$\dot{Q}_{\mathrm{hrr}} = At^2 \tag{1}$$

where A is the fire-growth strength [18]. The mass of fuel that is consumed is then determined by

$$\dot{m}_{\mathrm{f}} = \frac{\dot{Q}_{\mathrm{hrr}}}{\Delta H_{\mathrm{c}}} \tag{2}$$

where ΔH_c is the effective heat of combustion per mass of fuel, and it is assumed that all the fuel is burned with air. The mass of gases being transported to the hot layer are obtained through:

$$\dot{m}_{\mathrm{hl}} = \dot{m}_{\mathrm{f}} + \beta(1+S)\dot{m}_{\mathrm{f}} \tag{3}$$

where S is the stoichiometry air to fuel mass ratio and β is a plume entrainment constant parameter [19]. This equation assumes that flames do not extend into the hot layer. The volume of the hot layer is then calculated by:

$$V_{\mathrm{hl}} = \frac{\int_0^t \dot{m}_{\mathrm{hl}}\,\mathrm{d}\tau}{\rho_{\mathrm{g}}} \tag{4}$$

where ρ_{g} is the density of the gases in the hot layer at the estimated temperature using the simplified energy conservation equation:

$$T_{\mathrm{hl}} = \frac{\dot{Q}_{\mathrm{hrr}}}{\dot{m}_{\mathrm{hl}} c_{\mathrm{p}}} + T_0 \tag{5}$$

The soot and carbon monoxide concentrations at the ceiling layer are calculated by:

$$c_{\mathrm{s}} = \frac{y_{\mathrm{s}} \int_0^t \dot{m}_{\mathrm{f}}\,\mathrm{d}\tau}{V_{\mathrm{hl}}} \quad \text{and} \quad c_{\mathrm{CO}} = \frac{y_{\mathrm{CO}} \int_0^t \dot{m}_{\mathrm{f}}\,\mathrm{d}\tau}{V_{\mathrm{hl}}} \tag{6}$$

where y_{s} and y_{CO} are the yields of soot and carbon monoxide, respectively [20]. For the three models in this study, a smoke detector is considered to activate when the smoke concentration at its location in the room is larger than the threshold value of 0.018 g/m^3. This threshold value is taken from Mulholland [21], converted from the optical density set as the minimum detector sensitivity for gray smoke. Not considered here is the fact that smoke detectors have a time delay with respect to the instant when this threshold value has been achieved outside the detector's housing, as a result of smoke transport between the outside environment and the inside of the device. This time lag could be of considerable magnitude and primarily depends on the gas-velocity profile near the housing [22].

Before the ceiling layer reaches the floor, the oxygen volume fraction at the ceiling layer is given by:

$$c_{\mathrm{O}_2} = \frac{\overline{\mathrm{MW}}}{32} \frac{\int_0^t 0.23[\beta(1+S) - S]\dot{m}_{\mathrm{f}}\,\mathrm{d}\tau}{\int_0^t \dot{m}_{\mathrm{hl}}\,\mathrm{d}\tau} \tag{7}$$

where $\overline{\mathrm{MW}}$ is the molecular weight of the mixture in the ceiling layer. When there are no vents to the exterior and after the ceiling layer reaches the floor, the oxygen volume fraction is given by:

$$c_{\mathrm{O}_2} = \frac{\overline{\mathrm{MW}}}{32} \frac{0.23 m_{t,0} - \int_0^t 0.23 S \dot{m}_{\mathrm{f}} \, \mathrm{d}\tau}{\int_0^t \dot{m}_{\mathrm{f}} \, \mathrm{d}\tau + m_{t,0}} \tag{8}$$

where $m_{t,0}$ is the total mass of air in the enclosure before the fire started.

Equations (4)–(6) are used to determine the time at which the ceiling layer reaches a detector location and the time at which a smoke or a carbon monoxide detector would activate. Equations (7) and (8) are used to determine when the fire becomes vitiated or oxygen depleted.

The limitations of the model are several, the most important being that radiation is not considered; neither extinction nor flashover can be modeled; the enclosure has to be reduced to one global compartment without significant vents to the exterior and of uniform (or nearly uniform) cross section; the plume entrainment mechanism is elementary.

The major advantage of this model is that it requires only simple hand calculations and consequently has great flexibility and simple implementation. The disadvantage is that the analysis cannot provide accurate and local description of the fire characteristics.

Consolidated Fire and Smoke Transport (CFAST)

This is a zone model developed at the National Institute of Standards and Technology (NIST) [6]. It can easily be downloaded from the Internet. CFAST considers two (or more) distinct horizontal layers filling the compartment, each of which is assumed to be spatially uniform in temperature, pressure, and species, concentration, as determined by simplified transient conservation equations for mass, species, and energy. The hot products of combustion occupy the upper layer, while the cooler gas, mostly ambient air, occupies the lower layer. A fire in the enclosure is treated as a pump of mass and energy from the lower layer to the upper layer. As energy and mass are pumped into the upper layer, the layer volume increases, causing the interface between the layers to move toward the floor. Mass transfer between compartments can also occur by means of vents, such as doorways and windows. Heat transfer in the model occurs due to conduction to the various surfaces in the room. In addition, heat transfer occurs by radiative exchange between the upper and lower layers and between the layers and the surfaces of the room.

The most important limitations of the model are: radiation is elementary and cannot model properly fires in small enclosures; with no significant horizontal layer growth, the enclosure has to be of nearly uniform cross section; the plume entrainment mechanism is more elaborate, but still applies only to enclosures without complex geometry.

CFAST provides reasonable predictions for enclosure fires, as reported in Peacock et al. [6]. The major advantage of this method is that the implementation of the software is relatively simple, and the results are easily understandable. The primary inputs for a CFAST model are the geometry of the compartments, including all vents and windows, and the primary fire, in terms of heat release rate, fire area, and the yields of products. The user also has the option to add additional burning objects, which can be described in the same way as the primary fire or defined by CFAST from a database of objects.

Fire Dynamic Simulator (FDS)

This is a field model also developed by NIST [9], also available through the Internet. It has a companion package for post-processing and visualization, Smokeview [23], which is user friendly. This software numerically solves the transient conservation equations of mass, momentum, energy, and species for low-speed motion of a gas. It divides the three-dimensional space into small rectangular volumes. Within each volume, the gas variables are assumed to be uniform, but changing with time. For momentum conservation, FDS solves the Navier–Stokes equations using large eddy simulation (LES) to account for subgrid turbulence, and for the combustion reactions, it uses the mixture fraction model. Heat transfer to solid surfaces and convection within the fluid are taken into account. In addition, the radiative transport equation for an absorbing/emitting and scattering medium is also solved. The major advantage of this method is that it gives spatial variation and temporal evolution of the fire parameters, and visual information about the complex fire development. The disadvantage is the need for significant computing capabilities and a familiarization with the application of the software.

The most important limitations of the model are: validation of the transport equations is needed for special scenarios (currently set for smoke movement inside enclosures); the use of mixture fraction implies a potential excess of pyrolyzed gases to be burned; finer grid size does not always imply convergence.

The user has to describe the three-dimensional geometry of the scenario in detail, including the size and location of all objects, as well as boundary and initial conditions. All solid surfaces need to have assigned thermal properties, and for burning surfaces, also combustion characteristics. The mixture fraction model needs to have assigned a particular gas reaction. One important step while setting up the model is the size of the volumes composing the grid. The accuracy of field models could be potentially increased using smaller volumes, which increases the computer time as well. Usually, the smallest volume attainable is limited by the available computer time. It is worth noting that because of the sophistication of field models, simulations cannot be run blindly and their application requires the supervision of qualified individuals [24].

CASE 1: FIRE IN A RESIDENTIAL STORAGE ROOM

This case reconstructs a fire in a room used for storage of clothing and documents. The objective is to determine a reasonable ignition source.

The storage room was in the first floor of a two-story residence. The room was 3.66 m wide, 4.88 m long, and 2.43 m high (see Figure 1) and was used as a storeroom for clothing, documents, and electronic equipment. Most of the clothing was stored on movable racks, but wardrobe accessories were contained in stacked cardboard boxes. The room also contained a big printer, networked to various computers throughout the dwelling. The room was packed with these items plus some boxes containing documents distributed throughout. There was one big window to the west covered by Venetian blinds, two small uncovered windows to the north and a sealed fireplace. There were three doors, one to a small restroom, and two connecting to the rest of the first floor; the entry door, and another blocked by clothing racks. It is not clear whether the entry door was open or closed during the initial period of the fire.

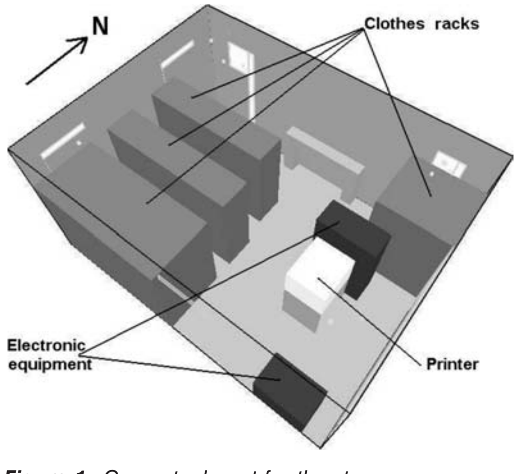

Figure 1. *Geometry layout for the storage room case.*

No one was in the house when the fire was initiated. The residents had been away for only a couple of hours when upon their return, they found the house fully ablaze and the fire department engaged in active suppression operations. Neighbors were alerted to the fire when they heard windows breaking and subsequently called the fire fighters, who observed the storage room fully ablaze.

The printer was the main operational appliance in the storage room. Fire investigators pointed to it as the ignition source because of the higher charring of the ceiling wood close to the printer location. Charring depth is only a general indicator of time exposure of heat flux and can be a misleading indicator of the origin [25]. Detailed inspection of the printer showed that the internal electrical insulation, power supplies, circuit boards, and loaded paper trays were not burned and that the effective fire damage to the unit was at the external surfaces. Moreover, inspection of the structural remains of the storage room revealed questionable electrical wiring and lighting practices, and the remains of other electrical devices. In addition, one of the occupants was a smoker.

There are many factors accounting for the fire damage including effect of different ignition sources, and ventilation patterns due to window breakage and the open or closed status of the entry door. To sort out these factors and to determine the viability of the printer as the ignition source, fire modeling of the compartment fire was conducted. The objective was to determine whether a fire initiating in the printer could have caused the observed fire damage, or if the fire was more likely caused by another source at a different location. For this objective, two different ignition sources were investigated: the printer and a standard wastebasket.

Model Results

The flammability characteristics of the polymeric covers of the printer were tested in a Cone Calorimeter, ASTM E1354 [26]. The heat release rate of a representative piece was measured by oxygen consumption calorimetry with an imposed heat flux of 25, 35, and 50 kW/m^2. The resulting curve for 35 kW/m^2 was selected as the intermediate case and then approximated with the polygonal curve shown in Figure 2 (expressed as power released per unit area) to model the burning behavior. The printer covers are made of a polymer material with similar thermal and fire properties to polystyrene. Thus the required properties of the covers are approximated by those of polystyrene. The other ignition source studied was a burning standard wastebasket, like those commonly encountered in residential dwellings or offices. Here, the wastebasket represents any of the multiple boxes arranged all around the room, which ignites by an unspecified cause

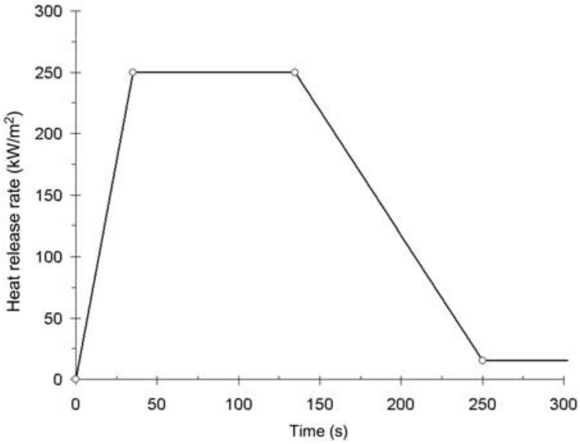

Figure 2. *Time curve for the heat release rate per unit area (approximated) of the printer's cover material (storage room case).*

(cigarette, electric or lighting failure, etc.). The composition of the wastebasket fuel is half plastic and half paper and its burning is modeled with a constant heat release rate of 40 kW for 200 s [27,28].

The outline of modeling assumptions for this case is as follows:

- Geometry of the essential elements in the fire development approximated, based on evidence and witness reports.
- Printer fire heat release curve reconstructed from small-scale experiments and modeled as a worst-case scenario where three sides ignite simultaneously. Combustion products are those of polystyrene.
- Wastebasket fire as an unknown fire source of low heat release rate at varied locations around the compartment.
- Clothing fabric in racks modeled as acrylic for thermal behavior. Once the cloth racks ignite, in CFAST, the fire is modeled as fast growing.
- For CFAST and FDS, windowpanes break as predicted by BREAK software [32] using the transient fire conditions simulated by the corresponding model as input.
- Smoke detector activated based on optical density and immersion in the hot layer.

Analytical Model

Two ignition scenarios were considered; the printer fire and a wastebasket fire, both with closed doors and no leaks. For the printer, three sides of the cover are ignited simultaneously assuming they burn uniformly over their entire area (total of $1.2\,m^2$), which gives a heat release rate curve analogous in time to Figure 2, but with a peak plateau of 305 kW. This fire significantly overestimates the power of a burning printer but it is modeled to study a worst-case scenario. The thermochemical properties used for the printer cover material are those of polystyrene [29].

To address whether the initial fire is able to ignite a second object, the total heat flux from a fire source to a target is calculated. The following relation adequately represents the peak heat flux to a vertical surface measured for several flames [30]:

$$\dot{q}''_{\max} = 200\left(1 - e^{-0.09\dot{Q}_{\mathrm{hrr}}^{0.333}}\right) \tag{9}$$

The heat flux from flames to a target at approximately the same height decreases with horizontal distance [30], as:

$$\dot{q}'' = 0.38\dot{q}''_{\max}\left(\frac{x}{0.5D}\right)^{-1.7} \tag{10}$$

where D is the diameter of the fire source and x the horizontal distance from the source. Equation (10) is only valid for $x > 0.5D$; if the object is closer, the maximum heat flux given by Equation (9) applies.

The heat transfer equation for a solid surface is integrated over time with the heat flux to provide the surface temperature history of the target. In this particular fire scenario, the clothes hanging in the racks are the targets and ignition is considered by integrating the heat equation for a thin solid composed of acrylic cloth:

$$\frac{dT_s}{dt} = \frac{\dot{q}'' - \sigma\varepsilon\left(T_s^4 - T_0^4\right) - h(T_s - T_0)}{\rho c \ell} \tag{11}$$

where T_s is the object temperature, T_0 the ambient temperature, σ the Stefan–Boltzmann constant, ε the emissivity of the surface, h the convection heat transfer coefficient, ρ the density, c the heat capacity, and ℓ the thickness of the solid.

For the printer fire, the aforementioned analysis gives time for the hot layer to reach the smoke detector location of 10 s, and at this time, the smoke concentration is $0.13\,g/m^3$, which will trigger the smoke alarm. The clothing rack closest to the printer is 1.4 m away in the horizontal direction. It faces the entire vertical extent of the flame and hence, the highest heat flux is at the same height as the flame. The highest heat flux from the flames to the clothing is calculated to be $3.6\,kW/m^2$ according to Equations (9) and (10). This is too low to ignite the acrylic fabric, which requires a critical heat flux for ignition above $10\,kW/m^2$ [31]. Integrating Equation (11) for this case, the maximum temperature reached at the surface of the cloth is 145°C, well below the piloted ignition temperature of 300°C for acrylic fabric [31].

If it is assumed that the wastebasket fire is located at the southwest corner, the clothing racks are very close to the flames, less than 0.15 m, and the radiation heat flux from the flames to the fabric is calculated to be 30 kW/m^2, which is able to heat up the acrylic cloth to 300°C and ignite it in 40 s. The smoke detector would have activated at 10 s.

CFAST

The model uses the overall dimensions of the room and includes the clothing racks and printer. The vents considered are the small leakages and the windows that open when glass breakage occurs as computed using BREAK [32] with the calculated fire conditions. The fire evolution is studied for both cases of the main door open or closed, whereas the other two doorways are considered blocked. The walls are modeled with the thermal properties of wood, and the floor and ceiling with those of gypsum board, all provided by the CFAST materials database. The ignition of cloth fabric is determined by integrating Equation (10) with the surface heat flux calculated from CFAST.

In the case of the printer fire, the main fire is specified as a fire having the heat release rate discussed above in the analytical case. The composition of the fuel and the yields of soot and carbon monoxide are taken as those of polystyrene [20,29]. CFAST predicts that the smoke detector would be activated after 4 s. For the nearest clothing rack, at a distance of 1.4 m, the highest radiation heat flux calculated is 7.6 kW/m^2. This is below the 10 kW/m^2 critical heat flux for piloted ignition [31] and therefore the clothing rack cannot be ignited by this fire. BREAK predicts no breakage of windows and the entry door being open or closed does not significantly change the fire conditions.

If it is assumed that the wastebasket fire is located near the southwest clothing rack, CFAST predicts that the smoke detector will be activated at 5 s. The highest heat flux to the nearby clothing racks is 22 kW/m^2, which ignites the clothing at 61 s. The clothing rack fire is modeled as a fast growing fire following tests by Stroup et al. [33]. In the case of the entry door being closed, the northwest window breaks at 168 s, the large east windowpane breaks at 172 s and flashover occurs at 260 s. In the case of the entry door being open, flashover occurs at the same time as with the door closed.

FDS

The full geometry of the room is modeled with a grid of 43,200 uniform-size volumes. Four clothing racks, two pieces of electronic equipment, and

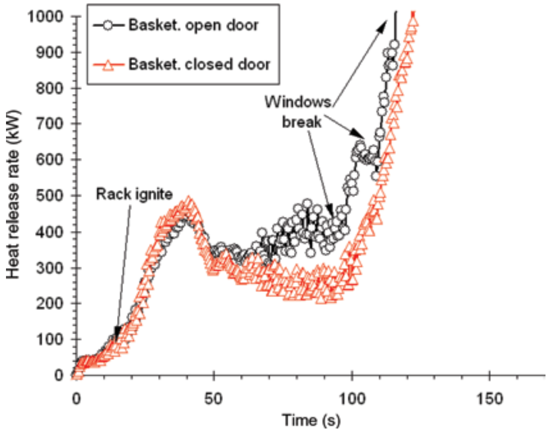

Figure 3. *Heat release rate vs time by FDS when the wastebasket fire is at the southwest corner (storage room case). Results for both entry-door open and closed cases. (The color version of this figure is available on-line.)*

the printer (Figure 1) are included. Air leaks are included as permanent vents around the doors and windows. The combustion reaction is set to be that of polystyrene from the FDS database.[1] The walls of the compartment are modeled as pine, and the electronic equipment as metal. The clothes hanging from the racks are modeled as acrylic upholstery. The time to breakage of the windowpanes was calculated using the computer program BREAK [32], and introduced in the FDS model as if at that time 30% of the pane starts to vent to the exterior.

The first ignition scenario simulates the printer fire, prescribed as explained for the analytic case. FDS predicts that the smoke detector would have activated at 9 s. The results also indicate that the fire does not ignite other objects, and maximum temperatures are 270°C at the ceiling directly above the printer and 170°C at the nearby clothing rack. BREAK predicts that not even the closest large east windowpane breaks, mainly because of the thermal blockage effect of the blinds covering it. The effect of the entry door being open or closed is negligible for this scenario.

The second ignition scenario simulates the wastebasket fire. The heat release rate curve of this simulation is shown in Figure 3. FDS predict that the smoke detector would have activated at 12 s. When the basket is located near the southwest clothing rack, the fire ignites the two adjacent clothing

[1]Material database from Fire Dynamics Simulator, FDS ver. 3, 2002. This database is not a reference item but the values in it represent good approximations to different material properties and are widely applied by FDS users.

racks in 14 s and then spreads rapidly over the clothes. In the case of the entry door being closed, the northwest window breaks at 95 s, the large east and northeast windowpanes break at 110 and 123 s, respectively, and flashover occurs at 140 s. As oxygen starts to be depleted in the room, flames move toward the broken windows. In the case of the entry door being open, the room is fully engulfed in flames at 140 s (flashover conditions). The southeast corner of the ceiling, where the entry door and the printer are, sustains the most severe burning due to the proximity of the bigger vents; either the large broken window or both the broken window and the entry door. This result accounts for the ceiling damage reported by the initial fire investigators. A similar fire behavior is observed when the wastebasket fire is located at the other corners of the room. In the case of the wastebasket near the printer location, neither ignition of any nearby object nor window breakage occurs, as expected since the wastebasket-fire power is significantly lower than the printer fire, which do not cause ignition.

Table 1 summarizes and compares the results from the three models. Municipal and private fire investigators focused on the printer as the originating source of the fire and bolstered their conclusions by contending that the fire damage in the storage room was consistent only with fire starting in the printer area. However, fire modeling of the scenario indicates that given its flammability properties and location, the printer was distant enough to be unable to ignite the clothing racks, whereas any other location was significantly more likely to ignite them. This is indicative that the vicinity of the printer is the area least prone to spread the fire to other objects, and therefore the least probable to have hosted the ignition source. Also, the fire patterns left at the scene as evidence could be explained by the trend of the flames to move towards the larger vents that the broken pane of the east window or the entry door represent.

The house was equipped with a burglar alarm system that had the capability of alerting a central station but it did not have an equivalent fire detection system. Results indicate that had there been a smoke detection system, the fire could have been discovered in less than 12 s.

Table 1. Comparison of results from the three fire models for the storage room case.

Computed times for each ignition scenario	Analytical		CFAST		FDS	
	Printer	Basket	Printer	Basket	Printer	Basket
Activation of smoke detector (s)	10	10	4	5	9	12
Ignition of nearby clothes (s)	No	40	No	61	No	14
Flashover conditions (s)	No	N/A	No	260	No	140

CASE 2: SOFA FIRE IN A SMALL DWELLING

This case involves a small apartment unit. Flames from a sofa produced severe damage in the living room and the hot layer produced thermal damage to plastic materials. The apartment completely filled with smoke and then self-extinguished. The objective of the analysis is to characterize the fire, to show that a smoke detector would have alerted an occupant in sufficient time to evacuate, and to calculate when O_2 depletion occurred.

A sketch of the floor plan of the apartment in which the fire occurred is shown in Figure 4. The unit had two closed windows and one closed door to the outside. The dimensions of the unit were 5.5 m by 9.3 m, and 2.4 m high. The estimated free volume (accounting for furniture, appliances, and cabinets) was $100\,m^3$. A smoke detector was located in the ceiling in a small alcove that served as an entry portal to both the bedroom and the bathroom. A sofa in the main room was the major source of fuel for the fire, and several pillows and blankets were scattered on the sofa and on the floor between the sofa and the television. There were two occupants in the apartment at the time of the fire.

Half of the sofa away from the wall was almost entirely consumed during the fire. In addition, a large proportion of the pillows and blankets on the floor were substantially burned. A partially burnt lighter was found on the floor in front of the sofa. Based on the evidence, the most probable ignition scenario is that a draped blanket was accidentally ignited with a lighter, which rapidly spread to involve the sofa. Charred wood and melted plastic materials in elevated locations throughout the apartment indicate that the upper layer temperatures were substantial during the period of active

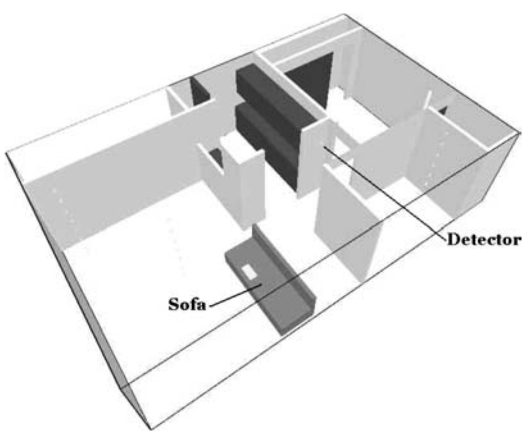

Figure 4. *Geometry layout for the small apartment case.*

burning. The door and all the windows were closed and did not break during the fire. The fire was apparently already self-extinguished when it was discovered, as there were no signs of flames.

Tests of fire spread rate of exemplar blanket materials were carried out to provide the initial heat release rate for the fire models. These tests show that the heat release rate is similar to a fast fire with a peak of 230 kW after 70 s, and then dies out when fuel is consumed.

The outline of modeling assumptions for this case is a follows:

- Geometry of the essential elements approximated for fire development, based on evidence and witness reports. No leaks to the exterior.
- The ignition source is an acrylic blanket with combustion properties approximated by those of PMMA since both materials have similar fire and smoke properties.
- The sofa heat release curve is modeled as a fast fire in analytical calculations and as a medium fire in CFAST.
- Smoke detector activated based on optical density and immersion in the hot layer.
- In the analytical model, the fire self-extinguishes when oxygen levels reach the threshold value.

Model Results

Analytical Model

Calculations for the time of smoke detector activation make use of the initial blanket fire, as it is calculated that the detector will be triggered while this fire dominates. The heat release rate of the fire is fast according to our experiments. The thermochemical properties used are those of the blanket, similar to acrylic [20,29]. The time for the hot layer to reach the smoke detector location is 35 s, and at this time the smoke concentration is 0.13 g/m^3, which would trigger the detector since it is larger than the threshold value of 0.018 g/m^3 [21]. The sofa, according to heat release rates measured by oxygen consumption calorimetry [34], burns as a fast fire with an incubation time of 60 s. The combination of a blanket and a sofa fire can be effectively modeled as a single fast fire without an incubation time.

The time for oxygen depletion is calculated assuming that the fire will extinguish when the sofa is fully immersed in a vitiated atmosphere. According to the experiments by Alger and Wirsma [35], the oxygen volume fraction at extinguishment for a polyurethane fire is in the range from 14 to 18%. Using Equation (4) the computed time for the hot layer to engulf the sofa is 101 s. By this time, the oxygen concentration of the hot layer is calculated using Equation (6) to be 19%. When the hot layer has filled the room, the oxygen concentration starts to decrease below 19%, and using Equation (7) it is calculated that at 142 s oxygen concentration is 18%, and at 191 s it is 14%. Therefore, the fire will extinguish between these two times.

CFAST

In the CFAST simulations, the apartment is modeled as a single compartment. The volume of the enclosure in the simulations is set to be the measured effective volume. No vents are included, since according to forensic evidence, the door and windows were closed and the glass did not break. The fire is prescribed as composed of two sources: the blanket fire located at the vertical elevation of the sofa, and the sofa fire itself. The blanket fire is described using the experimentally derived heat release rate expressed above, and the product yields for acrylic. The prescribed ignition of the sofa is treated separately, igniting at 60 s. The sofa fire is modeled using the CFAST-default sofa fire, which has a heat release rate approximately equal to that described by a medium growing t^2-law. Product yields for the sofa are those of polyurethane foam, which is the primary cushioning material in the sofa.

The heat release rate of the fire in Figure 5 shows that the blanket heat release rate peaks at 70 s and then drops. At this time, the sofa has been burning for 10 s, and the heat release is not significant. The sofa fire heat release rate increases approximately as a medium fire, and peaks at 277 s. At 284 s, the heat release rate drops precipitously, indicating oxygen depletion in the room. This is confirmed by examining the upper layer temperature

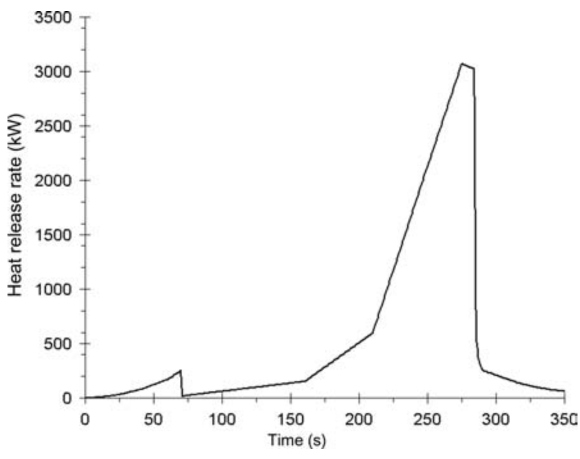

Figure 5. *Heat release rate vs time by CFAST for the small apartment case.*

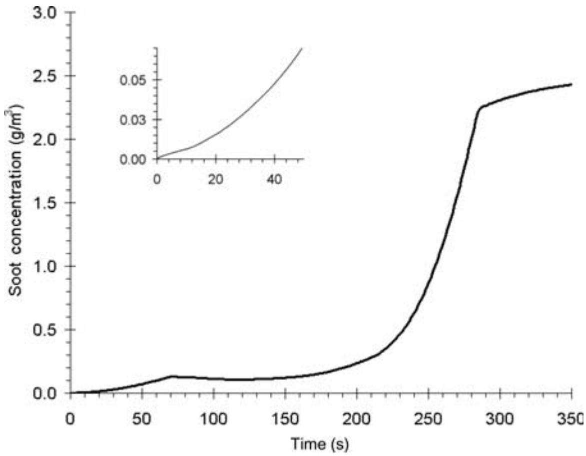

Figure 6. *Soot concentration at smoke detector location vs time by CFAST (the small apartment case).*

history, which shows that a sharp drop in the upper layer temperature occurs at 285 s. The addition of small leaks (vents to the exterior) in the simulations shows that they had little effect on the results. The soot concentration at the smoke detector can be seen as a function of time in Figure 6. Using the value above 0.018 g/m^3 for detector activation, CFAST predicts that the detector would be triggered at 23 s.

FDS

For the field model, the full geometry of the apartment is used with the detailed size and location of each of the relevant objects for the fire (Figure 4). The grid is composed of 17,300 uniform-size volumes. No vents are included. The combustion reaction is set to be that of polyurethane, based on the dominant fire being the sofa. The walls of the apartment are modeled with the thermal and combustion properties of gypsum board, and the sofa as upholstery foam from the FDS database. With the information from fire-spread experiments using the blanket, the single ignition source prescribed is a fast fire with a heat release rate of 230 kW after 70 s.

Fire dynamic simulations predict that the blanket fire ignites the sofa after 24 s. Almost half of the sofa is involved in the fire at 85 s. At 100 s, the hot layer has ignited some wood surfaces in the upper layer of the kitchen and the main room. Then the total heat release rate of the fire reaches a plateau and at 125 s starts to decay due to oxygen depletion (Figure 7). When the heat release rate starts to decay, oxygen concentration 200 mm above the sofa is 16%. At 140 s, oxygen concentration at the same location is 13% and

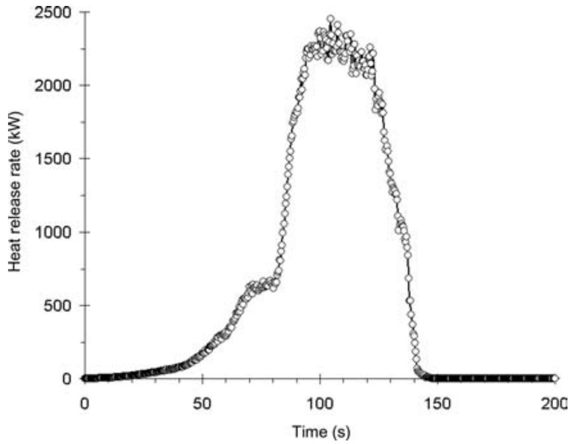

Figure 7. *Heat release rate vs time by FDS for the small apartment case.*

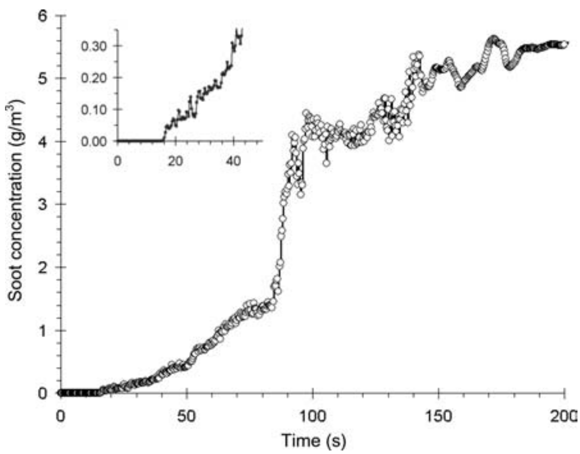

Figure 8. *Soot concentration at smoke detector location vs time by FDS for the small apartment case.*

the fire extinguishes. The soot concentration at the smoke detector can be seen as a function of time in Figure 8. FDS predicts that the smoke detector would activate at 15 s. The inclusion of small leaks had negligible effects on the results.

The results of the three models are summarized in Table 2. The time for smoke detector activation that is predicted by the models ranges from 15 s for FDS, to 33 s for the analytical model. All three models consistently show that the volume of the unit is small enough so that the fire

Table 2. Comparison of results from the three fire models for the small apartment case.

Computed times for	Analytical	CFAST	FDS
Activation of detector (s)	33	23	15
Peak heat release rate (s)	101	277	100
Oxygen starvation of fire (s)	142–191	285	140

self-extinguishes due to oxygen depletion in less than 5 min. FDS results show that fire spread was faster than that in the other two models. FDS modeling for this particular case predicts that when the sofa starts to burn, its heat release rate resembles ultra-fast fire growth rather than a fast fire, as determined by experiments at NIST [34], or a medium fire as is the CFAST default for a sofa fire. Both of these release rates for a burning sofa, NIST fast fire, and CFAST medium fire, are derived from oxygen consumption calorimetry conducted in a well-ventilated room that did not include the growth of the hot layer, whereas FDS simulations take into account the influence of the hot layer. Enclosure fires become more affected by heat transferred from the hot layer and the presence of the boundaries as the fire grows. Given the small size of the enclosure for the unit involved in this fire case, it is expected that a demarcation will be seen between FDS and the other two models. According to modeling results, a properly functioning smoke detector would have given the occupants an escape time of between 125 and 260 s.

CASE 3: FIRE CAUSED BY A RESIDENTIAL GAS HEATER

This case involves a fire initiated by a gas heater located in the living room of a house. The objective is to determine whether smoke produced by the resulting fire would have triggered a hallway smoke detector and to calculate the available time for the occupants to escape.

The one-story house had a living room, a kitchen, three bedrooms, and one bathroom. The fire was initiated in the living room, of rough dimensions 6.7 m by 10.5 m and 2.4 m high. There were two windows, one door to the outside, and a door connecting to the rest of the house. The forensic information available identifies the origin of the fire to be a gas heater located in the living room, caused by an apparent failure of the gas-line pressure regulator. This malfunction delivered more gas to the burner of the heater and forced it to operate at a higher rating than normal, causing flames outside the burner enclosure. Estimations of the resulting gas flow gave an average fire size of 60 kW. The flames ejected from the heater

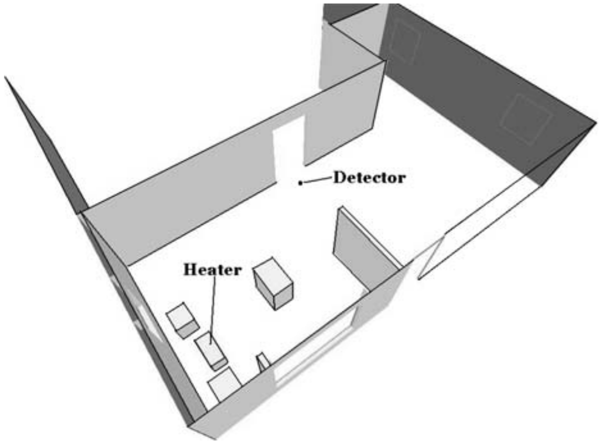

Figure 9. *Geometry layout for the gas heater case.*

ignited adjacent combustible surfaces (corner table, walls, television), and enhanced the subsequent spread of flames. Since the critical conditions for this case occurred during the initial stage of the fire, the analysis considers only the living room (Figure 9) with only one vent, the door, connecting to the rest of the house. The main door to the outside was closed according to a witness and the windows did not break until the fire spread was severe. There were several occupants in the house at the time of the fire.

The outline of modeling assumptions for this case is as follows:

- Geometry of the essential elements approximated for fire development, based on evidence and witness reports. No leaks to the exterior.
- Gas heater fire is the ignition source. It is modeled as a methane diffusion flame with a heat release rate calculated from the analysis of the malfunction.
- For hand calculations and CFAST, flame spread over the wood paneling is a medium-growing fire.
- Smoke detector activated based on optical density and immersion in the hot layer.
- Untenable fire conditions occur when the ceiling layer reaches 0.9 m from the floor.

Model Results

Analytical Model

These calculations treat separately the gas fire from the heater and the spread of flames over the walls adjacent to the heater. The calculations for the time of smoke detector activation only consider the methane fire (constant 60 kW). The time for the hot layer to reach the smoke detector location is 34 s, and at this time the smoke concentration is 0.033 g/m^3, which will trigger the smoke detector. When the fire from the gas heater ignites the wood of the walls adjacent to it (30 s according to FDS results), flames then propagate upward along the wood wall and the furniture. The heat from the gas fire assists the flame spread and it can be modeled as spreading in a wedge from a point near the heater location. Flame spread rate over wood is 10 mm/s and the mass burning rate is 6 g/m^2 s [36], which gives a medium fire for the heat release rate. Untenable fire conditions are assumed to occur when the ceiling layer reaches 0.9 m from the floor (the crawling space). Using Equations (2)–(4), it is calculated that the time for the hot layer to reach the height of 0.9 m from the floor is 162 s.

CFAST

The model considers the house to have several compartments representing each of the rooms in the house. The fire is initiated in the living room. A number of doors connect the rooms to each other. The fire is modeled in two stages: the first is the gas heater fire with a continuous heat release rate of 60 kW and combustion properties and product yields of a methane diffusion flame; the second is the burning of the wood paneling on the walls. The wood paneling is treated as a medium fire, with combustion properties of pinewood. The impinging flames ignite the wood paneling at 30 s, which is in agreement with FDS simulations. The soot concentration is tracked at the smoke detector location, giving a time for detector activation of 13 s, as shown in Figure 10. Hot layer growth indicates that the predicted time to reach a height of 0.9 m from the floor is 267 s.

FDS

The full geometry of the apartment is used, focusing on the living room where the fire originated (Figure 9). The grid is composed of 108,000 uniform-size volumes. No vents to the outside are included but the rest of the house is modeled as a large enclosure connected to the living room through the open door. The chemical proprieties for the fuel are those of methane with a radiative fraction of 0.5 corresponding to a sooty diffusion flame. The walls of the apartment have the properties of pinewood and there are also a TV, a wooden table, and a wooden chair close to the heater, plus a carpet over the floor (all property values from FDS database). The gas heater fire is modeled as a prescribed fire of 60 kW constant heat release rate.

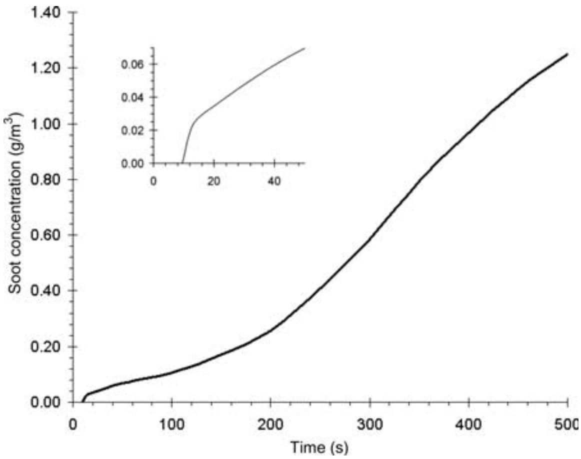

Figure 10. *Soot concentration at smoke detector location by CFAST for the gas heater case.*

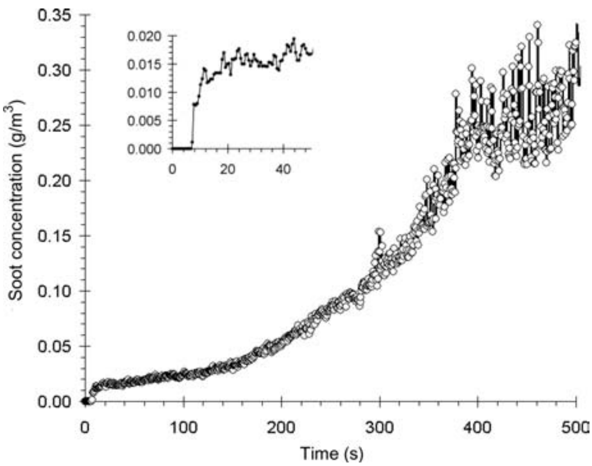

Figure 11. *Soot concentration at smoke detector location by FDS for the gas heater case.*

Fire dynamic simulator predicts that at 13 s, the hot layer reaches the smoke detector, but the smoke concentration is not high enough to trigger it until 41 s (Figure 11). The model predicts the evolution of the heat release rate to be initially a medium t^2-law fire, and after 130 s to be similar to a fast fire. FDS calculates the ignition of the combustible wood surface adjacent to the heater at 40 s. The hot layer growth indicates that untenable conditions, when the ceiling layer reaches 0.9 m and the temperature at this height is over 60°C, are reached at 490 s.

Table 3. Comparison of results from the three fire models for the gas heater case.

Computed times for	Analytical	CFAST	FDS
Ceiling layer to reach detector (s)	34	10	8
Smoke to reach detector activation levels (s)	34	13	41
Ceiling layer to reach 0.9 m from the floor (s)	162	267	490

The results of the three models are summarized in Table 3. The time for smoke detector activation that is predicted by the models ranges from 13 s for CFAST to 41 s by FDS. Heat release results by FDS show that the fire grows first as a medium fire and then as a fast fire, predicting a global heat release rate greater than the medium fire assumed for the other two models. Untenable fire conditions occur when the ceiling layer reaches 0.9 m from the floor (crawling space), and the temperature at this height is over 60°C. These conditions would have been reached at between 162 and 490 s at the hallway adjacent to the living room. Thus, according to modeling results, a properly functioning smoke detector would have given the occupants a time of between 128 and 450 s to escape the fire.

CONCLUSIONS

Three fire-modeling approaches with increased levels of complexity have been applied to describe three accidental compartment fires. The input to each model has been kept as independent from the others as possible to imitate the process followed by a fire modeler who has not interacted with the other models. In spite of the differences in the sophistication of these three approaches, it is found that the results are in relatively good agreement, particularly when describing simple aspects of the fire such as ceiling layer growth and smoke concentration in the early stages of the fire. This is understandable since the three methods are based on the solution of the governing conservation equations, although in an increasingly less approximate fashion. Moreover, the cases modeled were of simple geometry and consequently effects of material properties would not dominate in brief periods. However, there is disagreement between the predictions of the models in later stages of the fire. It would be easy for an experienced fire modeler to identify improvements for the models shown here, but it is the intention of the authors to present exemplar applications of fire modeling applied to real cases rather than exhaustive simulations with all the details.

The fact that the input data have been chosen differently for each model has implications worth noting in the discrepancy of the results. It is generally accepted that the three fire models chosen here give congruent results regarding the simulation of the transport processes alone, but that they diverge more when modeling the combustion source (namely, the heat release rate). The field model FDS used in these cases simulates the heat release rate from approximated fundamental laws and material effective properties, whereas the zone model CFAST and analytical model make use of more simplified sources of information, such as experimental heat release curves or t^2-curves. It is important to include these discrepancies in the input as an inherent element of the practical fire-modeling process, to assess the different results provided by each modeling approach in practical applications.

Particularly useful is the finding that the analytical approach provided reasonable results in the early stages of the fire, for example, the time for the smoke to reach detector activation levels. Alternatively, where fire spread was an important consideration (storage room and gas heater cases), only the FDS model was capable of providing detailed conditions after the initiation stages of the fire. The analytical model, and even CFAST in some aspects, was not able to provide enough details of the fire growth to allow one to reach further conclusions. Simpler models can be used as a first step towards less approximate modeling or to verify the order of magnitude of the zone and field results.

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