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A Comparison of Three Fire Models in the Simulation of Accidental Fires

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ABSTRACT: The assumptions and the results of applying three fire modeling approaches to study three accidental fires that occurred in single-family dwellings, are presented in this work. 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 evidences. The predictions from the models of the fires' characteristics are analyzed in the context of the forensic evidences 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 were in relatively good agreement, particularly in the early stages of the fire. Simpler models can be used as a first step towards less approximate modelling or to confirm the order of magnitude of the results from more complex models. The results of this work 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 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 modelling and the tenor of the assumptions made can indicate the validity of the application. The forensic evidences, as indications of the fire environment, provide a realistic verification of the model results. If the evidences are abundant, the constraints on 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 the 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 are fast to set up and easy to use because of the few mechanisms involved, however, the results are only correct in the order of magnitude. Nevertheless, they can serve as a baseline for more sophisticated computer modelling. Of a more complex approach are the 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 on a modern desktop-PC the computational time is in the order of seconds. Their main advantage is that this small computer-time allows for extensive parametric studies. Since they take into account more physical mechanisms and make fewer simplifications, they 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 evidences, which often are associated with significant uncertainties and require validation. The most complete approach is 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 set-up effort and longer computational time, in 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 its range of applicability widens, although it also implies an increased 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 modelling 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

freedoms and less limitations. However, there has to be a consideration also towards 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 et al. [12]; and the fire and subsequent structural collapse of the World Trade Center Towers of McGrattan et al. [13]. Also, some attempts at comparing directly the results from different models are available in the literature [14-16].

The objective of the paper 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 the output results. Frequently, modellers are required to choose the input data from sources of experimental information that apparently contradict each other, or the modeller needs some properties that are not well determined. The effect of this data inadequacy on the prediction capabilities of the fire model needs to be further explored.

The input to each model has been kept as independent from the others as possible to imitate the building process followed by a fire modeler who has not interacted yet with the other models. 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 whole 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. This form of working in real applications of fire modeling has practical implications and therefore has been transferred into this work. The reader will see that each model's input uses different sources of information while being kept consistent with the forensic evidences.

This work is an extension of an earlier paper [17] and presents the assumptions and results of applying all three fire-modelling 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 evidences 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 paper also helps to roughly 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 in this work.

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 this simple on purpose to give results in the correct order of magnitude and fast.

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 a 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 the variation with time of the smoke and CO concentration in the layer.

First, the growth of the fire is prescribed as:

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

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

$$\dot{m}_f = \frac{\dot{Q}_{hrr}}{\Delta H_c} \tag{2}$$

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:

$$\dot{m}_{hl} = \dot{m}_f + b(1+S)\dot{m}_f \tag{3}$$

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

$$V_{hl} = \frac{\int_0^t \dot{m}_{hl} dt}{\rho_g} \tag{4}$$

where ρ_g is the density of the gases in the hot layer at the estimated temperature using the simplified energy conservation equation:

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

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

$$c_s = \frac{y_s \int_0^t \dot{m}_f dt}{V_{hl}} \quad \text{and} \quad c_{CO} = \frac{y_{CO} \int_0^t \dot{m}_f dt}{V_{hl}} \tag{6}$$

where y_s and y_{CO} are the yields of soot and carbon monoxide respectively [20]. For the three models in this work, 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 pose a time delay 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:

$$c_{O_2} = \frac{\overline{MW}}{32} \frac{\int_0^t 0.23[b(1+S) - S]\dot{m}_f dt}{\int_0^t \dot{m}_{hl} dt} \tag{7}$$

where $\overline{MW}$ 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:

$$c_{O_2} = \frac{\overline{MW}}{32} \frac{0.23 m_{t,0} - \int_0^t 0.23 S \dot{m}_f dt}{\int_0^t \dot{m}_f dt + m_{t,0}} \tag{8}$$

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

Eqs. (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. Eqs. (7-8) are used to determine when the fire becomes vitiated or oxygen depleted.

The limitations of the model are several, being the most important: radiation is not considered; nor extinction or flash over 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 National Institute of Standards and Technology (NIST) [6]. It can be easily downloaded from the web. 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 concentrations, 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, its 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 fire in small enclosures; with no-significant horizontal layer's growth; the enclosure has to be of nearly uniform cross-section; the plume-entrainment mechanism is more elaborated but still it 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 computer code is relatively simple, and the results 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 the 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 code 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 simulations (LES) to account for sub-grid turbulence and for the combustion reactions it uses the mixture fraction model. Heat transfer to the 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 code.

The most important limitations of the model are: validation of the transport equations is needed for special scenarios (currently is set for smoke movement inside enclosures); the mixture fraction implies a potential excess of pyrolyzated gases 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 the boundary and initial conditions. All solid surfaces need to have assigned thermal properties, and for the burning surfaces also combustion characteristics. The mixture fraction model needs to have assigned a particular gas reaction. One important step when 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 the great sophistications of field models, simulations cannot be run blindly and its application requires the supervision of qualified individuals [24].

CASE 1. FIRE IN 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. Its size was 3.66 m width, 4.88 m long and 2.43 m high (see Fig. 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.

Nobody was in the house when the fire initiated. The residents had only been gone for a couple of hours when upon their return, they found the house fully involved in fire and the fire department engaged in active suppression operations. Neighbors were alerted to the fire when they heard windows

breaking and then called the fire department, who subsequently observed the storage room fully involved in fire.

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 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. Also, 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 by 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 is 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 the Cone Calorimeter ASTM 1354 [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 Fig. 2 (expressed as power released per unit area) to model the burning the behavior. The covers are made of a polymer material with similar thermal and fire properties to polystyrene. Thus the required properties of the covers are approximated with those of polystyrene. The other ignition source studied was the fire of a 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 (cigarette, electric or lighting failure, etc.). The composition of the wastebasket fuel is half plastic and half paper, and the fire modeled with a constant heat release rate of 40 kW for 200 s [27, 28].

Outline of modelling assumptions for this case:

- Approximated geometry of the essential elements to the fire development, based on evidences and witness reports.

- Printer-fire heat release curve reconstructed from small-scale experiments and model as a worst-case scenario where three sides ignite simultaneously. Combustion products are those of polystyrene.
- Wastebasket fire as an unknown fire source of small power which location is varied around the compartment.
- Clothing fabric in racks is 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 using as input the transient fire conditions simulated by the corresponding model.
- 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 on their entire area (total of 1.2 m^2), which gives a heat release rate curve analogous in time to Fig. 2 but with a peak plateau of 305 kW. This fire significantly overestimates the power of a burning printer but it is modeled so 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]:

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

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. Eq. (10) is only valid for $x > 0.5D$, if the object is closer, the maximum heat flux given by Eq. (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 hanging clothes in the racks are the targets and ignition is considered by integrating the heat equation of a thin solid of acrylic cloth:

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

where T_s is the object temperature, T_0 the ambient temperature, s the Stefan-Boltzmann constant, e the emissivity of the surface, h the convection heat transfer coefficient, r the density, c the heat capacity and ℓ the thickness of the solid.

For the printer fire, the aforementioned analysis gives a 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 closest clothing rack to the printer is 1.4 m away in the horizontal direction. It faces the whole vertical extent of the flame so 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 Eqs. (9-10). This is too low to ignite the acrylic fabric, which requires a critical heat-flux for ignition above 10 kW/m^2 [31]. Integrating Eq. (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 is 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 the 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. Ignition of cloth fabric is determined by integrating Eq. (10) with the surface heat flux calculated from CFAST.

For 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]. For 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. For 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 43200 uniform-size volumes. Four clothing racks, two pieces of electronic equipment and the printer (Fig. 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*. 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 big 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 Fig. 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 racks in 14 s and then spreads rapidly over the clothes. For the case of the entry door being closed, the northwest window breaks at 95 s, the big east and the northeast windowpanes break at 110 s and 123 s respectively, and flashover occurs at 140 s. As oxygen starts to be depleted in the room, flames move towards the broken windows. For the case of the entry door being open, the room is fully involved 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 big broken window or both the broken window and the entry door. This result accounts for the ceiling damage reported by the initial fire investigators. Similar fire behavior is observed when the wastebasket fire is located at the other corners of the room. For 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 did 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

* 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 materials properties and are widely applied by FDS users.

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 evidences could be explained by the trend of the flames to move towards the bigger 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.

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 for the apartment in which the fire occurred is shown in Fig. 4. The unit had two closed windows and one closed door to the outside. The dimensions of the unit are 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 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 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 burned lighter was found on the floor in front of the sofa. Based on the evidences, 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 substantially high during the period of active 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 done to provide the initial heat release rate for the fire models. These tests show that the heat released is similar to a fast fire with a peak of 230 kW after 70 s, and then dies out when fuel is consumed.

Outline of modelling assumptions for this case:

- Approximated geometry of the essential elements to the fire development, based on evidences and witness reports. No leaks to the exterior.
- The ignition source is an acrylic blanket which combustion properties have been approximated by those of PMMA since both material 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-extinguished when oxygen levels reach the threshold value.

Model Results

Analytical model: calculations for the time for 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]. For the sofa, according to heat release rates measured by oxygen-consumption calorimetry [34], it 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 incubation time.

Time for oxygen depletion is calculated assuming that the fire will extinguish when the sofa is fully immersed in a vitiated atmosphere. According to experiment by Alger et al. [35] the oxygen volume fraction at extinguishment for a polyurethane fire is in the range from 14% to 18 %. Using Eq. (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 can be calculated using Eq. (6) to be of 19 %. When the hot layer has filled the room, the oxygen concentration starts to decrease below 19%, and using Eq. (7) it can be calculated that at 142 s the oxygen volume fraction 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 evidences the door and the 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 fire of the sofa 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 of the sofa.

The heat release rate of the fire in Fig. 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 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 small effects on the results. The soot concentration at the smoke detector can be seen as a function of time in Fig. 6. Using the value above of 0.018 g/m^3 for detector activation, CFAST predicts that it would be triggered at 23 s.

FDS: For the field model, the full geometry of the apartment is used with detailed size and location of each of the relevant objects for the fire (Fig. 4). The grid is composed of 17300 uniform-size volumes. No vents are included. The combustion reaction is set to be that of polyurethane, based on that the dominant fire is 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 of fire-spread experiments of the blanket, the single ignition-source prescribed is a fast fire with a heat release rate of 230 kW after 70 s.

FDS 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 (Fig. 7). When the heat release rate starts to decay, the oxygen concentration 20 cm above the sofa is 16%. At 140 s, the oxygen concentration at the same location is 13% and the fire extinguishes. The soot concentration at the smoke detector can be seen as a function of time in Fig. 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 the Table 2. The time for smoke detector activation predicted by the models range 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 self-extinguishes due to oxygen depletion in less than five minutes. FDS results show that the fire spread was faster 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 in NIST [34], or a medium fire as it is the CFAST default for a sofa fire. Both of these release rates for a

burning sofa, NIST fast-fire and CFAST medium-fire, were derived from oxygen-consumption calorimetry conducted in a well-ventilated room and 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 of the unit involved in this fire case, it is expected to see a demarcation between the FDS and the other two models. Regarding the escape time, according to modeling results, a properly functioning smoke detector would have given occupants between 125 s and 260 s to escape the fire.

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 the 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 the 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 give an average fire-size of 60 kW. The flames ejected from the heater 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 (Fig. 9) with only one vent, the door, connecting to the rest of the house. The main door to the outside was closed according to 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.

Outline of modelling assumptions for this case:

- Approximated geometry of the essential elements to the fire development, based on evidences and witness reports. No leaks to the exterior.
- Gas-heater fire is the ignition source. It is model 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.

- Conditions of fire untenability occur when the ceiling layer reaches 0.9 m from the floor.

Model Results

Analytical model: these calculations treat separately the heater-gas fire and the spread of flames over the walls adjacent to the heater. The calculations for the time of smoke detector to activate 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 modelled 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^2s [36], which gives a medium fire for the heat release rate. Conditions of fire untenability are assumed to occur when the ceiling layer reaches 0.9 m from the floor (the crawling space). Using Eqs. (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 modelled 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 Fig. 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 (Fig. 9). The grid is composed of 108000 uniform-size volumes. No vents to the outside are included but the rest of the house is modelled as a large enclosure connected to the living room thought 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 carpet over the floor (all property values from FDS database). The gas heater fire is modelled as a prescribed fire of 60 kW constant heat-release rate.

FDS 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 (Fig. 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 combustible wood surface adjacent to the heater at 40 s. The hot layer growth indicates that untenable conditions, when ceiling layer reaches 0.9 m and the temperature at this height is over 60 °C, are reached at 490 s.

The results of the three models are summarized in Table 3. The time for smoke detector activation predicted by the models range 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. Fire untenability 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 s and 490 s at the hallway adjacent to the living room. Thus, according to modeling results, a properly functioning smoke detector would have given occupants between 128 s and 450 s to escape the fire.

CONCLUSIONS

THREE FIRE-MODELLING 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 building process followed by a fire modeler who has not interacted yet with the other models. In spite of the differences in the sophistication of these three approaches it is found that the results were 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 modelled were of simple geometry and consequently effects of material properties would not dominate in short times. 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 of 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 the analytical model make use of more simplified sources of information as experimental heat-release curves or t^2-curves. It is important to include these

discrepancies in the input as inherent element of the practical fire-modeling process to properly and globally 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 on 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 modelling or to verify the order of magnitude of the zone and field results.

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Table Captions

Table 1. Comparison of results from the three fire models for the storage-room case.
Table 2. Comparison of results from the three fire models for the small-apartment case.
Table 3. Comparison of results from the three fire models for the gas-heater case.

Figure Captions

Figure 1. Geometry layout for the storage room case.
Figure 2. Time curve for the heat release-rate per unit area (approximated) of the printer's cover material (storage-room case).
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.
Figure 4. Geometry layout for the small apartment case.
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).
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.
Figure 9. Geometry layout for the gas-heater case.
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.

Tables

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

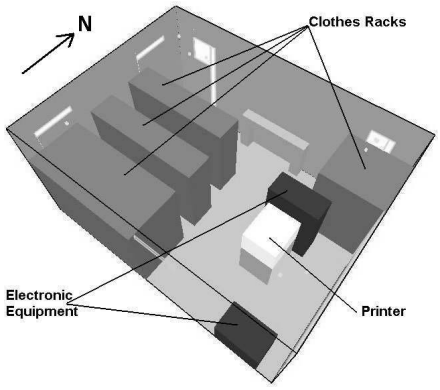
Table 1

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

Table 2.

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

Table 3.



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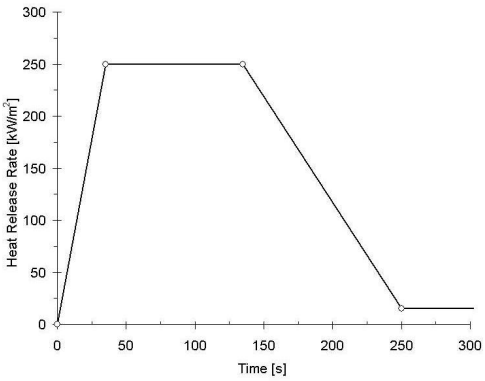

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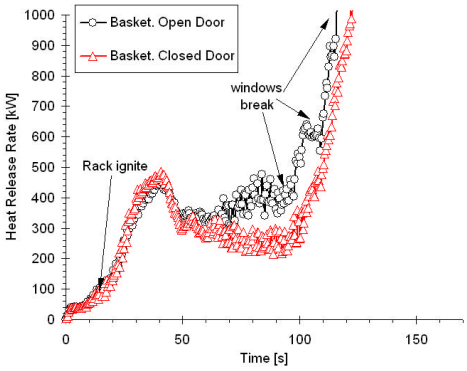

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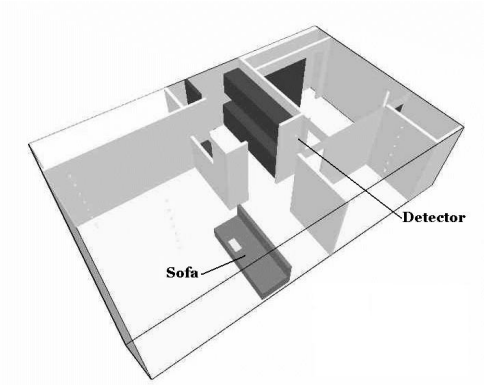

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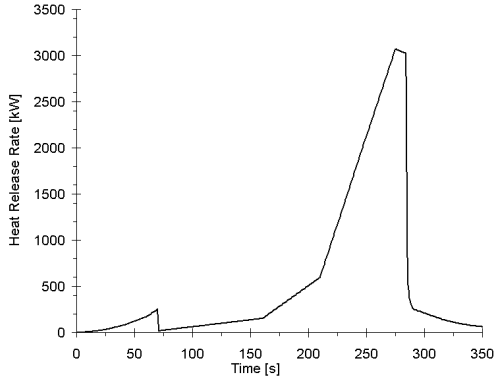

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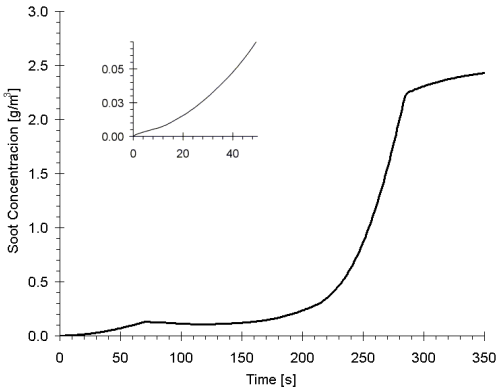

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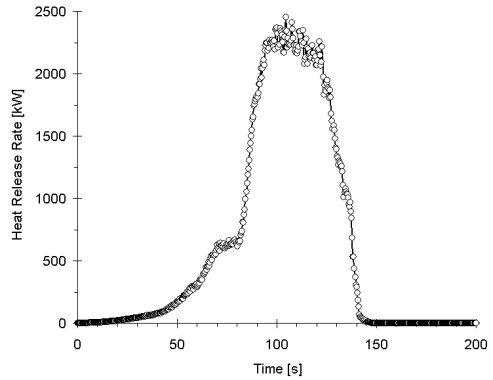

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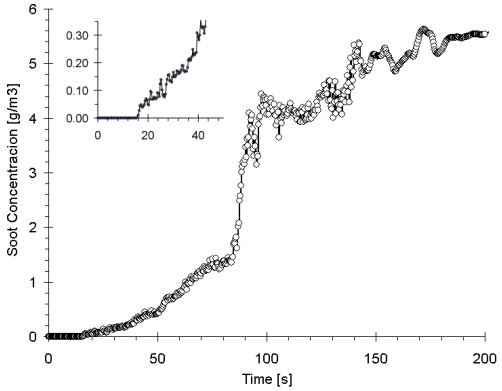

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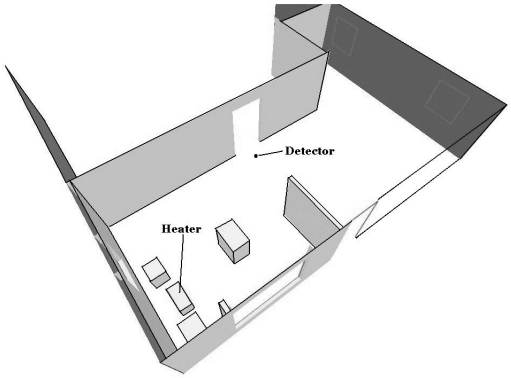

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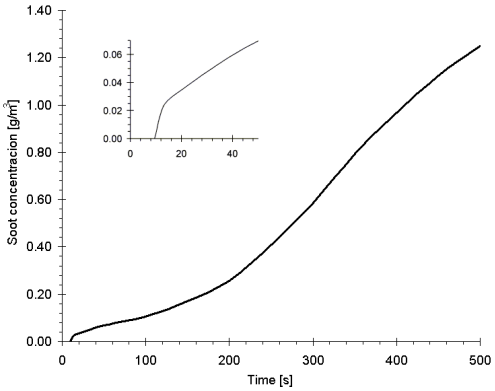

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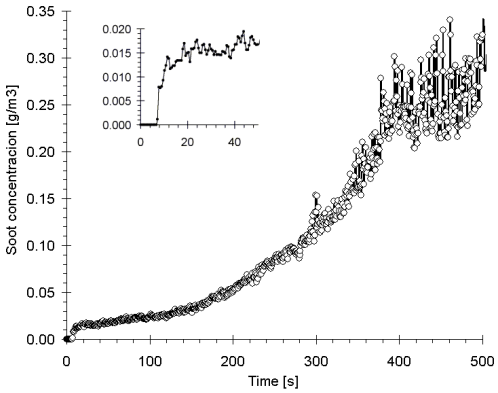

Figure 11.