Editor: Michael J. Potel
http://www.wildcrest.com

Understanding Fire and Smoke Flow Through Modeling and Visualization

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Structural fires cost the US economy more than $100 billion annually in property damage, fire department maintenance, and insurance premiums. A price can't be put on the human toll: each year on average, 4,000 civilians die and 23,000 get injured in fires. Approximately 80 percent of fire deaths occur in homes. Trying to put out these fires costs 80 to 100 firefighters their lives and 80,000 to 90,000 more are injured every year.[1]

Smoke and toxic gas inhalation cause the majority of fire fatalities. Flashover, illustrated in Figure 1, occurs when flames erupt and rapidly fill a compartment. Despite fire codes and improved building designs, flashover and smoke spread are still major problems and require a more complete understanding of fire behavior. Fortunately, we can use fire modeling and visualization tools to overcome these problems, ultimately leading to the prevention of smoke and fire spread.

Modeling fire without getting burned

The National Institute of Standards and Technology (NIST)—known as the National Bureau of Standards, or NBS, until 1988—first became involved with fire issues when a 1904 fire destroyed a large section of Baltimore. A contributing factor to the extensive damage was incompatible fire hydrant connections that prevented neighboring fire companies from obtaining water to fight the fire. NBS worked with the National Fire Protection Association to develop standards to prevent this from happening again. More formal work began at NBS in 1914 when they established a Fire Resistance Section. Annual losses related to fires then exceeded $250 million in the US, many times greater than any European country.[2]

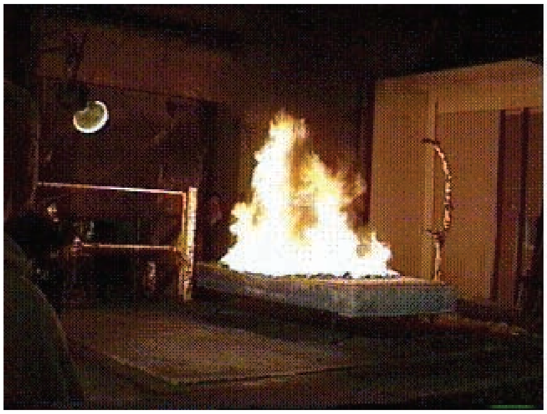
In 1974, the Federal Fire Prevention and Control Act established the Center for Fire Research. Today, the Building and Fire Research Laboratory—established in 1991—conducts fire safety research. An emphasis on modeling exists, resulting in the development of more than 15 fire simulation programs.

Zone fire models

In the 1970s, NIST and others developed zone fire models that describe how fires evolve in compartments. These models divide each compartment into two spatially uniform volumes or zones. The upper layer contains the hot smoke and combustion products from the fire and the lower layer contains air at near ambient temperatures. In this sense, the models support the often heard advice to drop to the floor during a fire. Zone fire models require solving a mass and energy conservation equation for both the upper and lower layers; that is, two control volumes. However, the models neglect the momentum equation within a zone, because they assume that flow within a layer is quiescent. A simple form of the momentum equation, Bernoulli's Law, is used though to compute vent flow between compartments, using pressure differences. Additional equations can describe other physical processes, such as fire plumes and radiative, convective, and conductive heat transfer. Zone fire models predict the interface height between the two layers and layer its gas temper-

1 A post-flashover fire set by the National Institute of Standards and Technology to study hazardous conditions in a college dormitory donated by the University of Arkansas.

Published by the IEEE Computer Society



(a)

(b)

2 Experimental fires set to measure the heat release rate used as input in fire models: (a) single mattress fire, heat release rate 0.5 megawatt, and (b) bunk bed fire (two mattresses), heat release rate: 4.6 megawatts.

atures remarkably well because of the tendency of hot gases to stratify or form layers due to buoyancy.

Interestingly, a zone fire model doesn't include the most critical parameter. The fire itself isn't modeled but inputted in the form of heat-release-rate data. We measure heat-release data by noting the oxygen reduction in the released smoke and fire gases. Figure 2 shows a burning mattress and bunk bed. You might think that a bunk bed (with two mattresses) would burn at twice the rate as a single mattress. The maximum heat release rate of the mattress burn was about 740 kilowatts, while the maximum heat release rate of the bunk bed burn was around 4.4 megawatts much greater than twice the mattress burn. It was concluded that the fire in the lower bunk preheated and dried out the upper bunk causing the upper bunk to burn much faster once it ignited. These two example fires along with plots of heat-release data confirming the experiment's observation are available at the NIST Web site (http://fire.nist.gov/fire). This site helps fire modelers enter proper fire data by showing on the same Web page pictures of example fires along with the corresponding numerical heat-release data. They can then visualize the answer to such questions as, How large is a 1-megawatt fire?

Computer modeling and visualization are important tools for understanding the processes of fire behavior. Fire models range in complexity from simple correlations for predicting quantities such as flame heights or flow velocities to moderately complex zone fire models for predicting time-dependent smoke layer temperatures and heights. Zone fire models' calculations can run on today's computers within minutes because they solve only four differential equations per room. Zone models approximate the entire upper layer with just one temperature. This approximation works remarkably well but breaks down for complicated flows or geometries. For such cases, computational fluid dynamics (CFD) techniques are required.

Fire simulation with CFD

The current state of the art in computer fire modeling is exemplified by NIST's latest contribution to fire modeling, the Fire Dynamics Simulator (FDS). FDS predicts smoke and/or hot air flow movement caused by fire, wind, ventilation systems, and other factors by solving numerically the fundamental equations governing fluid flow, commonly known as the Navier-Stokes equations. The downside is that CFD calculations can easily take days to run since they solve for many variables in each of hundreds of thousands or even millions of grid cells. These calculations generate far more output than the simpler zone models. While simple line plots are adequate for visualizing zone-fire-modeling results, we need more sophisticated techniques for interpreting the massive amounts of data generated by the CFD models. This is where visualization tools such as Smokeview, the companion to FDS, become essential.

FDS uses a form of CFD known as large eddy simulation (LES) to predict the thermal conditions resulting from a compartment fire. LES describes the effect of turbulence on the flow field. Turbulence is a phenomena that causes gases to mix over a wide range of length scales, making it hard to replicate with even the fastest computers. The fire itself is a source term in the governing equations, creating buoyant motion that drives the smoke and hot gases throughout the room. The chemistry of the combustion process is complicated by the fact that fuel for the fire might include room furnishings, ceiling materials, wall, and floor coverings—a wide assortment of different materials. FDS makes simplifications about the combustion, essentially saying that fuel and oxygen burn readily when mixed. Experiments give us the rate at which a fire generates energy. The method doesn't attempt to model the fire's fundamental chemistry, which can involve hundreds of chemical reactions.

FDS aims at solving practical fire problems in fire protection engineering, while simultaneously providing a tool to study fundamental fire dynamics and combustion. Smokeview helps make the results of FDS easily accessible to a broad range of fire safety professionals. Roughly half of the model's applications involve designing building features such as smoke handling and sprinkler systems. The other half consists of residential and industrial fire reconstructions. More recently, we've incorporated improved physics describing thermal radiation and combustion of common materials, allowing for complex scenarios.

Simulation details

Like any CFD model, FDS requires dividing the room or building of interest into small, rectangular control volumes called computational cells. The model then computes the density, velocity, temperature, pressure, and species concentration of the gas in each cell based on the conservation laws of mass, momentum, and energy. FDS also uses material properties of the furnishings, walls, floors, and ceilings to simulate fire spread.

The simulation's spatial resolution depends on the number of cells used to discretize the case, much like a digital photograph's quality depends mainly on the number of pixels. The available computing power ultimately limits the number of cells; current PCs can handle a few million. Users must decide how much detail they want to incorporate and the amount of computing required to produce an acceptable answer. In general, finer grids result in longer calculations, which produce better results. Ultimately, you can reach a point of diminishing returns where the answer becomes insensitive to the increasing resolution of the grid.

Grid resolution and flow speed determines the temporal resolution or time step size. FDS chooses the time step so that flow doesn't cross more than one grid cell during one time step. Run times can range from minutes to weeks depending on the number of grid cells and the duration of the calculation. The townhouse example used in several figures in this article required approximately 35 CPU hours to compute 1,200 simulated seconds for a $48 \times 80 \times 48$ grid on a 2.4-GHz PC. Each grid cell side was approximately 0.1 meter (4 inches). The average step size was 0.027 second, which on average required about 3 seconds of CPU time to compute. Most users try to set up cases that take no longer than a day or two, which is certainly quicker than a full-scale experiment. NIST is currently working toward reducing required run times by using Message Passing Interface libraries to parallelize FDS. Preliminary results are encouraging.

Work continues at NIST and elsewhere to improve the FDS program. Because it's open source, students, researchers, and engineers with a background in fire modeling can refine the various algorithms and test the improvements against experimental data. Because of the relative simplicity of the fire physics model, there is room for refinement in the submodels representing the combustion processes, thermal radiation, water sprays, fire suppression, and so on. Each of these topics could keep any researcher busy for a lifetime. The challenge to model developers assuring that the detail incorporated into each routine remains relatively consistent. There is no reason to refine one routine that might rely on another less accurate routine.

Both FDS and Smokeview would not have been possible without the recent advent of high-speed computers for performing computations, fast video cards for visualizing results, and the Internet for exchanging information and ideas. These programs also wouldn't have been possible without the research needed to develop the underlying fire models and the techniques needed to implement these models accurately and efficiently.

Providing insight not just numbers

The saying that "A picture is worth a thousand words" (or data points) is certainly true for understanding the predictions that computer fire models make. CFD models, fire models in particular, can easily result in more than 1 Gbyte of output data. The Smokeview visualization software program provides a better understanding and insight from these predictions. Smokeview version 1 was released in February 2000, and since then three subsequent versions have been released, the latest in April 2003.

Smokeview is written mostly in C using standard libraries such as OpenGL and its toolkit, GLUT (http://www.opengl.org/developers/documentation/glut.html) for graphics; GD (http://www.boutell.com/gd/), libpng (http://www.libpng.org/pub/png/), and libjpeg (http://www.ijg.org) for generating image files; and libzip (http://www.gzip.org/zlib/) for compression. A portion of Smokeview is written in Fortran 90 to read in the data that FDS generates. The use of portable libraries lets Smokeview run on many platforms including Windows, Unix, and Linux.

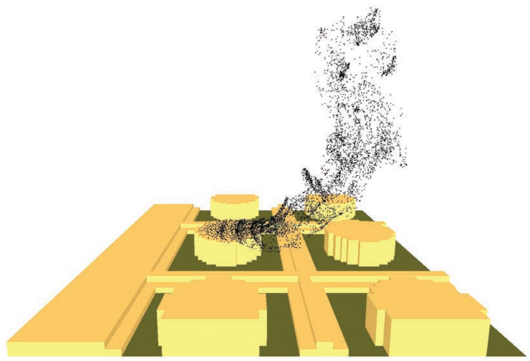
Smokeview visualizes FDS modeling results by displaying particle flow, 2D or 3D shaded contours of gas flow data such as temperature and flow vectors, and flow direction and magnitude. Smokeview also visualizes static data at specific times using the same type of data. Other features include animated isosurfaces (for representing flame boundaries), color contours of gas phase information, animated flow vectors, and particle animations for simulating smoke or water droplets. Each technique highlights a different aspect of the underlying phenomena. Visualization is essential at all stages of the process. Before a run visualization verifies the correctness of scenario geometry (locations and size of interior blockages, openings to the outside, and so on), during a run it monitors the simulation (ensuring boundary flows are behaving as intended), and after the run it analyzes the results.

Particles

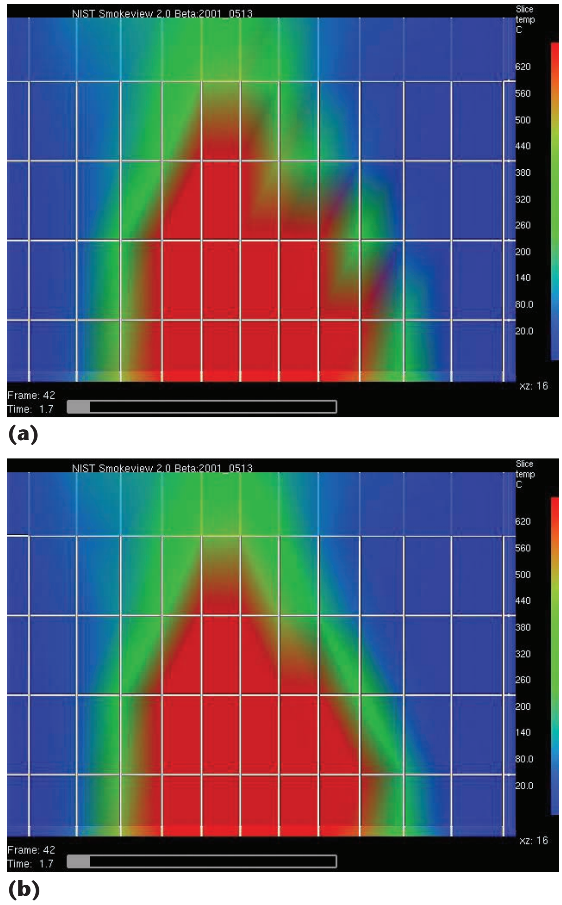
FDS/Smokeview enables the release of tracer particles at any defined boundary surface—which is often the fire source but could be an open vent, window, or other boundary. Particle animations reveal flow direction and speed and also the value of some quantity such as temperature.

Particles can help visualize sprinkler droplets; each visualized droplet is representative of many physical ones. FDS tracks each particle's position and velocity individually using motion equations involving drag computed from the underlying velocity field. This coupling lets the sprinkler spray interact with the induced gas flow and vice versa.

Figure 3 shows the use of particles to visualize the effect of wind on an oil tank fire. This calculation aimed at predicting whether a fire burning on one tank on a windy day could ignite an adjacent tank either by direct flame impingement or by thermal radiation (spacing



3 **Snapshot of a tank farm simulation showing the effect of wind on a fire plume. The Fire Dynamics Simulator calculation showed that the fire didn't affect the adjacent tanks.**



4 **Triangulating grid to minimize data extremes results in better visuals: (a) fixed triangulation and (b) triangulations formed to minimize data extremes.**

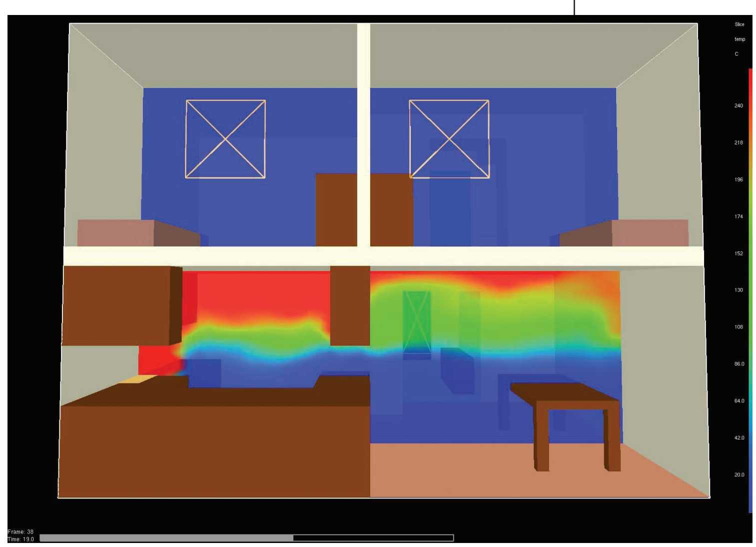
requirements in fire codes are based on calculations assuming no wind). This experiment found that neither scenario is likely due to the distance separating the tanks (at least one tank diameter) and the fact that the thick smoke surrounding the fire traps or absorbs much of the fire's radiant energy.

Slices–2D animated contours

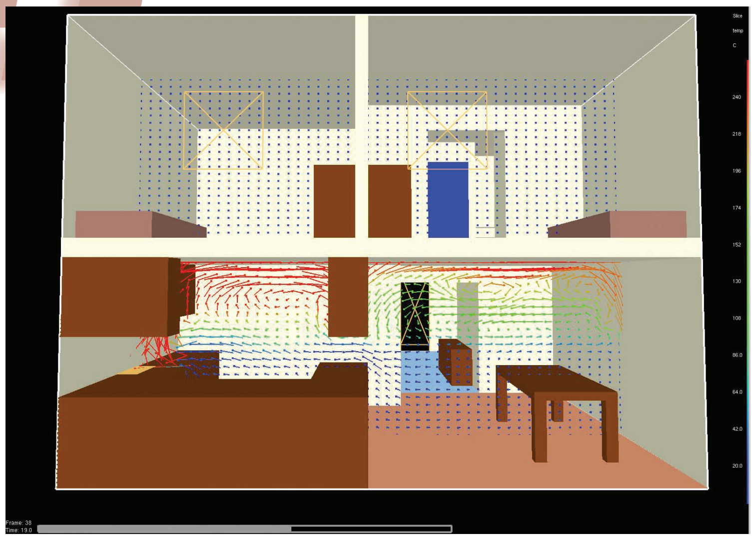
Smokeview enables drawing animated color-shaded contours for any horizontal or vertical plane in the simulation. Due to disk space constraints, it's not feasible to store all data at all times—the user must specify slice plane locations before a simulation begins. Smokeview draws shaded contour plots by specifying the color at each node based on a quantity's value such as temperature, velocity, or heat-release rate. OpenGL then blends colors from one node to the next. False colorings can result when large data changes occur between nodes. Smokeview triangulates grid cells so that resulting hypotenuses lie along rather than across saddle points, if present. Figure 4 shows two contour plots of a fire plume drawn using both triangulation choices. It's important to draw this correctly because of the expected temperature extremes near a fire.

Figure 5 illustrates temperature contours in a vertical plane through the fire center in a townhouse kitchen. The red near the ceiling is the ceiling jet, a region of hot, fast flowing gas formed soon after the fire started. This stratification exemplifies the motivation for zone fire models discussed previously. Vector slice animations use a similar approach but with three velocity components and some other quantity such as temperature to visualize the scene. Vectors are then used to indicate flow speed and direction and colors are used to indicate value. Vector animations are good at showing flow patterns in general and vortices or circular flow patterns in particular. Vector animations, as illustrated in Figure 6 (next page), highlight flow changes better than regular slice animations, especially in regions with uniform temperatures.

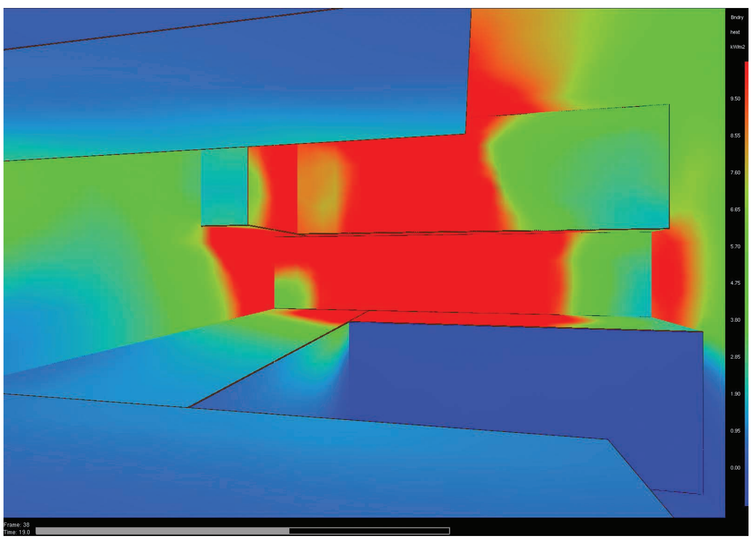
Boundary slice animations are another approach for visualizing data similar to slices. This method draws contours of quantities such as temperature or heat flux on solid surfaces or the external boundary. This is useful for showing flame spread or where burning is occurring. Figure 7 illustrates the region in the townhouse kitchen fire where burning has occurred.



5 **Shaded temperature contour plot in a vertical plane centered in a kitchen. The red region represents flashover, where temperatures exceed 600 degrees Celsius (1,100 degrees Fahrenheit).**



6 **Cross section of a house showing a vector temperature plot in a vertical plane centered in a kitchen. The vector length and direction indicates velocity magnitude and direction. The red region represents flashover, where temperatures exceed 600 degrees Celsius (1,100 degrees Fahrenheit).**



7 **Kitchen geometry showing a shaded contour plot of heat flux striking wall surfaces. The red region represents heat flux exceeding 10 kilowatts/meter^2. (A heat flux of 1 KW/m^2 at a sunny beach will cause sunburn.)**

Isosurfaces—3D animated contours

With Smokeview we can use isosurfaces to identify where rather than how often something occurs. For example, FDS uses a mixture fraction model to simulate combustion. A critical mixture fraction value in this model ensures that regions greater than the critical value are fuel rich and regions less than the critical value are fuel lean. Burning then occurs (according to the model) on the level surface where the mixture fraction equals the critical value. We can visualize these locations using animated isosurfaces.

A marching cube algorithm modified to remove ambiguities generates the isosurfaces at each desired time step. A decimation procedure reduces the number of resulting triangles by collapsing nodes of triangles with large aspect ratios and retriangulating. This makes the isosurface look better and reduces its storage requirements. Figure 8 illustrates a frame from the same fire scenario used to illustrate the kitchen fire in Figure 7.

Realistic smoke

Visualizing smoke realistically is a daunting challenge for at least three reasons. First, the storage requirements for describing smoke can easily exceed the disk capacities of present 32-bit operating systems (file sizes can easily exceed 2 Gbytes). Second, the computation required both by the CPU and the video card to display each frame can easily exceed even 0.1 second, the time corresponding to a 10-frame/second display rate. Third, the physics required to describe smoke and its interactions with itself and surrounding light sources is complex and computationally intensive. Approximations and simplifications are then clearly required.

Smoke visualization techniques described previously—such as tracer particles or shaded 2D contours—are useful for quantitative analysis but not for training applications, where displays must be realistic, fast, and accurate. A suitable approach is to display a series of parallel planes. Each plane is colored black with transparency values precomputed by FDS using the simulation's time-dependent soot densities (computed by FDS) and grid spacings. Smokeview adjusts the transparencies in real time to account for differing path lengths through the smoke as the view direction changes. The graphics hardware then combines the planes together to form one image, requiring approximately 0.14 second per frame. Figure 9 illustrates this technique for visualizing smoke in the stairway of a townhouse.

Case studies

Even though fire modeling is getting better and faster, we still need full-scale fire testing to perform reality checks. Full-scale fire experiments are expensive though, often costing $50,000 or more per test. Also, due to the length of time required to set up the tests and the limited availability of testing facilities, testing time is a scarce resource. So, it's important that testing be performed as efficiently and effectively as possible. FDS and Smokeview have helped in two important ways. First, these tools can help preplan the experiment, for example, by anticipating flows and temperatures. Sometimes modeling reveals unanticipated phenomena that merit further investigation in the experiments. Second, FDS and Smokeview can be verified against the full-scale tests run for one set of parameters then rerun for other scenarios that couldn't be tested.

One series of experiments conducted at the Underwriters Laboratory examined the effectiveness of various fire protection safety designs involving roof vents, sprinklers, and draft curtains. These curtains funnel smoke from a fire inside the building toward the vents. FDS predicted that the draft curtains and, to a lesser degree the roof vents, would interfere with sprinkler operation.

Iowa fire

On 22 December 1999, a fire in a two-story duplex house in Iowa claimed the lives of three children and three firefighters. The fire occurred in the right half of a two-story duplex.

At the request and under the sponsorship of the National Institute for Occupational Safety and Health (NIOSH), NIST examined the fire dynamics of this incident. NIST performed computer simulations of the fire using FDS and Smokeview to provide insight on the fire development and thermal conditions that might have existed in the residence during the fire (see http://fire.nist.gov/bfrlpubs/duplex).

Investigators from the Bureau of Alcohol, Tobacco, and Firearms (ATF) and NIOSH helped develop input for the Iowa input scenarios using material properties taken from the FDS database. Investigators developed an FDS model scenario that best represented the actual building geometry, material thermal properties, and fire behavior based on information and photographs from ATF.

These FDS calculations reported fire conditions that indicate a fire originating on the kitchen stove spread through the house resulting in flames that engulfed the stairwell to the second floor within approximately 9 minutes from the start of ignition on the stove. Figure 10 (next page) shows a picture of fire damage to the kitchen in the rear of the duplex. Figure 11 shows isosurfaces representing the computed flame boundary.

The critical event in this fire was the onset of flashover conditions in the kitchen. Within 60 seconds after the flashover occurred in the kitchen, the flames had spread through the dining room and living room and up the stairway.

Cherry Road fire

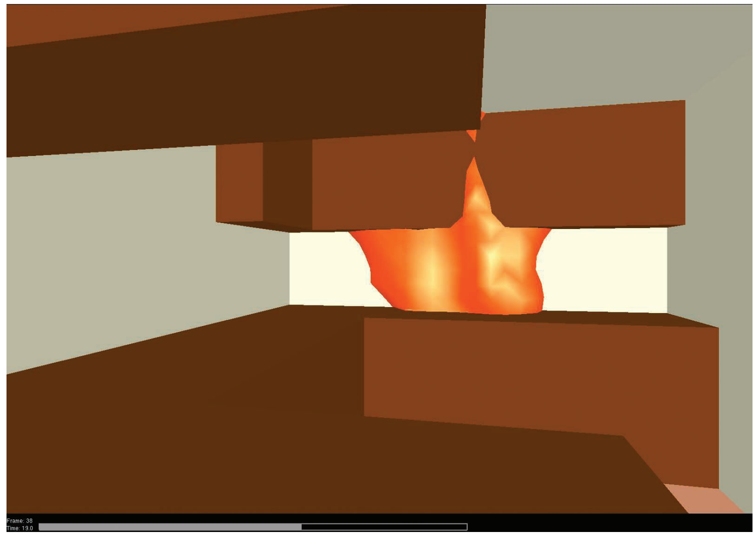
On 30 May 1999, a post-midnight townhouse fire in Washington, D.C., claimed the lives of two firefighters and seriously injured a third (see http://fire.nist.gov/6510). Firefighters first arriving on the scene described conditions as heavy smoke, with thick smoke pouring from the open front door. Some of the firefighters at the front of the townhouse opened the windows on the first and second floor. Other firefighters entered the front with hose lines in search of the fire. At the same time, another fire crew entered the basement-level sliding glass doors on the backside of the house to conduct a search. The basement was also fully charged with smoke from floor to ceiling. Several small fires that were burning on the floor rapidly increased in size after the sliding door was opened.

The firefighters searching the basement noticed the flames beginning to burn overhead and exited the basement. Shortly thereafter flashover occurred, filling the basement with fire. The fire continued to grow, sending flames up the backside of the townhouse. Before they could exit the building, other firefighters working on the first floor felt an intense blast of heat, which resulted in the loss of life of two firefighters and severe burn injuries to a third. It was later determined that the fire started near an electrical fixture in the basement ceiling.

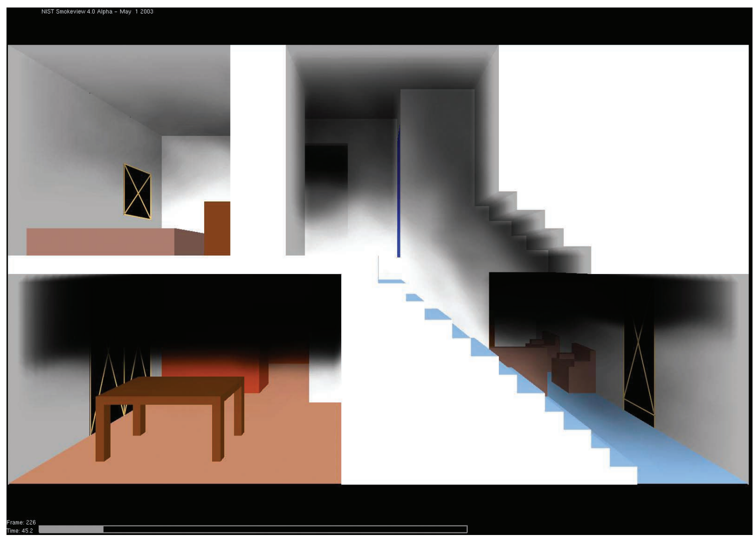
The District of Columbia Fire and Emergency Medical Services Department Reconstruction Committee asked NIST to examine the fire dynamics of this incident. The committee had questions regarding:

- the injuries that the firefighters had sustained,
- the lack of thermal damage in the living room where the fallen firefighters were found, and
- why the firefighters never opened their hose lines to protect themselves and extinguish the fire.

For the geometry, NIST used a rectangular volume of $10 \times 6 \times 5.1$ meters, which FDS divided into 76,500 computational cells. Because FDS adjusts the dimensions to the nearest computational cell, the cell size is the resolution limit of vents, openings, furnishings, or walls within the model.



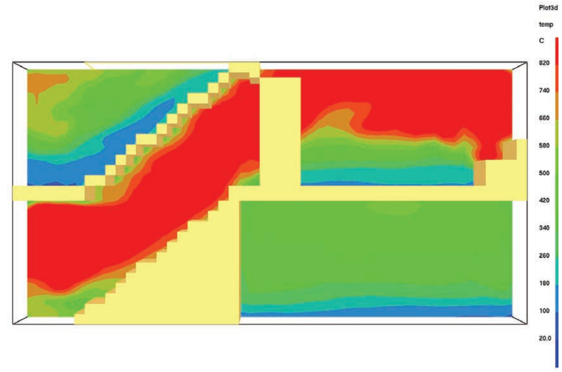
8 **Kitchen geometry showing the isosurface of the critical mixture fraction level (flame surface) where combustion will occur if the temperature is high enough.**



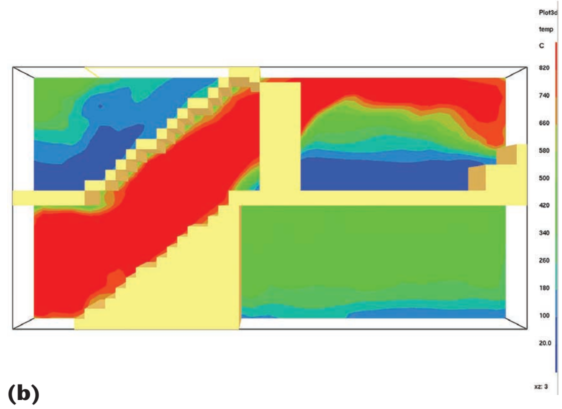
9 **Smoke rising in the stairwell of a townhouse. Smoke thickness is visualized by drawing a series of partially transparent planes. Each plane is colored black with transparency determined from the grid spacing, view direction, and soot density computed by FDS.**

10 Rear view of Iowa duplex showing damage to kitchen where the fire started.

11 Estimated flame boundary spreading through the dining room and into the living room at approximately 9 minutes after the emergency call to 911 at the time of the fire's ignition.



(a)



(b)

12 Side view of Cherry Road townhouse showing the temperature slice along stairway's centerline (lower left) at 200 seconds of simulation. Arched red flow patterns caused by hot gas flowing rapidly up the stairs. Venting the door, as expected, raises the interface between hot (red) and cool (blue) gases. (a) Sliding glass door not vented and (b) sliding glass door vented.

The FDS calculations that best represent the actual fire conditions indicated that the opening of the basement sliding glass doors provided outside air (oxygen) to a preheated, under-ventilated fire compartment, which then developed into a post-flashover fire within 60 seconds. Some of the resulting fire gases flowed up the basement stairwell with high velocity and collected in a preheated, oxygen-depleted first-floor living room with limited ventilation. The FDS predictions showed the hot gas flow moving across the living room ceiling and banking down the back wall of the townhouse, as illustrated in Figure 12a.

These hot gases impinged directly on the two firefighters that died, one was positioned in the doorway at the top of the basement stairs, and the other firefighter was located in front of the sofa opposite the doorway. Given the speed of the gases, thermal conditions were quickly changing. The superheated gases were traversing the townhouse in less than 2 seconds, giving the firefighters little time to respond. Firefighters typically work in conditions of little if any visibility due to the thick black smoke. As a result, the hose crews look for a glow that indicates the fire's position so they can extinguish it. The FDS calculation showed that the oxygen concentration in the living room wouldn't support flaming combustion, it was just superheated gas. As a result, the firefighters didn't have a visual cue that the thermal conditions in the room were changing dramatically until they felt it, and by then it was too late.

After seeing the results of the model simulating the incident as it happened, the committee asked NIST to model what would have happened if the sliding doors on the first floor were opened before the sliding glass doors in the basement. This approach is the standard operating procedure (SOP) that the fire department has in place. FDS/Smokeview output, as illustrated in Figure 12b, showed that temperatures in the range of 20 to 100 degrees Celsius were maintained for the area approximately 0.6 meter above the floor. Hence, the model supports maintaining the ventilation SOP currently in place. More than 12,000 copies of a CD-ROM of this report have been requested by fire departments around the world to use as a training aid, showing the benefits of ventilating a building from the top down (see the "Additional Information" sidebar for ordering information).

Since simulating the Cherry Road fire, NIST has worked with NIOSH on recreating several other fires to develop lessons-learned training tools for the fire service including a fast-food restaurant fire in Texas resulting in fire fighter fatalities.[3]

Future outlook

FDS was originally designed to analyze smoke and heat transport in relatively large industrial settings. For these problems, the model can predict flow velocities and temperatures to an accuracy of 20 percent compared to experimental measurements. However, work continues for residential fire scenarios where the focus of the analysis is usually material burning rates, soot and carbon monoxide production, and thermal radiation. NIST is working on improving the gas and solid phase descriptions of combustion in the model to achieve this goal.

NIST originally designed Smokeview for use by the FDS developers to diagnose problems and by FDS users to better understand and interpret results. Work is proceeding to make Smokeview accessible to those involved in fire fighting by providing a virtual reality-like environment suitable for training. Preliminary work on visualizing smoke and fire realistically at near real-time frame rates is encouraging, motivating us to further develop this capability. ■

Additional Information

Movies related to many of the article's figures are available at http://www.computer.org/cga/cg2003/g4toc.htm.

Fire on the Web (http://fire.nist.gov) contains information about fire including the Cherry Road and Iowa case studies, fire tests and data, software models, and publications. Each fire test Web page documents a test fire by displaying it in several forms including still photographs, movies, and heat-release-rate data.

CD-ROM versions of the Cherry Road and Iowa case studies containing animations of fire simulations are available at no cost by sending a request to daniel.madrzykowski@nist.gov. The Cherry Road report, NISTIR 6510, is available at http://fire.nist.gov/6510/ and the Iowa report, NISTIR 6854 is available at http://fire.nist.gov/bfrlpubs/duplex/. In addition to the reports, these CDs contain animations illustrating the flow dynamics for some of the fire scenarios.

FDS and Smokeview software (including source for FDS) and documentation is available at http://fire.nist.gov/fds.

Reference

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3. R. Vettori et al, *Simulation of the Dynamics of a Fire in a One-Story Restaurant—Texas, February 14, 2000*, tech. report, NISTIR 6923, Nat'l Inst. Standards and Technology, 2002.

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