Analysis of a Fatal Wind-Driven Fire in a Single-Story House

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PART OF THE MISSION OF THE FIRE RESEARCH Division at the National Institute of Standards and Technology (NIST) is to develop and apply technology, measurements, and standards to improve the understanding of the behavior, prevention, and control of fires to enhance firefighting operations and equipment, fire suppression, fire investigations, and disaster response. NIST has previously used the Fire Dynamics Simulator (FDS) to provide insight on the fire development and thermal conditions of other multiple-fatality fires.[1-7] The overriding objective of all of these studies is to improve the safety of firefighters.

On April 12, 2009, a fire in a one-story ranch home in Texas claimed the lives of two firefighters. Sustained high winds occurred during the incident. The winds caused a rapid change in the dynamics of the fire after the failure of a large section of glass in the rear of the house. At the request of the National Institute for Occupational Safety and Health (NIOSH) and the Houston Fire Department (HFD), NIST assisted with examining the fire dynamics of this incident. NIST performed computer simulations of the fire using NIST's FDS computer model and Smokeview, a visualization tool, to provide insight on the fire development and thermal conditions that may have existed in the residence during the fire. For the full details of the study, see the original report "Simulation of the Dynamics of a Wind-Driven Fire in a Ranch-Style House—Texas."[8]

This article describes the input and the results of two FDS simulations. The first simulation was completed to demonstrate fire dynamics in the structure in the absence of a wind condition at the time of the incident. The second simulation is used to contrast how the fire dynamics were affected with the addition of wind and to provide insight into the fire environment experienced by HFD members.

WIND-DRIVEN FIRES

Wind has been long recognized as a contributing factor to fire spread in wildland fires and large-area conflagrations. The Fire Department of New York (FDNY) identified that wind conditions significantly increased the severity of high-rise fires and that wind-driven fires were challenging their resources, tactics, and safety. As part of a collaborative effort with FDNY, the Chicago Fire Department, the NFPA Fire Protection Research Foundation, the Polytechnic Institute of New York University, and fire chiefs from 14 North American fire departments, NIST completed full-scale fire experiments in the laboratory and in a seven-story structure to enable a better understanding of wind-driven fire tactics, including structural ventilation and suppression.[9-11] As part of the laboratory experiments, it was found that wind speeds as little as 10 miles per hour are enough to generate a high-hazard flow path through a structure. More recently, wind-driven fire behavior also has been recognized in other types of structures, including single-family homes.[12]

The wind-driven fire experiments show the importance of understanding the ventilation flow path for a fire. (9) A flow path is composed of at least one inlet opening, one exhaust opening, and the connecting volume in between the openings. The direction of the flow is determined by differences in pressure. Heat and smoke in a high-pressure area will flow toward areas of lower pressure. The experiments consistently showed that being in the flow path downwind of the fire was tenable for a firefighter with full protective clothing and equipment only for a limited time, estimated to be 30 seconds or less. In other words, being in a position between the fire and the exhaust opening or vent, even in nonwind-driven, postflashover conditions, is not a position a firefighter or anyone else should be in.

Although structural fire departments have recognized the impact of wind on fires, in general, the standard operating guidelines for structural firefighting have not changed to address the hazards created by a wind-driven fire inside a structure.

FIRE DYNAMICS SIMULATOR AND SMOKEVIEW

FDS is a physics-based computational fluid dynamics (CFD) model designed to simulate low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires. Within FDS, the room or building of interest is divided into small three-dimensional rectangular computational cells. The cells are contained together within one larger volume known as a computational domain. The CFD model computes the density, velocity, temperature, pressure, and species concentra-

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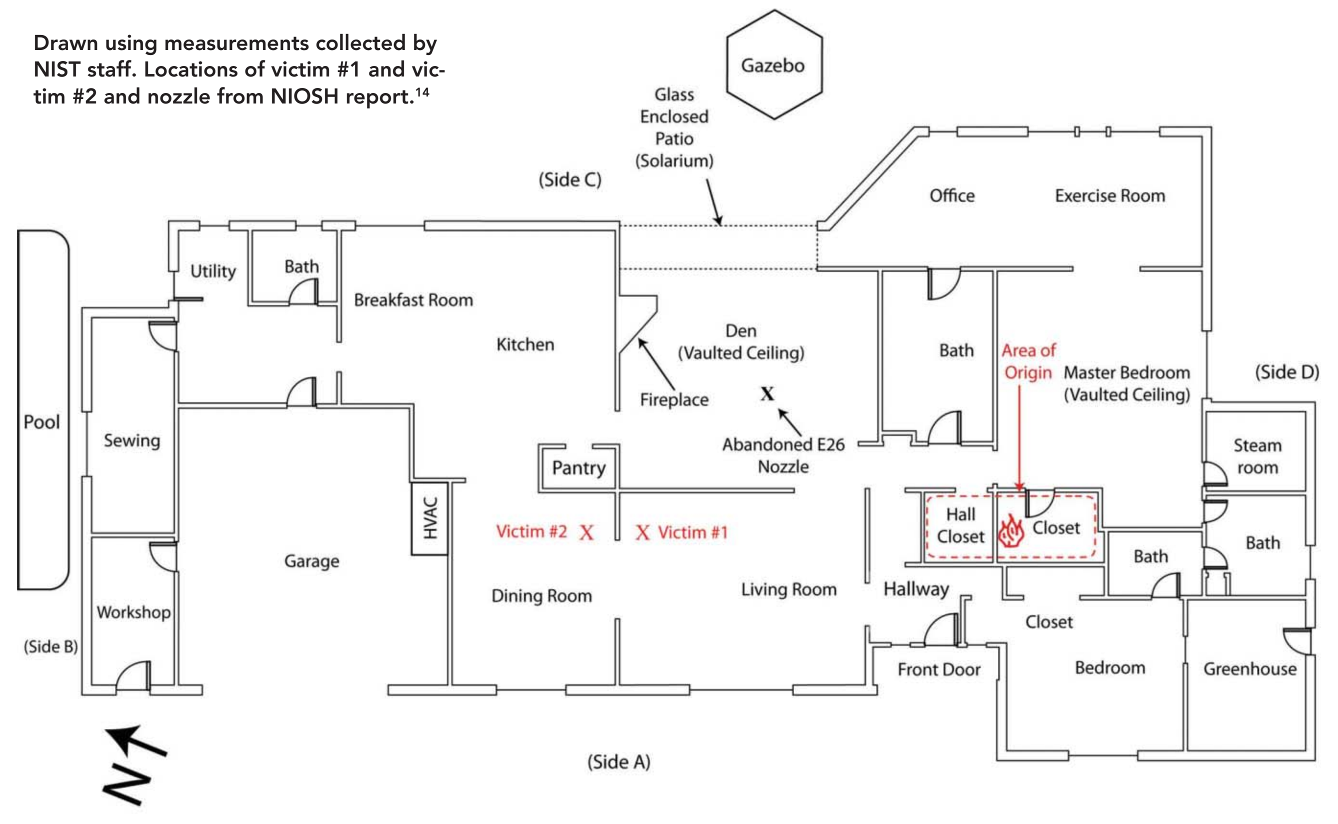
Figure 1. Plan View of Residence



tion of the gas in each cell. Based on the laws of conservation of mass, momentum, species, and energy, the model tracks the generation and movement of fire gases.

Smokeview is a software tool designed to visualize the results of the FDS. It visualizes smoke and other attributes of the modeled fire using traditional scientific methods such as displaying tracer particle flow, two-dimensional (2-D) or three-dimensional (3-D) shaded contours of gas flow data such as temperature and flow vectors showing flow direction and magnitude. Smokeview also visualizes fire attributes realistically so that one can visually experience the fire. Smokeview also visualizes static data at particular times using 2-D or 3-D contours of data such as temperature and flow vectors showing flow direction and magnitude. Full documentation for FDS and Smokeview, as well as the software, can be downloaded from www.fire.nist.gov/fds/.

FDS requires the following inputs: the geometry of the building compartments being modeled; the computational cell size; the location of the ignition source; the heat release rate (HRR) of the ignition source; physical and thermal properties of walls and furnishings; and the size, location, and timing of vent openings to the outside, which critically influence fire growth and spread.

In forensic reconstructions, FDS is used to simulate an actual fire based on inputs developed by the user from information collected after the event (e.g., eyewitness accounts, burned and unburned materials, physical dimensions, and so on). The purpose of the simulation is to connect a sequence of observations with fire development scenarios. A reconstruction is an example of an "ill-posed" problem. The outcome is known in advance, whereas the prefire conditions are often not well known. Subsequently, there is no single unique solution that matches the observed events, and it is possible to simulate numerous fires that produce the given outcome. There is no right or wrong answer. Instead, there is a small set of fire scenarios that are consistent with the collected evidence. These simulations are then used to demonstrate why the fire behaved as it did based on the current understanding of fire physics incorporated in the model. (5)

FIRE INCIDENT SUMMARY

The following account of events is based on information provided in the Texas state fire marshal's report[13] and the NIOSH report.[14] A summary of the events describing the conditions of the fire and fire department operations is provided in Table 1.

According to the Texas state fire marshal's investigation, the fire was ignited by overheated wiring in the ceiling light fixture in a closet. Figure 1 shows a plan view of the structure with the location of the area of fire origin marked, as well as the locations where each firefighter was found. It is unknown how long the fire had been burning before being detected by the occupants. While preparing for bed, an occupant in the master bedroom observed a flickering light coming from the closet. Upon inspection, flames and smoke were visible from "eye level to ceiling level inside the closet." (13) As the occupants exited, the interior and exterior overhead garage doors were left open.

Just before 12:08 a.m. on April 12, HFD dispatch received a call from a neighbor reporting that a house was on fire. Sustained winds blew from the ESE at approximately 17 miles per hour (mph) and gusted to approximately 26 mph. The first engine on scene, Engine 26 (E-26), arrived within five minutes at approximately 12:13 a.m. As E-26 approached the scene, smoke exhausting from the roof was of great enough quantity that the E-26 crew experienced significant difficulty locating the structure. E-26 advised dispatch that it would perform an aggressive interior attack. The E-26 crew, comprised of a probationary firefighter (victim #1), a captain (victim #2), and a third firefighter, advanced a preconnected hoseline to the front door and forced the door open. Ladder 26 (L-26) arrived within seconds of E-26, observed fire coming from a turbine vent near the peak of the roof, and radioed that L-26 would vent the roof.

Table 1. Abridged NIOSH Approximate Incident Timeline

Time (Min.)	Fire Behavior and Fireground Operations	Incident Time (Min.)
12:08 a.m.	HFD dispatches call.	0
12:13 a.m.	E-26 on scene; heavy smoke reported.	5
12:14 a.m.	E-26 crew forces open front door; L-26 captain reports "heavy smoke."	6
12:15 a.m.	E-26 crew advances hoseline into structure while walking upright.	7
12:16 a.m.	E-36 advances hoseline into the structure toward den. E-36 observes E-26 upright ~6 feet away toward Side C.	8
12:18 a.m.	Flames exit through roof saw cuts as L-26 crew operates. L-26 observes flames approximately 3 feet wide lapping from Side C eaves.	10
12:19 a.m.	L-26 completes roof vent, breaches first-floor ceiling. Roof conditions unsafe; L-26 exits roof. E-36 punches hole in ceiling near end of hall to search for fire in attic.	11
12:20 a.m.	Fire lapping from Side C eaves expands to ~20 feet wide. Flames extend several feet from vent opening. Temperature increases rapidly; E-36 forced to floor. L-29 observes legs of crew standing toward Side C in den.	12
12:20 a.m.	L-29 finds and operates abandoned E-26 hoseline, overhead and side to side.	12
12:21 a.m.	Temperature in den increases further. E-36 and L-29 operating from hallway.	13
12:22 a.m.	Fireground operations switched to defensive.	14
12:46 a.m.	Fire knocked down.	38

Engine 36 (E-36) arrived on scene at approximately 12:15 a.m. and observed the E-26 crew advance into the structure while walking upright. The third E-26 firefighter remained

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near the front door to pull slack for the hose and experienced high heat conditions just inside the doorway. The E-26 crew advanced the hoseline down the hallway toward the den. One wall of the den was composed of large glass panels.

Approximately one minute after E-26 crew members entered the structure (12:16 a.m.), E-36 advanced a second hoseline down the hallway. The E-36 captain peered beneath the smoke layer and briefly saw the legs of the E-26 crew five or six feet ahead, advancing down the hallway. At approximately the same time, E-26 firefighter #3 exited the structure to replace a dislodged helmet and observed flames rolling overhead at the front door.

E-36 advanced approximately 10 to 15 feet down the hallway and began pulling the ceiling. Suddenly, the temperature rapidly increased and forced the E-36 crew to the floor. An E-36 firefighter directed the hoseline toward a red glow observed through the hole but encountered disrupted water flow. In response, the E-36 crew backed down the hallway toward Side A and experienced further temperature increases accompanied by "whooshing" or "roaring" sounds. The E-36 crew then advanced a few feet into the living room and operated the hoseline overhead. Water from the 1¾-inch hoseline had little effect on the fire. This was the approximate location of a ceiling breach made by L-26 from the roof.

Simultaneously, L-26 was performing ventilation cuts on the roof. The L-26 captain observed that flames came through the kerf cuts. The L-26 captain also observed flames one to two feet wide lapping over the eaves in the rear of the structure, in the same location as the wall of windows in the den. At approximately 12:19 a.m., L-26 pried up the roof decking and used a pike pole to punch down through the first-floor ceiling. Immediately, flames exited the vent hole in a "swirling vortex" that extended several feet into the air. At approximately the same time, the L-26 captain observed the fire overlapping the eaves on Side C of the structure expand to the width of the glass wall of windows (approximately 20 feet).

At approximately 12:20 a.m., Ladder 29 (L-29) entered the front door on orders to assist E-26 with a primary search of the structure. The L-29 crew immediately dropped into a crawl because of the high heat conditions. The L-29 crew noted that thermal conditions continued to worsen as they advanced toward the den. At one point, the L-29 captain observed the legs of upright crew members advancing the hoseline forward toward the den. After clearing the debris that blocked the hall, the L-29 captain observed that the hoseline was no longer being advanced.

The L-29 crew found that the smoke layer dropped almost to floor level as they advanced toward the den. Eventually, the L-29 crew discovered the abandoned nozzle of E-26 in the den and began operating the hose overhead. The E-36 and L-29 crews both operated their hoselines until incident command (IC) radioed to switch to a defensive mode at approximately 12:21 a.m.

At 12:22 a.m., the IC requested a

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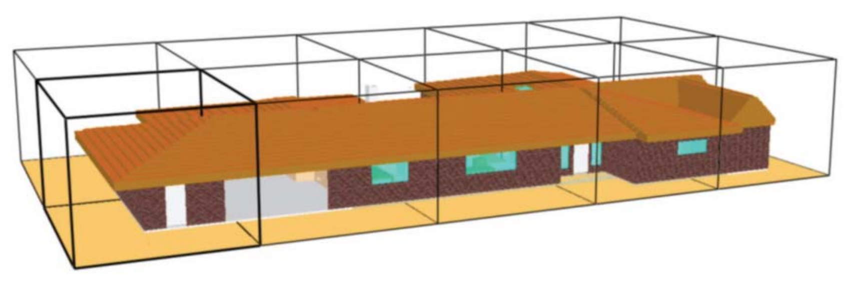
Figure 2. Computational Domain of the Simulation



Permit records indicate multiple modifications to the property. Portions of the roof were constructed over the original roof, which added to the combustible load in the attic, as well as created void spaces for pyrolyzed fuel to collect. The specific details of all the modifications are not known because of the extensive damage of the structure. Figure 3 shows an aerial view of the fire damage to the structure.

personnel accountability report (PAR) from all crews. The PAR indicated that all firefighters were accounted for except for the E-26 captain and probationary firefighter. Over the next 24 minutes, defensive operations were carried out using a ladder pipe and 2½-inch hoseline. At approximately 12:46 a.m., enough of the fire was extinguished so that HFD members could reenter the structure. At 12:51 a.m., the E-26 probationary firefighter was located in the living room. At 12:52 a.m., the E-26 captain was discovered in the dining room. Both firefighters died from injuries caused by the fire.

GEOMETRY OF STRUCTURE

The floor plan of the one-story ranch-style house involved in this incident is shown in Figure 1. Based on the NIOSH (13) and Texas state fire marshal (14) reports, the original structure was built in 1956. The structure measured approximately 108 feet long by 48 feet wide. The structure consisted of traditional stick-built wood construction with a brick veneer over the exterior walls. The interior finish of the structure was gypsum board walls and ceilings. Figure 2 shows a view of the structure as modeled in FDS.

IGNITION SOURCES

According to the Texas state fire marshal's report (13), the source of fire ignition was a "loose connection" in the porcelain light fixture in the closet adjacent to the bedroom. The loose connection "resulted in a glowing connection, causing localized heating that ignited adjacent combustible materials." (13) The actual fire may have taken several hours to develop to the flaming stage given the mechanism of ignition.

The FDS model is not used to explain how the fire ignited or spread to the attic. The complex physics and chemistry involved with overheated wiring connections that transition to flaming ignition occur on a physical scale that is much smaller than the computational cell size used in these FDS simulations. Instead, the fire simulation was initiated with two flaming ignition sources, on either side of the ceiling, to simulate the heating of the light fixture that eventually transitioned into flaming fires in the attic and closet.

Based on the timeline provided in Table 1, a minimum of six minutes elapsed between when the occupants observed flames in the closet and when E-26 forced open the front door. There are numerous possibilities for how the fire may have spread to the den during this period. Instead of assuming a

Figure 3. Aerial View of Damage to the Structure

Image used with permission of the Houston Fire Department. Enhancements by NIST.

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Table 2. Summary of Vent Times

Incident Time (Min.)	Fire Behavior	Simulation Time (Min.)	Simulation
–	Occupants exit, leaving garage door open.	0	Ignition sources activated in attic and closet.
0	Fire incident dispatched.	2.3	-
6	E-26 forces open front door.	8.3	Front door opened.
7.7	Partial failure of vaulted ceiling in den.	10	Vent opened in den ceiling.
9.7	L-26 observes flames approximately 3 feet wide lapping over Side C eaves.	12	One horizontally oriented pane of solarium glass removed.
11	L-26 completes roof vent, breaches first-floor ceiling. E-36 pulls ceiling near end of hall.	13.3	Roof vent opened/ceiling holes added underneath vent. Hole added in ceiling for E-36 vent.
12	Fire lapping from Side C eaves expands to approximately 20 feet wide.	14.3	Remaining solarium glass removed.
14	IC orders operations to switch to defensive.	16.3	End of simulation.

means of fire spread, the ignition times of the two couches in the den were delayed so that their combined burning produced thermal and fire conditions that resemble the "intense heat" descriptions provided by HFD members.[15]

MATERIALS AND VENTILATION

The quantity of fuel in the den was burning significantly enough that the E-26 crew was operating their hoseline in the den. The contents of the den were approximated with two upholstered couches on a wood floor. During a postfire analysis of the scene, it was noted that the den contained upholstered furniture as well as additional common household items that contribute to fuel loading (e.g., area rugs, lamps, end tables, and so on). Although less fuel was used in the simulation, the simulated quantity of fuel was adequate to create ventilation-limited conditions. Data from a couch burned in the NIST Large Fire Laboratory were used as the HRR input for each couch. Each couch had a peak HRR of approximately 2.4 MW.

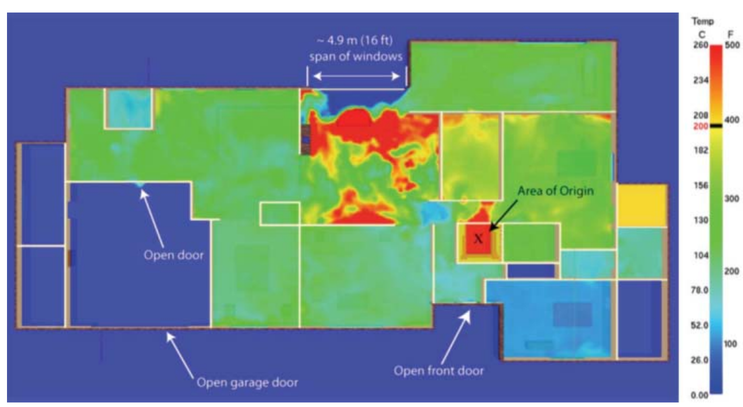
For the purpose of simulation, a vent is considered an opening that will allow fire gases and ambient air to communicate between spaces within the structure as well as between spaces in the structure and the environment outside the structure. This simulation included vents to account for ventilation designed as part of the structure (e.g., heating, ventilation, air-conditioning; attic vents), the approximate leakage of the building envelope, and changes in ventilation caused by a combination of fire department operations and fire acting on the structure. The time that each vent was opened is provided in Table 2. The timing and locations of three of the vent openings, the front door, the roof vent, and the hole created by E-36, are based on HFD radio traffic. (13-14)

The times of the partial failure of the den ceiling, failure of one solarium window pane, and total failure of the solarium glass are estimated based on the fire behavior observations in the NIOSH report (14) and from HFD members. (15) The failure of the solarium glass windows were timed based on the observations of the L-26 captain, who observed flames approximately one to three feet wide overlapping the eaves at the rear (east) of the structure approximately 10 minutes after the incident dispatch. This was simulated by removing a single panel of glass. About two minutes later, the L-26 captain observed the flaming area to expand to approximately 20 feet wide. Subsequently, the remaining glass panels were removed after 14.3 simulation minutes.

COMPARISON OF WIND AND NO-WIND SIMULATION RESULTS

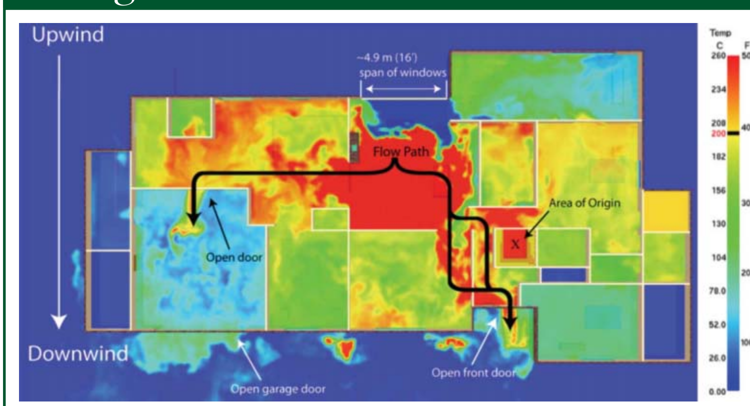
Figure 4 shows the temperatures at five feet above the floor (the approximate height of the face piece of a standing firefighter) for the nonwind-driven fire simulation, 10 s after

Figure 4. Nonwind-Driven Simulation



Simulated temperatures at five feet above the floor throughout the house 10 s after solarium failure. Overhead view of floor plan.

Figure 5. Wind-Driven Simulation



Temperatures at five feet above the floor throughout the house 10 s after solarium failure. Overhead view of floor plan.

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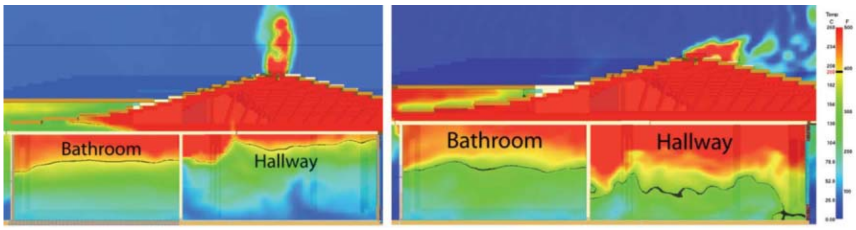
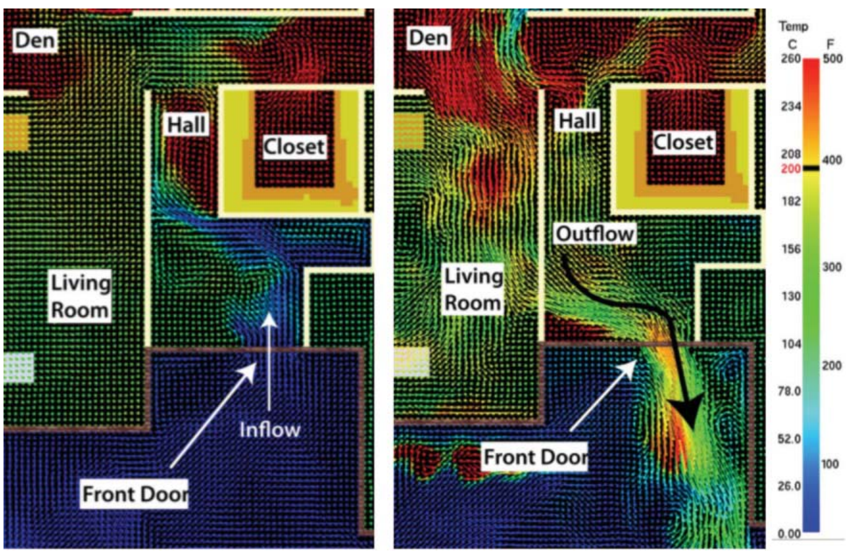
Figure 6. Hallway Temperatures



Comparison of nonwind (left) and wind (right) simulations in the hallway area, 10 s after the failure of the solarium glass.

Figure 7. Front-Door Air Flow



Flow into front door 10 s before (left) and 10 s after (right) the failure of solarium glass at a plane five feet above the floor. Overhead view of floor plan.

the wind-driven case compared to the nonwind-driven case. In the nonwind-driven case, the higher heat conditions [greater than 100˚C (212˚F)] in the gas layer only exhaust out of the top quarter of the doorway opening. In the wind-driven case, the high heat condition exists from the ceiling down to the floor of the hallway, and hot gases flow out of the front door, top to bottom. Cool air no longer flows into the front doorway. After the failure of the solarium glass, the high pressure from the wind pushed fire gases through the structure from the rear to the front. The front doorway became an exhaust vent, as did the garage door.

Figure 7 presents visualizations of the direction of gas flow at the five-foot position above the floor in the front doorway and the front hall, looking down at a plan view of the structure. On the left, Figure 7 shows the thermal conditions 10 s before the failure of the solarium glass (no wind effect). At this time, cool air is being drawn into the structure through the front doorway. After the solarium glass failed, the wind caused a flow reversal at the front doorway. The wind entering the structure through the broken solarium glass increased the pressure at the rear of the structure and forced the fire gases through the den into the front hall and out the front door. The same was true for the flow through the kitchen and out through the garage door.

the solarium windows failed. From the fire in the den, most of the heat exhausted from the opening in the solarium or into the attic space through the hole in the den ceiling. Some of the heat and smoke flowed out of the upper portion of the open front door. In this case, the front doorway serves two functions: The lower portion of the doorway is an inlet opening for fresh air, and the upper portion of the doorway is the exhaust for a portion of the fire gases.

Figure 5 shows the temperatures at the same elevation for the wind-driven fire simulation 10 s after the solarium windows failed. The main inlet opening for the flow path is now the solarium windows on the upwind side of the house. Fresh air, driven through the failed solarium panels, interacts with the body of the fire in the den and the attic. The flow path splits, with exhaust into the attic space as before. In addition, the wind forces fire gases though the house to the exhaust openings at the front doorway and the garage doorway. This change in conditions caused by the wind may explain the "whooshing" sounds and increasing temperatures experienced by E-36 and the conditions that disoriented and overwhelmed the E-26 crew.

Figure 6 shows the increased simulated temperatures in the hallway 10 s after the failure of the solarium windows in

In the den, the temperatures decreased because of the influx of fresh air; however, temperatures in the areas downwind increased. In data collected from full-scale laboratory and field experiments, downwind temperatures have been shown to increase to an even greater extent than shown with this wind-driven simulation. (9-10) The heat losses and the split flow paths may have provided the time to enable the firefighters closest to the front door to escape. Notice that the highest average temperatures are in the flow path, which includes the den, kitchen, and hallway (Figure 5). The lower average temperatures are found in the living room and the dining room. These rooms, although downwind, are not directly in the flow path. However, the temperatures were still too high for a firefighter in a full structural firefighting protective ensemble to be exposed to without injury or death. As noted in the *Emergency First Responder Respirator Thermal Characteristics Workshop Proceedings*, the polycarbonate in firefighter self-contained breathing apparatus begins to soften when the material temperature reaches approximately 140˚C (284˚F).[16] Even though firefighter structural firefighting coats and pants are tested to withstand temperatures of 260˚C (500˚F),[17] the firefighter inside is susceptible to second-degree burn injuries when the inside temperature of the gear exceeds 55°C (130°F).[18]

TACTICAL CONSIDERATIONS

The results of the "no-wind" and "wind" fire simulations demonstrate how wind conditions can rapidly change the thermal environment from tenable to untenable for firefighters working in a single-story residential structure fire. These results are in agreement with NIST studies conducted to examine wind-driven fire conditions in high-rise structures. This emphasizes the importance of including wind conditions in the scene size-up before beginning and while performing firefighting operations and adjusting tactics based on the wind conditions. It is critical for firefighters to stay clear of the exhaust portion of the fire flow path.

The directional nature of the fire gas flow path results in higher temperatures than the area adjacent to the flow path or upwind of the fire. The flow path can be controlled by limiting ventilation. In this incident, if the front and the garage doors were never opened, the only direction for the hot gases to travel would have been up through the vents in the roof. Previous studies (9-11) demonstrated that applying water from the exterior into the upwind side of the structure can have a significant impact on controlling the fire prior to beginning interior operations. Current fire control training guides state, "Whenever possible, approach and attack the fire from the unburned side to keep it from spreading throughout the structure."[19-20] It should be made clear that in a wind-driven fire, it is most important to use the wind to your advantage and attack the fire from the upwind side of the structure, especially if the upwind side is the burned side. The unexpected ventilation from a broken window can suddenly change the interior thermal conditions. Interior operations need to be aware of potentially rapidly changing conditions. ●

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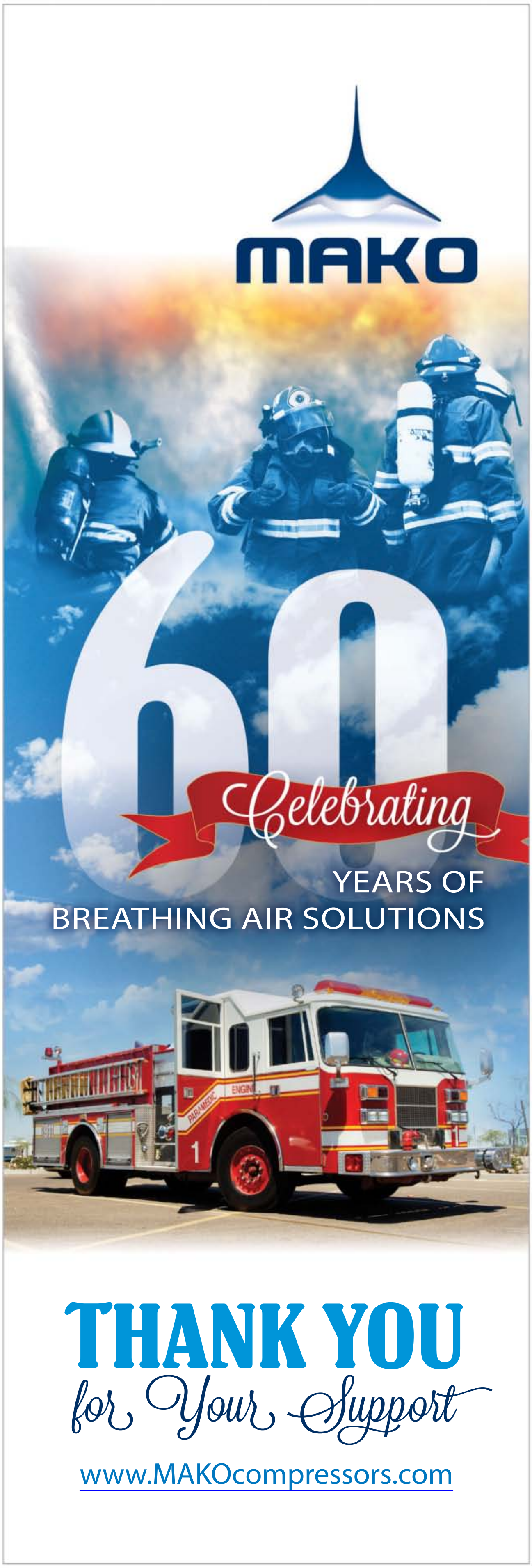

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