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Fire Dynamics: The Science of Fire Fighting

Abstract

Fire dynamics can provide a fire officer or a firefighter with means to understand how a fire will grow and spread within a structure and how best to control that growth. Researchers have generated experimental results and computer models to explain how fire dynamics taken at the most basic level, the fire triangle, applies to the fireground. This paper will provide a brief overview of the research that demonstrates the impact that changes in fuel and construction methods have had on the fire environment. These changes have altered the model of fire behavior taught to the fire service for decades. In addition, firefighter protective equipment has also changed over the years. All these factors lead to an assessment that fire-fighting tactics may need to evolve in order to keep in balance with the changing conditions on the fireground.

These findings are the result of research conducted in conjunction with the fire service. The overarching objectives were to increase the safety and the effectiveness of firefighters. These studies were designed to focus on research results that had application on the fireground. In order for these studies to occur, it took leadership within the fire service to question the status quo. Leadership will be required in every fire department to educate the fire service as a whole and implement needed changes to the current fire-fighting practices, which have been shown to make fire conditions worse before fire control and rescue can be achieved. Leadership is needed to embrace the knowledge of fire dynamics, employ a size-up of every fire scene, and then choose the fire-fighting tactics and task assignments based on that assessment.

Introduction

In the United States (U.S.), a fire department responds to a fire every 23 seconds (National Fire Protection Association® [NFPA®], 2011). Each of these fires occurs under different conditions, hence the fire service mantra — *Every fire is different*. Yet from a science perspective, most fires share some basic similarities. The fire-heat release is due to exothermic, gas-phase, chemical reactions that produce heat and light, and they require three components to sustain the chemical reaction — fuel, oxygen, and heat. This information has been taught to fire service personnel for many decades. Only during the past 12 years or so, fire experiments and computer models have been used to explain how the fire triangle applies to the fireground and affects the design of protective equipment and the choice of fire-fighting tactics.

This article provides a brief overview of research that demonstrates how changes in fuel and construction methods have affected the fire environment. These changes, taken separately and in combination, have altered the model of fire behavior taught to the fire service for decades. All these factors lead to an assessment that fire-fighting tactics and firefighters' protective gear must evolve to correspond with fire dynamics on the modern fireground.

Fire Dynamics

Fire dynamics is the field of study that encompasses how fires start, spread, develop, and extinguish. To characterize fire behavior meaningfully, fire dynamics must incorporate the interaction of chemistry and material science and the engineering disciplines of fluid mechanics and heat transfer. In addition, one must also consider the interactions of fire with structures, materials, and people in order to fully understand the fire dynamics of a given fire incident.

The paper "Microstratigraphic evidence of in situ fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa" (Berna, 2012), which was published in April of 2012, shows that Homo erectus used fire productively about 1 million years ago, more than 300,000 years earlier than previously thought. Since that time, hunters, farmers, cooks, scientists, chemists, engineers, and firefighters have studied one aspect of fire or another. Each group focused on its specific area of interest in or the use of fire. For example, some studied the use of fire to form metal while others analyzed the combustion of fuel as a means to optimize the use of fuel in boilers, automobiles, aircraft, etc. For more than 100 years, National Institute of Standards and Technology (NIST), Underwriters Laboratories (UL®), and Factory Mutual Global (FM Global), and other organizations have studied how to protect buildings from fire by examining the fire resistance of columns and walls with furnace tests (Gross, 1991). Yet it was not until 1985 that the first textbook on fire dynamics was written (Drysdale, 1985).

In response to the 1973 report, "America Burning" (National Commission on Fire Prevention and Control, 1973), Congress passed U.S. Public Law 93-498, the "Federal Fire Prevention and Control Act of 1974." The Act called for the establishment of (1) National Fire Prevention and Control Administration (now the U.S. Fire Administration [USFA]), (2) National Academy of Fire Prevention and Control (now the National Fire Academy [NFA]), and (3) Center for Fire Research at the National Bureau of Standards (currently NIST). The Act gave NIST the mission of performing and supporting research on all aspects of fire, with the aim of "providing scientific and technical knowledge applicable to the prevention and control of fires" (Public Law 93-498, p.1546). More specifically, the Act required NIST to conduct research on "the dynamics of flame ignition, flame spread and flame extinguishment" (Public Law 93-498, p.1546). As the result of U.S.-based research programs conducted and supported by NIST in the 1970s and 1980s, as well as a significant level of fire-research activity in Canada, Japan, and the United Kingdom, a body of knowledge developed on fire chemistry, fire plumes, compartment fires, and simple models of fire phenomena. This information provided a foundation for fire-protection engineers to consider fire dynamics when designing buildings and reconstructing fires.

Changes on the Fireground

While fire researchers were making gains on understanding fire dynamics in the laboratory, the hazards on the fireground and fire dynamics that accompanied them were changing. For example, the construction techniques and materials used to build and furnish a house have changed significantly over the last 50 years.

Engineered wood products have been incorporated into the design and construction of modern structures. Engineered wood joists and trusses enable longer spans and open areas (less compartmentation) for improved use of living space in homes. Since the 1970s, the median size of a single-family home in the U.S. has increased. According to data from the U.S. Census, in 1973 the median size was 1,600 ft^2. By 2008, the floor area of the median house had increased by more than 50% to 2,500 ft^2 (U.S. Census, 2011).

In order to increase the energy efficiency of houses, insulation has improved, walls are wrapped in plastic to limit infiltration of air and water, and multi-pane windows are now the norm. When a fire occurs in an energy-efficient house, the insulation works to keep the heat and combustion products from the fire trapped in the house and limits the amount of outside air that can be drawn inside to complete the fire triangle, provided that no doors or windows are open. As a result, fires have less oxygen. We can describe this in either of two ways: a ventilation-limited or a fuel-rich fire condition.

The objects and materials inside homes have changed as well. The design and construction of furnishings have evolved dramatically in the past 50 years. In the 1950s, a wide range of synthetic materials called *polymers* became available for use in clothing, furniture, interior finish, and insulation. Within a few years of their commercial introduction, the use of polyester, nylon, and polyurethane foam became commonplace in homes. Durability, comfort, and economics all play a role in the design and manufacturer of furnishings that people choose to buy. Today, flexible polyurethane foam is one of the most common materials in upholstered furniture. According to industry statistics, more than 1.7 billion pounds of polyurethane foam are produced and used every year in the U.S. (Polyurethane Foam Association, 2007).

These new materials, energy efficiencies, and construction methods have led to changes in the fire environment that a firefighter must face. Have fire departments added staffing, altered their training, or modified their tactics to respond to these changes?

Protective Equipment

Firefighters use protective equipment to increase their safety and effectiveness on the fireground. New materials and advances in technology offer improved protection to the firefighter from thermal hazards and toxic gases. Since the 1960s, new materials, such as aramid fibers (Nomex® and Kevlar®) and polybenzimidazole (PBI), have been introduced that do not melt and have a high resistance to ignition. These materials are now in common use as part of firefighters' protective clothing and equipment.

The evolution of the self-contained breathing apparatus (SCBA) to include lighter materials, increased air supply, electronic monitoring, and warning devices has made working in a smoke-filled building safer. Continued developments in the fields of electronics and sensing have produced improvements in situational awareness for firefighters, mainly through the use of thermal imaging. However, over the last decade, we have learned that electronic safety devices, such as Personal Alert Safety System (PASS) devices, radios, and polycarbonate SCBA facepieces are not as thermally robust as other fire-fighting personal protective equipment (PPE) components. The National Institute of Occupational Safety and Health (NIOSH) documented a series of line-of-duty deaths (LODDs) involving specific types of protective equipment. Thereafter, NIST worked with NFPA® and with equipment manufacturers to improve the standard test methods and requirements in order to improve the thermal resistance of the equipment and, thereby, to improve firefighter safety. Even with these improvements, conditions in a fully developed compartment fire can still exceed the capabilities of the best protective equipment.

These changes on the fireground bring us to a very disturbing trend. Between the late 1970s and the late 2000s, the annual number of structure fires in the U.S. decreased by more than 50%. During the same period, the overall annual number of firefighter LODDs also declined. However, the rate of firefighter deaths due to traumatic injuries on the fireground increased during the same period from 1.8 deaths to 3.0 deaths per 100,000 fires (Fahy, 2010). This is an increase of more than 60% at a time when firefighters have access to the best equipment and technology ever available.

As I close this section about changes on the fireground, it is worth noting that during this time of change, the typical firefighter is getting: less fire-fighting training, less fire-fighting experience, and less understanding of the technology that he or she rely on to keep him or her safe.

Fire Behavior

Typically, firefighters have been taught about fire behavior in structures with pen and ink drawings and a simple graph (see **Figure 1**). The idealized, qualitative graph shows that the fire begins with ignition. The fire is then in the growth phase, where the heat-release rate increases until the fire is fully developed. In a compartment fire, the transition from the growth stage to the fully developed stage may involve a flashover. *Flashover* is a transition in the development of a contained fire. In flashover, surfaces exposed to thermal radiation from fire gases in excess of 600°C (1,100°F) reach ignition temperature more or less simultaneously. Fire spreads rapidly through the compartment, with burning from floor to ceiling. Without an intervention, the fire transitions to the decay stage as the fuel is depleted. This ideal curve is best suited for describing a fuel-controlled fire, in other words, a fire that has all of the oxygen it needs to sustain the heat-generating chemical reaction with the fuel. In such cases, the peak heat-release rate is limited by the amount of fuel available for combustion, and the decay stage is typically related to the reduced amount of fuel available for burning. Heat-release-rate curves from free-burn sofa fires with no compartmentation effects are shown in **Figure 2**. For a typical, residential-scale room with

Figure 1: Traditional idealized fire-behavior graph showing a typical fuel-controlled fire.

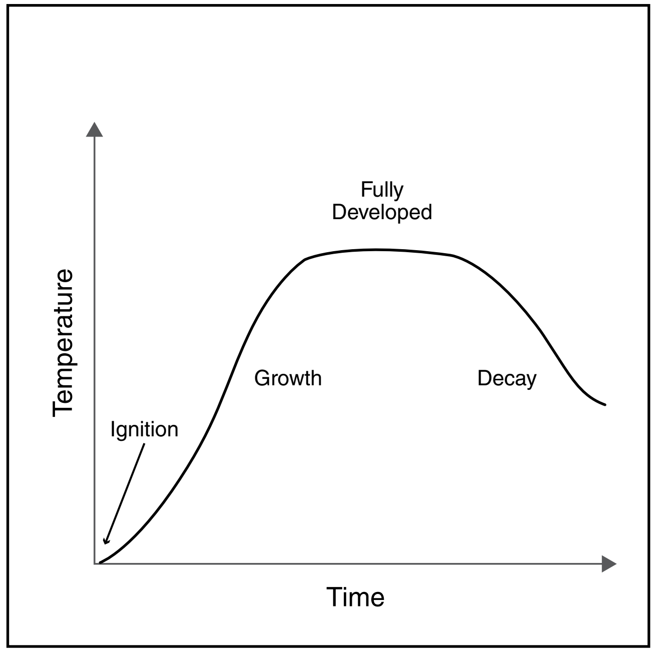


Figure 2: Heat-release rate time history from sofa "free burns."

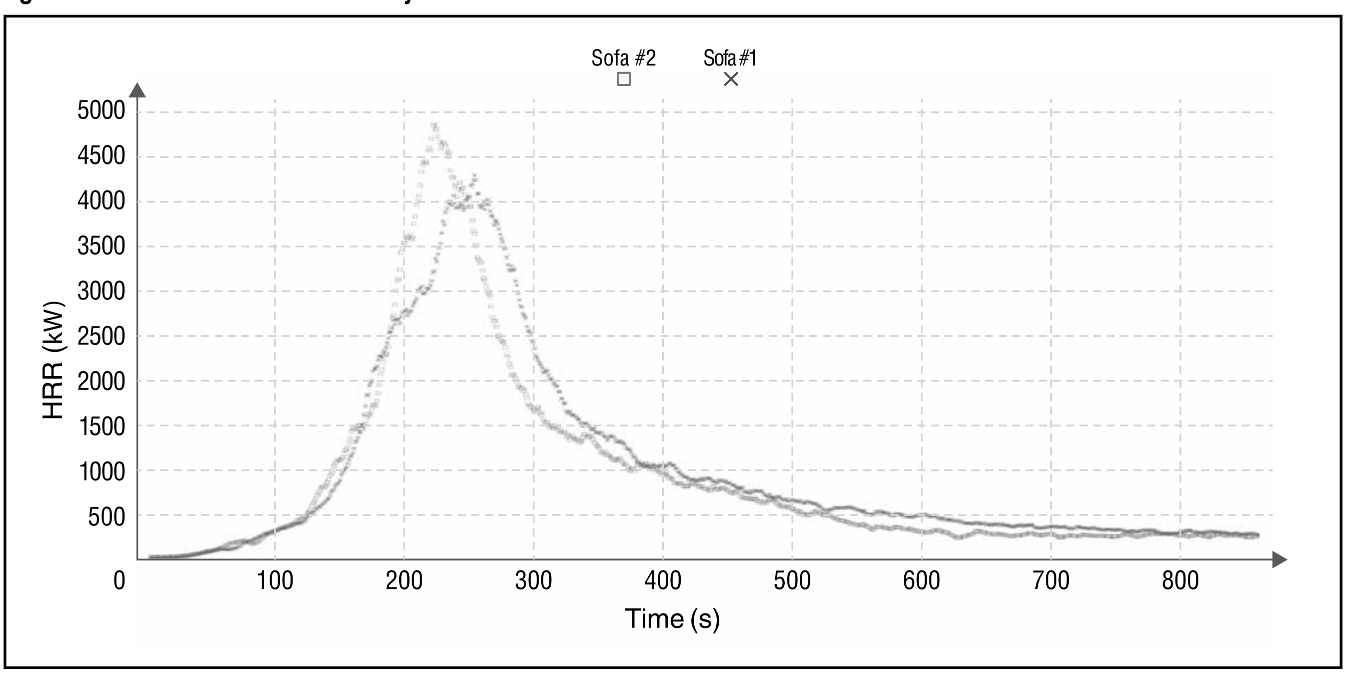
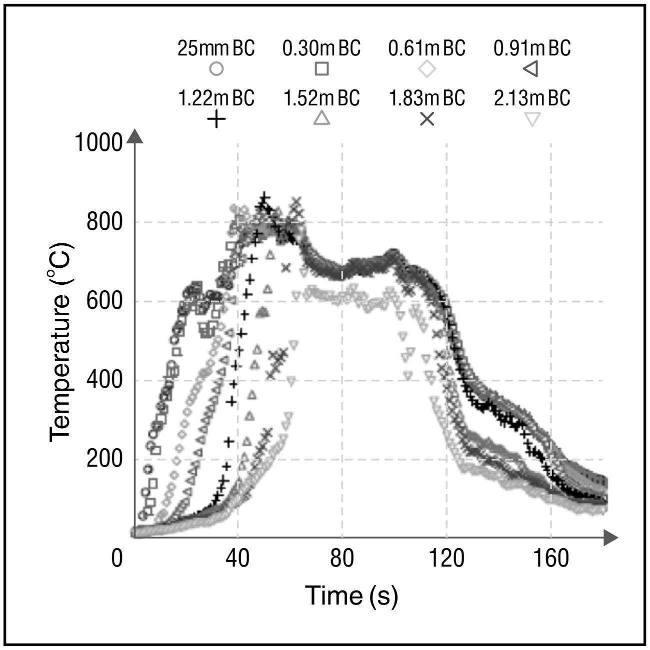


Figure 3: Temperature time-history curves from a furnished room fire with an open doorway.



a doorway approximately 0.9 m (3 ft) wide by 2.0 m (6.6 ft) high, the minimum heat-release rate required to flashover the room is about 2,000 kW. You can see from Figure 2 that a sofa has twice the peak heat-release rate needed to flashover the room. **Figure 3** is a graph of temperature vs. time-history curves shown from a sofa fire in a compartment with an open doorway, which allows for the continuous flow of oxygen from the outside of the compartment to the fire. Notice that in each case, the free burn and the open-room burn, the fuel-controlled pattern pertains: basic growth, fully developed, and decay.

As new homes retain heat and the gaseous fuels better than old homes and as synthetic fuels burn faster than wood and cotton, the probability of arriving to a preheated, fuel-rich fire environment has increased in recent years. As a result, fires are controlled by the amount of oxygen available to them. An idealized curve of a ventilation-controlled fire is shown in **Figure 4**. As in the fuel-controlled case, the fire begins with ignition and the growth stage. As the high-heat-of-combustion fuels burn in the nearly air-tight house, fire begins a decay stage due to limited availability of oxygen for the combustion process. As the available oxygen decreases, the heat-release rate of the fire decreases, along with the gas temperatures in the house. If a door or a window is opened while the fire is still burning, although at a reduced level, and if additional fuel is available, the introduction of outside air can result in a rapid increase in the heat-release rate of the fire and may enable enough energy generation to flashover the room. This transition has been referred to as a *ventilation-induced flashover*. Once enough oxygen has been made available to allow the fire to reach the fully developed stage, it may become fuel-controlled again until decay or until suppression by the fire department.

NIST has had the opportunity to measure this type of fire behavior many times while conducting fire experiments in acquired structures. For example, NIST had the opportunity, with the Chicago Fire Department, to burn several townhouses after equipping the structures with fire-monitoring instruments. Each townhouse was furnished with a sofa, upholstered chairs, a futon, wooden bookcases, a dinette set, kitchen cabinets, and bedroom furniture. In one case, a small flame ignited the sofa, which was on the first floor in the living room. All of the exterior doors and windows were closed. Within 120 seconds after ignition, flames from the sofa impinged on the living room ceiling, and combustion products spread to every first- and second-floor room with an open door. By 210 seconds after ignition, smoke was down to the floor throughout the open areas of the townhouse, and the fire was in a decay stage due to the reduced level of oxygen inside the townhouse. At approximately 215 seconds after ignition, the front door was opened. This action resulted in a bidirectional flow at the front door. Hot, higher-pressure fire gases were flowing out of the top of the doorway and cool, lower-pressure outside air was being entrained into the fire room through the lower portion of the doorway. Smoke near the floor in the living room cleared, and the fire began to increase in heat-release rate and in physical size. At 250 seconds after ignition, the living room window was vented by a firefighter. The window glass was completely cleared from the window frame within 20 seconds. Given the hot, fuel-rich conditions in the living room, the additional ventilation resulted in flames coming out of the window and doorway by 280 seconds after ignition. A full transition through flashover in the living room occurred within a minute of venting the living room window.

Figure 4: Idealized fire-behavior graph showing a typical ventilation-controlled fire.

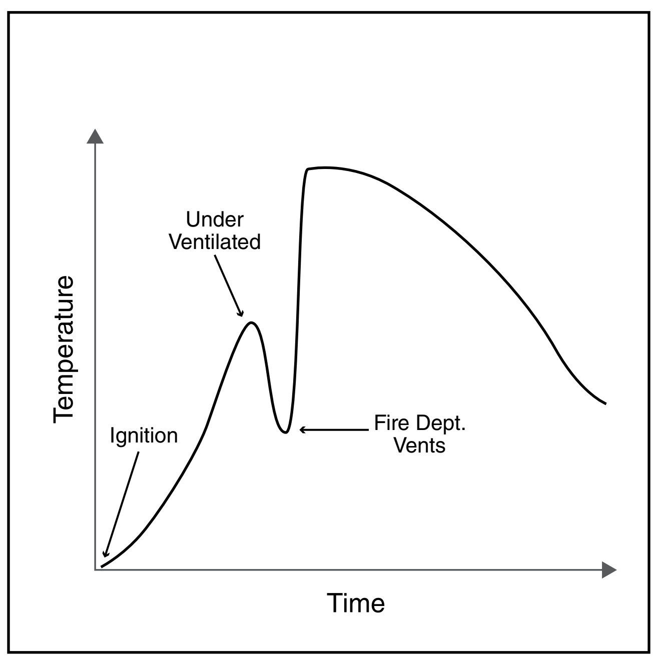


Figure 5 shows the temperature in the living room during the experiment described in the previous paragraph. Notice the shape of the temperature curves with respect to time: fire growth, followed by decay, or a decrease in heat-release rate, which is then followed by a significant and rapid increase in heat-release rate and gas temperature because of the increased availability of oxygen to the fuel-rich environment of the fire room.

Flow Path

Flow path is another concept central to fire dynamics in structures. The *flow path* is the volume between an inlet and an exhaust that allows the movement of heat and smoke from a higher-pressure area within the fire area towards lower-pressure areas accessible via doors, windows, and other openings. Depending on its configuration, a structure can have several flow paths. Operations conducted in the flow path, between where the fire is and where the fire wants to go, places firefighters at significant risk due to the increased flow of fire, heat, and smoke toward their positions. This risk is true for natural-ventilation cases with or without wind. In cases with the potential for wind to affect the heat-release rate and the movement of the fire, it is important to keep the wind at your back and to attack the fire from the upwind side.

Several LODDs have occurred where quite literally the difference between life or death depended on whether or not a glass window broke. In effect, death occurred due to a change in ventilation, while firefighters worked in a space between the fire and a lower-pressure area where the fire wanted to go — the path of least resistance. This was the case with the three Fire Department of New York City (FDNY) firefighters who lost their lives in the Vandalia fire in Brooklyn (Madrzykowski & Kerber, 2009), the two Houston firefighters who lost their lives in a ranch house fire (Barowy & Madrzykowski, 2012), and the two San Francisco firefighters who were killed in the Diamond Heights fire (San Francisco [CA] Fire Department, 2011).

NIST conducted measurements to examine the impact of flow path and wind on fires in a mock-up apartment built in its laboratory. The fires were ignited in the bedroom of the apartment. Prior to the failure or venting of the bedroom window, which was on the upwind side of the experimental apartment, the heat-release rate from the fire was on the order of 1 megawatt (MW). Once the bedroom window was opened, the heat-release rates from post-flashover structure fires were typically between 15 MW and 20 MW. When the door from the apartment to the corridor was open, temperatures in the corridor area near the open doorway, 0.9 m (3 ft) above the floor, exceeded 600°C (1,112°F) for each of the experiments. The heat fluxes measured in the same location, during the same experiments, were in excess of 70 kW/m². Even in full protective gear, a firefighter cannot survive these extreme thermal conditions. These conditions occurred within 30 seconds of the window failure. The study also found that application of water from the exterior through the vent on the upwind side significantly cooled the fire gases and suppressed the fire (Madrzykowski & Kerber, 2009).

Figure 5: Temperature time-history curves from a furnished room fire that was initially closed and then vented to the outside by opening the front door and venting the living room window.

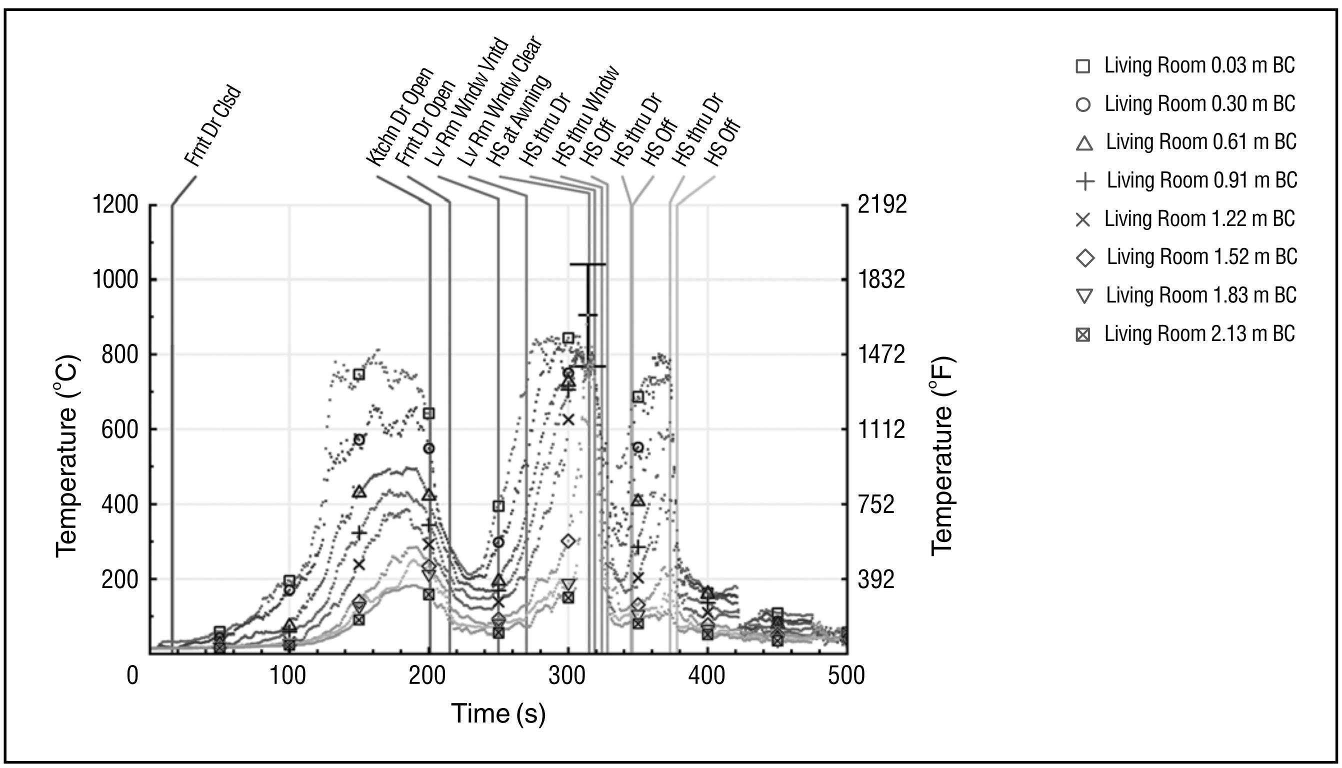
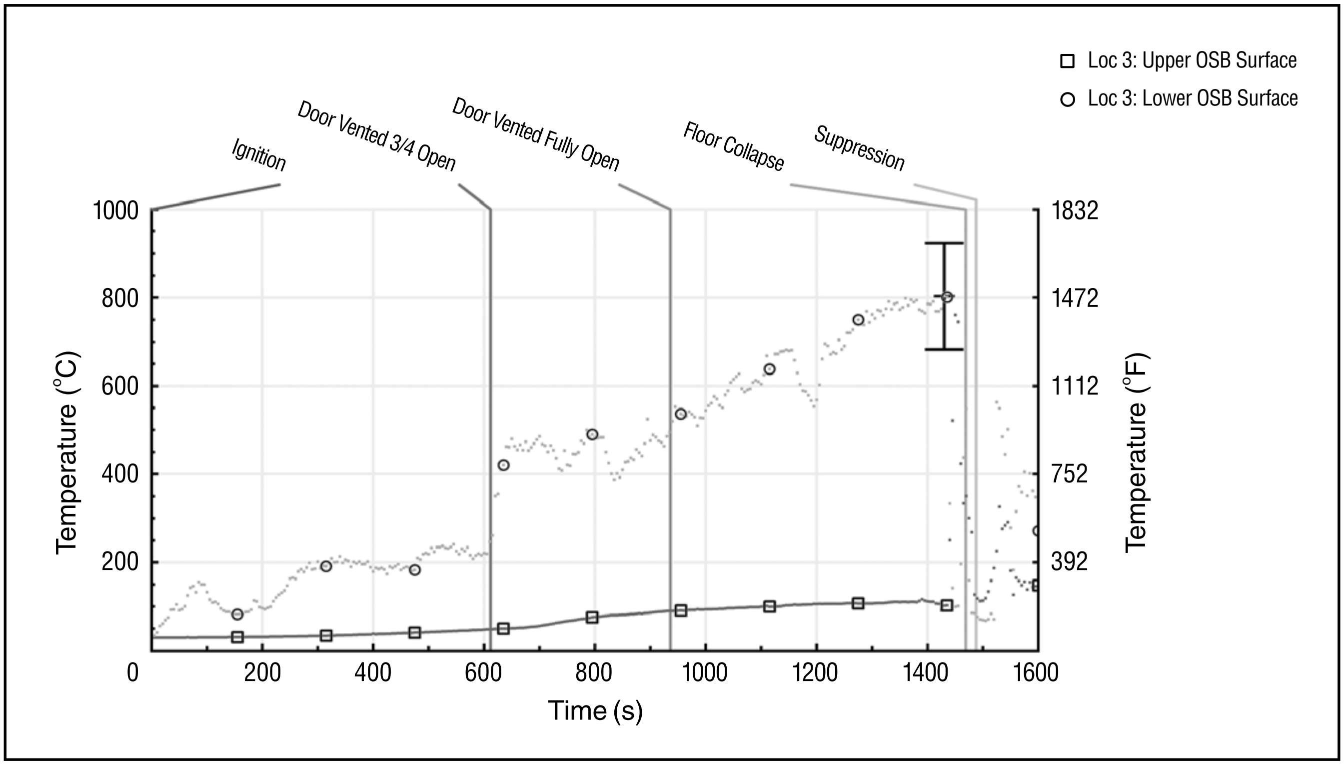


Figure 6: Temperature time-history curves comparing the temperature of the fire-compartment (lower) side of oriented strand board (OSB) subflooring and the temperature of the upper-level room side of the OSB. The measurement locations are separated only by the OSB, which is approximately 18 mm (0.75 in) thick.



Operating Above the Fire

Fire operations above a fire in a wood-framed structure with an unprotected engineered-wood floor assembly bring together several of the risk factors that we have been discussing. In a basement fire, the exposed wood-floor assembly is a sufficient and well-placed fuel load that can support rapid-fire growth and the transition through flashover if there is enough ventilation available. Due to the excellent insulation capabilities of wood-based subflooring and floor coverings, even firefighters with thermal imagers might be unaware that a post-flashover fire burns below them and that the structural integrity of the floor on which they are standing is compromised until they fall through it. The thermal imager can only sense increased temperature due to heat flow through the floor and floor coverings. During basement fire experiments, NIST has measured temperatures in excess of 800°C (1,400°F) on the lower (fire side) of the floor assembly while the temperature on the upper side of the flooring was 100°C (200°F) or less just prior to the collapse of the floor as shown in **Figure 6** (Madrzykowski & Kent, 2011).

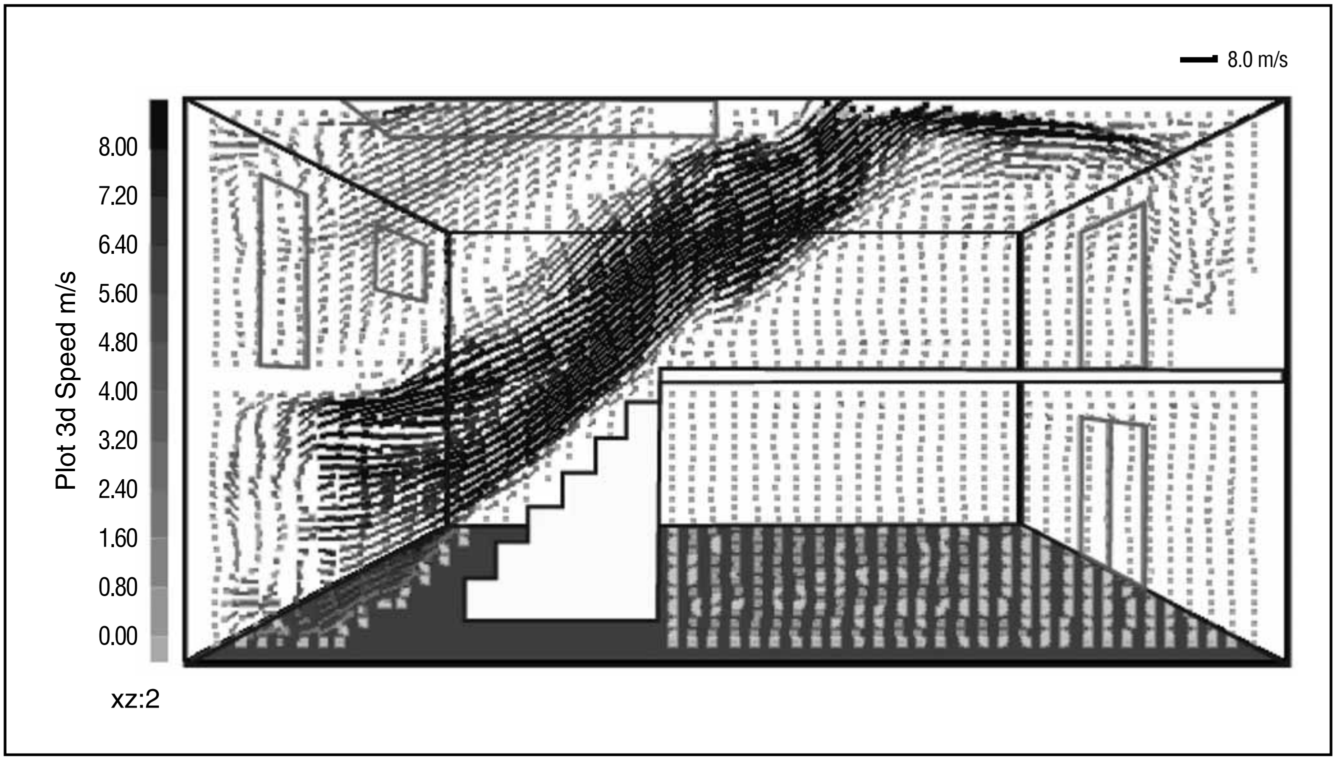
In basement fires, current practice calls for firefighters to fight their way down the stairs to suppress the fire. If the firefighters survive crawling on a floor assembly that may be burning underneath them, they will find the stairway and place themselves in the flow path between the fire in the basement (high temperature/high pressure area) and the open front door (exhaust vent to lower temperature/lower pressure area) through which they entered the house. In other words, the firefighters are trying to work their way down the chimney of a burning fireplace. This is a high-hazard location with the potential for high convective heat transfer. This scenario is similar to the one that claimed two firefighters' lives in the Cherry Road fire in Washington, DC (Madrzykowski & Vettori, 1999). The flow path from the post-flashover fire in the basement up the stairs is shown in **Figure 7**.

What approach works with this difficult fire scenario? Is it water applied from the exterior through a basement window or door? This exterior offensive tactic is known by many names: *early water, blitz attack, resetting the fire, softening the target,* and *hitting it hard from the yard*, to name a few. In basement-fire experiments NIST conducted with FDNY and UL®, flowing a hose stream into a basement window for 60 seconds reduced the temperatures from 900°C (1,700°F) to 150°C (300°F) in the basement. The temperatures at the top of the stairs leading to the basement decreased from 300°C (600°F) to 100°C (200°F). In addition, the temperatures throughout the rest of the townhouse also decreased due to the exterior hose-stream application. Applying water through the window did not push or spread the fire, and no excess steam was forced throughout the structure. Applying water through the window into the fire area quickly mitigated the hazard. **Figure 8** shows this example in graphic form.

Research Summary

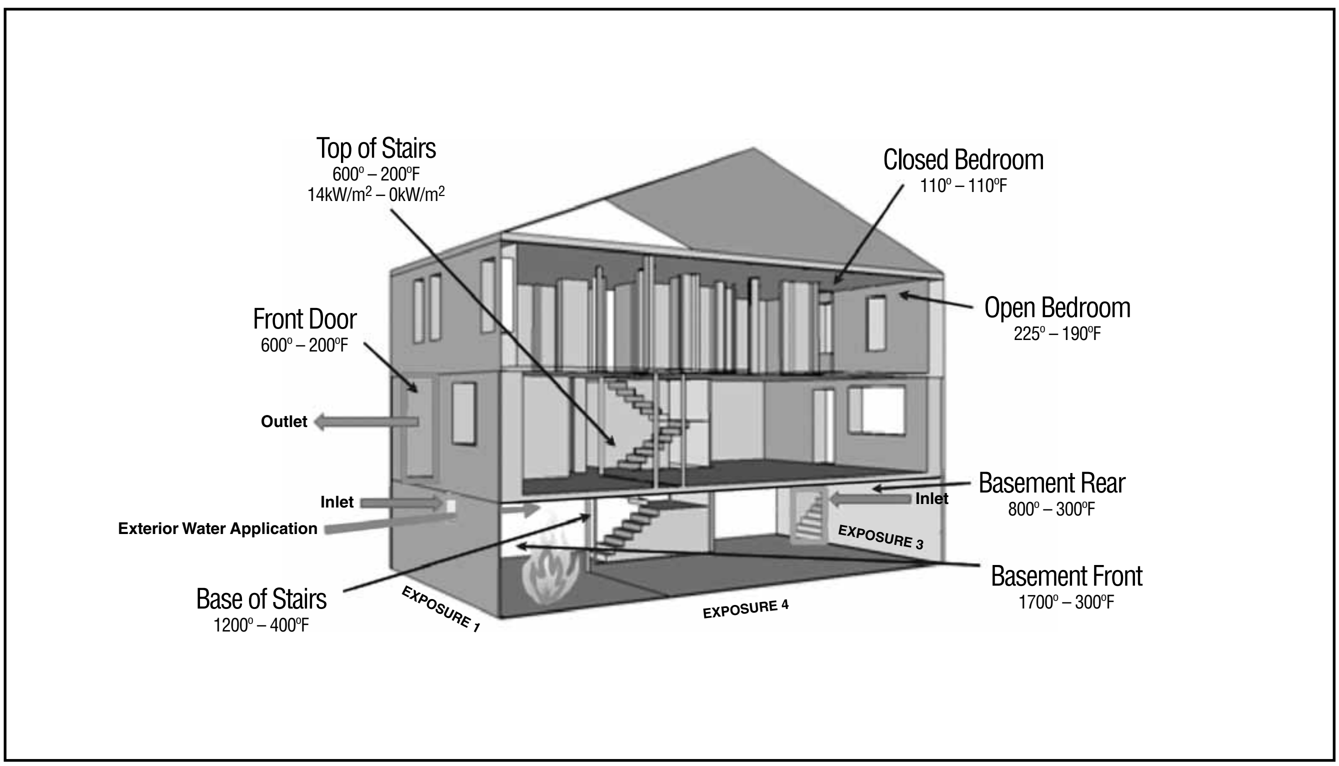
Many of the fire-dynamic applications on the fireground presented above earlier were intuitive. Some were not.

Figure 7: The flow path of high-momentum fire gases going up the stairs can be seen in this NIST Fire Dynamics Simulator model of the Cherry Road fire. The firefighter victims were all working in the room at the top of the stairs.



While many in the fire service recognized some of the increased hazards in residential fires individually, few understood the synergy between the synthetic fuel loads, reduced compartmentation, and the lightweight and energy-efficient construction. Fire-test results have shown that the synthetic-fuel fire is more reactive to the introduction of oxygen than are fires fueled by wood and cotton. For the fire service, this fact? means that synthetic-fuel fires are less forgiving in terms of how quickly conditions on the fireground can change. The thermal conditions generated by a fire can exceed the material limitations of firefighters' personal protective equipment (PPE) by more than 500°C (1,000°F). Of course, human thermal limitations are significantly

Figure 8: The impact of flowing a hose stream into a basement fire through the basement window at 180 gpm for 60 seconds.



lower than that. To escape harm, firefighters must understand the capabilities and the limitations of their PPE.

Given the firefighter fatality and injury rates and the challenges faced, fire department leaders need to consider revising their tactics to improve firefighter safety and effectiveness. Controlling the oxygen leg of the fire triangle through door and flow-path control and controlling the heat side of the fire triangle through early suppression from the exterior must be considered, even if these tactics go against current practice.

Firefighters at all levels need to be armed with improved knowledge about fire dynamics, their workplace, and the equipment that they use to protect themselves. For example, smoke is fuel??, venting does not always equal cooling, and most structure fires are ventilation-limited (fuel-rich) and therefore very reactive to additional oxygen.

Fire officers need to locate and assess the fire and then consider all available tactics before directing their crews, using the safest and most effective tactics possible. This option is good not only for the firefighters but also for victims trapped in the building. What are some of these tactical options? Keep the wind at your back, and stay upwind of the fire. Identify and control potential flow paths by managing ventilation (i.e., open doors and windows). An exterior direct attack on the fire from the burned side may be the best option. Use all available options to prevent firefighters from working above a fire with an unrated floor assembly.

Leadership and Implementing Change

Now that research has elevated our understanding of fire dynamics within structures, fire service leaders must use the data to develop educational and training tools and to share information across the ranks and generations of firefighters. Standard operating procedures (SOPs) must be revised to incorporate our new understanding. All of the elements of training, certification, and practice must be coordinated to make the most effective use of the knowledge.

As a result of the assistance of the U.S. Department of Homeland Security/Federal Emergency Management Agency (DHS/FEMA) to firefighter research and development grants, more high-quality research is being conducted with the fire service than at any other time in history. The research yields not only reports and numerical data but also experiment videos useful for educating the fire service. Producers of training materials such as the International Fire Service Training Association (IFSTA) are incorporating the research results in its manuals and online training apps.

Fire service leaders must embrace research-based tactics in order to motivate their instructors and get buy-in from their staff. Annual training needs to be conducted and SOPs need to be revised so that all members of the fire department, not just the new candidates, are aware of flow-path hazards and the new technology capabilities. It will also be important to work with mutual-aid fire departments to ensure that they understand that you have added new tools and options to your department's playbook.

Implementation

Being a leader in changing the status quo requires knowledge, fortitude, and diplomacy. It will require hard choices in times of lean resources to dedicate effort to revising SOPs and to developing and providing additional training for your seasoned firefighters. Change is best accepted in a supportive environment when leadership is leading by example.

A great example of implementing change is available from the largest fire department in the U.S.: FDNY. FDNY had a history of injuries and deaths in wind-impacted fires in high-rise buildings. They embraced researchers and representatives from fire departments across the country and around the world to understand the problem and possible solutions. They supported real-scale fire experiments in a high-rise building as a means to find a better way of fighting a high-rise fire (Madrzykowski & Kerber, 2009; Kerber & Madrzykowski, 2009).

Once the findings from the NIST laboratory and high-rise studies were presented to them, the leadership in FDNY moved swiftly to implement changes to improve the safety of their firefighters. They started a pilot program in two areas of the city. The firehouses in these areas received additional training and new equipment such as positive-pressure ventilation fans, wind-control devices, and high-rise nozzles. A DVD-based training program was developed on the hazards of wind-impacted fires and the use of flow-path control, positive-pressure fans, and exterior hose streams. That program was distributed across the department. For annual training day, a program was developed in which firefighters conducted hands-on training evolutions with the new equipment and learned about the fire dynamics behind the new tactics. Then FDNY installed the *Diamondplate* system, computer kiosks in all firehouses that allow the department to push training materials on a weekly basis to the firefighters. FDNY partnered with Polytechnic Institute of New York University (NYU-Poly) to develop an interactive computer-based training program, ALIVE, on wind-driven fires based on the FDNY materials and the NIST reports (NYU-Poly Fire Research Group, 2008). Within 18 months after the completion of the experiments on Governors Island, NY, FDNY firefighters were using the new tools and tactics and saving their own.

FDNY then reexamined their ventilation practices on non-wind-impacted fires, based on what was learned about the modern fire environment and flow paths from the wind-driven study and additional research conducted with NIST and UL®. As a result, a new ventilation bulletin has been issued by the department that is based on and incorporates the science of fire fighting (FDNY, 2013).

Summary

These findings are the result of research that has been conducted in conjunction with the fire service. The overarching objective of all of the studies was to increase the safety and the effectiveness of firefighters. These studies were designed to focus on research results that had application on the fireground. In order for these studies to occur, it took leadership within the fire service to question the status quo. It took leadership to engage the researchers and ask the hard questions. Now that researchers and members of the fire service have a better understanding of the fire dynamics of a structure fire, that information must be shared. Now that the reports, data, videos, and training materials are available, that information must be taught. Leadership will be required in every fire department to educate the fire service as a whole and to implement needed changes to current fire-fighting practices that make fire conditions worse before fire control and rescue can be achieved. Now is the time to embrace the knowledge of fire dynamics based on chemistry and physics, employ a size-up of every fire scene, and then choose the fire-fighting tactics and task assignments based on that assessment.

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