ISSN 1554-3439

International Fire Service Journal of Leadership and Management

Building Theory to Impact Practice

IFSJLM

Volume 15
2021

Peer-Reviewed Article

Dr. Lori Moore-Merrell, International Public Safety Data Institute, Chantilly, VA, USA
Dr. Steve Kerber, Fire Safety Research Institute, Underwriters Laboratories, Columbia, MD, USA
Dr. Gavin P. Horn, Fire Safety Research Institute, Underwriters Laboratories, Columbia, MD, USA, and University of Illinois, Fire Service Institute, Urbana-Champaign, IL, USA
Dr. Denise L. Smith, University of Illinois, Fire Service Institute, Urbana-Champaign, IL, USA, and Skidmore College, Saratoga Springs, NY, USA

Effects of Crew Size on Firefighter Health and Safety

Abstract

Firefighters' safety during fire responses depends on sound policies and procedures that ensure they can do their jobs efficiently and effectively. Decisions on *vehicle crew size* and *total effective response force deployment* should be based on the best available evidence. It is imperative that fire department leaders and political decision makers understand how the fire department resource deployment impacts community safety related to civilian injury and death, firefighter injury and death, and property loss. This state-of-the-art review provides a comprehensive examination of (a) results from multidisciplinary (e.g., engineering, medicine, fire technology, and social sciences) research efforts, (b) published data, (c) industry standards, and (d) expert opinion. The review examines the effect of emergency response vehicle crew size and total effective response force deployment on firefighters' health and safety risks, recognizing that firefighter health and safety is necessary to ensure that firefighters can effectively perform their jobs and protect their community. We conclude, based on available evidence, that the crew sizes and the effective response force sizes recommended in NFPA 1710*, Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments,* should be considered the ***minimum*** to provide for firefighters' health and safety. Whenever possible, additional resources should be provided to address firefighter physiological stress, limit fire growth, and mitigate occupational exposure in today's rapidly evolving fireground.

Keywords: firefighter, crew size, health and safety, effective response force

Introduction

Fire chiefs are often faced with policies created by municipal officials who are challenged to balance community service expectations with finite budgetary resources. Unfortunately, many officials who are acutely aware of budgetary challenges often lack the solid technical foundation they need to properly evaluate the impact of staffing and deployment decisions on the safety of the public and firefighters. This often results in planning fire department resources to meet budget needs, rather than budgeting to ensure the proper resource allocation and deployment to meet critical service and safety needs.

Effectively managing a fire department requires proper emergency resource allocation to known risk environments in local communities. It is imperative that fire department leaders, as well as political decision makers, consider how fire department resource deployment in their local community affects community outcomes in three important areas: (1) civilian injury and death, (2) firefighter injury and death, and (3) property loss. This article focuses on fire department response to structure fires and the resulting impact on firefighter safety, injury, and death.

Fire continues to be a devastating event in communities across the country, with structure fires accounting for most civilian casualties. National Fire Protection Association (NFPA) estimates indicate that structure fires account for only 38% (499,000) of fires nationwide, and 72% (357,000) of structure fires in homes. Structure fires account for a disproportionate share of losses: 77% (2,630) of fire deaths, 83% (12,160) of fire injuries, and $10.7 billion of direct dollar losses (Evarts, 2018).

Community leaders recognize that fire protection is an essential service, and more than 32,000 fire departments operate with a mandate to protect lives and property of residents and visitors in their community. Although the overarching goal of the fire service is to prevent fires by ensuring proactive protections like fire alarms, smoke alarms, and automatic sprinklers are in place, the sad reality is that structure fires still occur. Therefore, there is an obligation to assess personnel resources deployed to these events, the environment in which they work, and the physical effects on responding firefighters.

Fire departments must establish policies on response crew size and total effective response force (ERF) deployment, incident arrival, and assembly in order to ensure operational effectiveness and fulfill their responsibility to protect their communities. In addition, fire departments have an obligation to consider the health and safety of the firefighters they deploy to face hazardous working conditions. These conditions are becoming more hazardous due to changes in building construction and modern furnishings.

NFPA 1500™, *Standard on Fire Department Occupational Safety, Health, and Wellness Program*, addresses response resources in the context of firefighter health and safety, but it stops short of definitively linking the effects of different crew sizes on responding vehicles to the health and safety of firefighters. The industry standard — NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments* — details the resources needed to adequately respond to different types of hazards and has implications for firefighter health and safety. NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments,* is a companion document for volunteer fire departments, but it is not based on performance objectives as is NFPA 1710.

Regardless of fire department organization and the NFPA standard(s) followed, protecting firefighter health and safety is an obligation of the fire chiefs and elected officials who oversee fire departments. This obligation is critical to protecting the community, as it ensures that firefighters can perform their essential public safety work. To make staffing decisions, leaders must understand how the size of responding crews and the timeliness of ERF assembly affect firefighter health and safety.

This review synthesizes research from multiple disciplines in order to:

- Detail the health and safety risks that firefighters face as they perform firefighting work
- Describe the work activities that firefighters must perform
- Characterize the work environment in which firefighters perform their duties
- Discuss the effect of response crew size and the timing of ERF assembly on firefighter health and safety
- Provide recommendations for policy makers to ensure effective and safe deployment of resources

Firefighter Health and Safety Risks

Firefighting is widely acknowledged as a dangerous occupation. Between 2009 and 2018, NFPA reported that 701 firefighters died in the line of duty, including 599 municipal firefighters from career and volunteer departments (Fahy & Molis, 2019, and reports from previous years). **Table 1** presents the number of fatalities for municipal firefighters by cause and nature for the 10-year period between 2009 and 2018 as reported by the NFPA. In 323 (53.9%) of the 599 duty-related municipal firefighter deaths in the past ten years, overexertion/stress/medical was listed as the cause of death. Sudden cardiac death was the nature of fatality most commonly reported by the NFPA. Stroke, a condition related to blood vessels in the brain, was identified as the nature of the fatality in another 29 firefighters, meaning that cardiovascular disease was responsible for more than half of line-of-duty deaths reported by the NFPA in the past 10 years. Internal trauma and crushing, asphyxiation and smoke inhalation, and burns were responsible for another 252 firefighter fatalities.

In addition to the fatalities addressed above, **Table 2** shows over 665,000 injuries were reported during this 10-year period, and it is widely acknowledged that injuries are underreported (see Campbell & Molis, 2019, and previous reports in the series). The majority of injuries were due to strains, sprains, and muscular injury. Some of these injuries include serious back or joint injuries that can require long treatment periods and expensive backfilling of positions. Over 7,000 firefighters suffered non-fatal cardiac events and strokes during the 10-year period. Burns, smoke inhalation, or the combination of the two resulted in injuries to 48,550 firefighters.

Table 1
Career and Volunteer Municipal Firefighter Fatalities Over a 10-Year Period (2009-2018)

Cause of the Fatality as Reported by the NFPA	Number of Fatalities	Percent of Total Fatalities
Overexertion/stress/medical	323	53.9%
Struck by object	61	10.2%
Motor vehicle crashes	47	7.9%
Lost inside/caught or trapped	41	6.8%
Fell	35	5.8%
Struck by vehicle	27	4.5%
Structural collapse	25	4.2%
Rapid fire progress	23	3.8%
Other[a]	17	2.8%
Nature of the Fatality as Reported by the NFPA	**Number of Fatalities**	**Percent of Total Fatalities**
Sudden cardiac death	287	47.9%
Internal trauma & crushing	179	29.9%
Asphyxia including smoke inhalation	51	8.5%
Stroke	29	4.8%
Burns	22	3.7%
Other[b]	31	5.2%
TOTAL	**599**	**100%**

Source: Campbell & Molis, 2019, and previous reports in the series.

Note. This table does not include data from non-municipal firefighters, which may include employees of forestry agencies, industrial fire brigades, the military, the federal government, prison crews, and impressed civilians as described at https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders/Firefighter-fatalities-in-the-United-States/Firefighter-deaths. This list does not include firefighters at the World Trade Center, September 11, 2001.

[a] Other includes assault/murder, exposed to electricity, exposure, and caught underwater.
[b] Other includes gun shot, unspecified medical, drowning, electrocuted, suicide, drug overdose, asthma, and pneumonia.

Table 2
Firefighter Injuries over a 10-Year Period (2009-2018)

Nature of the Injury as Reported by the NFPA	Number of Injuries	Percent of Total Injuries
Burns (fire or chemical)	20,720	3.2%
Smoke or gas inhalation	20,445	2.9%
Burns and smoke inhalation	7,385	1.0%
Other respiratory distress	9,280	1.4%
Strain, sprain, muscular pain	365,860	55.3%
Wound, cut, bleeding, bruise	100,345	15.2%
Thermal stress (frostbite, heat exhaustion)	25,765	3.8%
Dislocation, fracture	17,380	2.7%
Cardiovascular disease (heart attack/stroke)	7,955	1.2%
Other	90,835	13.6%
TOTAL	**665,970**	**100.0%**

Source: Campbell & Molis, 2019, and previous reports in the series.

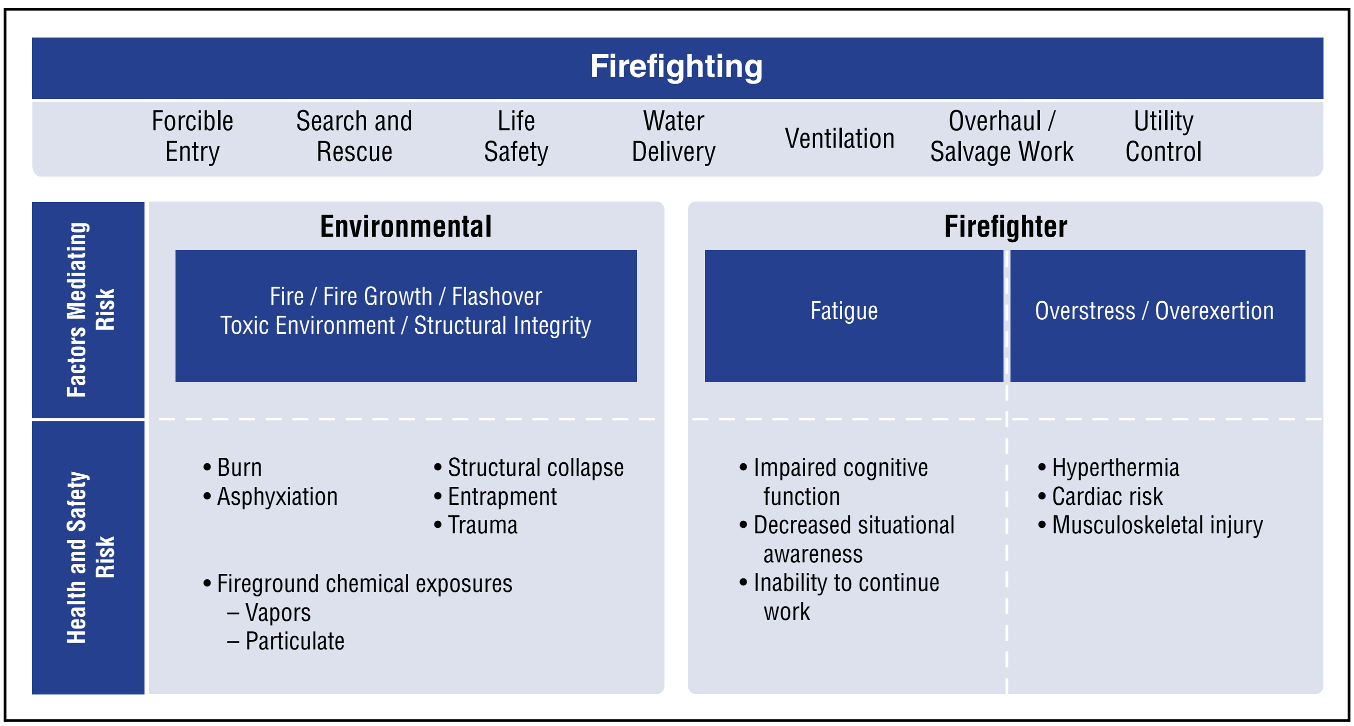
Calculating the number of injuries and fatalities may be easier than understanding what causes them. There are many hazards that lead to injury and fatalities, including fire, smoke, building components that fail and collapse, and pathophysiological responses to the stress of firefighting. A firefighter may be injured or killed by one acute event or a combination of events. One event may lead to another more serious injury, such as trauma from a fall leading to burns or asphyxiation when the firefighter becomes trapped under debris. Fire departments must understand the risks that firefighters face and plan their responses to ensure they can meet the operational needs of firefighting and mitigate risk appropriately. By considering these factors, policy makers can take meaningful steps to mitigate risk.

In addition to the acute risks that firefighters face, chronic exposure to products of combustion can have long-term impacts on firefighters' health. The National Institute for Occupational Safety and Health (NIOSH) has found cancer incidence and mortality rates in firefighters to be significantly higher than the national average. Mesothelioma and cancers of the esophagus, intestine, kidney, and oral cavity are particularly prevalent in firefighters. Research also shows an exposure-response relationship for lung cancer and leukemia (Daniels et al., 2014, 2015; Pinkerton et al., 2020). The International Association of Fire Fighters (n.d.) reports that occupational cancers accounted for 66% of the line-of-duty deaths among their membership of active and retired firefighters between 2002 and 2019. It is important to note that cancer-related deaths are not included in the NFPA statistics reported earlier.

Figure 1 depicts the health and safety risks that a firefighter faces in the context of the firefighting work performed, the environment in which it is performed, and the physical, physiological, and psychological strain it places on the firefighter. The following subsections address some of the major health and safety risks that firefighters face and discuss the complex interactions between different types of risk that increase the potential for injury and death in the line of duty.

Figure 1

Relationship Between Firefighter Health and Safety Risks, and Firefighting Work, and the Firefighting Environment



Burns and Asphyxiation

Perhaps the two most readily recognized risks that firefighters face are burns and asphyxiation due to the hot, smoke-filled environment in which they work. These conditions can occur separately or in combination. Burns and asphyxiation occur most often when fire conditions change rapidly, overcoming a firefighter. They also occur when a firefighter becomes lost or trapped due to the collapse of building structures or the excessive fatigue that makes escape impossible or that impairs cognitive function. Burn injuries vary in severity, depending on the type, depth, and extent of the burning. Severe burns can be fatal.

Structural Collapse/Trauma/Entrapment

Traumatic injuries are a broad category of sudden onset physical injuries that require immediate medical attention and can lead to death. Any part of the body can be injured by trauma, and traumatic injuries can vary greatly in severity. Traumatic injuries include crushing injuries, head injuries, and back injuries. While the traumatic fatalities are devastating, traumatic injuries can lead to multiple surgeries and require months or years of rehabilitation.

There are numerous ways that a firefighter can be injured or killed by traumatic events on the fireground. Building components can collapse and fall on a firefighter, or firefighters can fall through floor or roof systems that have been structurally compromised. Firefighters can fall from ladders or elevated work locations that are necessary to complete fireground missions. Uncontrolled fire growth provides the greatest risk for structural collapse. Structural collapse can lead to trauma, entrapment, and/or burns and asphyxiation, further exemplifying the overlapping nature of the risks that firefighters face.

Chemical Exposure Risk

More than ever, firefighters are becoming aware of chemical exposure risks on the fireground. Fires involving common household furnishings in residential structures can produce hundreds of compounds, including those that exist primarily in the vapor phase (e.g., benzene, styrene, 1,3-butadiene, formaldehyde, vinyl chloride, dioxins) and those that exist primarily in the solid phase (Austin et al., 2001; Jankovic et al., 1991). Many of these compounds are known or probable human carcinogens.

Fireground exposures can be experienced through inhalation, ingestion, and dermal absorption. Inhalation is the most direct route of exposure for firefighters who do not wear respiratory protection inside or outside the structure. Products of combustion may also be absorbed through the skin. The longer a chemical is present on the skin, the more time is available for transdermal absorption.

Fatigue

Fatigue is a natural result of firefighting activity because firefighters perform heavy muscular work while wearing heavy, insulative, and protective clothing. However, the potentially dangerous results of excessive fatigue are seldom addressed. In addition to causing medical events related to overexertion, fatigue can decrease the physical work firefighters can perform. An impaired ability to perform the time-critical work of applying water to the fire can allow the fire to grow, placing both civilians and firefighters at greater risk. Fatigue can also decrease situational awareness because changes in cognitive function may jeopardize a firefighter's ability to make sound decisions.

Overexertion/Medical Events

There are numerous injuries and fatalities that are broadly attributed to overexertion. The most common medical issue encountered on the fireground is heat exhaustion. Firefighters who perform heavy muscular work while wearing personal protective equipment (PPE) have an increase in core body temperature that can lead to heat exhaustion. Most firefighters who suffer heat exhaustion will recover if they are provided with appropriate cooling, hydration, and rest. Heat stroke, the complete breakdown of the body's ability to thermoregulate, is a more serious and rarer condition than heat exhaustion.

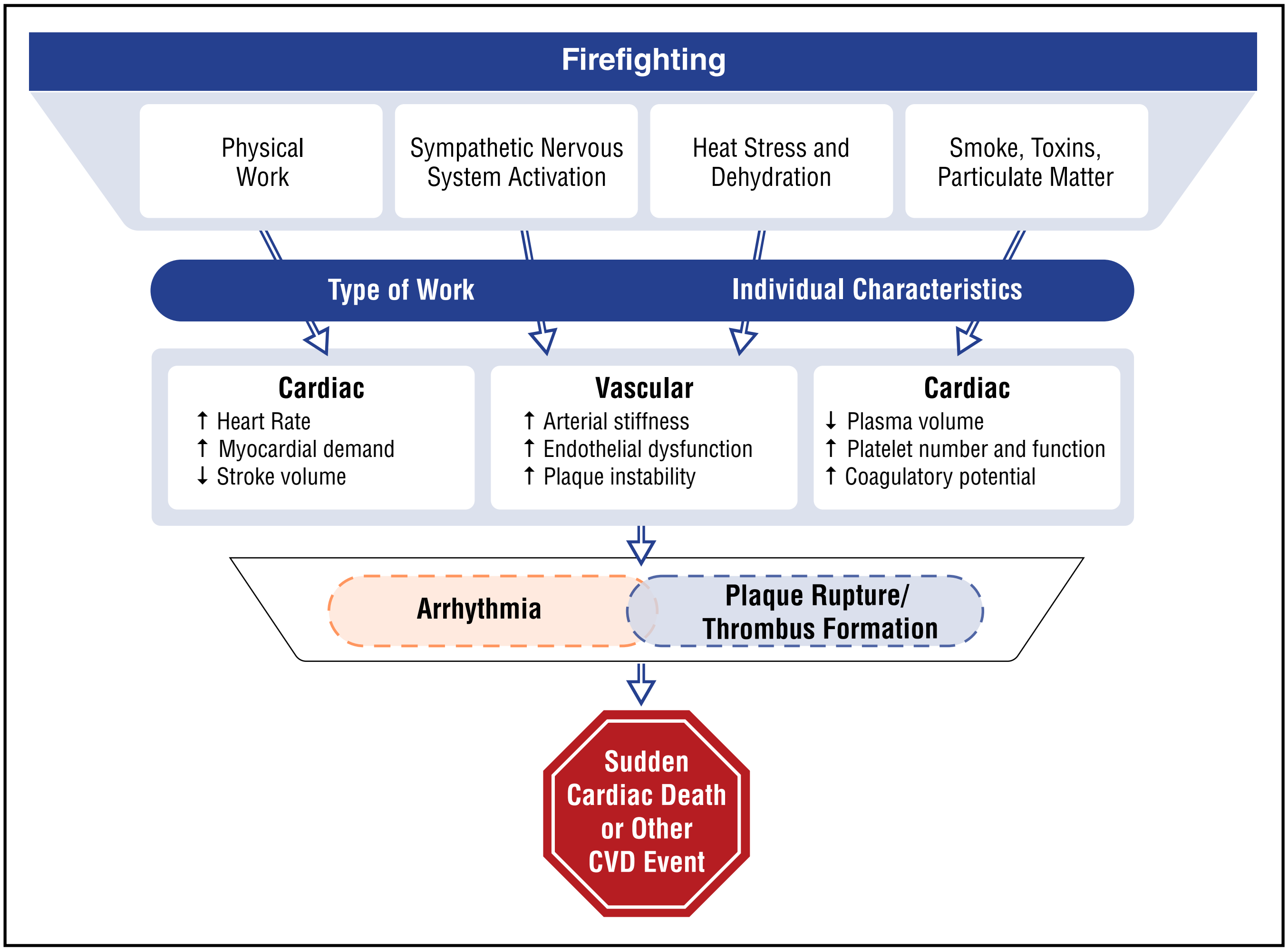
Musculoskeletal injuries are also more likely in a firefighter who is fatigued. Deteriorating biomechanics and/or impaired cognitive functions make recognizing hazards more difficult. These injuries, including sprains and strains, result in more than 50% of reported injuries.

Cardiovascular Events

Cardiovascular events are a major concern in the fire service. Research demonstrates that firefighting activity dramatically increases the risk of suffering a sudden cardiac event. In fact, a firefighter is 10 to 100 times more likely to suffer sudden cardiac death after firefighting than a firefighter engaged in non-emergency duties (Kales et al., 2007; Smith, Haller et al., 2019). More than 7,000 firefighters suffered non-fatal, duty-related cardiovascular events in the last 10 years (Campbell & Molis, 2019, and previous reports in the series).

As outlined in **Figure 2**, cardiovascular events may be triggered in vulnerable individuals by multiple stressors that are part of firefighting work, including physical exertion, activation of the sympathetic nervous system, heat stress and dehydration, and exposure to smoke and particulate matter. Research of the general population has shown that strenuous physical work, sympathetic stimulation, and particulate matter are all factors that increase the risk of sudden cardiac death (Mittleman, 2007; Willich et al., 1993). Firefighters are exposed to all these risk factors and often to a greater extent than the public.

Figure 2
Model Linking the Physical and Physiological Stress of Firefighting to Cardiovascular Responses and to Potential Triggering of a Cardiovascular Event



Source: Smith et al., 2013.

Firefighting Work

The health and safety risks that firefighters face are multifactorial and often overlap. These risks are directly related to the work firefighters perform and their work environment.

Firefighting crews must address four priorities at a fire scene:

1. Life safety of occupants and firefighters
2. Confinement and extinguishment of the fire
3. Property conservation
4. Reduction of adverse environmental impact

Firefighting personnel conduct interdependent and coordinated activities to meet these priority objectives. Specific tasks, such as advancing a hose line to the fire, ventilation, and search and rescue, can be conducted simultaneously or sequentially. Conducting these activities simultaneously is the most efficient manner. Performing tasks sequentially can limit coordination and delay tasks on the fireground, contributing to rapid fire growth and escalating risk.

Each arriving emergency vehicle (fire engine or truck) transports firefighters to the scene. The group of firefighters associated with a particular emergency vehicle is called a *fire crew* or *fire company*. According to NFPA 1710 (2020), the minimum crew size is four firefighters, including one designated as an officer. This requirement is important to understand as on scene tasks and risks are explained.

Because every fire can present a unique set of conditions, fire department leaders should match the mobile and personnel resources they deploy to the risks they are likely to encounter at the scene. The risks vary according to building size, structure type, and occupancy load. NFPA 1710 identifies four structure categories:

1. Single-family
2. Open-air strip malls
3. Garden-style apartment buildings
4. High-rise buildings greater than 75 feet (23 m)

The standard also indicates the minimum number of firefighters who must be available on scene for "low hazard" single-family dwelling responses (16), "medium hazard" strip malls or garden apartment responses (27), and "high hazard" high-rise fires (43). The resources deployed include firefighters, vehicles, and equipment. Another element that must be considered in the resource/risk match is each crew's arrival, overall assembly, and intervention time(s). The arrival and intervention time of the responding vehicles and crews often depends on how many fire stations are in the community, where the stations are located, and whether the stations are sufficiently staffed with vehicles and crews to be effective during an emergency response. Fire department total response time calculations must include call intake and dispatch, turnout time for firefighters, and travel time for each responding fire crew to arrive on scene. For safe and effective firefighting operations, it is critical that ERFs arrive, assemble, and engage on the scene in a timely manner.

Local communities preplan emergency response deployments based on building sizes, structure types, and occupancy types. It is critical that fire suppression activities and search and rescue operations begin as quickly as possible. Because many cities lack resources to ensure an ERF is available from the same station, fire crews are often deployed from multiple fire stations. Fire departments assign geographic areas in close proximity to each fire station as first due areas. Each fire station in the U.S. has a predetermined first due area. If a fire or emergency incident occurs at an address inside that geographic area, the vehicles (companies) in that fire station are dispatched to respond and arrive first on the scene. The second and subsequent crews that are part of the ERF often respond from other stations outside the immediate area to work with the first-arriving crew. Communities unable to send an ERF on their own may rely on mutual or automatic aid. Mutual aid is an agreement between or among fire departments to help each other across jurisdictional boundaries and occurs only when local emergencies exceed local resources. Automatic aid is a more formal agreement to send the additional resources automatically.

At all fires, the first-arriving emergency response vehicle and crew must complete several tasks quickly. The officer from this crew establishes Incident Command, completes a scene size-up, and then determines the operational plan for the incident. The driver secures a water supply and engages and monitors the hydraulic pump on the engine to ensure water is available for fire attack. The remaining firefighters assigned to that initial crew position hose lines and prepare to intervene in fire suppression through a combination of exposure control, fire confinement, and fire extinguishment.

Figure 3 depicts how different crew sizes may be deployed at a representative point in time prior to structure entry. At a minimum, two firefighters are assigned to position a hoseline to apply water to the fire, and another member is charged with operating the pumping apparatus. As more members are available on the scene, a dedicated Incident Commander (IC) and an Intial Rapid Intervention Crew (IRIC) are established. A 3-person crew does not allow firefighters to enter the structure because there are not enough firefighters on the outside to facilitate a rescue should the fire dynamics change quickly and the entry crew become trapped. By comparison, a crew size of five provides enough firefighters to deploy the attack line for interior fire suppression and a back-up hoseline with an IRIC ready to engage should fire dynamics change for the worse. More firefighters in the initial crew means more required tasks can be done simultaneously and safely. Larger crews can also apply water to a fire from an interior position more quickly.

Figure 3

Deployment Scenarios at a Representative Point in Time prior to Structure Entry for Crew Sizes of (Top) Three, (Middle) Four, and (Bottom) Five Firefighters

Note. A 3-person crew does not allow firefighters to enter the structure while also supporting the "two in/two out" rule.

Additional vehicles/crews are dispatched at the same time as the first-arriving vehicle, but they may come from farther away and arrive minutes/seconds after the initial vehicle. As these additional crews arrive on scene, they provide firefighting resources to control the incident, stop risk escalation, and support a host of other activities. Because life safety is a priority, crews are often assigned to conduct search and rescue throughout the structure. Additional arriving crews may be tasked with laddering the building to support rescue, providing additional exterior means of egress, or assisting in ventilation to control smoke and increase survivability. Additional crews assigned to ventilate the structure may remove windows from the structure at the same level as the fire (horizontal ventilation) or create openings above the level of the fire through the roof, attic, or upper-story windows (vertical ventilation).

Firefighters assigned to overhaul use a variety of tools to locate hidden fires throughout the structure, particularly in wall and ceiling voids, and check to ensure the fire has been fully extinguished. Overhaul involves heavy physical work and may continue long after the initial fire has been extinguished. Salvage operations are conducted during fire suppression and/or overhaul to protect as much of the building and contents from smoke and water damage as possible.

Figure 4 provides an example of how an ERF of 16 firefighters and one IC may be deployed for a low-hazard, residential fire. (The figure shown wearing a white helmet is labeled the IC.) In this example, the fire department has responded with three engines and a ladder truck. Each vehicle is staffed with four firefighters (including one crew officer). The first engine to arrive on scene (labeled E1) is considered the fire attack engine and is the first to get water to the fire. The first engine officer assumes the role of IC until a higher-ranking officer (e.g., Battalion Chief, etc.) arrives, and command is officially transferred. Two of the firefighters on this crew take the attack line to the fire. The remaining crew member is the pump operator at

Figure 4
An Example Effective Response Force (ERF) of 16 Firefighters Deployed for a Low-Hazard Residential Fire with Firefighters Assigned to Engine 1 (E1), Engine 2 (E2), Engine 3 (E3), and Truck 1 (T1); Incident Commander (IC) Responds in a Command Vehicle

the engine who, along with the engine officer, remains outside the fire environment to be the IRIC. They are prepared to rescue the two firefighters entering the structure (as shown in the middle diagram in Figure 3).

In this scenario, the crew from the first ladder truck to arrive (T1) divides into two teams of two firefighters to conduct search and rescue throughout the structure, raise ladders to second-story windows to provide egress for trapped occupants and firefighters, and ventilate the structure as needed to assist with fire extinguishment and the release of toxic gases. The second engine to arrive (E2) establishes a sustained water supply to the first engine using a nearby fire hydrant and connects a backup attack line to get water to the fire. The crew members on the third engine (E3) become the designated RIC, which allows the E1 officer to move up to supervise and assist the members on the initial attack line (if Command has been transferred to another IC).

Depending on the structure type and fire growth, the initial full-alarm ERF may require more crews and can be upgraded if the IC calls for more resources. **Table 3** provides the crew size and ERF that NFPA 1710 (2020) recommends for different hazard levels. In addition to the work that firefighters perform, their work conditions greatly influence the health and safety risks they face.

Table 3
Crew Size and Effective Response Force Recommendations from NFPA 1710

Crew Size	Engine	Truck
Minimum on duty	4	4
High volume/geographic restrictions, isolation/urban area	5	5
Tactical hazards, dense urban area	6	6
Effective Response Force	Minimum	If Aerial Used
Low hazard	16	17
Medium hazard	27	28
High hazard	43	43

Source: NFPA, 2020

The Work Environment: Fire Dynamics

Fire growth is the primary factor that drives the need for sufficient available resources to intervene in a structure fire in a timely manner. Knowledge of fire dynamics and the associated potential for risk escalation can be used proactively to assist in planning firefighter staffing patterns and fire station locations.

Flashover is a significant transition in fire behavior. When flashover occurs, fire may quickly engulf the room. A compartment fire that has flashed over generates a tremendous amount of heat, smoke, and pressure with enough force to spread fire beyond the room of origin. This situation presents a serious threat to firefighters operating in the vicinity.

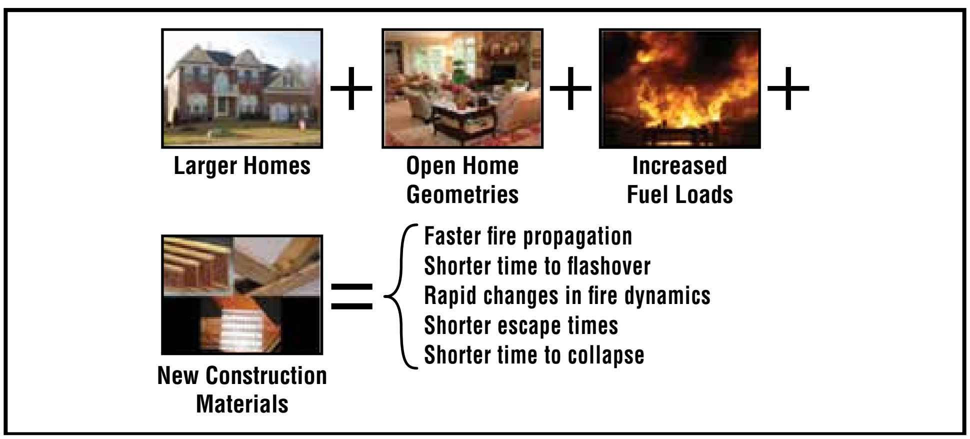
Flashover is a significant transition point of fire development for several reasons:

- The likelihood of survival and the chances of saving any occupants from the fire compartment drop dramatically.
- Flashover is associated with a rapid increase in the rate of combustion. The resulting increase in heat release rate and smoke production raises the health and safety risk for firefighters.
- More water is needed to absorb the increased energy being released and extinguish the burning material.
- More firefighters are required if fire spreads to different compartments and assemblies in the structure.

Larger hose streams or multiple handlines that require more firefighting personnel may become necessary to flow enough water fast enough to extinguish the fire. After flashover, the deteriorating conditions can compound the search and rescue task in the remainder of the structure, again requiring greater resources to mitigate the incident.

Recent changes in the built environment have necessitated changes in the way firefighters must respond to and work within structure fires. Societal priorities and personal preferences have also contributed to changes in the residential fire environment (Kerber, 2012). These residential structure changes include larger homes, open floor plans with spacious rooms, increased usage of synthetic furnishings and materials, and changing construction materials (see **Figure 5**). At the same time, residential fires continue to be the leading cause of fire fatalities in the U.S. (NFPA, 2014–2018).

Figure 5
Fire Dynamics Formula Representative of Early 21st Century Fireground Environments

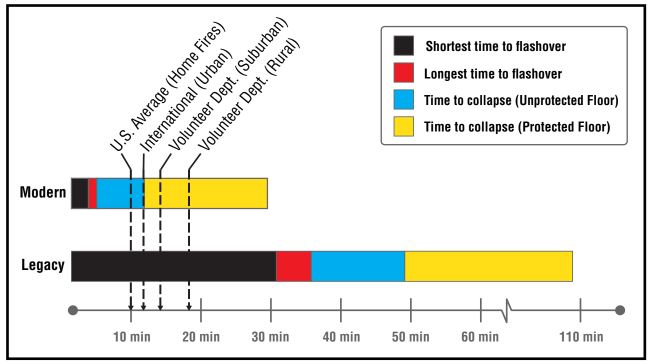


Source: Kerber, 2012.

Researchers at UL have conducted several experiments to compare the impact of changing fuel loads in residential houses. These experiments show that once living room fires have transitioned to flaming fires, flashover times of less than five minutes may be expected in today's fire environment. Flashover times were closer to 30 minutes in the mid-twentieth century. Other experiments demonstrate that the failure time of wall linings, windows, and interior doors has decreased over time, which also affects fire growth and firefighter tactics. Related research has shown that an engineered I-joist floor system, common in today's construction, can collapse in less than one-third the time it takes a dimensional lumber floor system to fail (Kerber, 2012; Kerber et al., 2012). This change in fire development and collapse risk impacts the necessary firefighter response times and operational timeframes once on scene. Responding crews must be able to assemble in a timely manner and quickly initiate application of water on the fire to stop continued risk escalation.

Understanding fire behavior, particularly flashover, is key to designing an emergency response system. Enough firefighters and equipment must be strategically located throughout the community to ensure the minimum acceptable response force can be assembled to engage in a fire before substantial risk escalation occurs. **Figure 6** shows how the timeline for major events has changed from legacy construction to the modern fire scenario and superimposes a timeline that represents, on average, how long it takes for fire departments to arrive on the scene. To save lives and limit property damage, firefighters must be properly trained and arrive at the right time with adequate resources to do the job.

Figure 6
The Relative Timeline of Hazard Progression Flashover to Structural Collapse and the Relationship to Average Fire Department Response Times (US Average, International, Volunteer Suburban, Volunteer Rural)



Source: Kerber, 2012.

Note. The legacy home timeline, which may be used by some jurisdictions for staffing and response policies, is misleading because it suggests there is more time to assemble an ERF than there actually is prior to significant risk escalation.

Regulations Addressing the Effect of Staffing/ Crew Size on Firefighter Health and Safety

The number of personnel assigned to each emergency response vehicle (crew size) and the number of firefighters deployed to the entire event (ERF) directly influence operational effectiveness. Operational effectiveness has a significant effect on firefighter health and safety risks because it influences firefighters' ability to control fire growth, the risks associated with fire growth, and the amount and pace of work that must be performed to limit additional risk.

There are valuable resources available to assist decision makers and fire service leaders in planning for adequate emergency resource deployment in their community to ensure that firefighter intervention occurs in a timely and coordinated manner. These resources are designed to address health and safety to varying degrees, but they all seek to limit risk escalation, civilian and firefighter injury and death, and property loss. These regulations and standards, and their recommendations relative to firefighter health and safety, are described below.

Department of Labor Occupational Safety and Health Administration "Two In/Two Out" Policy

The "two in/two out" policy is part of paragraph (g)(4) of the revised respiratory protection standard, 29 CFR 1910.134, of the Occupational Safety and Health Administration (OSHA). This paragraph applies to private sector workers engaged in interior structural firefighting and to federal employees covered under Section 19 of the Occupational Safety and Health Act. States that have chosen to operate OSHA-approved occupational safety and health plans are required to extend their jurisdiction to include employees of their state and local governments. OSHA requirements for the number of workers who must be present for operations in immediately dangerous to life and health (IDLH) atmospheres also apply to the number of persons who must be on scene before firefighting personnel can initiate an attack on a structural fire.

Conducting firefighting operations in an interior structural fire is considered working in an IDLH atmosphere and requires the use of respirators. At least two standby persons must be present before a minimum of two firefighters may enter the building to fight the fire. In order to comply with this standard, a minimum of four firefighters must arrive on the scene. This regulation allows an exception for rescue operations conducted in the event of an imminent life-threatening situation where immediate action may prevent the loss of life or serious injury.

NFPA 1500™, *Standard on Fire Department Occupational Safety, Health, and Wellness Program*

NFPA standards are industry standards developed through the consensus of experienced leaders, relevant experts, and where it exists, scientific empirical data. NFPA 1500™ sets the minimum safety guidelines for personnel involved in rescue, fire suppression, emergency medical services, hazardous materials operations, and special operations. NFPA 1500™ is designed to help prevent and reduce the severity of accidents, injuries, and exposures. Like NFPA 1710, NFPA 1500™ also sets requirements for the minimum number of personnel on an emergency scene.

Specifically, the standard addresses the following:

- the organization of a safety and health program
- the training requirements of personnel
- maintenance and operation requirements of vehicles and equipment
- protective clothing requirements
- emergency operations management
- medical and physical requirements of firefighters
- wellness programs

The NFPA 1500™ Annex A (2018) specifically notes that to reduce the risk of firefighter death or injury due to understaffing, emergency scene operations should be limited to those that can be safely conducted by the number of personnel on scene. Personnel can be assigned to and arrive at the scene of an incident in many ways, but it is strongly recommended that interior firefighting operations not be conducted without an adequate number of qualified firefighters operating in crews under the supervision of company officers. Annex A further recommends a minimum acceptable staffing level that matches the recommendations in NFPA 1710.

These recommendations, based on experience derived from actual fires and in-depth fire simulations, are the result of critical and objective evaluations of fire crew effectiveness. Averill et al. (2010, 2013) also indicate significant reductions in performance and safety when crews have fewer members than the above recommendations. Five-member crews were found to provide a more coordinated approach for search and rescue and fire-suppression tasks than crews with fewer members.

NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*

NFPA 1710 sets minimum standards for firefighter crews, response times, and other factors involved in determining the organization and deployment of firefighting and emergency medical systems. NFPA standards apply to jurisdictions regardless of their geography, topography, fiscal capacity, service burdens, population density, or local variations.

NFPA 1710 (2020) states that fire engines (pumper) and fire trucks (ladder) companies shall be staffed with a minimum of four on-duty personnel. The standard also requires these companies be staffed with a minimum of five on-duty members in first-due response zones with a high number of incidents, geographical restriction, or geographical isolation. Although NFPA 1710 defines operating units as a fire crew with staffing requirements based on minimum levels necessary for safe, effective, and efficient emergency operations, this standard establishes the floor, not the ceiling, for staffing of each vehicle.

According to NFPA 1710, the number of on-duty firefighters shall be sufficient to perform the necessary firefighting operations given the expected firefighting conditions. Additionally, the fire department shall identify minimum vehicle crew size as necessary to ensure that a sufficient number of members are available to respond with each vehicle. The deployment section of the standard identifies the fireground tasks that must be completed for each structure category as described in Table 3.

Timely Response

In addition to having enough firefighters to respond, it is important that they respond in a timely manner. NFPA 1710 defines dispatch, turnout, and travel times to the emergency scene. These times are relevant to the discussion of firefighter safety as the intent is to arrive at the scene in a timely manner with enough trained personnel to reduce the potential for further risk escalation. The criteria listed in NFPA 1710 establish the following times based on the science of fire dynamics previously discussed and the experience and consensus of NFPA 1710 technical committee members:

- 80 seconds turnout time for fire and special operations,
- 240 seconds or less travel time for arrival of a first engine crew,
- 360 seconds or less travel time for arrival of the second crew (engine or truck) with a minimum of four personnel,
- 480 seconds or less travel time for arrival of the full ERF for structures other than high-rises, and
- 610 seconds or less travel time for arrival of the full ERF for high-rises.

On Scene Safety: Rapid Intervention Crews (RIC)

In NFPA 1710, the RIC is defined as a dedicated crew of at least one officer and three members, positioned outside the IDLH atmosphere, appropriately trained and equipped, and assigned for rapid deployment to rescue lost or trapped members. NFPA 1710 specifically states that, at a minimum, an IRIC may be assembled from the initial attack crew and, as the ERF arrives, a full and sustained RIC should be established with four personnel (NFPA 1710, 2020). If the first-arriving crew is short-staffed with less than the minimum four persons, this safety mechanism cannot be put in place. A crew of fewer than four firefighters cannot intervene in the emergency without increased risk to their own safety and well-being.

Research Addressing the Effect of Crew Size on Firefighter Safety

Recent research has helped to better understand the effects of crew size on key operational milestones, as well as the physical and physiological responses and chemical exposure risk of firefighters. A National Institute of Standards and Technology (NIST) study on staffing and deployment in a low-hazard residential fireground environment (Averill et al., 2010) quantified the effects of crew sizes, ERF assembly, and arrival times on firefighting operations. Important outcomes included factors that influence fire growth and exposure risk, and thus affect occupant survivability and firefighter health and safety. The project included multiple components, including the effect of crew size and computer modeling to predict fire growth and environmental toxicity.

NIST Residential Fireground Field Experiments

The residential fires component of this study evaluated how long it took different crew sizes (two to six firefighters) to complete a series of 22 essential fireground tasks in single-family dwellings. The study included acquisition of air samples to assess toxicity levels and computer modeling to understand how fire growth rate affected the survivability of citizens trapped within the structure.

Of all the essential tasks studied, “time to water on fire” had the most significant impact on successful operations. Importantly, there was a 6% difference in the “water on fire” time between the 3- and 4-person crews and an additional 6% difference between the 4- and 5-person crews. The 4-person crews completed laddering and ventilation (for life safety and rescue) 25% faster than the 3-person crews. In other findings, the 4- and 5-person crews started and completed a primary search 6% faster than the 3-person crews. The 4-person crews were nearly 25% faster than 3-person crews on overall scene time necessary to complete all tasks. These results clearly demonstrate the impact of crew size on the operational effectiveness of firefighters: the larger the crew, the greater its ability to limit fire growth and save lives.

The NIST study also found that survivability of potential trapped occupants was affected by crew size and time of arrival. Independent of fire size, there was a significant difference in the exposure to toxic compounds, expressed as fractional effective dose (FED), in occupants at the time of rescue depending on arrival of the ERF. The smaller or later the responding crews, the greater the risk to trapped occupants.

NIST High-Rise Fireground Field Experiments

NIST researchers and study partners also conducted a resource deployment study in a high hazard, high-rise fireground environment (Averill et al., 2013). When responding to fires in high-rise buildings, firefighting crews of five or six members—compared to three or four members—are significantly faster in putting out fires and completing search and rescue operations.

In the high-rise component of this study, an analysis of 14 “critical tasks”—those undertaken when potential risks to building occupants and firefighters are greatest—found that 3-person crews took almost 12 minutes longer than 4-person crews, 21 minutes longer than 5-person crews, and 23 minutes longer than 6-person crews to complete all tasks.

Computer modeling with data from live experimental burns was also conducted in the Averill et al. (2013) study. The results indicated that smaller crews would be required to engage and work for a longer period of time to suppress larger fires than would a larger crew, as shown by the additional time required to complete all necessary firefighting tasks. A 3-person crew, for example, may battle a medium-growth rate blaze that is almost 60% larger than the fire faced by a larger crew. The larger crew would start extinguishing a fire roughly three-and-one-half minutes earlier than the smaller crew.

The research team also evaluated whether dispatching more 3- or 4-member crews to a high-rise fire would be as effective as sending a smaller contingent of emergency response vehicles staffed by larger crews of firefighters. The research found that a smaller contingent of vehicles with crews of four or five firefighters outperforms a response of similar manpower delivered using more vehicles with crew sizes of three firefighters. For example, there was a 2-minute and 14-second (8.1 %) difference in the time to put the fire out between the 3- and 4-person crews. There was an additional 1-minute and 15-second (5.0 %) difference in this time between the 4- and 5-person crews. In other words, 5-person crews extinguished the fire 3 minutes and 29 seconds faster than 3-person crews. Finally, there was a 7-minute and 2-second (25.6 %) difference in the time to put the fire out between the 3- and 6-person crews.

When assessing task end times and incrementally increasing crew size by a single firefighter (i.e., 3 to 4, 4 to 5, and 5 to 6), time improvements were reported with expanded crew size. As firefighter crews navigated the later tasks in an event, like laddering a building, the time gains reached the 10- to 15-minute range. Time improved for search and rescue tasks (over 11 minutes) when crew size increased from four to five members. The improvements in the times to complete all tasks were substantial (9 to 12 minutes) when crew size increased from three to four or from four to five members.

Overall, the results of this study showed that the number of firefighters in each responding crew had a dramatic effect on the ability to protect lives and property. When responding to a medium growth rate fire on an upper floor of a high-rise structure, 3-person crews ascending to the fire floor confronted an environment where the fire had released 60% more heat energy than the fire encountered by the 6-person crews. As described earlier, larger fires expose firefighters and occupants to greater risks and are more challenging to extinguish. Thus, deployment of smaller crews on each vehicle increases the health and safety risks that firefighters face.

FSRI Study of Coordinated Attack in Acquired Structures

UL's Fire Safety Research Institute (FSRI) team conducted 40 full-scale, live-fire experiments in acquired structures slated for demolition. These structures included single-family homes (Regan et al., 2020), apartments within larger multi-family dwellings (Stakes et al., 2020), and units within a strip mall (Weinschenk & Zevotek, 2020). The study was designed to increase the understanding of suppression and ventilation tactics to improve firefighter safety and effectiveness. Importantly, occupant safety improves with increases in firefighting effectiveness.

While the focus of the study was not on staffing levels, key findings showed the importance of coordinating firefighting crews. Ventilation actions coordinated within 30 seconds of suppression limited additional fire growth in all experiments using this approach. In general, the effectiveness of post-suppression ventilation varied substantially between structures. However, the experiments in which toxic gas concentrations remained highest for the longest were those in which no timely ventilation actions were performed close to the occupant location. Ventilation post-suppression should be focused on the areas of greatest exposure hazard for potentially trapped occupants. The more staffing available, the more operations can be coordinated in order to suppress the fire, ventilate the areas where occupants may be located, search for them, and remove them from the hazard.

Research Addressing the Effect of Crew Size on Firefighter Health

As noted in the Firefighter Health & Safety Risk section, significant advances have been made in the understanding of the immediate hazards associated with structural firefighting. A number of scientific studies have been conducted to understand how firefighting affects the physical and physiological state of firefighters.

Risk for Acute Fatigue

Acute fatigue is a common occurrence during firefighting tasks (see Figure 1). Increased body temperature due to strenuous work and exposure to high temperatures has been shown to have detrimental physiological and psychological effects on firefighters, including a rapid onset of muscular fatigue. Fatigue can have significant impacts on firefighters' ability to safely navigate the fireground. For example, movement errors often lead to trips and falls. Research has confirmed that walking stability can be affected by strenuous firefighting activity and associated fatigue caused by heat and stress (Park et al., 2011). Fatigue from simulated firefighting activity has been shown to decrease clearance and increase contact errors during obstacle crossing, which increases trip and fall risk (Angelini et al., 2018). Kesler et al. (2016) observed significant effects of firefighting-induced fatigue on stair ascent and descent that could also increase the risk of falling.

When firefighters are called upon to work through a second cylinder of air, as often occurs during firefighting activities with limited manpower available, additional deficits in their ability to work and safely move about the fireground are expected. When firefighters were tasked with working through a second cylinder of air after a short break, significant declines (between -10% and -27%) in simulated firefighting work output were measured in the second bout when compared to the first bout of work (Kesler, Ensari, et al., 2018). Importantly, extended duration of simulated firefighting activity resulted in changes in gait performance (Kesler, Bradley, et al., 2018) and significant declines in firefighters' functional balance (Kesler, Deetjen, et al., 2018). The increased physiological strain induced by a second round of activity and cumulative fatigue may have contributed to reduced performance. Fatigue may also compromise cognitive function and impair situational awareness (Smith et al., 2001).

Cardiovascular Risk

Sudden cardiac events account for approximately 50% of firefighter line-of-duty deaths reported by the NFPA (Table 1), and these events are much more likely to occur after firefighting (Kales et al., 2007; Smith, Haller, et al., 2019). Data in Table 1 clearly indicates that fire suppression activities can trigger sudden cardiac events in individuals with underlying heart disease. The physical work, environmental stressors, and psychological stress associated with firefighting can all contribute to cardiac events in vulnerable firefighters (Soteriades et al., 2011; Smith et al., 2018). Research has proven that firefighting leads to significant cardiovascular strain, including increased cardiac work, decreased stroke volume, impaired diastolic function, vascular stiffness, changes in ECG, and a procoagulant state (Smith et al., 2001; Fahs et al., 2011; Fernhall et al., 2012; Smith et al., 2011; Burgess et al., 2012; Smith et al., 2014; Smith, Horn, Woods, et al., 2016; Smith, Horn, Fernhall, et al., 2019). Firefighting may also trigger an arrhythmia or plaque rupture which leads to sudden cardiac death or a non-fatal cardiac event (see Figure 2).

Cardiac strain related to crew size was assessed during the NIST residential fireground field experiments (Barr et al., 2014). Cardiac monitors were worn by study participants during the live-fire experiments. Heart rate data were compiled and analyzed according to job assignment and crew size. Average working heart-rate responses in firefighters on the engine declined as crew size increased from a 3-person to a 4-person to a 5-person crew. This study concluded that average working heart rates of firefighters were higher when smaller crews were deployed. The combination of longer work times and higher working heart rates when 2-person crews were deployed demonstrates that smaller crews experienced considerably more cardiovascular strain than larger crews deployed to fight a fire of the same size.

Occupational Exposure Risk

Occupational exposures of firefighters have received considerable attention because they are linked to occupational cancer. Occupational exposures to asphyxiants and particulate matter also increase the risk of sudden cardiac events. The number of firefighters responding to an incident can affect this exposure risk in multiple ways.

Water on Fire More Rapidly

Studies show that techniques to get water on the fire more rapidly may translate to reduced uptake of chemicals (Fent et al., 2020). While Fent and colleagues focused on fireground tactics (interior vs transitional attack), there may be limited options available for the location where the first application of water can take place based on the relative location of the fire and the personnel available. The more rapidly an effective firefighting force is assembled, the more rapidly interior suppression activities may begin. Rapid suppression may translate to a reduced uptake of fireground chemicals.

Overhaul Requirements

In recent years, the need for firefighters to wear SCBA to protect their airway throughout the firefight has become apparent. Inhalation of fire effluent is likely the most direct route for uptake of fireground contaminants. However, enforcing SCBA usage brings with it increased weight and restrictions for movement during overhaul operations that often require long periods of physical activity. Core temperatures measured from firefighters conducting overhaul with SCBA may exceed the temperature increases measured during fire suppression (Horn et al., 2018). Furthermore, firefighters who operate on a second cylinder of air after conducting initial fire suppression or ventilation activities often begin overhaul with an elevated core temperature.

With enough staffing available on the scene, the IC can send a fresh crew in for overhaul and feasibly enforce SCBA usage without further increasing the risk for heat injuries to the initial attack crews. This approach will also reduce the time required to implement hygiene practices for the initial crews with the highest level of exposure (Fent et al., 2017).

Hygiene Requirements

While PPE provides substantial protection against fireground chemical exposures, firefighters experience some level of contamination reaching their skin (Fent et al., 2017). In these cases, rapid implementation of hygiene practices is recommended. While skin-cleansing wipes can be used on the fireground, they have been found only partially successful at removing contamination (Fent et al., 2017). It is recommended that firefighters shower as rapidly as possible but, to do so, crews must be taken out of service for a period of time. Implementation of such a policy must be supported by enough personnel to maintain assembly of an effective firefighting crew while appropriate hygiene activities take place.

Rehabilitation (Rehab)

Rehab provides a critical fireground function by providing hydration, nutrition, rest, and potentially medical monitoring of the crews to help control heat stress and physiological strain (Burgess et al., 2012; NFPA, 2014-2018; Smith, Haller, et al., 2016). Fireground hygiene is commonly integrated into rehab to formalize rapid skin cleansing, reduce opportunities for ingesting fireground contaminants, and mitigate the spread of contamination to other skin sites. Rehab is a critical health and safety function made possible by appropriate staffing levels at the incident scene.

Recommendations

Based on a review of published research, industry standards, and expert opinion, we make the following recommendations:

1. All fire chiefs and individuals who are responsible for fire department budgets should use NFPA 1500™ and the performance objectives in NFPA 1710 to ensure adequate resources are deployed to protect communities and to minimize risks to firefighter health and safety.

2. Adequate resources, including properly trained firefighters and appropriate vehicles, should be deployed to arrive on scene in an appropriate timeframe to limit fire growth. Firefighters are facing an unprecedented level of risk in today's fires because of widespread use of synthetic building materials and furnishings, lightweight construction, larger buildings, and more open floor plans. In order to meet these challenges, enough firefighters must arrive on scene and initiate fire suppression activities as quickly as possible.
3. Firefighter health and safety is the responsibility of the entire fire department, but the ultimate accountability resides with the fire chief and city/county management. Adequate personnel are necessary to successfully perform firefighting operations without undue risk to citizens and/or firefighters.

Summary

Firefighters perform hazardous work that is critical for public safety, but most standards are not focused directly on the health and safety of firefighters. Instead, standards address crew size and ERF based on operational needs. This review considered firefighter injury and fatality statistics, the work that firefighters perform, the environment in which the work is performed, relevant standards, and multidisciplinary research about firefighter physical stress and fatigue, cardiovascular risk, and occupational exposure. It is essential that resources devoted to a structure fire enable firefighters to meet the risk they encounter and do so in a way that is consistent with their oath to protect people and property. It is also critical that resources be deployed in a way that considers firefighter health and safety.

Based on the available evidence, the ERF and crew sizes recommended in NFPA 1710 should be considered the ***minimum*** to provide for firefighter health and safety. Whenever possible, additional resources should be provided to address firefighter physiological stress, ensure that fire growth can be limited to the extent possible, and mitigate occupational exposure in today's rapidly evolving fireground.

Glossary of Terms

Crew – A team of two or more firefighters. (NFPA 1500™, 2021, 3.3.22).

Effective Response Force (ERF) – The minimum number of firefighters necessary to be assembled on the scene of an emergency to engage and stop the emergency while minimizing the probability of firefighter injury and death.

Flashover – A transition phase in the development of a compartment fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space, resulting in full room involvement or total involvement of the compartment or enclosed space. (NFPA 1700, 2021, 3.3.84).

Immediately Dangerous to Life and Health (IDLH) – Any condition that would pose an immediate or delayed threat to life, cause irreversible adverse health effects, or interfere with an individual's ability to escape unaided from a hazardous environment. (NFPA 1500™, 2021, 3.3.59).

Incident Commander (IC) – The individual responsible for all incident activities, including the development of strategies and tactics and the ordering and the release of resources. (NFPA 1500™, 2021, 3.3.62).

Initial Rapid Intervention Crew (IRIC) – Two members of the initial attack crew, positioned outside the IDLH, trained and equipped as specified in NFPA 1407, *Standard for Training Fire Service Rapid Intervention Crews*, who are assigned for rapid deployment (i.e., two in/two out) to rescue lost or trapped members (NFPA 1710, 2020, 3.3.53.1).

Rapid Intervention Crew (RIC) – A dedicated crew of at least one officer and three members, positioned outside the IDLH, trained and equipped as specified in NFPA 1407, who are assigned for rapid deployment to rescue lost or trapped members. (NFPA 1710, 2020, 3.3.53).

Declarations of Interest

Dr. Lori Moore-Merrell is deemed a subject matter expert in many of the topics covered in this manuscript. Dr. Moore-Merrell has no pending commitments to deliver testimony at the time of submission.

Dr. Denise Smith has served as a subject matter expert regarding the physiological strain of firefighting, cardiovascular risks associated with firefighting, and medical evaluation of firefighters.

References

Angelini, M. J., Kesler, R. M., Petrucci, M. N., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2018). Effects of simulated firefighting and asymmetric load carriage on firefighter obstacle crossing performance. *Applied Ergonomics, 70*, 59–67.

Austin, C. C., Wang, D., Ecobichon, D. J., & Dussault, G. (2001). Characterization of volatile organic compounds in smoke at municipal structural fires. *Journal of Toxicology Environmental Health, Part A, 63*(6), 437–458.

Averill, J. D., Moore-Merrell, L., Barowy, A., Santos, R., Peacock, R., Notarianni, K. A., & Wissoker, D. (2010). *Report on residential fireground field experiments* (NIST Technical Note 1661). National Institute of Standards and Technology. https://tsapps. ov/publication/get_pdf.cfm?pub_id=904607

Averill, J. D., Moore-Merrell, L., Ranellone Jr., R. T., Weinschenk, C. G., Taylor, N., Goldstein, R., Santos, R., Wissoker, D., Notarianni, K., & Butler, K. M. (2013). *Report on high-rise fireground field experiments* (NIST Technical Note 1797). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.1797

Barr, D. A., Moore-Merrell, L., Benedict, R., & Smith, D. L. (2014). The deployment of resources at residential structural fires and cardiovascular strain in firefighters. *International Fire Service Journal of Leadership and Management*, *8,* 17–22.

Burgess, J. L., Duncan, M. D., Hu, C., Littau, S. R., Caseman, D., Kurzius-Spencer, M., Davis-Gorman, G., & McDonagh, P. F. (2012). Acute cardiovascular effects of firefighting and active cooling during rehabilitation. *Journal of Occupational and Environmental Medicine*, *54*(11), 1413–1420.

Campbell, R., & Molis, J. L. (2019). United States firefighter injuries in 2018. *NFPA Journal®, 113*(6).

Daniels, R. D., Bertke, S., Dahm, M. M., Yiin, J. H., Kubale, T. L., Hales, T. R., Baris, D., Zahm, S. H., Beaumont, J. J., Waters, K. M., & Pinkerton, L. E. (2015). Exposure-response relationships for select cancer and non-cancer health outcomes in a cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950-2009). *Occupational and Environmental Medicine*, *72*(10), 699–705.

Daniels, R. D., Kubale, T. L., Yiin, J. H., Dahm, M. M., Hales, T. R., Baris, D., Zahm, S. H., Beaumont, J. J., Waters, K. M., & Pinkerton, L. E. (2014). Mortality and cancer incidence in a pooled cohort of US firefighters from San Francisco, Chicago and Philadelphia (1950-2009). *Occupational and Environmental Medicine, 71*(6), 388–397.

Evarts, B. (2018). Fire loss in the United States during 2017. *NFPA Journal®*. National Fire Protection Association. https://www.nfpa.org/News-and-Research/ Publications-and-media/NFPA-Journal/2018/September- October-2018/Features/2017-US-Fire-Loss-Report

Fahs, C. A., Yan, H., Ranadive, S., Rossow, L. M., Agiovlasitis, S., Echols, G., Smith, D., Horn, G. P., Rowland, T., Lane, A., & Fernhall, B. (2011). Acute effects of firefighting on arterial stiffness and blood flow. *Vascular Medicine*, *16*(2), 113–118.

Fahy, R., & Molis, J. (2019). Firefighter fatalities in the United States – 2018. *NFPA Research*. National Fire Protection Association. https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Emergency-responders/2019FFF.ashx

Fent, K. W., Alexander, B., Roberts, J., Robertson, S., Toennis, C., Sammons, D., Bertke, S., Kerber, S., Smith, D., & Horn, G. (2017). Contamination of firefighter personal protective equipment and skin and the effectiveness of decontamination procedures. *Journal of Occupational and Environmental Hygiene, 14*(10), 801–814.

Fent, K. W., Toennis, C., Sammons, D., Robertson, S., Bertke, S., Calafat, A. M., Pleil, J. D., Geer Wallace, M. A., Kerber, S., Smith, D., & Horn, G. (2020). Firefighters' absorption of PAHs and VOCs during controlled residential fires by job assignment and fire attack tactic. *Journal of Exposure Science and Environmental Epidemiology*, *30*(2), 338–349.

Fernhall, B., Fahs, C. A., Horn, G. P., Rowland, T., & Smith, D. L. (2012). Acute effects of firefighting on cardiac performance. *European Journal of Applied Physiology*, *112*(2), 735–741.

Horn, G. P., Kesler, R. M., Kerber, S., Fent, K. W., Schroeder, T. J., Scott, W. S., Fehling, P. C., Fernhall, B., & Smith, D. L. (2018). Thermal response to firefighting activities in residential structure fires: Impact of job assignment and suppression tactic. *Ergonomics, 61*(3), 404–419.

International Association of Fire Fighters. (n.d.). *Line of duty death database*. https://lodd.iaff.org/

Jankovic, J., Jones, W., Burkhart, J., & Noonan, G. (1991). Environmental study of firefighters. *The Annals of Occupational Hygiene, 35*(6), 581–602.

Kales, S. N., Soteriades, E. S., Christophi, C. A., & Christiani, D. C. (2007). Emergency duties and deaths from heart disease among firefighters in the United States. *The New England Journal of Medicine*, *356*(12), 1207–1215.

Kerber, S. (2012). Analysis of changing residential fire dynamics and its implications on firefighter operational timeframes. *Fire Technology, 48*, 865–891.

Kerber, S., Madrzykowski, D., Dalton, J., & Backstrom, B. (2012). *Improving fire safety by understanding the fire performance of engineered floor systems and providing the fire service with information for tactical decision making.* UL Firefighter Safety Research Institute.

Kesler, R. M., Bradley, F. F., Deetjen, G. S., Angelini, M. J., Petrucci, M. N., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2018). Impact of SCBA size and fatigue from different firefighting work cycles on firefighter gait. *Ergonomics, 61*(9), 1208–1215.

Kesler, R. M., Deetjen, G. S., Bradley, F. F., Angelini, M. J., Petrucci, M. N., Rosengren, K. S., Horn, G. P. & Hsiao-Wecksler, E. T. (2018). Impact of SCBA size and firefighting work cycle on firefighter functional balance. *Applied Ergonomics, 69*, 112–119.

Kesler, R. M., Ensari, I., Bollaert, R. E., Motl, R. W., Hsiao-Wecksler, E. T., Rosengren, K. S., Fernhall, B., Smith, D., & Horn, G. P. (2018). Physiological response to firefighting activities of various work cycles using extended duration and prototype SCBA. *Ergonomics, 61*(3), 390–403.

Kesler, R. M., Horn, G. P., Rosengren, K. S., & Hsiao-Wecksler, E. T. (2016). Analysis of foot clearance in firefighters during ascent and descent of stairs. *Applied Ergonomics, 52*, 18–23.

Mittleman, M. A. (2007). Air pollution, exercise, and cardiovascular risk. *The New England Journal of Medicine*, *357*, 1147–1149.

National Fire Protection Association. (2014–2018). *Fires by occupancy or property type.* National Fire Protection Association. Retrieved June 26, 2020, from https://www.nfpa.org/News-and-Research/Data-research-and-tools/US-Fire-Problem/Fires-by-occupancy-or-property-type

National Fire Protection Association. (2018). NFPA 1500™: *Fire department occupational safety and health program*. National Fire Protection Association.

National Fire Protection Association. (2021). NFPA 1700: *Guide for structural firefighting.* National Fire Protection Association.

National Fire Protection Association. (2020). NFPA 1710: *Standard for the organization and deployment of fire suppression operations, emergency medical operations, and special operations to the public by career fire departments*. National Fire Protection Association..

Park, K., Rosengren, K. S., Horn, G. P., Smith, D. L., & Hsiao-Wecksler, E. T. (2011). Assessing gait changes in firefighters due to fatigue and protective clothing. *Safety Science, 49*(5), 719–726.

Pinkerton, L., Bertke, S. J., Yiin, J., Dahm, M., Kubale, T., Hales, T., Purdue, M., Beaumont, J. J., & Daniels, R. (2020). Mortality in a cohort of US firefighters from San Francisco, Chicago and Philadelphia: An update. *Occupational and Environmental Medicine*, *77*(2), 84–93.

Regan, J., Bryant, J., & Weinschenk, C. (2020). *Analysis of the coordination of suppression and ventilation in single-family homes*. UL Firefighter Safety Research Institute.

Smith, D. L., Barr, D. A., & Kales, S. N. (2013). Extreme sacrifice: Sudden cardiac death in the US fire service. *Extreme Physiology & Medicine, 2*(1), Article 6.

Smith, D. L., Haller, J. M., Benedict, R., & Moore-Merrell, L. (2016). Firefighter incident rehabilitation: Interpreting heart rate responses. *Prehospital Emergency Care*, *20*(1), 28–36.

Smith, D. L., Haller, J. M., Korre, M., Fehling, P. C., Sampani, K., Grossi Porto, L. G., Christophi, C. A., & Kales, S. N. (2018). Pathoanatomic findings associated with duty-related cardiac death in US firefighters: A case-control study. *Journal of the American Heart Association*, *7*(18), Article e009446.

Smith, D. L., Haller, J. M., Korre, M., Sampani, K., Grossi Porto, L. G., Fehling, P. C., Christophi, C. A., & Kales, S. N. (2019). The relation of emergency duties to cardiac death among US firefighters. *American Journal of Cardiology*, *123*(5), 736–741.

Smith, D. L., Horn, G. P., Fernhall, B., Kesler, R. M., Fent, K. W., Kerber, S., & Rowland, T. W. (2019). Electrocardiographic responses following live-fire firefighting drills. *Journal of Occupational and Environmental Medicine*, *61*(12), 1030–1035.

Smith, D. L., Horn, G. P., Petruzzello, S. J., Fahey, G., Woods, J., & Fernhall, B. (2014). Clotting and fibrinolytic changes after firefighting activities. *Medicine & Science in Sports & Exercise*, *46*(3), 448–54.

Smith, D. L., Horn, G. P., Woods, J., Ploutz-Snyder, R., & Fernhall, B. (2016). Effect of aspirin supplementation on hemostatic responses in firefighters aged 40 to 60 years. *American Journal of Cardiology*, *118*(2), 275-280.

Smith, D. L., Manning, T. S., & Petruzzello, S. J. (2001). Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit firefighters. *Ergonomics*, *44*(3), 244–254.

Smith, D. L., Petruzzello, S. J., Goldstein, E., Ahmad, U., Tangella, K., Freund, G. G., & Horn, G. P. (2011). Effect of live-fire training drills on firefighters' platelet number and function. *Prehospital Emergency Care*, *15*(2), 233–239.

Soteriades, E. S., Smith, D. L., Tsismenakis, A. J., Baur, D. M., & Kales, S. N. (2011). Cardiovascular disease in US firefighters: A systematic review. *Cardiology in Review, 19*(4), 202–215.

Stakes, K., Bryant, J., Dow, N., Regan, J., & Weinschenk, C. (2020). *Analysis of the coordination of suppression and ventilation in multi-family dwellings*. UL Firefighter Safety Research Institute.

Weinschenk, C., & Zevotek, R. (2020). *Exploratory analysis of the impact of ventilation on strip mall fires*. UL Firefighter Safety Research Institute.

Willich, S. N., Lewis, M., Lowel, H., Arntz, H-R, Schubert, F., & Schroder, R. (1993). Physical exertion as a trigger of acute myocardial infarction. *The New England Journal of Medicine*, *329*, 1684–1690.

About the Authors

Lori Moore-Merrell is the President and CEO of the International Public Safety Data Institute. Lori began this role in 2019 after serving 26 years as a senior executive in the International Association of Fire Fighters. As a Doctor of Public Health and a data scientist, she recently served on the Biden-Harris Transition Team to conduct agency review for DHS/FEMA as part of the COVID-19 national response plan. Lori is considered an expert in emergency response system evaluation, public safety resource deployment, and community risk assessment. She serves as corresponding author and can be reached at: **lori@i-psdi.org.**

Steve Kerber is the Vice President of Research for Underwriters Laboratories and Director of UL's Fire Safety Research Institute. He has led research in the areas of fire safety engineering, firefighter safety, fire forensics, and fire science. Steve is also a 13-year veteran of the fire service, with most of his service at the College Park Fire Department in Prince George's County, Maryland, where he served at ranks up through Deputy Chief.

Gavin Horn is a Research Engineer with UL's Fire Safety Research Institute (FSRI). Prior to joining the UL FSRI team, he served as the Director of IFSI Research Programs at the University of Illinois Fire Service Institute for 15 years and as a firefighter, apparatus engineer, and fire investigator with the Savoy (IL) Fire Department. Gavin's research interests range from firefighter health and safety to first responder technology development.

Denise Smith is a Professor of Health and Human Physiological Sciences at Skidmore College (NY) where she is director of the First Responder Health and Safety Lab. She is also a research scientist at the University of Illinois Fire Service Institute. Denise has published over 90 scientific papers with a focus on firefighter health and safety. She is a member of the NFPA 1500™ committee and an investigator for the NIOSH firefighter fatality investigation and prevention program.

FPP
FIRE PROTECTION PUBLICATIONS

IFSTA
INTERNATIONAL FIRE SERVICE TRAINING ASSOCIATION