Interim Report

Cardiovascular & Chemical Exposure Risks in Modern Firefighting

Gavin P. Horn, Steve Kerber, Kenneth W. Fent, Bo Fernhall, Denise L. Smith

IFSI Research; UL FSRI; NIOSH; UIC

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Illinois Fire Service Institute – IFSI Research
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Foreword

The health and safety risks and hazards of firefighting on the men and women that make up the profession is increasingly well studied and documented. Meaningful and sound research has led to changes in individual fitness priorities, personal protective equipment, first responder personnel activities on the fire-ground, and a better understanding of the overall health risks increasingly associated with firefighting.

Cardiovascular and chemical exposure risks from the combustion of common household contents inside modern structures is understood to be very real. However, researchers have yet to be able to recreate the physical environment of a real modern day fire in such a way that meaningful data could be collected and analyzed.

This study, through amazing partnerships and collaboration between the Illinois Fire Service Institute, UL Firefighter Safety Research Institute, National Institute for Occupational Safety and Health, Globe Manufacturing Company and U.S. Department of Homeland Security - Federal Emergency Management Agency Assistance to Firefighters Grants Program, has recreated virtually every aspect of firefighting realistically, yet safely and in a way that researchers could capture essential data. Using modern building materials and room contents; employing real firefighters executing commonly employed tactics, techniques, and procedures of entry, search, extinguishment, ventilation and overhaul, this study will enable researchers to truly assess risk.

This study is the logical next step in our refinement of what we know, what we think, and what we suspect. It will inform the next steps in research and more importantly, it will help the firefighting profession better protect its most important resource - the firefighter.

Respectfully,

Royal P. Mortenson
Director
Illinois Fire Service Institute, University of Illinois-Urbana/Champaign

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Abstract

Firefighting poses immediate and long-term health risks to firefighters. While we and others have documented the thermal and cardiovascular strain of firefighting activity in training buildings, there is limited information available on the thermal and cardiovascular responses of firefighters responding to realistic modern fire environments. Given the well-documented concerns about cardiovascular events (NFPA reports ~45% LODD each year) and cancer in the fire service (781 IAFF LODD [2004-2014]), there is an urgent need to consider both the acute thermal and cardiovascular strain of firefighting and the long-term exposure to products of combustion. In order for this work to be relevant to different departments and to individual firefighters, it is critical to understand how the acute and chronic risks of firefighting are modulated by tactical choices and firefighting assignment. This study examined acute physiological responses and markers of toxic exposure of firefighters for 12 hours following realistic modern fire scenarios and how these outcomes were affected by fire size, firefighting tactics and firefighting assignments.

The purposes of this interim report are to:

1. **Provide an introduction to the project along with motivating factors,**
2. **Describe the instrumentation that was used to address these risks on the fireground, and**
3. **Introduce some preliminary data and examples for the Fire Service in advance of full results that will be made available in the coming months.**

While this document is intended for a Fire Service audience, the description of instrumentation and methods is provided at a high level in order for the Fire Service to understand the rigor necessary to conduct such research. While this chapter was written with significant scientific terminology, the latter chapters are intended to help begin the translation process. As the project progresses over the coming years, specific outcomes will be translated and disseminated broadly in a means that would allow incorporation into tactics and operating procedures.

I. Introduction & Motivation

There has been a tremendous increase in scientific research to support the adoption of evidence-based strategies and best practice in the fire service. These advances have largely been the result of Assistance to Firefighter Grant (AFG)-funded studies. Specifically, in recent years we have:

- Dramatically increased our understanding of the cardiovascular strain of firefighting;
- Documented increased risk of specific cancers among firefighters and markers of toxic exposure associated with firefighting;
- Made remarkable advances in scientific understanding of fire dynamics. Fires with modern furnishings progress more rapidly and produce more toxic products of combustion than fires with legacy furnishings.

Despite all these advances, what is still sorely missing—and desperately needed to devise policies and create technologies to protect firefighters— is meaningful integration of these three important lines of research. What we really need is rigorous scientific data describing the effects of firefighting in modern structures with realistic fuel loads on firefighter cardiovascular and cancer risk. Furthermore, we need to know how these risks are affected by firefighting tactics and assignment. At the National Fallen Firefighters Foundation (NFFF) 2nd Fire Service Research Agenda Symposium, the key need identified by the Technology & Science task group was, “Identify and disseminate standard best practices for structural firefighting operations based on science.” This broad, multi-disciplinary project scientifically investigated the impact of real structural firefighting operations on the most important clinical health concerns of the fire service—cardiovascular risk and toxic exposures.

The vast majority of research that has investigated the physiological responses to firefighting has been done in training structures using wood and straw (Class A materials) as fuel or in laboratory conditions in a warm room. These were of course the logical place to begin rigorous, well-controlled examination of physiological responses, and have conclusively shown that firefighting caused significant cardiovascular strain and several changes that could be linked with sudden cardiac events in vulnerable individuals. However, the physiological disruption caused by actual firefighting activities could result in even more exaggerated physiological experiences. Recent work by the National Institute of Standards and Technology (NIST) and Underwriters Laboratories (UL) has shown temperatures during live burns in buildings using modern construction materials and polymer based furnishings are far in excess of temperatures reported using legacy furnishings of natural materials, similar to the pallet and straw fuels used during the existing physiological response research studies. Realistic modern fire environments also produce products of combustion that contain far more toxicants and carcinogens that may have multiple effects on the human body. Despite all the efforts in the Fire Service to develop protective equipment and clothing and to devise policies and procedures to protect firefighters from exposure to the detrimental effects of heat and toxic exposures, there are no good scientific data on the physiological responses of firefighters who perform their work in a realistic modern fire environment. Such information is critical to developing protective tools and to enacting policies and procedures that minimize or mitigate risks.

This research study leveraged our position as a State Training Academy located in a nationally recognized research university to bring together a multidisciplinary team of researchers with expertise in fire dynamics, cardiovascular physiology, engineering and industrial hygiene. This comprehensive study investigated realistic fireground conditions using sophisticated, state-of-the-art equipment and considered firefighting tactics and assignment to better characterize fireground risk.

I.A. Sudden Cardiac Events in the Fire Service

Based on reporting from the National Fire Protection Association (NFPA) and the United States Fire Administration (USFA), it is well established that sudden cardiac events are the leading cause of duty-related deaths among firefighters [1]. Research has also found that sudden cardiac events are far more likely to occur after fire suppression activity. Kales et al determined that firefighters spend 1–5% of their professional time each year involved in fire suppression activity, yet, fire suppression activities led to 32% of deaths from coronary heart disease [2]. Thus, fire fighting was associated with a 10–100 times greater risk of suffering sudden cardiac death compared with the risk associated with non-emergency duties [2]. These data clearly suggest that fire suppression activities can *trigger* sudden cardiac events in vulnerable individuals with underlying heart disease.

Epidemiological evidence obtained over the past several years indicates that strenuous physical activity can serve as a *trigger* for an acute cardiac event [3-5]. Triggers represent the final step in the pathological process leading to cardiovascular events [6]. Disruption of plaque and the development of a procoagulatory state are well-characterized mechanisms by which a trigger may lead to an occlusive thrombus and a sudden cardiac event [7]. However, even in the absence of an occlusive thrombus, triggers may lower the threshold for cardiac electric instability thereby evoking fatal arrhythmias [6]. These two important mechanisms of sudden cardiac events strongly suggest the need for clinically relevant measures of coagulatory potential and electrocardiogram (ECG) during and after firefighting to better understand sudden cardiac events in the fire service.

I.A.1. Cardiovascular Strain of Fire Fighting

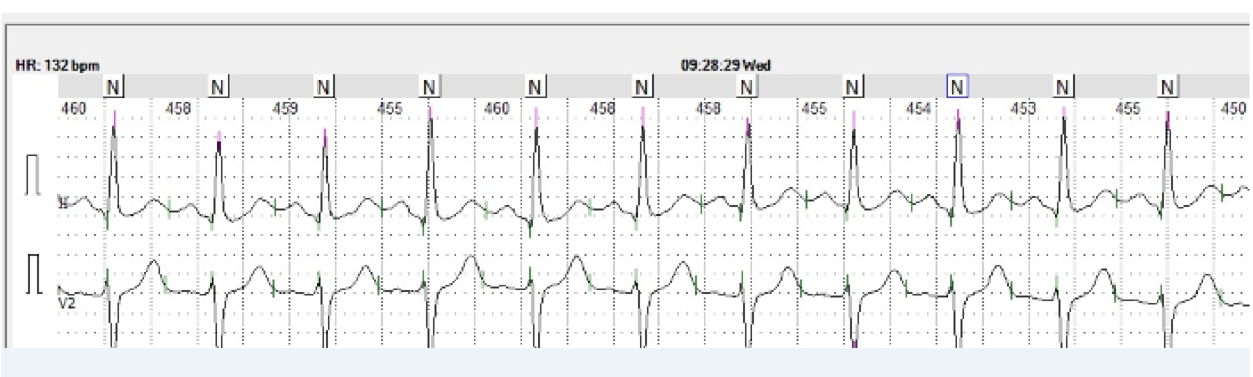
It is well known that firefighting is strenuous work that results in significant cardiovascular strain. Over the past 15 years, we have conducted a series of studies documenting that cardiovascular strain. Specifically, we have shown that firefighting produced rapid increases in heart rate (HR) and maximal or near-maximal heart rates were achieved during strenuous firefighting activities [8-11]. In addition, we have shown that firefighting resulted in decreased stroke volume, impaired diastolic function and increased arterial stiffness [12-14]. We have documented a reduction in plasma volume (-14.8%) following only 18 minutes of firefighting [8]. Hypovolemia increases blood viscosity, thereby increasing the risk for negative cardiovascular outcomes.

Importantly, we have documented that firefighting increased platelet aggregation and coagulation potential [15,16], increasing the risk of thrombus formation. Despite the importance of this work, these studies likely underestimated the true physiological burden imposed by modern fires because they were conducted in concrete training structures and used only wood and straw fuel sources. The fires we face in the 21st century use energy efficient building materials and methods along with polymer based furnishings that have been shown to result in more rapid fire growth, higher heat release rates and additional toxic exposures that may exacerbate cardiovascular strain.

Despite the high risk of cardiac events associated with firefighting, relatively few studies have employed ambulatory ECG monitoring during firefighting activity. Barnard and Duncan (1975) monitored ECG and HR responses for firefighters during a normal 24-hour shift and obtained data on 35 firefighters who responded to 185 alarms. In many cases movement artifact prevented the accurate analysis of the ECG; however, some ECG changes were noted 15 to 30 seconds post-alarm [17]. Kournika and Korhonen (1981) investigated 22 firefighters' reactions to alarm with 24-hour ECG monitoring [18]. The researchers analyzed ECGs during the 2 minutes prior to the fire alarm and the 5 minutes after the alarm. Although no signs of coronary ischemia or related S-T or T changes were seen, several nonpathologcial deviations were identified. Kurt and Peters (1975) obtained Holter ECGs from 28 firefighters during 12-hour periods at work [19]. The researchers reported arrhythmias in 11 firefighters, S-T depression (> 1.0 mm) in 5 firefighters, and S-T elevation in 1 firefighter; however, the activity at the time of the occurrences was not indicated.

Angerer et al. (2008) used Holter monitors to obtain ECGs on 29 young (age: 24.5 ± 3.3 years; range 19–32 years), professional firefighters during a 30-minute simulated live-fire operation [20]. In contrast to previous studies, the investigators did not identify abnormal ECG changes or signs of disordered heart rhythm. Absence of identifiable ECG changes could be attributed in part to the subject population as the participants in the study by Angerer et al. were younger than participants in previous studies [17-19]. Carey and colleagues (2 studies) used a 12-lead ECG to obtain high-resolution ECG tracings from firefighters during 24-hour shifts. In the pilot feasibility study [21], 28 firefighters (age range 35–56 years) wore the 12-lead ECG Holter monitor for 24 hours (16 on-duty and 8 post-duty). On average, 92% of recording were able to be analyzed. Six episodes of nonsustained ventricular tachycardia (NSVT) were identified, with the episodes occurring among three (11%) of the firefighters. Although most episodes of NSVT occurred during sitting/talking activities, one episode occurred during emergency activities. The mean spatial QRS-T angle was 104 ± 17 degrees (range 78–132 degrees). The QRS-T angles (an indicator of risk from cardiac death) reported by Carey and Thevenin suggest some firefighters may be at increased risk for a fatal cardiac event [21]. In a follow-up study with 112 firefighters wearing 12-lead ECGs during 24-hour shifts, Al-Zaiti and Carey et al. (2015) reported the presence of a widened QRS-T angle in 10% of firefighters [22]. In this larger study population, only one episode of NSVT was identified. The study also determined that eight other ECG variables exceeded the cut-point for cardiovascular risk.

Studies that have investigated the effects of prolonged strenuous exercise have found increased electromechnical delay (an increased delay from electrical activation to the onset of mechanical left ventricular (LV) contraction) and this was associated with reduced systolic and diastolic function. This is consistent with our data showing acute strenuous exercise increases the time of depolarization–repolarization of the left ventricle, as evidenced by a prolonged the QT-interval [23,24]. Overall, these changes are linked to exercise induced left ventricular vulnerability, as an increase in QT-interval is associated with electrical instability and sudden death. However, there have been no studies to assess ECG responses during and following live-fire in modern environments. This is an important need since toxicants in the smoke are one factor that may affect ECG changes resulting from firefighting work. In addition to causing changes in the



ECG, we have recently shown that live firefighting decreases both systolic and diastolic function in young firefighters [25].

Summary

In summary, it is known that sudden cardiac events are the leading cause of line of duty death among firefighters, and substantial evidence suggests that firefighting leads to significant cardiovascular strain. However, there are several critical gaps that still exist in the scientific literature. Key questions that remain include:

- How do clinically relevant cardiovascular parameters (ECG and coagulatory variables) change with firefighting activity in realistic modern environments? This is an important distinction since most previous research has been done in training buildings using only wood and straw.
- How do parameters related to firefighting (firefighting tactical decisions, assignment) affect the cardiovascular responses to firefighting? There is likely considerable variability in cardiovascular responses based on the type of tactics used by the department and the individual work that is performed.
- How do these cardiovascular parameters change over the 12-hour period post–firefighting? A large portion of firefighter fatalities occur *after* fire suppression activities.

I.B. Toxic Exposures Associated with Fire Fighting

Several epidemiology studies have been conducted to determine the risk of cancer in the fire service. In the largest cohort mortality study ever conducted in firefighters (involving 30,000 career firefighters), the National Institute for Occupational Safety and Health (NIOSH) found statistically significant mortality and incidence rates of all cancers and cancers of the esophagus, intestine, lung, kidney, and oral cavity, as well as mesothelioma for firefighters compared with the general population [26]. The NIOSH study also found excess risk of bladder and prostate cancers at younger ages. LeMasters et al. (2006) conducted a meta-analysis of several epidemiology studies from 1975–2003 and found an elevated risk for multiple types of

cancer [27]. Recent studies conducted throughout the world (Nordic countries, Australia, and California) identified increased risks among firefighters for multiple types of cancer [28-30], many of which were also identified in the NIOSH study [26]. Comparing cancer rates to surrogates for exposure, NIOSH found an exposure-response relationship between fire hours and lung cancer mortality and incidence, and a similar relationship between fire runs and leukemia [31]. These are important findings because if the risk of disease increases with increasing exposure, the likelihood of causality is enhanced. All together, these studies suggest that the firefighting occupation may put firefighters at an increased risk for multiple types of cancer.

There are a number of factors that can increase someone's risk of cancer. These include smoking, alcohol consumption, diet, obesity, sun exposure, and exposure to chemical carcinogens. Several studies have been conducted to assess firefighters' exposure to combustion byproducts [32-36]. These studies have identified numerous carcinogenic compounds in the fire atmosphere, including benzene, certain polycyclic aromatic hydrocarbons (PAHs), 1,3-butadiene, formaldehyde, vinyl chloride, and other halogenated compounds [37-41]. Firefighters can also be exposed to diesel exhaust, a known human carcinogen [42], at the fire ground or fire station. When firefighters wear positive-pressure self-contained breathing apparatus (SCBA), inhalation of these toxicants is essentially eliminated [43]. However, it has been observed that firefighters do not always wear SCBA, for example, when sizing up the fire, when working as the engineer or incident commander, or when conducting overhaul operations. Some of these compounds can also be absorbed through the skin either directly in vapor form (e.g., benzene) or through deposition or contact-transfer of particulate to the skin (e.g., PAHs) [34,44,45]. In a recent study, NIOSH measured firefighters' dermal exposure to PAHs on the neck, face, arms, and scrotum following controlled burns where laundered or new gear was used. NIOSH found a statistically significant increase in PAHs on the neck, which the investigators attributed to the lower dermal exposure protection afforded by fire hoods [34]. In this same study, PAH metabolites in urine appeared to be elevated 3 hours after firefighting (most likely from dermal uptake) and exhaled breath levels of benzene were significantly elevated immediately after firefighting. The NIOSH investigators postulated that the increased breath levels of benzene were due to absorption of vapor through skin or inhalation of benzene off-gassing from contaminated gear. Other studies have found elevated biological levels of PAHs and benzene after firefighting activities despite the use of turnout gear and SCBA [46,47].

Firefighting gear that becomes contaminated may be an important source for dermal exposure, whereby firefighters touch the contaminated gear and spread it to other areas of their bodies. Studies have quantified numerous contaminants on firefighting gear including PAHs, phthalates, flame retardants, and metals [48-50]. Two studies have found elevated levels of a variety of brominated flame retardants in the serum of California firefighters compared with the general population [51,52]. In the most recent study, routine cleaning of turnout gear after use in firefighting was associated with reduced serum levels of some flame retardants, while interior fire suppression within the last month was associated with elevated levels of these compounds in serum [51]. Chlorinated and brominated dioxins and furans, which can be produced from the combustion of halogenated organic compounds, have also been detected in firefighters' serum. Some types of flame retardants, dioxins, and furans are persistent organic pollutants, meaning they can remain unchanged in the environment for long periods of time and can bioaccumulate in the body. These findings suggest that the act of firefighting and contamination of gear may contribute to the internal dose of these persistent organic pollutants. However, the magnitude and biological significance of this contribution to firefighters' internal dose are not well understood.

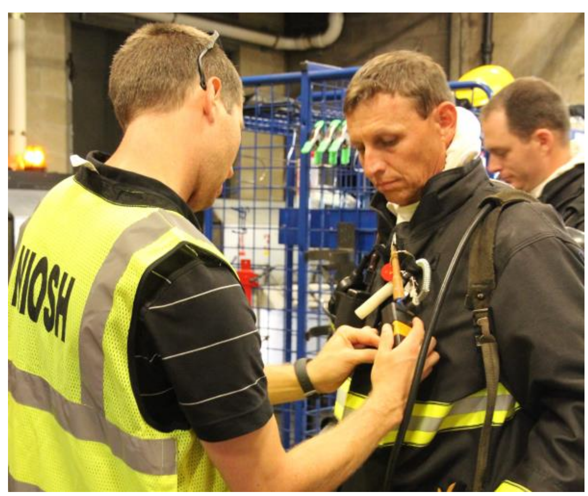
In addition to the concern for dermal exposure, contaminated gear may increase firefighters' exposure through the inhalation route. Two recent studies found elevated levels (compared to background) of several volatile organic compounds (VOCs) off-gassing from contaminated gear soon after doffing [53-54]. This off-gassing of VOCs could expose firefighters if they rehab near contaminated gear, continued to wear their gear post-fire, or wear or store their gear in the apparatus cabin on the drive back to the station. Although not evaluated in either of these studies, contamination and off-gassing of semi-volatile compounds could result in even longer term inhalation exposures.

Summary

In summary, it is known that exposure to chemicals produced in fires may lead to significant health risks including statistically significant increase in certain cancers among firefighters. However, a number of knowledge gaps still exist in the scientific literature. Key questions that remain include:

- What is the effect of different attack methods on firefighters' airborne, dermal, or systemic exposures as well as turnout gear contamination and off-gassing? This is important information because it could provide direction for policy and procedures.
- How are these exposure risks modified by a firefighter's specific role or position? For example, we do not have sufficient data on chemical exposures among firefighters or other personnel at the scene who do not enter the structure (e.g., pump operator, truck company operating on the roof). Collecting chemical exposure and determinant information (e.g., effect of wind direction) on these individuals is especially important because they often do not wear respiratory protection in these positions.
- What is the effectiveness of decontaminating turnout gear in reducing dermal exposures (due to contaminant transfer) or inhalation exposures (due to off-gassing)?
- How effective are skin cleaning towellettes at removing fireground contamination from the firefighters' skin immediately after firefighting activities?

By monitoring firefighters' airborne, dermal, and systemic exposures to these compounds, it is possible to fill in many of the knowledge gaps that exist, particularly with respect to the effect of attack methods, firefighter's job task, and skin cleaning on his/her chemical exposure levels under field conditions. Additionally, assessing the contamination of turnout gear before and after fires as well as before and after decontamination by measuring surface levels of PAHs, flame retardants, dioxins and furans, and by measuring concentrations of VOCs off-gassing from the gear, will provide an indication of the non-volatile and volatile contamination levels that may be expected following common structural fire responses and will also provide quantitative evidence of the effectiveness of on-scene fire ground decontamination.



I.C. Fire Dynamics and Fireground Tactics

A significant contributing factor to the continued tragic loss of firefighters' and civilian lives is the lack of understanding of fire behavior in residential structures resulting from the changes that have taken place in several components of residential fire dynamics. The changing dynamics of residential fires as a result of revolutions in home size, geometry, contents and construction materials over the past 50 years add complexity to the fire behavior [55].

NFPA estimates that from 2009-2013, U.S. fire departments responded to an average of 357,000 residential fires annually [56]. These fires caused an estimated annual average of 2,470 civilian deaths and 12,890 civilian injuries. More than 70% of the reported home fires and 84% of the fatal home fire injuries occurred in one- or two-family dwellings, with the remainder in apartments or similar properties. For the 2007-2011 period, there were an estimated annual average 34,065 firefighter fire ground injuries in the U.S. [57]. The rate for firefighter deaths' occurring inside structures has continued to climb over the past 30 years [58]. Additionally, on average firefighters in the United States receive less than 1% of their training on the subject of fire behavior [59]. The changes in the residential fire environment combined with the lack of fire behavior training are significant factors that are contributing to the continued climb in firefighter traumatic deaths and injuries.

As homes become more energy efficient and fuel loads increase, fires will become

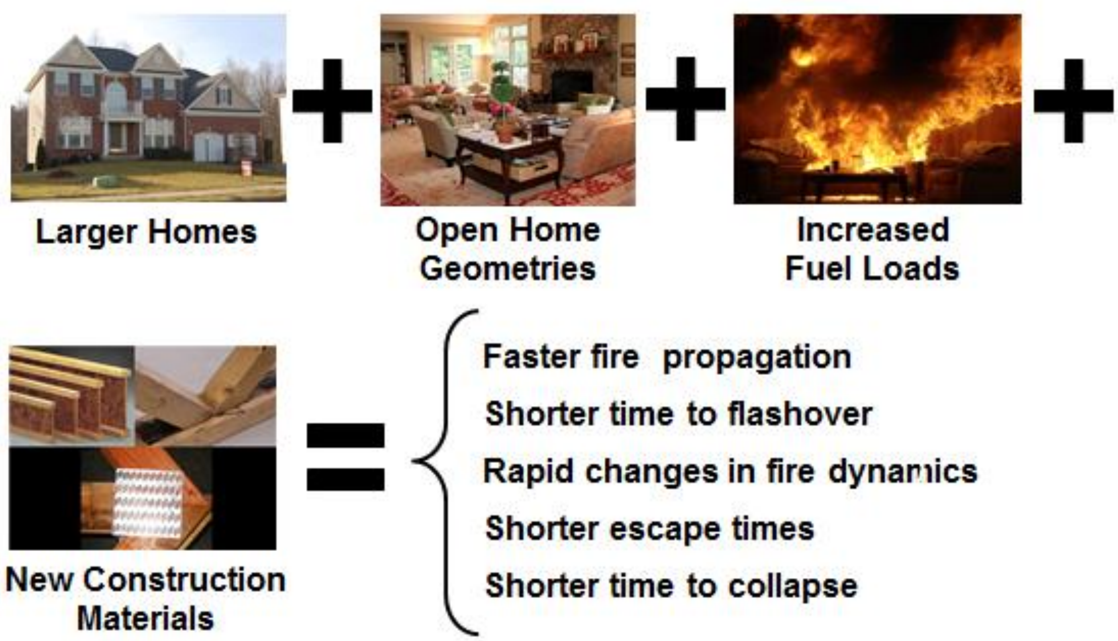


Figure 1. Modern Fire Formula [55]

ventilation limited making the introduction of air during a house fire extremely important. If ventilation is increased, either through tactical action of firefighters or unplanned ventilation resulting from effects of the fire (e.g., failure of a window) or human action (e.g., door opened by a neighbor), heat release will increase, potentially resulting in flashover conditions. These ventilation induced fire conditions are sometimes unexpectedly swift, providing little time for firefighters to react and respond.

Firefighters today are being challenged by different fireground hazards due to today's construction practices and the use of synthetic materials in furniture and building products [60]. These changes have made structure fires more challenging than ever before and have led to reevaluation of firefighting tactics. One of these considerations is the location from which water is applied to the fire. Exterior attack tactics matter because, although they go against traditional practices, they represent an effective way to make the fireground safer for both building occupants and firefighters.

The changes in modern building design and materials have altered the nature of structure fires, with modern homes able to reach flashover eight times faster than homes built 50 years ago [60]. This change is largely behind the 67% increase in the rate of firefighter deaths due to traumatic injuries while operating inside of structures over the past 30 years [58]. And although the overall fire death rate in the U.S. has decreased by 64% during the same period [61], it is clear that modern structure fires can be deadly to both firefighters and building occupants.

Many of the tactics employed by the American fire service have been developed based on personal experience—of individual firefighters and as passed down by their predecessors [62]. As mentioned by Kerber and Sendelbach (2013), "To the credit of many, these tactics have proven successful in controlling and mitigating the hazards of fire for more than 250 years" [62]. However, the number of structure fires has decreased by 53% over the past 30 years [58], which has had an unintended consequence of limiting the opportunities for firefighters and fire officers to gain the necessary experience to understand the increasingly complex fires they fight [63].

UL has long been in the forefront of fire safety research to support efforts that prevent unnecessary fire-related deaths. Much of this research has been directed toward developing a better understanding of the characteristics of the modern residential fire, and providing members of the fire service with the information and knowledge needed to modify key firefighting tactics. While firefighting will never be without risk, UL research represents a vital contribution to overall efforts to reduce risks and to save lives.

UL and UL FSRI have conducted research on many aspects of the fireground, with specific focus on risk faced in 21st century firefighting. A series of studies has improved understanding the impacts of engineered structural components under fire conditions [64] with specific emphasis on basement fires [65]. Lightweight wood trusses and engineered lumber are increasingly replacing conventional solid joist construction in roof and floor designs in residential structures. UL researchers

compared the fire performance of conventional solid joist lumber with that of lightweight lumber and demonstrated that, under controlled conditions, fire containment performance of an assembly supported by solid joist construction was significantly better than an assembly supported by an engineered I joist. Standard integrity assessments, such as sounding the floor, floor sag, gas temperatures on the floor above and thermal imaging, are often misguided indicators of the actual integrity of a floor over a burning fire. A number of tactical issues were identified for firefighters to consider when making a determination about dealing with residential basement fires.

The impact of firefighting tactics such as ventilation (horizontal [66], vertical [67] and positive pressure [68]) and water application from the exterior [69,70] have been carefully studied. Among the important findings of these studies is the critical importance of coordinating ventilation with the application of water or another type of fire suppressant in achieving a successful firefighting outcome. The studies also affirmed that the simple act of closing a door between a firefighter and a fire can provide tenable

temperature and oxygen concentrations behind the closed door, increasing the chances of survival. These data will be disseminated to provide education and guidance to the fire service in proper use of ventilation as a firefighting tactic that will result in reduction of the risk of firefighter injury and death associated with improper use of ventilation and to better understand the relationship between ventilation and suppression operations. As part of this series of studies, UL partnered with the National Institute of Standards and Technology (NIST), the Fire Department, City of New York (FDNY), and the Governors Island Preservation and Education Corporation to utilize rigorous scientific methods to advance firefighter safety. Ventilation and suppression procedures were analyzed during basement, first floor and second floor fires during 20 townhouse fire experiments. The live burn tests were aimed at quantifying emerging theories about how fires are different today, largely due to new building construction and the composition of home furnishings and products that in the past were mainly composed of natural materials, such as wood and cotton, but now contain large quantities of petroleum-based products and synthetics that burn faster and hotter.

UL also conducted a seminal study on firefighter exposures to smoke particulates in 2011 [71]. In this study, UL partnered with the Chicago Fire Department and the University of Cincinnati, College of Medicine to collect data on the smoke and gas effluents to which firefighters are exposed during routine firefighting operations and from contact with contaminated personal protective equipment. The project included investigations on three fire scales: 1) fires in the Chicago metropolitan area; 2) residential room content and automobile fires; and 3) material-level fire tests. The study determined that the combustion of materials in a fire generates asphyxiants, irritants and airborne carcinogenic byproducts that can be debilitating to firefighters. These byproducts are also found in smoke during the suppression and overhaul phases of firefighting, and carcinogenic materials can be inhaled from

the air or absorbed through the skin through contact with contaminated equipment.

The full reports on the above completed studies are available at the UL Firefighter Safety Research Institute website at www.ULfirefightersafety.com.

Summary

As the above research demonstrates, significant progress has been made understanding the modern residential fire environment and the fire service has been provided with important tactical guidance that can increase firefighter effectiveness. However, there is still much to learn and it is through partnerships like the one between UL FSRI, IFSI and NIOSH that are necessary to understand firefighting holistically. Key questions that remain include:

- How do the tactical choices made by the fire service impact their risk for cardiovascular and chemical exposure?
- What is the physiological and chemical impact of the different exposures experienced by different roles on the fireground?
- What is the best way to train firefighters when it is not possible to create a "realistic" fire environment during training?
- Under which variables should a transitional attack be chosen versus and interior attack?

II. Goals, Objectives & Specific Aims

II.A. Goals and Objectives

The goal of this study was to conduct an integrated, comprehensive research project to investigate the effects of modern fire environments on the two most pressing concerns in the fire service, namely cardiovascular and carcinogenic risks (Figure 2). This research was needed so that policies and procedures to minimize these risks to firefighters can be developed. In order to ensure that our findings are broadly applicable across the fire service, we worked with our Advisory Committee of national leaders to investigate how fire size, tactical decisions, and job assignment affected cardiovascular parameters and carcinogenic markers following firefighting work.

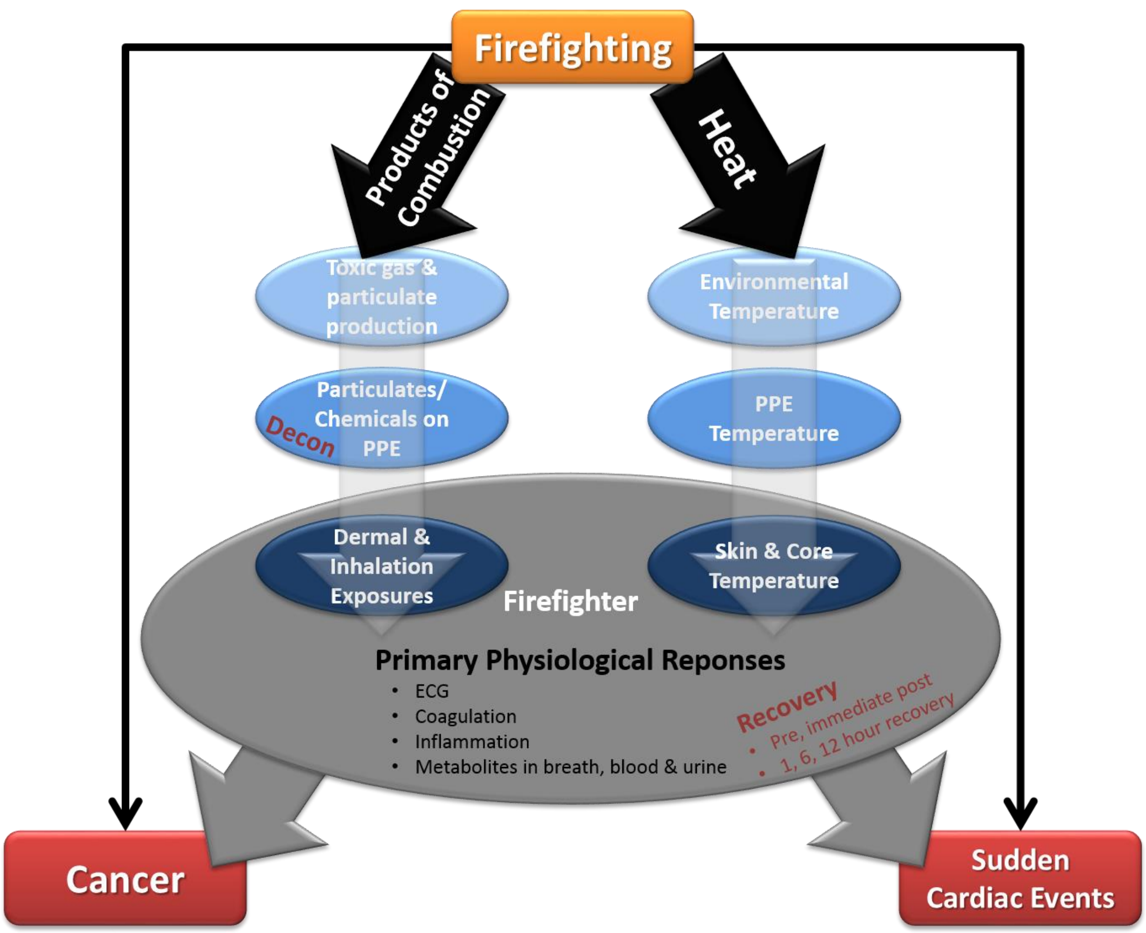
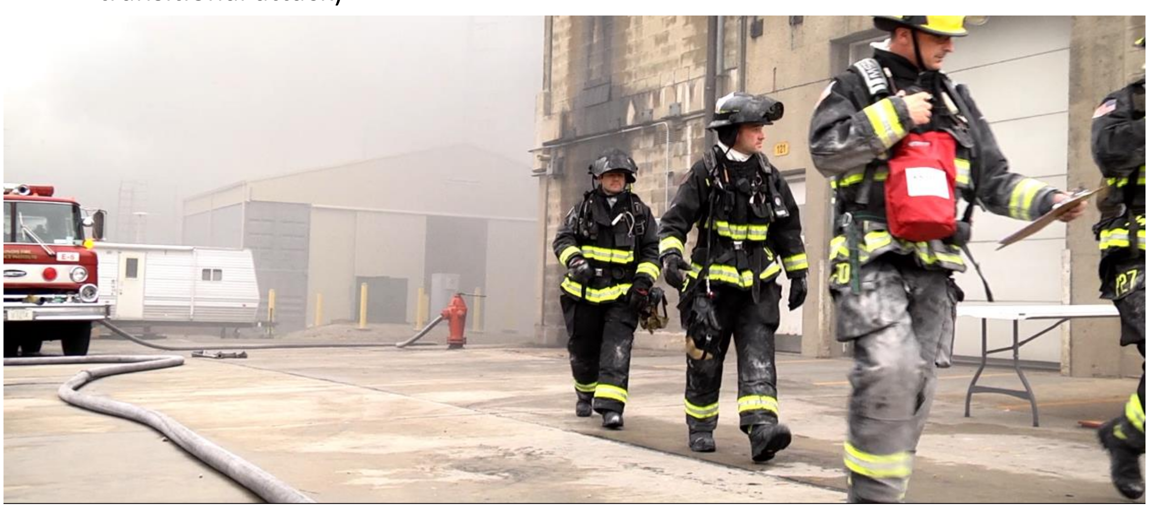


Figure 2. Comprehensive model of Cardiovascular and Chemical Exposure Risks in Modern Firefighting goals and objectives.

II.B. Specific Aims

The specific aims of the study were to:

- Conduct realistic firefighting tactics with 12-person teams responding to residential fire environments that contain building materials and furnishings common in the 21st century.
- Measure the production and transfer of thermal energy and products of combustion through modern personal protective equipment (PPE) and onto/into firefighters' bodies and evaluate how these variables are influenced by:
    - Tactical decision (interior only vs. transitional attack)
    - Operating location (interior fire suppression/search vs. exterior operations vs. interior overhaul)
- Measure cardiovascular disruption (ECG, coagulatory variables) for up to 12 hours following firefighting and evaluate how these variables and recovery from firefighting activities are influenced by:
    - Tactical decision (interior only vs. transitional attack)
    - Operating location (interior fire suppression/search vs. exterior operations vs. interior overhaul)
- Measure markers of toxic exposure (chemicals or their metabolites in blood, urine and breath) for up to 12 hours following firefighting and evaluate how these variables are influenced by:
    - Tactical decision (interior only vs. transitional attack)
    - Operating location (interior fire suppression/search vs. exterior operations vs. interior overhaul)
    - Skin cleaning and/or use of decontaminated gear
- Evaluate effectiveness of:
    - Skin cleaning procedures in reducing contamination on the skin, particularly on the neck.
    - Gross on-scene fireground decon procedures in minimizing secondary exposure risk from off-gassing PPE.



III. Methods

Participants were recruited through a nationwide recruiting effort along with a focused effort by a statewide network of firefighters who teach and train at the Illinois Fire Service Institute's (IFSI) Champaign campus. As a result, 40 firefighters participated in this study from departments in Illinois, Georgia, Indiana, Ohio, South Dakota and Wisconsin. Most firefighters attended four sessions of the study, although a small group were only available for a single pair of experiments. For each 'pair' of experiments, the firefighters operated in the same job assignment (e.g. attack, overhaul), but the fires were suppressed with a different tactic (interior vs exterior transitioning to interior) on the two days. For firefighters who participated in two pairs of experiments, they completed a different job assignment for the second experiment 'pair'.

Figure 3 provides a rough schematic of the study protocol. Following recruitment, subjects completed all required paperwork (including an informed consent document, health history questionnaire, and diet recall) and anthropomorphic measurements (height, weight) were collected. Firefighters received a core temperature pill that they ingested 6–12 hours prior to data collection. After they arrived at IFSI (at least one hour prior to firefighting), the firefighters were instrumented with a portable ECG monitor that they wore throughout the study period.

Multiple pretest measures were collected prior to the initiation of live fire training. Venous blood samples were drawn from the anticubital vein by a trained phlebotomist at various times throughout the study. Blood samples were subsequently analyzed to assess hemostatic balance (via platelet number and function and coagulatory variables - section III.B.2.), as well as markers of toxic exposure.

The firefighter subjects then commenced their firefighting work in a purpose-built live-fire research test fixture (see section III.A). Teams of 12 firefighters completed different scenarios that included a fire involving multiple rooms (M. Bedroom, BR2) with windows vented using two separate firefighting strategies: (a) traditional interior attack from the "unburned side" and (b) initial exterior attack to darken the fire, then transitioning to interior attack. The teams were separated into pairs that completed specific tasks. The first arriving complement of 4 firefighters was split into: Engine 1 – interior firefighters responsible for the attack line and exterior based command and pump operator positions. One minute later the second group of 4 firefighters arrived and was split into: Truck A – interior firefighters responsible for forcible entry into the structure as well as search and rescue and Truck B that conducted exterior ventilation (horizontal and vertical). The last arriving complement of 4 firefighters was split up into initial exterior tasks that transitioned into overhaul. Engine 2A pulled a back-up line and supported the first-in engine prior to overhaul operations. Engine 2B initially set up as a rapid intervention team (RIT) then transitioned to overhaul operations after the fire was suppressed.

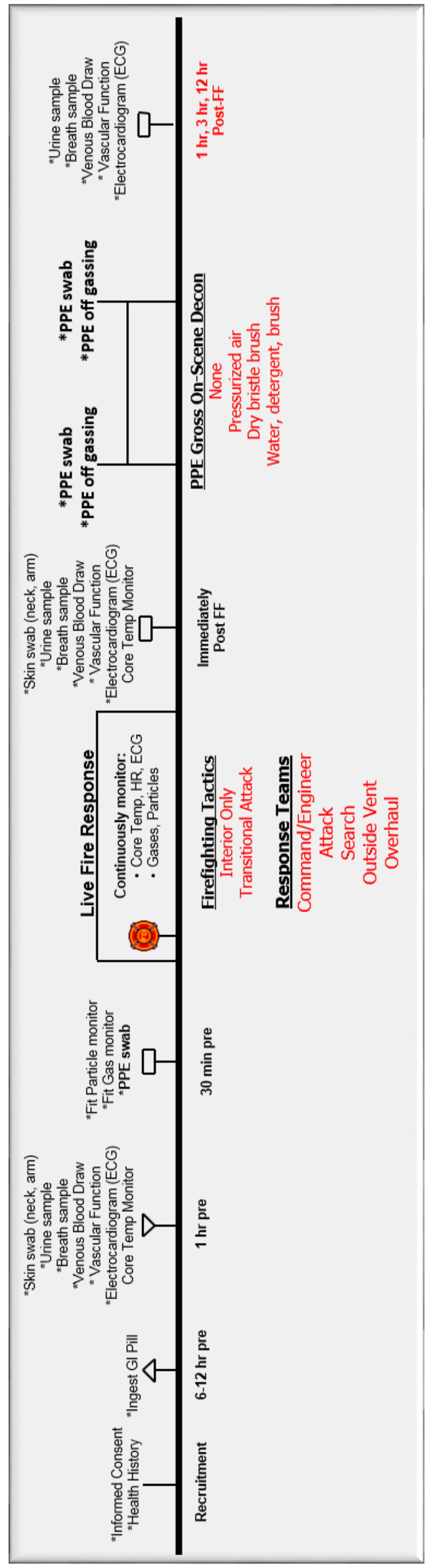


Figure 3. Data collection protocol and timeline.

III.A. Live Fire Research Test Fixture Design

In order to safely and reliably conduct this study, we designed and built a structure that had all of the interior finishes and features of a single family dwelling, yet contained safety systems and hardened construction techniques that ensured our participants' safety. In their laboratory-based research, UL has repeated burns in a structure simulating a common one-story ranch type house. The house was designed by a residential architectural company to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 8 ft. ceilings. To allow for the potential comparison between our live-response results and their laboratory burns, our research structure replicated their design with some modification.

The original UL design was modified slightly to allow burns to be conducted on consecutive days. The house had an area of 1200 ft^2, with 4 bedrooms, 1 bathroom (closed off during experiments) and 8 total rooms. The home was a wood frame, type 5 structure with a wood truss constructed roof, finished with ½" oriented strand board and shingles. To maximize the use of the structure and minimize time between experiments the house was mirrored so that there were 2 bedrooms on each side where the fire would be ignited. During each experiment a wall was constructed at the end of the hallway to isolate 2 bedrooms so that they could be repaired and readied for the next experiment. Figure 4 shows the two configurations used. Bedrooms 1 and 6, Bedrooms 2 and 5, Bedrooms 3 and 4, and the Living Room and Dining Room were interchangeable between experiments. The front and rear of the structure were covered with cement board to limit exterior fire spread (Figure 5). Figure 4 is a 3D rendering of the house with the roof cut away to show the interior layout with furniture and floor coverings. The tan floor shows the carpet placement and the grey floor shows the cement floor or simulated tile locations.

To ensure safety of the participants, all structural elements in the burn rooms were protected by a layer of ⅝" Type X gypsum board with a second layer of ⅝" fiberglass mat gypsum sheathing. Furring strips (2×4) were then attached to the walls and ceiling and another layer of ⅝" Type X gypsum board was attached to the ceiling and ½" gypsum board was attached to the walls. After each fire, the overhaul teams completely stripped the finish layer down to the 2×4 furring strips. Between each scenario, the structure was inspected to ensure the base layer had not been penetrated to the structural elements. A deluge style sprinkler system was installed in the burn rooms and charged prior to each scenario. An exterior safety officer was stationed by this valve to immediately suppress the fires if any scenario arose that required rapid suppression.

Figure 4. Layout of burn structure showing false wall set up for the (top) right side experiment layout and (bottom) left side experiment layout.

Overhead View & Apparatus layout

Side A (North)

Side B (East)

Side C (from Southeast Corner)

Side D (West)

Figure 5. Exterior photographs of the test structure.

III.A.1. Fuel load

Furniture was acquired for the experiments such that each room of furniture was the same from experiment to experiment (Figure 6). Bedrooms 1/6 and 2/5 were furnished with a double bed (covered with a foam mattress topper, comforter and pillow), stuffed chair, side table, lamp, dresser and flat screen television. The floors were covered with polyurethane foam padding and polyester carpet. Bedrooms 3 and 4 were furnished with a double bed (covered with a comforter and pillow), side table, lamp, and dresser. The living room was furnished with a sleeper sofa, 2 stuffed chairs, end table, coffee table, television stand and flat screen television. The living room floor was also covered with padding and carpet. The kitchen and dining room were both furnished with a table and 4 chairs.

Living Room

Kitchen

Bedroom 1/6

Bedroom 2/5

Bedroom 3/4

Dining Room

Figure 6. Fuel load in each of the rooms of the structure – identical for every experiment.

Fires were ignited in the stuffed chair in both Bedroom 1/6 and Bedroom 2/5 depending on which side was being utilized (Figure 7). The fire was ignited using a remote ignition device comprising of a book of matches and electrically energized with a fine wire to heat the match heads, and create a small flaming ignition source. The ignition source was placed on the back corner of the seat of the chair that was adjacent to the bed in each bedroom.

Figure 7. Ignition location and setup in the bedrooms

III.A.2. Live fire response timeline

The experimental timeline for all scenarios was consistently timed and executed to standardize the scenarios and response timeframe as closely as possible (see Figure 8 for an example). Typical fireground conditions at critical time points can be seen in Figure 9. All of the experiments started with the front window open in Bedroom 1/6 and the side window open on Bedroom 2/5 and both doors to the common hallway open. Bedroom 3 and 4 doors and all other exterior doors and windows were closed. The fire was ignited using a remote ignition device in the chair of Bedroom 1/6 followed 2 minutes later by ignition in the stuffed chair in Bedroom 2/5. The flaming fire was allowed to grow until it began to become ventilation limited and the fire department was dispatched. The time of dispatch was between 4 minutes and 5 minutes after ignition for all 12 experiments.

Prior to dispatch the firefighters were given their responsibilities which included either a transitional fire attack (water applied into Bedroom 1/6 and Bedroom 2/5 prior to advancing through the front door to extinguish the fire) or interior fire attack (advancement through the front door to extinguish the fire). At the time of dispatch 4 firefighters walked approximately 500 ft to the structure and began their operations. The first 4 firefighters assumed the roles of incident commander, pump operator, fire attack (nozzle firefighter, back-up firefighter). The incident commander completed a 360 degree lap of the structure and gave a radio return and orders to his team. The attack team deployed a 200 ft, 1¾" hoseline with a smooth bore nozzle and conducted either a transitional or interior attack.

One minute after the dispatch of the first 4 firefighters, a second 4 firefighters were released to walk to the scene. Two of these firefighters were the search team. They were responsible for forcing entry through a door prop so that the attack team could enter and for conducting search and rescue. They had to locate and remove 2 occupants from the structure. The second 2 firefighters were the outside ventilation team. They were tasked with coordinating horizontal ventilation with the attack team and performing vertical ventilation after placing 2 ladders.

One minute after the dispatch of the second 4 firefighters a third 4 firefighters were released to walk to the scene. Two of these firefighters were the backup team. They were responsible for deploying a second hoseline to the front of the structure and assisting with overhaul. The second 2 firefighters were the RIT team. They were tasked with deploying their tools, conducting a 360 size up and performing overhaul.

Time (mm:ss)	Description
00:00	Ignition BR 6/1
02:00	Ignition BR 5/2
04:30	FD Dispatch
06:39	Water in BR 6/1 Window Start
06:54	Water in BR 6/1 Window Stop
07:01	Water in BR 5/2 Window Start
07:17	Water in BR 5/2 Window Stop
07:56	Front Door Open
09:12	Nozzle FF Reaches Hallway
09:27	BR 6/1 Window Cleared
09:34	BR 5/2 Rear Window Open
11:28	Victim 1 Out
16:12	Victim 2 Out
19:34	Living Room Right Window Open
19:39	Living Room Left Window Open
20:33	Kitchen Window Open
35:32	End of Experiment
08:12	Fire Attack Enters
18:17	Fire Attack Exits
08:30	Search Enters
18:02	Search Exits
19:58	Overhaul Enters
35:38	Overhaul E2A Exits
35:42	Overhaul E2B Exits

Figure 8. Experimental timeline from a transitional attack scenario conducted on 06/14/2015.

Conditions at dispatch

Attack Team deploying transitional attack

Attack Team transitions to front door as Search Team forced door prop

Attack Team makes entry followed by Search Team

Backup line is deployed as outside ventilation is taking place

Roof is ventilated as fire is suppressed

Figure 9. Images from typical fireground operations incorporating a transitional attack

Simulated occupant is rescued by Search Team

Overhaul Teams remove debris and drywall from fire rooms

Figure 9 cont. Images from typical fireground operations incorporating a transitional attack

III.A.3. Operational Safety Protocols before and during Response

To further ensure participant safety, strict adherence to best practices in the fire service for command and control of large events and live-fire training was mandated. Throughout the scenarios, the research team followed National Incident Management System (NIMS) procedures, including utilization of IFSI's Incident Management Team trainers and the development of an Incident Action Plan (IAP). A single incident commander from IFSI who had intimate knowledge of IFSI safety policies and procedures as well as intimate working knowledge of the live-burn structure was the overall Incident Command for the event. An interior safety officer accompanied each of the interior teams operating as attack/search and then during overhaul operations. They both carried portable thermal imaging cameras to allow assessment. Additional exterior safety officers were assigned to maintain contact with the deluge system valve, to maintain visual awareness of the Charlie-side conditions and to provide an overall Safety Officer role. Prior to initiating any of the drills, a dedicated RIT team (with no responsibilities as part of the study) was established. An additional exterior back-up line was staged and manned for additional water if it became necessary.

UL staff continuously monitored temperatures, heat flux values, visible light and infrared camera feeds to ensure progress was being made during the scenario. An exterior safety officer was stationed at the deluge system valve to immediately activate the interior system had any of the interior camera views or radio transmission from the firefighting teams indicated its need. Finally, prior to completing any activity, the firefighters were escorted through the burn structure to ensure their familiarity with the structural layout. Prior to each scenario, a command briefing was conducted with all staff and participants to ensure safety policies were understood and expectations were clear. In addition to reviewing the safety plan for each day, the following potential scenarios requiring exiting the structure before completion of assigned tasks were reviewed.

- If conditions did not improve as expected upon initial interior attack, operations would be halted by Incident Command (as determined by Safety) and all interior personnel would retreat from the building in an orderly manner. Interior operations would again resume once tenable conditions were established through the safety team.
- If a Mayday was called at any point during the scenario, the research tasks were immediately halted and the Reponses Team would be deployed as RIT under the command of Interior. All personnel were to immediately evacuate the building and a personnel accountability report (PAR) was to be conducted.

Neither of these conditions were experienced during any of the study evolutions.

III.A.4. Human Subject Protections

The health of the research subject population was ensured through a strict inclusion criteria in order to minimize the likelihood of a cardiac event. All participants were required to have completed an NFPA 1582 based physical examination prior to enrolling in the study. Many of the firefighters had this completed by their home departments, while others were provided by the study. We recruited relatively experienced firefighters who had up to date training, could complete the assigned tasks as directed, and were familiar with live-fire policies and procedures. Throughout the study protocol, all firefighters were required to wear their SCBA prior to entering the structure. The research team supplied all PPE for the research participants to ensure that all protective equipment passed required NFPA standards.

III.B. Project Measurements

Measurements of cardiovascular function (hemostatic balance, ECG, autonomic function) and toxic exposure (metabolites in blood, breath and urine) were obtained before, immediately post-firefighting activity, and after 2 or 12 hours of recovery.

III.B.1. Assessment of Core and Skin Temperature

Skin (neck and arm) and core body temperature was continuously measured throughout all data collection sessions. Prior to completing each firefighting scenario, participants were provided with a Mini Mitter VitalSense Monitor to carry in their bunker coat. This unit communicated with and recorded data from the core temperature pill and local skin temperature patches. Participants swallowed a small disposable core temperature sensor capsule (the size of a multivitamin), which is designed to pass through the body and be eliminated in feces within ~24 hours. While the sensor was in the GI tract it transmitted temperature information to the remote recording device.

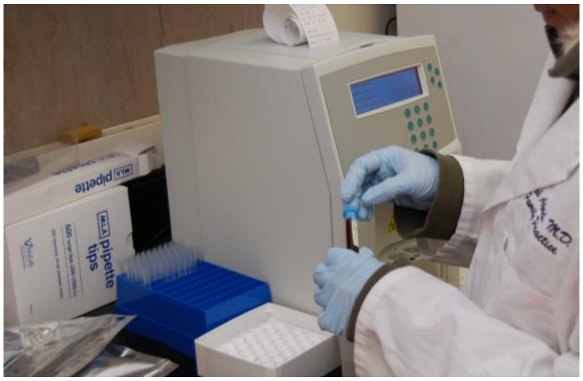
III.B.2. Assessment of Cardiovascular Function

Hemostatic Balance

Blood samples were collected by trained phlebotomists before, immediately after, and 2 or 12 hours post-firefighting activity. Venous blood samples were drawn from the antecubital vein directly into vacutainers with little or no stasis using a 21-gauge needle.

Platelet Number and Function

Platelet count, total leukocyte count, and differential leukocyte analysis were conducted from venous whole blood as part of a complete blood count (CBC) analysis, using the electrical impedance method (with an instrument such as the COULTER® LH 700 Series (Beckman Coulter, Inc., Fullerton, California) to analyze cell number and size. Platelet function was assessed by epinephrine (EPI)-induced and adenosine 5'-diphosphate (ADP)-induced platelet aggregability using a patelet function analyzer (PFA-100, Dade Behring; Deerfield, Illinois, USA). The PFA-100 aspirated whole blood under high shear rates through an aperture cut into the membrane coated with collagen and ADP (collagen-ADP) or EPI (collagen-EPI) (12). Blood was pipetted (800µl) into the disposable cartridges containing collagen-EPI and collagen-ADP within 2 hours of sampling and was analyzed for time to occlusion (in seconds).



Coagulation

Activated partial thromboplastin time (aPTT), a measure of functional coagulation, was assessed with the use of an automated coagulation machine (Sysmex CA-1500 - Sysmex America, Inc, Mundlein, Illinois).

Electrocardiogram

Firefighters wore a Holter monitor during firefighting activity and for up to 12 hours post-firefighting. Firefighters also wore a Holter monitor for a 12-hour period (control) that did not include firefighting as a baseline for comparison. The ECGs were reviewed by an investigator with expertise in ECG analysis and blinded to subject identity and to condition (firefighting and control). The ECGs were characterized as no arrhythmia, atrial arrhythmia or ventricular arrhythmia. The QT-interval analysis was conducted from Lead II (or V_5 if Lead II were technically unsatisfactory). A 2-minute ectopy free epoch was evaluated using commercially available software (Win CPRS, Turku, Finland) as we have previously described [72]. The QT-interval was defined as the time difference between the Q peak and the end of the T-wave. Autonomic function was assessed as we have previously described [73] using beat-to-beat HR variability recorded using ECG.

III.B.3. Assessment of Toxic Exposure

NIOSH conducted comprehensive exposure monitoring that included:

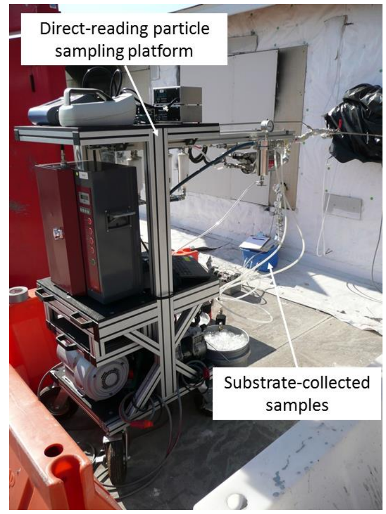
(1) Bulk sampling
(2) Area air sampling
(3) Personal air sampling
(4) Skin wipe sampling
(5) Biological monitoring (exhaled breath, urine, and blood)
(6) Turnout gear sampling (off-gas air sampling and surface wipe sampling)

Bulk sampling

Samples of foams and plastics as components of the furnishings and other items used in the bedrooms as fuel for the fires were collected for the analysis of flame retardants. There are many different types of flame retardants and they are commonly known by their abbreviations. Our analyses focused on polybrominated diphenyl ethers (BDE-28, 47, 66, 85, 99, 100, 153, 154, 183, 206, and 209), other brominated flame retardants (TBB, TBPH, BTBPE, DBDPE, HBCD, and TBBPA), and phosphorylated flame retardants (TCEP, TCPP, TDCPP, TDCPP, TPP, and TCP). Most PBDEs have been phased out, but are likely to be present in existing material stock for years, including the fuel packages such as those used in this study.

Area air sampling

Area air sampling was conducted during all 12 burns. Table 1 provides a summary of the direct-reading and substrate-collected samples that were taken. Direct-reading meters provided an immediate and continuous measurement of the air contamination, while substrate-collected samples amassed air contaminants on a filter or other substrate for subsequent analysis in a laboratory. Air was drawn from the living room during active fire and from either bedroom 1 or 6 (depending on location of the fire) during overhaul.



Samples collected at the fire ground were positioned near Engine 1 or Truck 1 (Figure 5), depending on the wind direction, to maximize the potential of being within the path of the smoke plume, while also representing areas where firefighters were commonly stationed during a response.

Table 1. Summary of area air sampling performed during the burns.

	Number of samples collected		
	Within living room during active fire	Within one of the bedrooms during overhaul	Fire ground (downwind of structure)
Direct reading samples			
Particle number concentration	12	12	12
Particle mass concentration	12	12	12
Particle active surface area	12	12	12
Particle bound PAH concentration	12	12	
Substrate-collected samples			
PAHs	12	12	12
Volatile organic compounds	12	12	12
Hydrogen cyanide (HCN)	12	12	
Flame retardants	12	12	
Acid gases	12	12	
Dioxins and furans	12		
Perfluorinated compounds	12		

Personal air sampling

Each firefighter wore three sampling trains on the exterior of the turnout jacket for measuring air concentrations of PAHs, hydrogen cyanide (HCN), and aromatic hydrocarbons (e.g., benzene, toluene, xylenes). The sampling pumps were started before firefighting commenced and stopped when the firefighters returned to the bay for doffing of their gear. Air concentrations were determined based on the time that the sampling pumps operated during the fire response. A total of 144 personal air samples for each class of compounds was collected.

Skin wipe sampling

Table 2 presents the total number of skin wipe samples collected. Wipe sampling of one side of the neck and both hands was conducted to assess firefighters' dermal exposure to PAHs. The wipes used corn oil as a wetting agent to facilitate the collection of PAHs, which are fat soluble. Before each scenario, firefighters first cleaned their neck and hand skin with commercial baby wipes. After this cleaning step, pre-exposure wipe samples were collected from the neck and hand of the nozzle firefighter (as a representative of the entire team). This was done to ensure firefighters' skin was virtually free of PAH contamination. After each scenario, once the firefighters had doffed their gear, post-exposure wipe samples were collected from their neck and hands. Four firefighters in each group then cleaned their neck skin using baby wipes, after which subsequent wipe samples were collected from their neck (opposing side as the previous wipe sample). This was done to assess the cleaning efficiency of baby wipes.

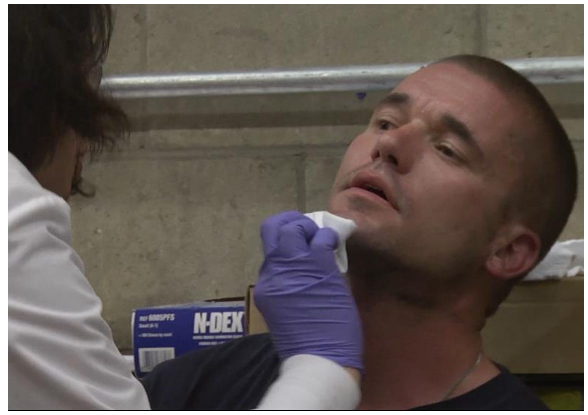


Table 2. Total number of skin wipe samples collected for PAH analysis.

Pre-exposure neck wipe samples	Post-exposure neck wipe samples	Post-exposure hand wipe samples	Post-cleaning neck wipe samples
12	142*	142*	48

** One participant dropped out during the group's first scenario and was replaced in time for the group's third scenario.*

Biological monitoring: exhaled breath sampling

Firefighters gave an exhaled breath sample for the analysis of VOCs approximately 1 hour before (n = 143), immediately after (n = 142), and 1-hour after (n = 142) each scenario. The firefighters exhaled into a collection device until they were out of breath. This measurement technique collected alveolar air from the gas-exchange region of the lungs and was an effective way of measuring systemic exposure to volatile substances. The four firefighters assigned to attack and search in each scenario were instructed to remain on air after being released from the exercise, during doffing of their gear (with assistance), and until they got to the breath collection station. This was done to eliminate the inhalation route of VOCs from off-gassing gear. Theoretically,

any elevated VOCs in the exhaled breath of these particular firefighters would be due to dermal absorption or, in some cases, inhalation exposure during the sizing up of the fire.

Biological monitoring: urine sampling

Urine samples were collected from firefighters approximately 1 hour before and 3 hours after each scenario. Urine samples were also collected 6 hours and 12 hours after firefighting during the extended observation period (EOP) from each group. The samples were analyzed as described in Table 3 for exposure biomarkers, cotinine (marker of tobacco smoke exposure), creatinine (marker of kidney function), and specific gravity (marker of hydration). Creatinine and specific gravity can be used for standardizing the urinary biomarker results.

Table 3. Summary of urine sampling and analysis.

Compounds measured	Collection periods
PAH and benzene metabolites, cotinine, creatinine, and specific gravity	Pre- and 3-hr post exposure for all scenarios except interior attack with EOP (n = 106* for each compound and collection period)
Compounds listed above and organophosphate flame retardant metabolites	Pre-, 3-hr post, 6-hr post, and 12-hr post exposure for interior attack with EOP (n = 36 for each compound and collection period)

** One participant dropped out during the group's first scenario and was replaced in time for the group's third (EOP) scenario.*

Biological monitoring: blood sampling

Blood samples were collected from firefighters approximately 1 hour before, immediately after, and 2 hours after each scenario. Blood samples were also collected 12 hours post-firefighting during the EOP scenario. The blood samples were analyzed for exposure biomarkers as described in Table 4 and other metrics as described in section III.B.2. Because the analysis of dioxins and furans requires more blood than most analyses, the samples were pooled across job assignments (or similar exposure groups) for each group of firefighters.

Table 4. Summary of blood sampling and analysis.

Compounds measured	Collection periods
HCN	Pre- and immediately post-exposure for all interior attack scenarios (n = 71*)
Flame retardants, dioxins and furans, perfluorinated compounds	Pre- and 24-hr post exposure during the EOP scenario (n = 36 for each compound)

** One participant dropped out during the group's first scenario and was replaced in time for the group's third (EOP) scenario.*

Turnout gear sampling: off-gas air sampling

Turnout gear for each firefighting team was split evenly by job position into two groups: red or green. Red gear did not undergo field decontamination, while green gear did. Generally, the gear maintained these red or green assignments for the duration of the study. Before and after each scenario, the turnout gear was separated into the two groups and placed inside 250 ft^3 enclosures for testing the off-gassing of substances contaminating the gear.

The enclosure was intended to represent the volume of a typical 6-seat apparatus cabin. Air sampling was conducted for VOCs (n = 12 for each group) and HCN (n = 12 for each group) over a 15-min period, intended to represent the driving time to and from the station.

Afterwards, the green gear was decontaminated in the field using a dry brush (4 scenarios), air-based (4 scenarios), or wet detergent method (4 scenarios).

Following field decontamination, all of the gear (green and red gear) were returned to the enclosure and tested again for off-gassing VOCs (n = 12 for each group) and HCN (n = 12 for each group).

Turnout gear sampling: surface wipe sampling

In addition to off-gas sampling, wipe samples were collected from a variety of surfaces from turnout gear, including jackets, gloves, and helmets. Table 5 summarizes the wipe samples that were collected. A 15 in^2 template was used to standardize the surface area for collection. Wipes pre-wetted with isopropanol were used for the collection of PAHs and flame retardants, while hexane was used as the wetting agent for collection of dioxins and furans.

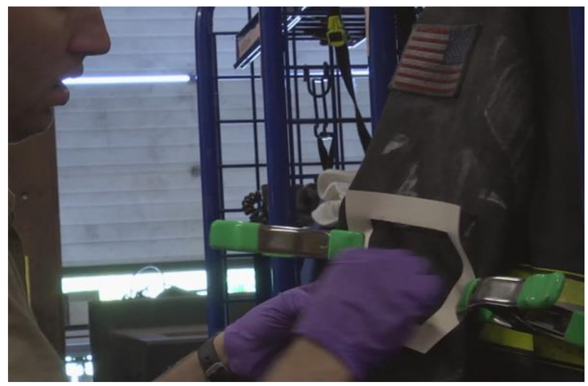


Table 5. Summary of surface wipe samples collected from turnout gear.

Compounds measured	Wipe samples collected from:
PAHs	3 sets of green jackets per scenario, pre-exposure (n = 36), post-exposure (n = 36), and post-decontamination (n = 36)
	3 sets of red jackets per firefighting group after scenario 2 (n = 9)
	3 sets of red jackets per firefighting group after scenario 4 (n = 9)
	4 helmets from interior firefighters after scenario 4 (n = 4)
Flame retardants	6 sets of red jackets after scenario 4 (n = 6)
	6 sets of green jackets (post-decontamination) after scenario 4 (n = 6)
	3 red right gloves per firefighting group after scenario 4 (n = 9)
	1 helmet from an interior firefighter after scenario 4 (n = 1)
Dioxins and furans	3 red left gloves per firefighting group after scenario 4 (n = 9)
	1 helmet from an interior firefighter after scenario 4 (n = 1)

III.B.4. Building Fire Dynamic Measurements

To assess fire dynamics throughout the fire scenarios, measurements included gas temperature, gas concentrations, pressure, heat flux, thermal imaging, and video recording. Detailed measurement locations can be found in Figure 10.

Gas temperature was measured with bare-bead, ChromelAlumel (type K) thermocouples with a 0.02-in nominal diameter. Thermocouple arrays were located in every room. The thermocouple locations in the living room, dining room, hallway, Bedroom 4, and kitchen had an array of thermocouples with measurement locations of 1 in, 1 ft, 2 ft, 3 ft, 4 ft, 5 ft, 6 ft and 7 ft below the ceiling. The thermocouple locations in Bedroom 1, Bedroom 2, and Bedroom 3 had an array of thermocouples with measurement locations of 1 ft, 3 ft, 5 ft, and 7 ft below the ceiling.

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured in 4 locations in the structure. Concentrations were measured at 1 ft from the floor in the hallway, Bedroom 3, Bedroom 4 and outside the door of Bedroom 4. Gas concentration measurements after water flow into the structure may not be accurate due to the impact of moisture on the gas measurement equipment.

Pressure measurements were made in every room at 3 elevations; 1 ft, 4 ft, and 7 ft above the floor. The pressure recorded was a differential pressure between the inside and outside of the structure.

Heat flux (the speed of thermal energy transfer) measurements were made using a 1-in nominal diameter water-cooled Schmidt-Boelter heat flux gauge. The gauges measured the combined radiative and convective heat flux. Heat flux was measured at 3 elevations, 1 ft, 4 ft, and 7 ft above the floor in two locations. The first was in the hallway wall facing Bedroom 2 and the second was in the wall outside Bedroom 4 facing away from the fire rooms. It should be noted that the convective contribution to the heat flux is dependent upon the surface temperature of the heat flux gauge. The manufacturer gives an uncertainty of ±3% and results from a study on heat flux calibration found the typical expanded uncertainty to be ±8%.

Video cameras and a thermal imaging camera were placed inside and outside the building to monitor both smoke and fire conditions throughout each experiment. Six video camera views and two thermal imaging views were recorded during each experiment.

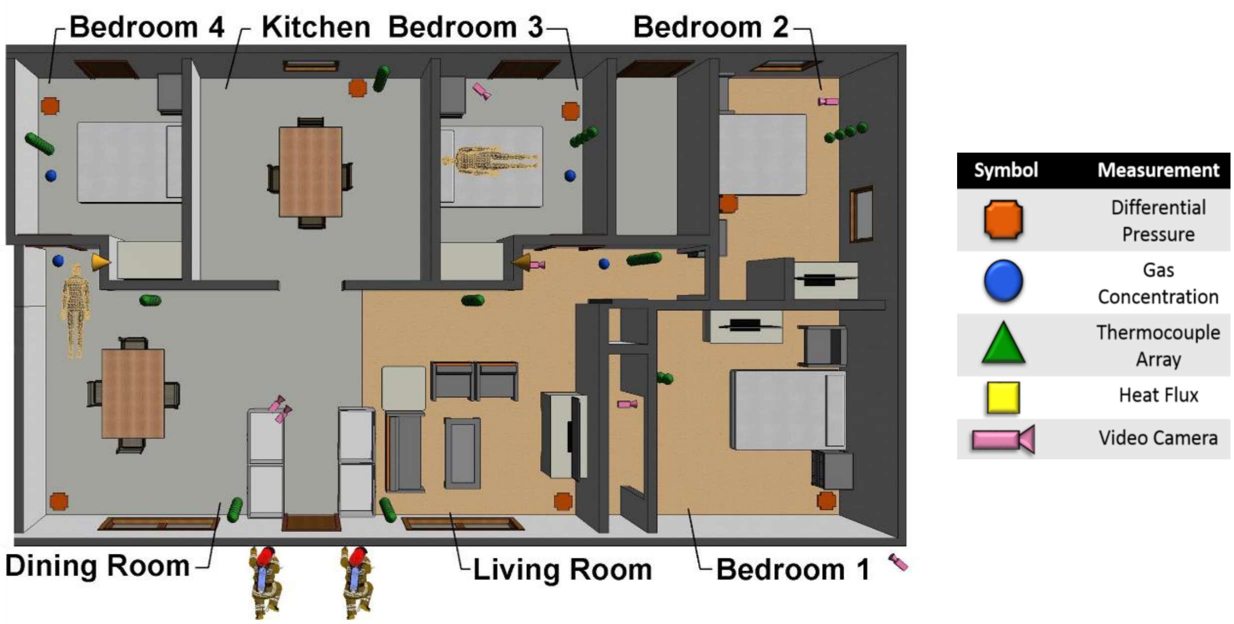


Figure 10. Measurement layout in the right side configuration

III.B.5. Simulated Occupant Exposure Measurements

Additional measurements were made on 2 simulated occupants. Portable temperature sensors, gas meters and video cameras were fixed to the head of a fire service rescue mannequin. The mannequins were placed on the bed in Bedroom 3 and sitting directly outside of Bedroom 4. These measurements were unique in that they were wireless and were recorded through the duration of the experiment, including as the mannequins were rescued by the firefighters and removed from the structure.

Gas temperature was measured with bare-bead, ChromelAlumel (Type K)

thermocouple with a 0.02-in nominal diameter located at the mouth of the mannequin. Carbon monoxide (CO), hydrogen sulfide (H_2S), oxygen (O_2), carbon dioxide (CO_2), and hydrogen cyanide (HCN) gases were analyzed using MX6 Ibrid portable personal gas monitor using electrochemical sensors. Electrochemical sensors operate by reacting with the gas of interest and producing an electrical signal proportional to the gas concentration. In order for gases to contact the sensor surface, they must pass through a small capillary-type opening and then diffuse through a hydrophobic barrier. Video was recorded utilizing a GoPro camera in a plastic protective casing.

IV. Example Results

The vast dataset that has been collected during this study is undergoing rigorous scrutiny to clean up any incorrect parameters, combine data sets and statistically analyze the outcomes. To provide the Fire Service with a glimpse of the powerful information to come, we have included a few sample values. Much of what is presented here can be understood by the Fire Service and together we can start to discuss what this information means and how it can be implemented. After the entire analysis has been completed, we will be able to provide detailed recommendations and tactical considerations.

IV.A. Example of Physiological Data

IV.A.1. Core Temperature

Core temperature, along with neck and arm skin temperature were measured from each of the twelve participants from the time they arrived on campus to the end of their data collection session. Figure 11 shows core temperature data from firefighters who completed four different job assignments (Interior – search, Exterior – engineer, Outside Vent, and Overhaul) from a single scenario, which in this case utilized a Transitional Attack. The data presented are focused on the timeframe around the response to highlight important changes with time. Shortly after firefighting activities, all temperatures recovered to physiologically normal values.

From this dataset, calculations of maximum core temperatures experienced and rate of rise in core temperature throughout the activities was calculated. In some scenarios, core temperature rose quite rapidly, while others resulted in more modest increases over the relatively short timeframes. For the first time, we will be able to compare the impact of different fireground job functions on core temperature as well as the effect of cooling the environment prior to the firefighter making entry on heat stress. While core temperature was expected to be elevated during interior firefighting operations, significant elevations were also seen for exterior vent and forcible entry operations as well as overhaul operations that required heavy muscular work. Consideration for the entirety of heat exposure is necessary. The rapid rate of rise should be considered during these operations if low manpower requires firefighters to conduct overhaul after they have completed interior suppression or rescue operations on their first cylinder of air.

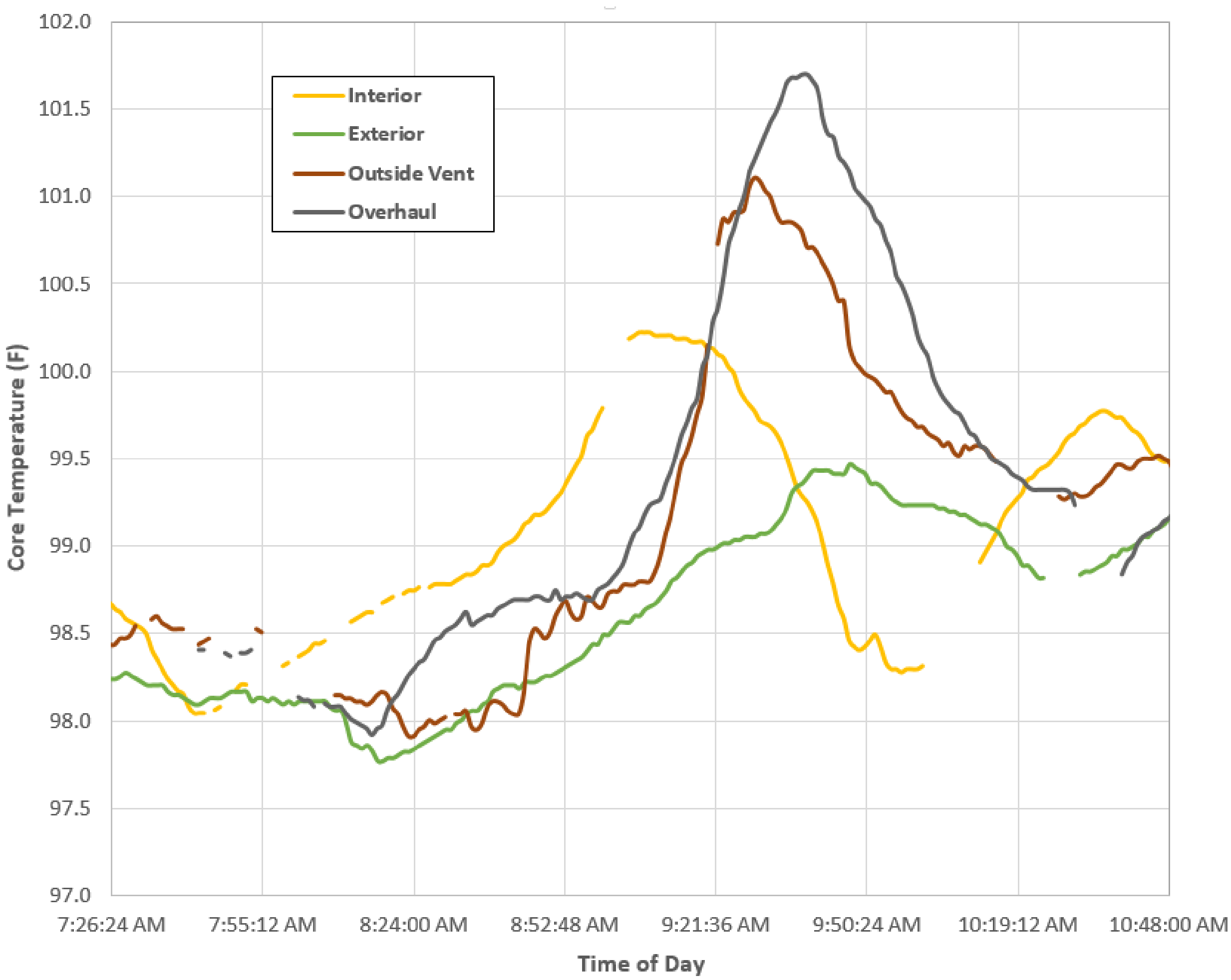


Figure 11. Typical core temperature data from firefighters operating at 4 different job assignments on the fireground. While data is collected throughout the study timeframe, this is shown around the time of the response to highlight differences in the acute responses to the different activities from 06/28/2015.

Maximum skin temperatures and core temperature values are shown as a function of job assignment and attack tactic in Figure 12. All firefighters completed the scenarios with interior attack (Blue – 06/27/2015) and transitional attack (Orange – 06/28/2015). The ability to quantify changes in skin temperature as a function of both tactic and assignment may be important when considering the body's ability to dissipate heat as well as potential changes in the absorptivity of the skin for specific chemical exposures. The impact of tactic on skin temperature is of particular interest as the Transitional attack may theoretically reduce exposure to radiant heat as well as fire smoke, especially in the neck area for the interior firefighters. The neck is provided relatively less protection by a knit hood compared with other parts of the body.

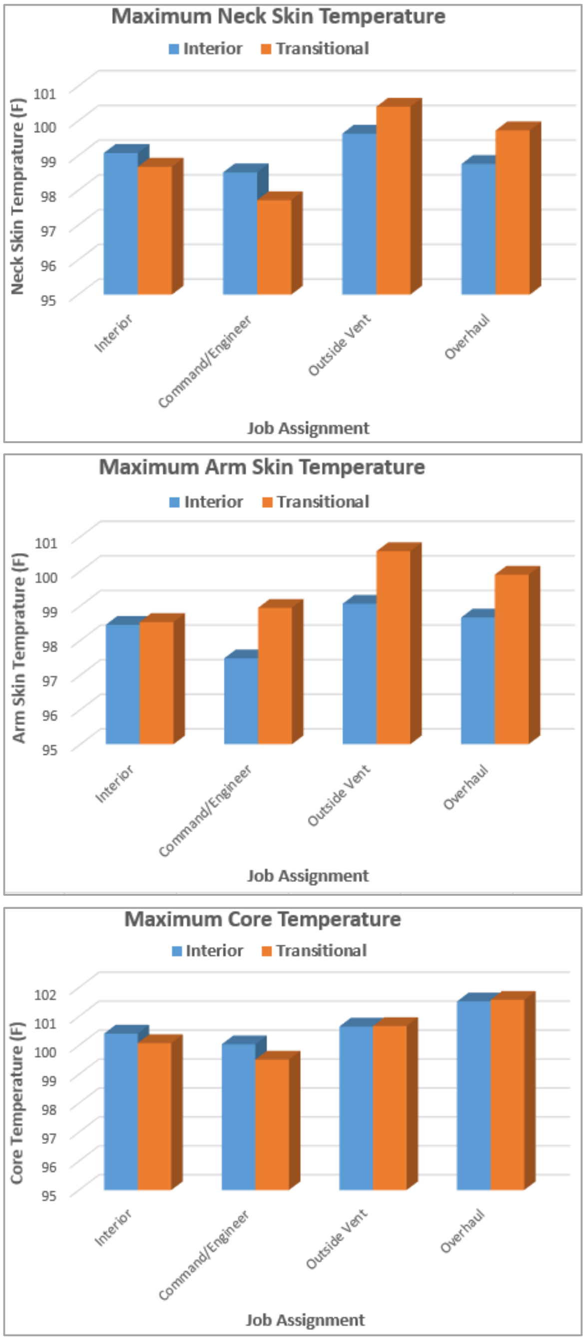


Figure 12. Typical maximum skin and core temperature data from firefighters completing different job assignments.

IV.A.2. Platelet Function

Platelet function was assessed when firefighters arrived for the beginning of the test session, immediately after firefighting.

Figure 13 shows one of the measures of platelet function (EPI) averaged over two scenarios from Group B firefighters working in four different job functions. While existing data have commonly characterized reductions in platelet function after live-fire training activities or simulated firefighting, these data provide the first glimpse into the impact of typical fireground activities by job assignment. The typical large decline in closure time is measured after Interior firefighting activities and Outside Vent, but interestingly did not result in as pronounced of a reduction after the Overhaul activity that resulted in the most significant elevation of core temperature during these response scenarios. By combining all of these data sets together, a more complete picture of the cardiovascular impact of firefighting activities and risk for sudden cardiac death will be available.

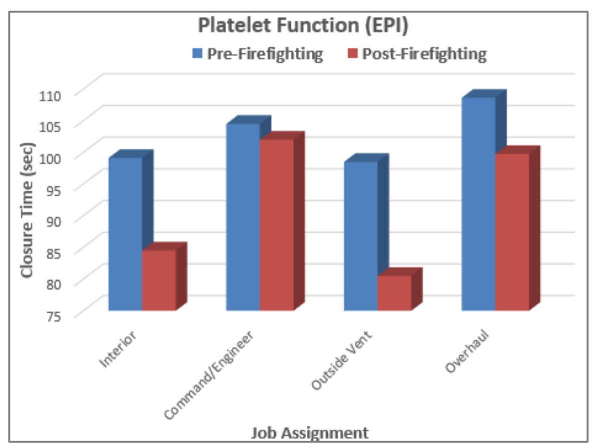


Figure 13. Typical platelet function data from firefighters completing different job assignments (Interior, Command/Engineer, Outside Ventilation, Overhaul). Blood is collected prior to firefighting activities (blue) and immediately after firefighting (red) from 06/24/2015 and 06/25/2015.

IV.B. Preliminary Exposure Data

IV.B.1. Flame Retardants in Bulk Samples

Table 6 gives the range of concentrations of PBDEs and 9 other flame retardants measured in bulk samples of the fuel package. Gray shading was used to identify the bulk items that contained the highest levels of each compound. For example, the headboard padding contained the highest levels of BDE-47 through BDE-183.

Table 6. Concentrations of flame retardants (ug/g) in bulk samples of the burn room furnishings*

Compound measured	Carpet padding (n = 3)	Curtain liner (n = 1)	Inner spring mattress foam (n = 2)	Foam topper for bed (n = 2)	Head-board padding (n = 1)	Chair cushion (n = 2)	Chair cushion liner (n = 1)	Flat screen TV plastic (n = 1)
Polybrominated diphenyl ethers								
BDE 47	< 0.1 - 0.41	0.19	< 0.1	< 0.1 - 0.74	5,600	< 0.1 - 4.1	< 0.1	< 0.1
BDE 85	< 0.1	< 0.1	< 0.1	< 0.1	840	< 0.1 - 1.6	< 0.1	< 0.1
BDE 99	0.11 - 0.56	0.25	< 0.1 - 0.44	< 0.1 - 2.9	15,000	< 0.1 - 25	< 0.1	< 0.1
BDE 100	< 0.1	< 0.1	< 0.1	< 0.1 - 0.6	2,500	< 0.1 - 3.8	< 0.1	< 0.1
BDE 153	< 0.1 - 5.6	< 0.1	< 0.1	< 0.1 - 2.0	2,000	< 0.1 - 13	< 0.1	< 0.1
BDE 154	< 0.1	< 0.1	< 0.1	< 0.1 - 0.69	1,400	< 0.1 - 5.0	< 0.1	< 0.1
BDE 183	< 0.1 - 1.1	< 0.1	< 0.1	< 0.1 - 2.0	67	< 0.1	< 0.1	< 0.1
BDE 206	< 0.1 - 14	2.8	< 0.1 - 6.3	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
BDE 209	0.41 - 102	440	< 0.1 - 61	< 0.1	< 0.1	< 0.1 - 0.68	< 0.1	< 0.1
Other brominated flame retardants								
TBBPA	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
TBB	0.38 - 3.2	910	< 0.1 - 0.5	< 0.1 - 7.5	< 0.1	18,500 - 26,750	68.5	< 0.1
TBPH	0.22 - 5.7	340	< 0.1 - 1.2	< 0.1 - 3.7	< 0.1	5,800 - 6,380	19.6	< 0.1
DBDPE	< 0.1 - 0.53	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Phosphorylated flame retardants								
TCEP	< 0.1	1.4	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
TCPP	59 - 630	5.4	< 0.1	< 0.1	8.4	< 0.1 - 1.3	< 0.1	< 0.1
TDCPP	240 - 9,100	1.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
TPP	0.43 - 3.8	4.0	0.16 - 0.23	< 0.1 - 1.3	1,690	1,400 - 7,380	22.6	19
TCP	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

**Flame retardants analyzed but not listed (BDE-28, BDE-66, BTBPE, and HBCD) were not detected (< 0.1 ug/g). TBBPA = tetrabromobisphenol-A, TBB = 2-ethylhexyl 2,3,4,5-tetrabromobensoate, TBPH = 2-ethylhexyl 2,3,4,5-tetrabromophthalate, DBDPE = decabromodiphenyl ethane, TCEP = tris (2-chloroethyl) phosphate, TCPP = tris (1-chloro-2-propyl) phosphate, TDCPP = tris (1,3-dichloro-2-propyl) phosphate, TPP = triphenyl phosphate, TCP = tricresyl phosphate*

IV.B.2. Air concentrations of contaminants measured from burn structure

Table 7 presents the air concentrations of PBDEs and 9 other flame retardants measured from the living room during active fire and from the initial burn room during overhaul for the scenario that took place on June 25, 2015. During this scenario, a variety of flame retardants were detected in the air during active fire. Only two flame retardants (TPP and TCP) were detected during overhaul. Interestingly, TCP and TBBPA were not detected in any of the bulk samples but were found in the air during the fire. This suggests that our bulk sampling regimen failed to capture all sources of flame retardants. This is not surprising given the wide-spread use of flame retardants. Note that the fire period results do not adjust for particle losses within the sample lines, which would cause a slight underestimation. We cannot compare these results to occupational exposure limits (OELs), because such limits do not currently exist.

Table 7. Flame retardant air concentrations (μg/m^3) measured from living room during active fire and from initial burn room (bedroom) during overhaul on 6/25/2015.

Compound measured	Fire period	Overhaul period
BDE 47	9.6	< 0.04
BDE 85	< 0.17	< 0.04
BDE 99	7.4	< 0.04
BDE 100	< 0.17	< 0.04
BDE 153	< 0.17	< 0.04
BDE 154	8.7	< 0.04
BDE 183	< 0.17	< 0.04
BDE 206	< 0.17	< 0.04
BDE 209	14	< 0.04
TBBPA	12	< 0.04
TBB	9.2	< 0.04
TBPH	1.2	< 0.04
DBDPE	< 0.17	< 0.04
TCEP	< 0.25	< 0.06
TCPP	< 0.25	< 0.06
TDCPP	< 0.25	< 0.06
TPP	2000	14
TCP	220	1.9

Table 8 provides the HCN and VOC air concentrations measured from the living room during active fire and from the initial burn room during overhaul for the scenario taking place on June 25, 2015. Table 9 provides the applicable OELs and Immediately Dangerous to Life and Health (IDLH) values for these compounds. Because these measurements were collected over short periods of time (< 20 min), comparing them to IDLH and short-term exposure limits is most appropriate. The HCN concentration during active fire was well above IDLH (NIOSH, 2010). The benzene concentration during active fire was above its short-term exposure limit. All other measurements collected during fire and overhaul were below short-term exposure limits.

Table 8. HCN and VOC air concentrations (ppm) measured from living room during active fire and from initial burn room (bedroom) during overhaul on 6/25/2015

Compound measured	Fire period	Overhaul period
HCN	340	1.2
Benzene	15	0.17
Toluene	0.069	0.0038
Ethyl benzene	< 0.0004	0.0014
Xylenes	< 0.0008	0.0038

Table 9. Occupational exposure limits and IDLH values for HCN and VOCs (ppm)

Compound	NIOSH REL	OSHA PEL	ACGIH TLV
HCN	ST 4.7, IDLH 50	TWA 10	C 4.7
Benzene	TWA 0.1, ST 1, IDLH 500	TWA 1, ST 5	TWA 0.5, ST 2.5
Toluene	TWA 100, ST 150, IDLH 500	TWA 200, C 300	TWA 20
Ethyl benzene	TWA 100, ST 125, IDLH 800	TWA 100	TWA 20
Xylenes	TWA 100, ST 150, IDLH 900	TWA 100	TWA 100, ST 150
Styrene	TWA 50, ST 100. IDLH 700	TWA 100, C 200	TWA 20, ST 40

ACGIH = American Conference of Governmental Industrial Hygienists, C = ceiling limit (should not be exceeded at any point in time), IDLH = immediately dangerous to life and health, OSHA = Occupational Safety and Health Administration, PEL = permissible exposure limit, REL = recommended exposure limit, ST = short-term exposure limit (should not be exceeded by measurements collected over 15 min), TLV = threshold limit value, TWA = time weighted average (over an 8-hr work shift)

Other air measurements collected from the structure but not presented here include PAHs, acid gases, perfluorinated compounds, dioxins and furans, and particles (in real-time). Results from many of these measurements are still pending.

IV.B.3. Air concentrations of contaminants measured in the fire ground.

Table 10 presents the air concentrations of VOCs measured in the fire ground, just south of Engine 1 (see Figure 5), during two scenarios. Figures 14 and 15 present the particle number concentrations (for particles 0.01 to > 1 µm) measured in the fire ground for the same two scenarios. For the scenario on June 27, 2015, the wind was out of the north/northwest, so the fire ground samples were not directly in the path of the smoke plume from the structure fire, but were downwind of the engine's diesel exhaust. The diesel exhaust was the primary contributor to the particle counts that were well above background levels (background ~ 10,000 particles/cc) throughout this scenario. For the scenario on June 30, 2015, the wind was predominately out of the west, so the fire ground samples were in the path of the smoke plume for some of the time. The smoke plume was the primary contributor to the particle counts and VOC concentrations during active fire for this

scenario. The particle counts measured downwind of the structure fire on June 30, 2015 were similar to those measured downwind of the engine's exhaust on June 27, 2015. However, the VOC air concentrations were higher on June 30, 2015, which suggests that the structure fire emissions were the predominant source of VOCs on the fire ground. Because these measurements were collected over approximately 15 min, comparing them to short-term exposure limits is most appropriate. The VOC concentrations were well below applicable short-term exposure limits.

Table 10. Air concentrations of VOCs (ppm) measured in the fire ground (south of Engine 1) on 6/27/2015 and 6/30/2015.

Compound measured	6/27/2015	6/30/2015
Benzene	0.029	0.060
Toluene	0.0034	0.0061
Ethyl benzene	< 0.0004	0.0012
Xylenes	< 0.0008	0.0032

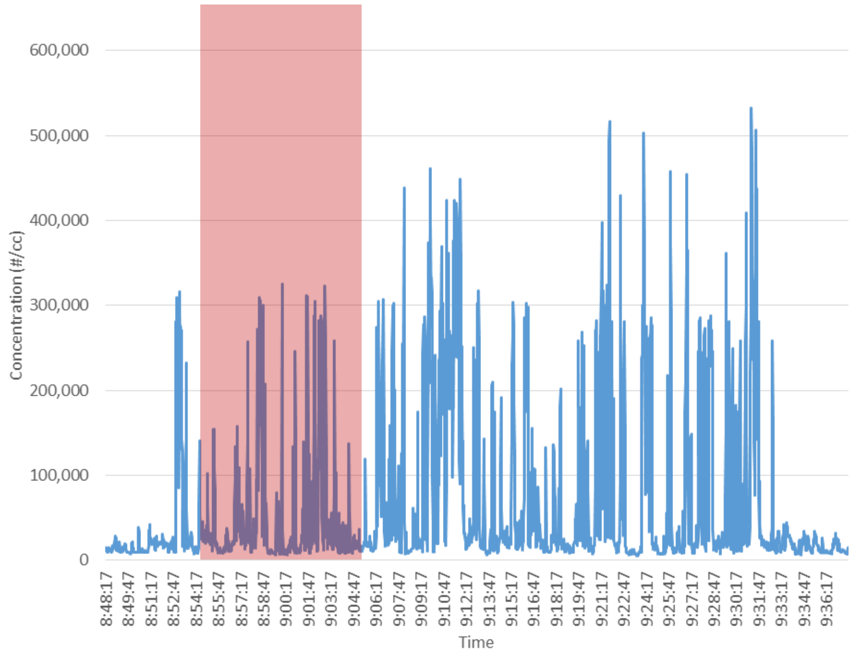


Figure 14. Particle number concentration (for particles 0.01 to > 1 µm) measured at the fire ground (south of Engine 1) on 6/27/2015. Red shading represents the period between structure fire ignition and suppression/start of overhaul.

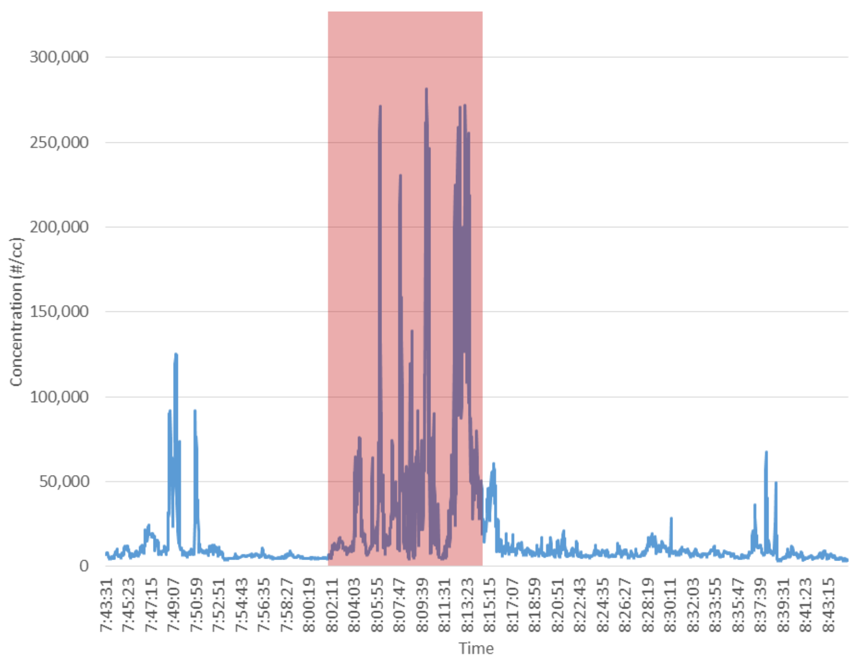


Figure 15. Particle number concentrations (for particles 0.01 to > 1 µm) measured at the fire ground (south of Engine 1) on 6/30/2015. Red shading represents the period between structure fire ignition and suppression/start of overhaul.

IV.B.4. Turnout gear surface contamination

Tables 11 and 12 present the wipe sampling results collected from the surface of turnout gear worn by firefighters assigned to search during two scenarios. PAHs measured from the firefighter's "green" turnout jacket during his/her first scenario are intended to show the change in contamination from pre-fire (baseline) to post-fire to post-decontamination, where wet-detergent decontamination was employed.

Table 11. Surface contamination levels (ng/100 cm^2) of total PAHs measured from "green" turnout jacket worn by search during the team's first scenario on 6/22/2015

Pre-fire	Post-fire	Post-decon
< 300*	3,800†	< 300*

** Based on limit of detection for fluoranthene.*
† Sum of 15 PAHs; PAH measurements below their limit of detection were assigned zero values.

As expected, we see a marked increase in total PAHs post-fire, with a subsequent reduction post-decontamination. Flame retardants measured from the firefighter's "red" turnout jacket and glove after his/her last scenario are intended to show accumulation of the persistent chemicals over 4 scenarios, where no decontamination was employed. Several flame retardants were detected on the jacket and glove. Once we have all of the data, not only can we assess accumulation of PAHs, flame retardants, and other contaminants over time (red group data), but we can also further assess the effectiveness of decontamination at reducing that accumulation (green group data).

Table 12. Surface contamination levels (ng/100 cm^2) of flame retardants from "red" turnout gear worn by search during the team's last scenario on 6/30/2015.

Compound Measured	Post-fire (jacket)*	Post fire (glove)
BDE 47	48	35
BDE 85	< 1	< 1
BDE 99	< 1	40
BDE 100	< 1	12
BDE 153	< 1	< 1
BDE 154	< 1	< 1
BDE 183	< 1	< 1
BDE 206	< 1	< 1
BDE 209	1,200	1,200
TBBPA	< 1	30
TBB	22	30
TBPH	11	14
DBDPE	140	290
TCEP	5.5	< 1.5
TCPP	< 1.5	200
TDCPP	190	460
TPP	2	3,100
TCP	< 0.2	360

** Quality control samples were 60–80% less than expected, so measurements may be underestimated.*

IV.B.5. Off-gassing of turnout gear

Table 13 provides the VOC air concentrations measured off-gassing from turnout gear during the first scenario for Group C while Table 14 provides the off-gas concentrations of HCN during the first and last scenarios for Group C. As expected, the levels of VOCs and HCN increased post-fire, with a subsequent decrease post-decon. These results suggest that firefighters could be exposed to these compounds during the ride back to the station after firefighting. However, the post-fire concentrations (measured in ppb) were well below applicable OELs (provided in ppm, Table 9). Because the compounds we measured are volatile, they are expected to evaporate from clothing within an hour. Nearly an hour passed between doffing and decontamination of gear. This probably explains why the post-decon measurements were comparable between the green (decon) and red (no decon) groups. It also explains why the HCN off-gas concentrations did not appear to increase with consecutive use over time (as evidenced by comparison between last scenario "red" pre-fire measurements and first scenario pre-fire measurements).

Table 13. Air concentrations of VOCs (ppb) measured off-gassing from green (wet decon) and red (no decon) gear pre-fire, post-fire, and post-decon during the first scenario (6/22/2015) for Group C.

Compound Measured	Green (wet decon)			Red (no decon/control)		
	Pre-fire	Post-fire*	Post-decon	Pre-fire	Post-fire*	Post-decon
Benzene	< 0.6	75	< 0.6	< 0.6	66	0.84
Toluene	< 0.5	19	< 0.5	< 0.5	16	< 0.5
Ethyl benzene	< 0.4	3.3	< 0.4	< 0.4	2.8	< 0.4
Xylenes	< 0.4	2.2	< 0.4	< 0.4	2.1	< 0.4
Styrene†	< 0.4	120	0.42	< 0.4	98	0.95

** Quality control samples were 50% less than expected, so measurements may be underestimated.*
† Results based on calibration curve for toluene.

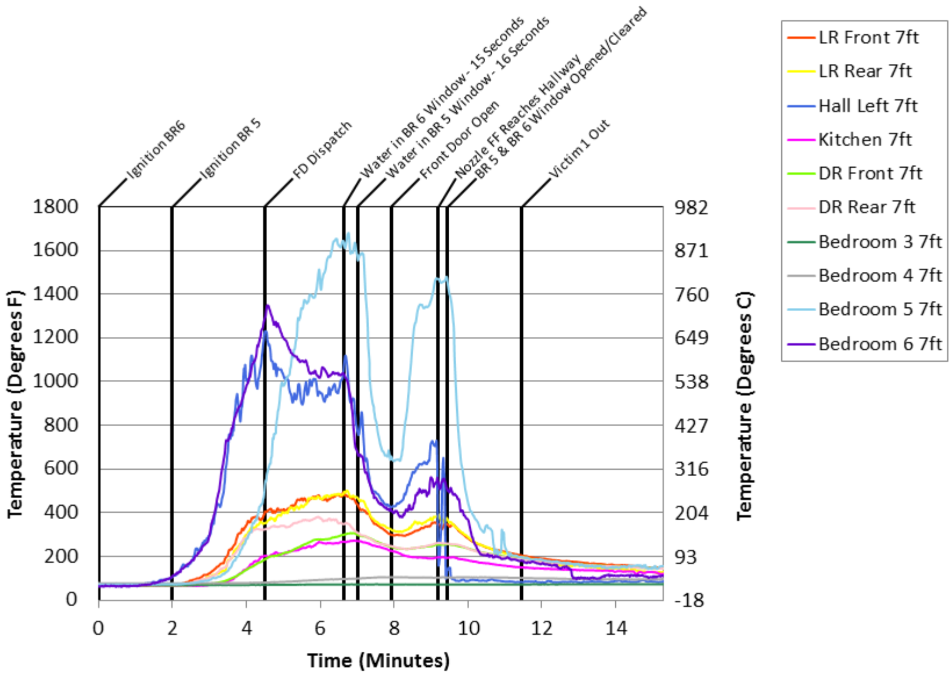
Table 14. Air concentrations of HCN (ppb) measured off-gassing from green (wet decon) and red (no decon) gear pre-fire, post-fire, and post-decon during first and last scenarios for Group C.

Scenario	Green (wet decon)			Red (no decon/control)		
	Pre-fire	Post-fire	Post-decon	Pre-fire	Post-fire	Post-decon
First (6/22/2015)	< 20	140	71	42	130	49
Last (6/30/2015)	< 20	120	< 20	< 20	120	< 20

IV.C. Preliminary Fire Dynamics Data

IV.C.1. Building Temperature profiles

Figure 16 provides the gas temperatures at each of the 10 different measurement locations at the ceiling (7 ft) and at the crawling level of a typical firefighter or trapped occupant (3 ft) for one scenario. In this scenario, firefighters initially applied water to the fire rooms from the exterior for a short period of time (~15 seconds per room) and then transitioned to the interior of the structure to complete suppression. Each fire room transitioned to flashover prior to firefighter intervention, yet temperatures in both rooms were quickly reduced upon application of approximately 35 gallons of water per room (on average). However, it is also apparent that in the time these firefighters transitioned back to the interior of the structure, the fire began to regrow and again flashed over in Bedroom 5. Each of the 6 different firefighting teams that conducted Interior and Transitional approaches had slightly different style and duration of water application, resulting in slightly different fire response and exposure conditions. However, these scenarios represent a wide range of typical conditions that would be experienced on the fireground for some of the most realistic fireground fire dynamics data sets currently available.



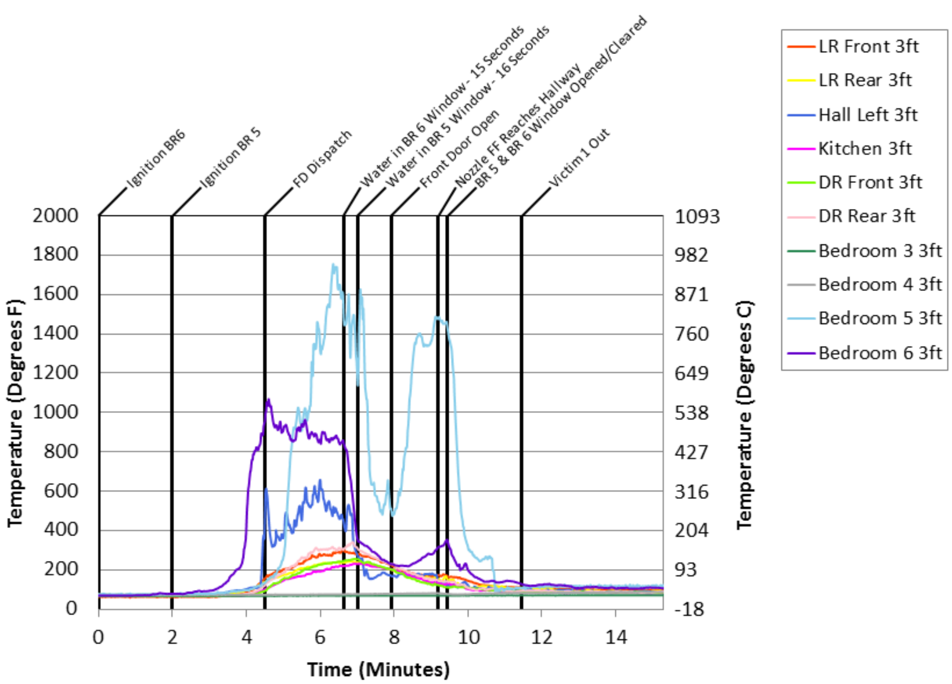


Figure 16. Building gas temperatures at each of the measurement locations of the structure (LR = Living Room, DR = Dining Room) for an example transitional attack scenario (06/14/2015).

IV.C.2.Heat flux in hallway connecting fire rooms

Hallway heat flux data from this same scenario is shown in Figure 17. Data from 3 different heights in the hallway provides an indication of the heat flux that might be experienced by a victim attempting to self-evacuate prior to firefighter intervention (i.e. 1-3 ft data prior to 8 minutes) and the heat flux firefighting PPE would be exposed to while making the hallway either standing (5 ft) or crawling (3 ft). One interesting observation from this data is that upon application of water into the Bedroom 5 and 6—which were immediately adjacent to this hallway, with doors open—there is no apparent increase in heat flux in the hallway.

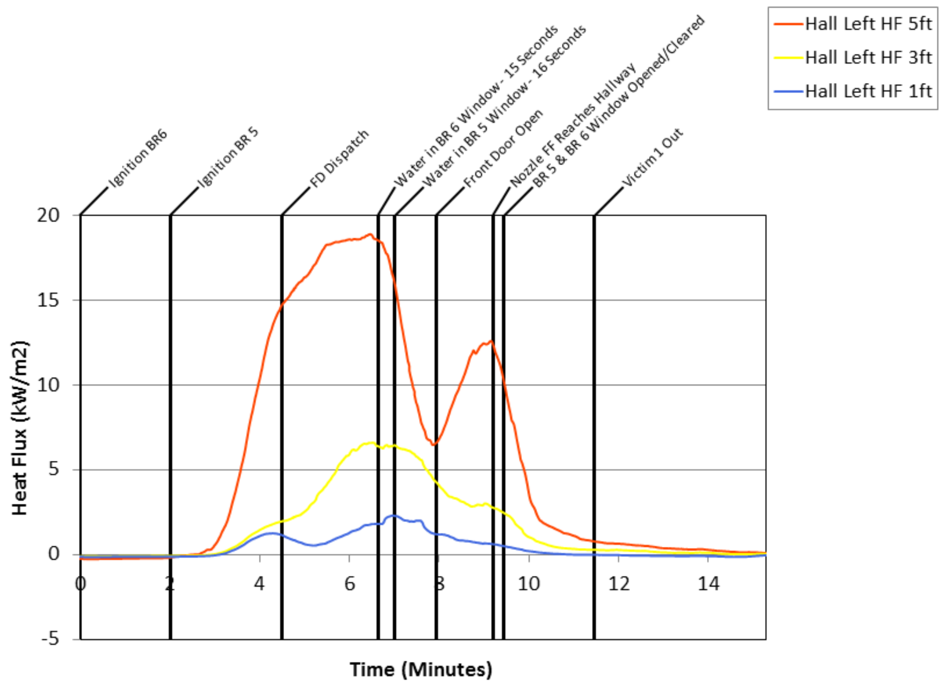


Figure 17. Heat flux measurements from the hallway immediately adjacent to the fire rooms (BR 5 and 6) with open doorways for an example transitional attack scenario (06/14/2015).

IV.C.3. Gas concentrations

Gas concentrations from the hallways and closed bedrooms from the same scenario are presented in Figure 18. These data provide important information regarding the toxic gas concentrations in survivable rooms as well as conditions in rooms through which victims might be evacuated from the structure. Behind closed bedroom doors, the conditions remained relatively stable until the bedroom doors were open. However, even after the fire was largely suppressed (Figure 16), oxygen concentrations were low and CO concentrations elevated in the hallway outside of the closed bedroom, even as the first victim was being removed from the structure.

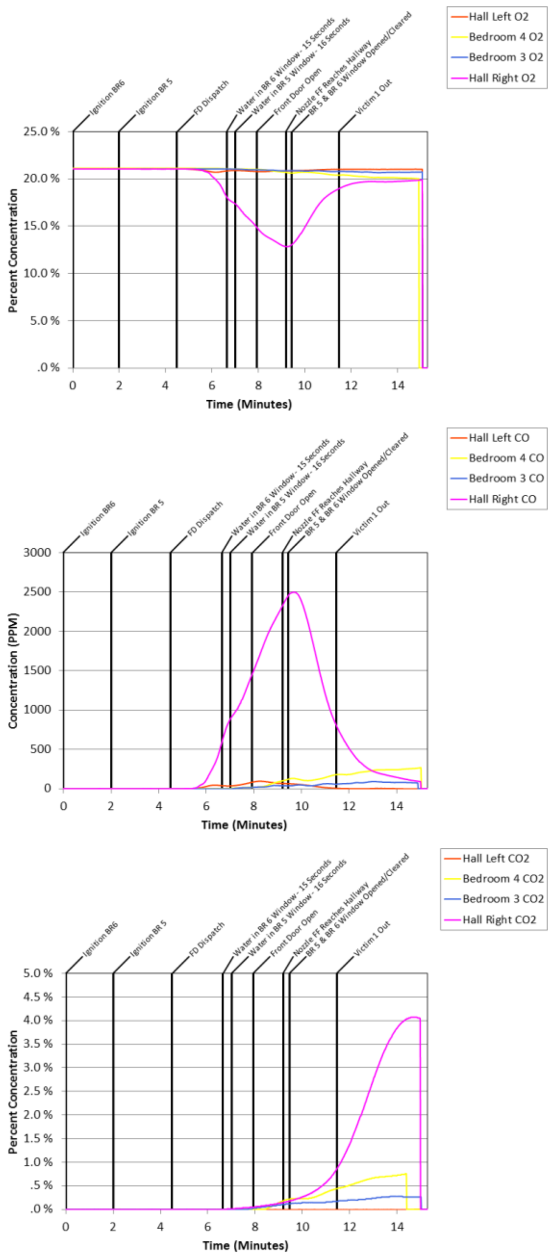


Figure 18. Gas concentrations from closed bedrooms and hallway locations, including (top) oxygen, (middle) carbon monoxide and (bottom) carbon dioxide (06/14/2015).

IV.C.4. Firefighter Temperature Exposure Data

Figure 19 provides the helmet mounted temperature sensors on the nozzle firefighter and lead search team member from the same scenario as above. In these plots, the orange data provides the gas temperature in which the firefighters were operating.

This data set provides the first measurement of thermal exposure to firefighters operating in a structure with typical room and contents fires. This information is valuable to understand the external thermal conditions as they compound heat stress and risk for compromised PPE. As the nozzle firefighter was operating much closer to the fire, his/her thermal exposure was much more severe than the search team even though they were both operating on the interior of the structure. Comparisons between thermal exposures for interior and transitional attack tactics on the nozzle firefighter will be completed in the near future.

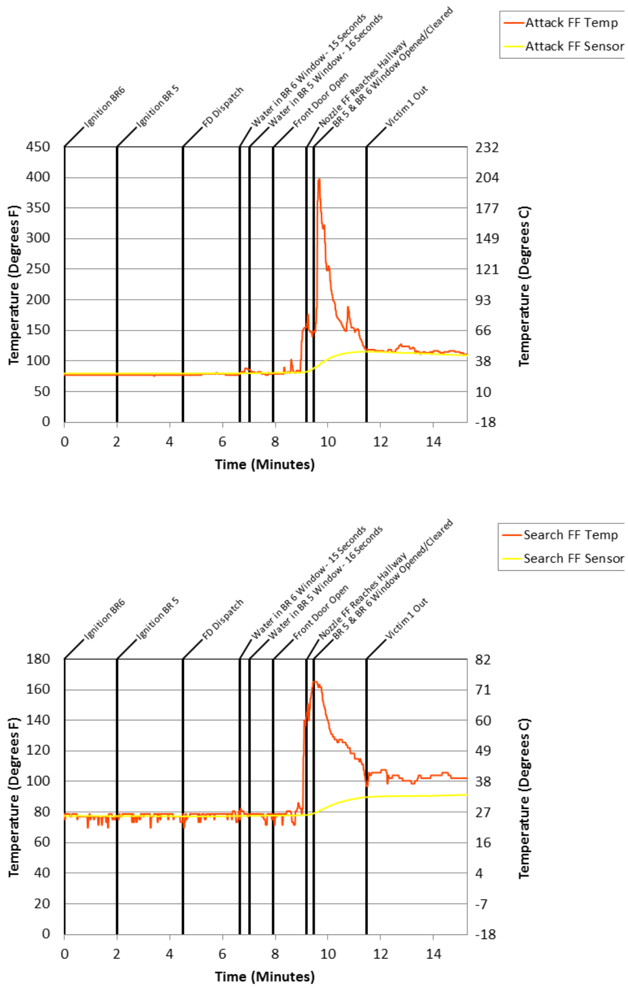


Figure 19. Helmet mounted temperature measurements collected from (top) nozzle firefighter on the attack team and (bottom) lead search team member (06/14/2015). The orange line is the gas temperature in the vicinity of the firefighter, while the yellow line is the internal sensor temperature (can be ignored for now).

IV.C.5. Simulated Occupant Exposure Data

Figure 20 includes the temperature profile from the portable sensors located on the simulated occupants (mannequins). These sensors were incorporated after the first scenario, so this data is provided from Day 2.

The simulated occupant (instrumented mannequin) behind a closed bedroom door but closer to the fire was exposed to much lower temperatures and gas concentrations than the other simulated occupant that was remote from the fire but not protected by a closed door.

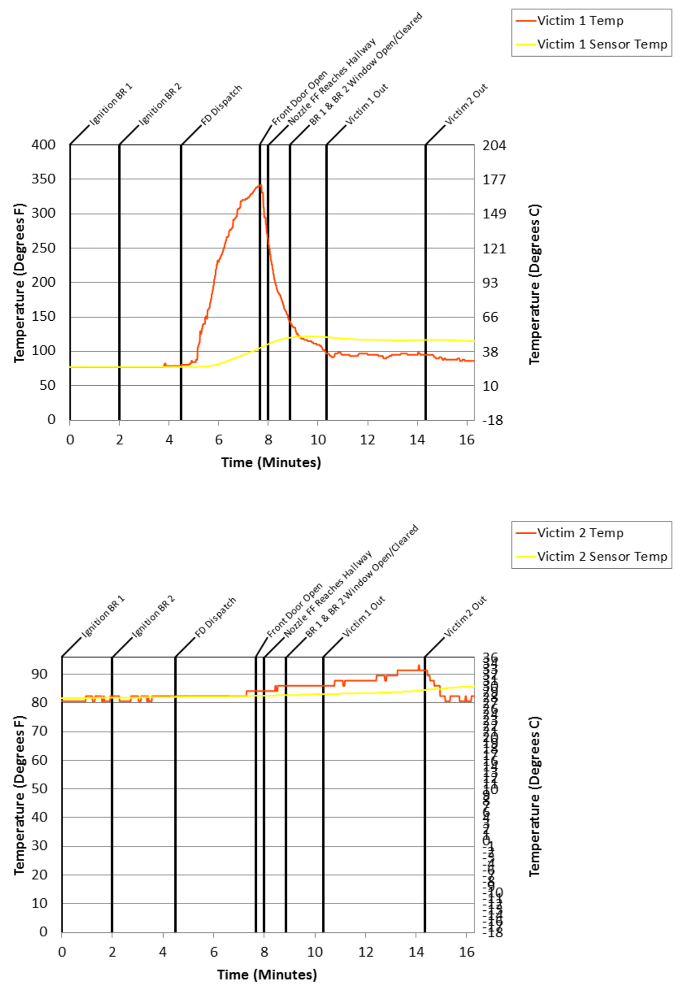


Figure 20. Mannequin temperature measurements collected from (top) outside Bedroom 4 and (bottom) inside Bedroom 3 (06/15/2015). The orange line is the gas temperature around the victim, while the yellow line is the internal sensor temperature (can be ignored for now).

V. Next Steps

The results presented in this interim report are only a snapshot of what has been collected and is currently being analyzed. For example, we did not present any of the personal exposure (air and dermal wipe) or biomarker (urine, blood, and breath) results. Many of the results presented herein are only from one or two days of the 12-day study. All results will need to be analyzed together to determine the statistical significance of our findings. The study design should allow us to answer the following questions:

V.I. Cardiovascular Strain

1) How are coagulatory and ECG responses affected by firefighting tactic and job assignment?

2) What is the variability in coagulatory and ECG changes? Do detrimental changes in these variables tend to occur in the same individual? That is, is a vulnerable individual likely to experience a change in both of these variables, or are they distinct phenomenon?
3) Is the magnitude of disruption affected by changes in core temperature?
4) What is the timecourse of recovery for changes in coagulatory measures and ECG variables?

V.II. Exposure Assessment

1) Are external exposure levels (air and dermal wipe) correlated with biomarker levels (urine, blood, and breath)?
2) What are the primary factors associated with the external exposure and biomarker levels?

   a. Possible factors to be investigated include: assignment, response tactic, use of SCBA, time in smoke plume, cleaning neck skin and wearing decontaminated turnout gear and laundered hoods.

3) What is the efficacy of using baby wipes to clean neck skin?

4) What are the composition and magnitude of the airborne particles, gases and vapors produced during the fires?
   a. What are the air concentrations inside the building during fire and overhaul?
   b. What are the personal air concentrations for each firefighter and how do those levels vary by position and tactic?
   c. What are the air concentrations in the fire ground and how do those levels vary by environmental conditions?
   d. How do the air concentrations compare to applicable OELs.

5) What are the composition and magnitude of contaminants depositing on and off-gassing from turnout gear?
   a. How do the contamination levels vary by position and tactic?
   b. How much contamination accumulates from repeated use of turnout gear?

6) What is the efficacy of field decontamination of turnout gear (based on surface contamination and off-gas measurements)?
   a. How do the three decontamination methods compare?

b. What is the efficacy of field decontamination over repeated use of turnout gear?

V.III. Fire Dynamics

1) Under which variables might a transitional attack be considered advantageous versus an interior attack in terms of:
    a. Victim exposure risk
    b. Firefighter health and safety
2) What is the impact of different scenario timing (based on differences in firefighter responses) to a similar controlled fire scenario?
    a. Impact on thermal/gas concentration conditions in structure
    b. Subsequent impact on chemical and cardiovascular exposure/risk
3) How do the tactical choices made by the fire service impact exposures for the victims being rescued?
4) What is the best way to train firefighters when it is not possible to create a "realistic" fire environment during training?

V.IV. Firefighter toolkit

The project team will design and develop an interactive online training program with the fire service advisory panel. The course will contain data, pictures, video and professional narration and allow firefighters of all levels to navigate through the course at their own speed. This program will include results from this study and present them in a way that important lessons learned will be shared with the fire service community.

VI. Interim Recommendations

Although we have not yet performed an in depth analysis of the results, there are actions that the fire service can take now to better protect firefighters from chemical exposures, heat stress, and other stressors and lessen their risk of cardiovascular disease, cancer, and other illnesses or injuries.

VI.I. Cardiovascular Risk

To minimize cardiovascular strain associated with fire response and decrease the risk of a sudden cardiac event:

- Ensure that all firefighters have received a proper medical evaluation consistent with NFPA 1582 guidelines and performed by a physician familiar with the physiological demands of firefighting; and that cardiovascular risk factors, if present, are being aggressively treated.
- Utilize incident scene rehabilitation to provide rest, hydration and cooling; and medically monitor firefighters for signs and symptoms of heat-related illness or cardiovascular events.
- Ensure that all firefighters are physically fit so that they can meet the physical demands of the job and so that they can do so with lower risk of cardiovascular events.

VI.II. Chemical Exposures

To minimize inhalation of contaminants during a fire response:

- Wear SCBA during knockdown, overhaul, and other firefighting activities where exposure to combustion byproducts is likely. This includes when walking through the smoke plume during the sizing up of the fire or when making openings to ventilate the structure.
- Remain upwind of fires if not directly involved in the fire attack. If this cannot be accomplished, SCBA should be worn. Fire personnel should also remain upwind of diesel exhaust emitted from the apparatus.

To minimize inhalation of contaminants off-gassing from contaminated gear:

- Doff gear before entering the rehab area.
- Do not store or wear contaminated turnout gear inside the apparatus during the ride back to the station.
- Do not store gear in personal vehicles or living areas.

To minimize skin absorption of contaminants during (or after) a fire response:

- Decontaminate and/or launder turnout gear, fire hoods, and other equipment that readily contact the skin after each fire response. Do not take gear or other equipment home.
- Wash hands and neck skin immediately and shower as soon as possible after a fire response. Data acquired in this study will help us determine the cleaning efficiency of commercial baby wipes, which can be used in the field to quickly clean skin.

VI.III. Fire Dynamics

- Apply water to the fire rapidly. Conditions improved throughout the structure after application regardless of where the water was from.
- Train on coordinated attack for successful response. From time of dispatch to water on the fire, front door forced open, victim 1 removal, victim 2 removal and attack team into the fire rooms varied widely amongst the crews. For example, the time to get both victims out of the house varied from 6:02 to 11:42.
- Stress the importance of closed doors to the public and firefighters. The simulated occupant behind a closed bedroom door but closer to the fire was exposed to much lower temperatures and gas concentrations than the simulated occupant remote from the fire but not protected by a closed door.

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